NAVAL ELECTRICIANS' TEXT BOOK

VOLUME I
THEORETICAL

BY

CAPTAIN W. H. G. BULLARD, U. S. N.
Superintendent U. S. Naval Radio Service

REVISED BY

COMMANDER J. T. TOMPKINS, U. S. N.
Head of Department of Electrical Engineering and Physics, U. S. Naval Academy

ASSISTED BY

LIEUT. COMMANDER AMON BRONSON, U. S. N.

AND

PROFESSOR L. A. DOGGETT, M. E. E.
Of the Postgraduate Department, U. S. Naval Academy

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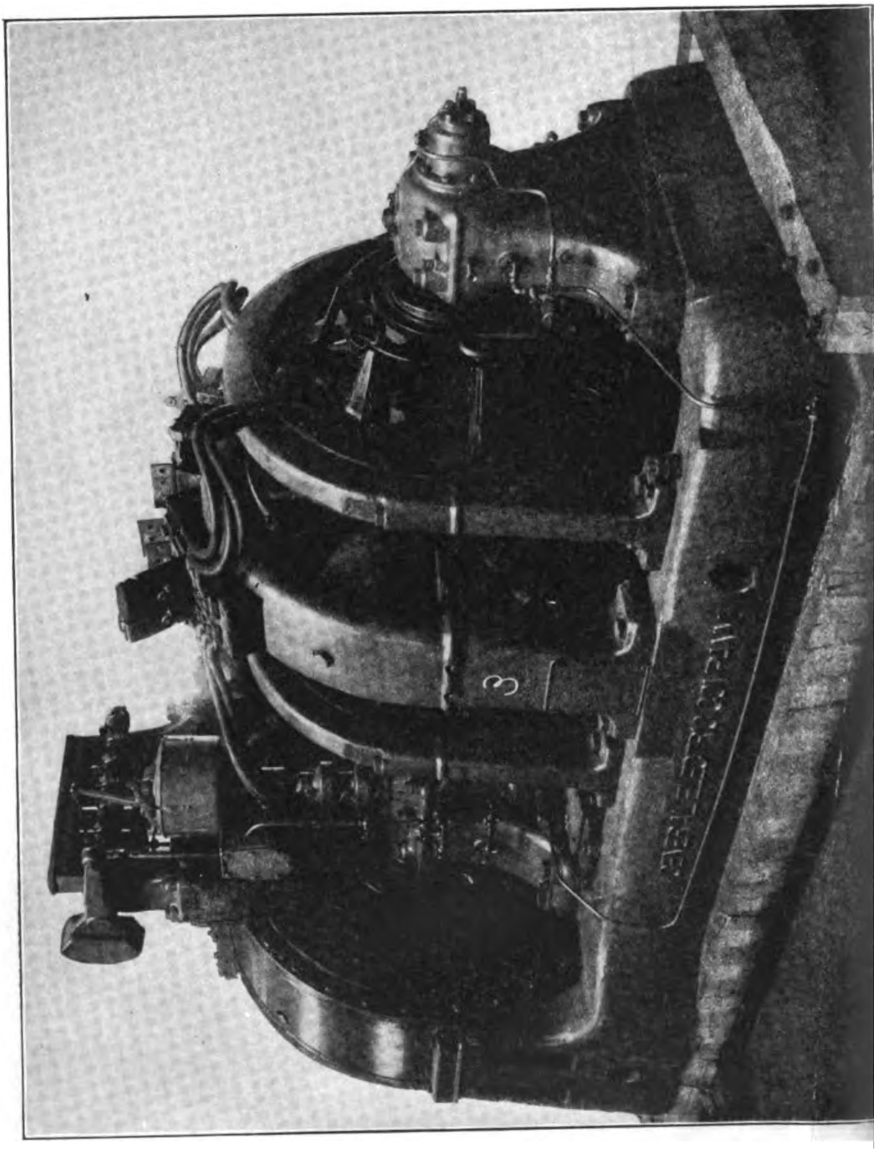

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PREFACE TO FIRST EDITION

This book is a revised and enlarged edition of the Naval Electricians' Text and Hand Book. Many new chapters have been added to the original manuscript and all have been more or less rewritten and to such an extent that it has lost its hand-book characteristics. As stated in the first edition, there is probably little or nothing contained in it that cannot be found elsewhere, but an attempt has been made to collect complete information concerning the principles and uses of electricity as applied to our ships of war.

It is primarily intended for use as a text book by midshipmen at the Naval Academy, but officers and the enlisted personnel and electricians should find it a fairly complete treatise on electricity as far as it relates to the subject of our warship installation.

It would be difficult to give credit to all those who have made suggestions for improvement of the book, but special mention should be made of the officials of the General Electric Company who have contributed many illustrations of the appliances made by them and furnished much valuable manuscript. Due credit has been given to other manufacturers and to those who have allowed the results of their experiments to be used.

W. H. G. Bullard,
Lieut. Commander U. S. Navy.

PREFACE TO SECOND EDITION

The first edition of the Naval Electricians' Text Book was published in one volume. In an endeavor to bring the subject matter up to date and to keep pace with a constantly increasing installation of electrical material and apparatus in our ships of war, as well as to make it a complete text book covering all electrical principles concerned, the manuscript has grown beyond the proper proportions for a single volume. The present edition has accordingly been made up in two volumes, in one of which the purely theoretical matter has been placed, and in the other, descriptive matter of material, apparatus, methods of control, etc. The division is somewhat arbitrary, but the aim has been to keep the theoretical matter separated from the practical as far as possible.

Much new matter has been added, and while it is impossible to furnish descriptions of every piece of electrical apparatus that is installed on our ships of war, enough typical equipments have been described to illustrate the general subject and to show the electrical principles involved.

The compiler wishes to take this opportunity to express his appreciation of suggestions by many officers of the service, and particularly the assistants in the Department of Electrical Engineering, leading to changes and improvement in the manuscript, and of the courtesies extended to him by manufacturers of electrical apparatus, particularly the officials of the General Electric Company, the Cutler Hammer Electric Manufacturing Company, the Diehl Electric Manufacturing Company, the Walker Electric Company, the Holtzer Cabot Electric Company, the Cutter Electrical Company, the Sangamo Electric Company, the Reliance Electric Engineering Company and Chas. Cory & Son, all of whom have freely furnished much valuable information and data.

W. H. G. Bullard,
Commander U. S. Navy.

July 1, 1911.

PREFACE TO THIRD EDITION

VOLUME I

The second edition of the Naval Electricians' Text Book having been exhausted, it was desired to revise the book before issuing another edition. Captain W. H. G. Bullard, U. S. N., the author, was unable to undertake this revision for the reason that his important duties as Superintendent U. S. Naval Radio Service required his undivided attention.

At the request of the U. S. Naval Institute and Captain Bullard this revision was made by the undersigned with the assistance of Lieutenant Commander Amon Bronson, U. S. N., who prepared the manuscript for Chapters X, XI, XII, XIII and XIV, and Professor L. A. Doggett who revised Chapters XVIII, XXI, XXII, XXIII and XXIV and prepared the manuscript for Chapter XVI.

The first volume has been thoroughly revised and many new chapters and numerous illustrations have been added. This was found to be desirable on account of the changes in the course of electrical engineering at the U. S. Naval Academy, due to the recent developments in the service. The order of treatment of the various subjects, as given in the second edition, has been followed as nearly as possible. An attempt has been made to present the fundamental principles in various ways and illustrate them by the solution of numerous examples in order that the work of the student might be made easier. In preparing this volume the requirements of the student officers of the postgraduate department were duly considered. In the preparation of this volume much assistance was received through suggestions from the assistants in the Department of Electrical Engineering and Physics and especially from Professor of Mathematics, G. K. Calhoun, U. S. N., who also prepared several problems and sketches and assisted in the correction of proof. The work of Professor C. L. Dawes, of Harvard University, in criticising the rough manuscripts and assisting in the preparation of several chapters in the latter part of the book, is greatly appreciated. The chapter on Storage Batteries was greatly enlarged, and thanks are due to Mr. A. V. Morris, of The Electric Storage Battery Company, for valuable assistance in criticising the galley proofs and supplying cuts and valuable data, and to Mr. M. R. Hutchinson, of the Edison Storage Battery Company, who kindly supplied the manuscript referring to the Edison Storage Battery. The American Institute of Electrical Engineers kindly permitted the use of its publications in compiling information in regard to standard definitions and classification of electric machines. The following manufacturers supplied valuable data and assisted in various ways: The General Electric Company, The Westinghouse Electric Manufacturing Company, The Holtzer Cabot Electric Company, The Wireless Improvement Company, The Wireless Specialty Company, The De Forest Radio Telephone and Telegraph Company, The National Electric Signaling Company, The Federal Telegraph Company.

The following standard text books and reference books used in the Department of Electrical Engineering and Physics were frequently consulted in connection with the revision, and it is desired to express appreciation for the assistance derived from these sources: Elements of Electrical Engineering by Franklin and Esty, Electrical Engineering by Christie, Experimental Electrical Engineering by Karapetoff, The Standard Hand Book for Electrical Engineers, Electricity and Magnetism by Brooks and Poyser, Dynamo Electric Machinery by S. P. Thompson, Dynamo Electric Machinery by Sheldon and Hausmann, Publications of the Westinghouse Electric Manufacturing Company and of the General Electric Company, Manual of Wireless Telegraphy (Radio) by Captain S. S. Robinson, U. S. N., and Principles of Wireless Telegraphy by Pierce.

The compiler wishes particularly to thank Gunner R. O. Williams, U. S. N., for valuable assistance rendered in many ways, and Chief Electrician A. W. Warren, U. S. N., whose assistance in the preparation of the chapters on Radio is greatly appreciated.

J. T. TOMPKINS,
Commander U. S. Navy.

NOVEMBER 15, 1914.

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SYMBOLS AND ABBREVIATIONS*

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Electromotive force, abbreviated E. M. F.	E, e	volt	....
Potential difference, abbreviated P. D.	V,v or E,e	"	....
Voltage	E,e or V,v	"	....
Current	I, i	ampere	....
Quantity of electricity	Q, q	coulomb or ampere-hour	....
Power	P, p	watt	....
Electrostatic flux	Ψ	....	....
Electrostatic flux density	D	....	....
Electrostatic field intensity	F	....	....
Magnetic flux	Φ, ϕ	maxwell †	....
Magnetic flux density	B, $\mathfrak{B}$	gauss †	....
Magnetic field intensity	H, $\mathfrak{H}$	gilbert per centimeter or gauss	gilbert per cm.
Magnetomotive force, abbreviated M. M. F.	$\mathfrak{F}$	gilbert †	....
Intensity of magnetization	J	....	....
Susceptibility	$\kappa = J/H$	....	....
Permeability	$\mu = B/H$	....	....
Resistance	R, r	ohm	....
Reactance	X, x	"	....
Impedance	Z, z	"	....
Conductance	g	mho	....
Susceptance	b	"	....
Admittance	Y, y	"	....
Resistivity	ρ	‡ ohm-centimeter	ohm-cm.
Conductivity	γ	‡ mho per centimeter	mho per cm.
Dielectric con[illegible]t	[illegible] or k	....	....

* Standar[illegible] Ru[illegible] American Institute of Electrical Engineers.

† An add[illegible] F. is the "amp[illegible]-turn"; for flux, the "line"; [illegible] y, "maxwel[illegible] in."

‡ [illegible] of these q[illegible] re *ohms resistance* [illegible] two oppo[illegible] a cm. cube of the [illegible] rrect na[illegible] iven, not ohms and [illegible] y stated.

SYMBOLS AND ABBREVIATIONS*

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Power	P, p	watt	....
Electrostatic flux	Ψ	....	....
Electrostatic flux density	D	....	....
Electrostatic field intensity	F	....	....
Magnetic flux	Φ, ϕ	maxwell †	....
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Conductance	g	mho	....
Susceptance	b	"	....
Admittance	Y, y	"	....
Resistivity	ρ	‡ ohm-centimeter	ohm-cm.
Conductivity	γ	‡ mho per centimeter	mho per cm.
Dielectric constant	ϵ or k	....	....

* Standardization Rules of the American Institute of Electrical Engineers.

† An additional unit for M. M. F. is the "ampere-turn"; for flux, the "line"; for magnetic flux-density, "maxwells per sq. in."

‡ NOTE.—The numerical values of these quantities are *ohms resistance* and *mhos conductance* between two opposite faces of a cm. cube of the material in question, but the correct names are as given, not ohms and mhos per cm. cube as commonly stated.

Name of Quantity.	Symbol for the Quantity.	Unit.	Abbreviation for the Unit.
Reluctance	$\mathcal{R}$	....	....
Capacitance (Electrostatic capacity)	C	farad	....
Inductance (or coefficient of self-induction)	L	henry	....
Mutual inductance (or coefficient of mutual induction)	M	henry	....
Phase displacement	θ, ϕ	degree or radian	deg.
Frequency	f	cycle per second	~
Angular velocity	ω	radians per second	....
Velocity of rotation.......	n	revolutions per second	rev. per sec.
Number of conductors or turns	N	convolutions or turns of wire	....
Temperature	T, t, θ	degree centigrade	deg. cent.
Energy in general........	U or W	joule or watt-hour	....
Mechanical work	W or A	joule or watt-hour	....
Efficiency	η	per cent	....
Length	l	centimeter	cm.
Mass	m	gram	g.
Time	t	second	sec.
Acceleration due to gravity	g	centimeters per second per second	cm. per sec. per sec.
Standard acceleration due to gravity (at about 45° latitude and sea level) equals 980.665 *	g_0	centimeters per second per second	cm. per per sec. per sec.

* This has been the accepted standard value for many years and was formerly considered to correspond accurately to 45° latitude and sea level. Later researches, however, have shown that the most reliable value for 45° and sea level is slightly different; but this does not affect the standard value given above.

CHAPTER I.

DERIVATION AND DEFINITION OF UNITS.

All units used in the science of electricity are based on the units of the metric system, a system in which certain standards are adopted for measuring the three fundamental quantities of **length, mass** and **time.**

Standards of the Metric System.

Length.—The unit of length in the metric system is a **meter** and was originally intended to be the one ten-millionth part of the distance from the earth's equator to the pole measured over the surface of the earth along the meridian passing through Paris. The present standard of length is the International Meter, and is the distance at 0° C. between the ends of a platinum rod preserved in the Archives of the French Capital. This distance is slightly less than that originally intended, as the earth's quadrant is now found to measure 10,000,880 meters. Two copies of this meter, called the "National Prototypes," are kept at the Bureau of Standards in Washington. The meter is the fundamental standard of length for the United States, the yard being defined by law as $\frac{3600}{3937}$ meters.

Each meter is equal to 10 decimeters, or
100 centimeters, or
1000 millimeters,
and 1000 meters make a kilometer.

A meter is 39.37 inches, or 3.28 feet.

A decimeter is very nearly 4 inches (3.937 inches).

A millimeter is very nearly equal to $\frac{1}{25}$ of an inch.

The kilometer is about $\frac{5}{8}$ of a mile, or 1093.6 yards.

Mass.—The unit of mass is the kilogram, and is equal to the mass of the standard kilogram, a piece of platinum preserved with the standard meter in the Archives at Paris. It was intended to have the same mass as a cubic decimeter of water at its temperature of maximum density, 3.9° C. Although a more exact determination has shown that this relation is not absolutely accurate; for all practical purposes, the mass of one cubic centimeter of distilled water at its maximum density may be considered equal to one gram. Two copies of this standard kilogram called the "national prototypes" are kept at the Bureau of Standards in Washington. The kilogram is the fundamental standard for the United States, the pound being defined by law as $\frac{1}{2.2046}$ kilogram.

Time.—The unit of time is the **second**, and is the $\frac{1}{86400}$th part of a mean solar day.

C. G. S. (Centimeter, Gram, Second) System.

In the C. G. S. system, the **centimeter,** $\frac{1}{100}$th part of a meter is taken as the unit of length; the **gram,** $\frac{1}{1000}$th part of a kilogram is taken as the unit of mass and the **second** is taken as the unit of time.

Derived Units of the C. G. S. System.—There are certain units derived from the three fundamental units, such as *area, volume, velocity, acceleration, force, work, power,* and *heat.* In order that the definitions of the electrical units may be understood, it is first necessary to define these units.

Area.—The unit of area is the square of the unit of length, or *square centimeter.*

Volume.—The unit of volume is the cube of the unit of length, or *cubic centimeter.*

Velocity.—The unit of velocity is the velocity of a body that moves through unit length in unit time, or it is a velocity of *one centimeter per second.* It is called the **kine.***

Acceleration.—The unit of acceleration is the acceleration which gives unit velocity change in unit time, or an acceleration of *one centimeter per second.*^{2} It is called the **spoud.***

* The names "kine" and "spoud" are rarely used. Per second^2 signifies per second per second.

Acceleration is the rate of change of velocity. If at a certain instant a moving body has a velocity V, and at the end of a given interval t, its velocity has increased uniformly to V', its change of velocity has been $V' - V$, and the acceleration or rate of change of velocity is

$$a = \frac{V' - V}{t}.$$

One of the most common examples of acceleration is that due to the attraction of the earth, and bodies falling freely under the action of gravity have an acceleration of 32.2 feet per second.^{2} This means that at the end of each second, its velocity is 32.2 feet per second greater than the velocity at the beginning of the second.

A body falling from rest will fall 16.1 feet in the first second, as its acceleration is 32.2 feet per second.^{2} Its velocity at the end of the second is 32.2 feet per second, since $V = at$ and $t = 1$. The average velocity then is

$$V = \frac{0 + 32.2}{2} = 16.1 \text{ feet},$$

and the distance fallen is the time multiplied by the average velocity, or

$$l = Vt = 16.1 \times 1 = 16.1 \text{ feet}.$$

At the end of the second second, its velocity has been increased by 32.2 feet, or it is now $32.2 + 32.2 = 64.4$ feet, and the average velocity in the second second is

$$V = \frac{32.2 + 64.4}{2} = 48.3 \text{ feet},$$

and the distance fallen in the second second is

$$l = Vt = 48.3 \text{ feet}.$$

At the end of the third second, its velocity has been increased by 32.2 feet, or it is now $64.4 + 32.2 = 96.6$ feet, and the average velocity in the third second is

$$V = \frac{64.4 + 96.6}{2} = 80.5 \text{ feet},$$

and the distance fallen in the third second is

$$l = Vt = 80.5 \text{ feet}.$$

The total distance fallen in three seconds is

$$16.1+48.3+80.5=144.9 \text{ feet.}$$

This is also derived as follows:

$$V'-V=at \text{ and } l=\left(\frac{V'+V}{2}\right)t,$$

or eliminating V',

$$l=Vt+\tfrac{1}{2}at^2$$

in starting from rest $V=0$, or

$$l=\tfrac{1}{2}at^2,$$

and in the case above

$$l=\tfrac{1}{2}\times 32.2\times 3^2=144.9 \text{ feet.}$$

Examples of Acceleration.

1. A body travels at the rate of 12 feet per second; in 10 seconds it is moving at the rate of 7 feet per second; what is the mean acceleration? *Ans.* **— ½ ft. per second.[2]**

2. A body starting from rest moves in the first second through a space of 16 feet and in the fourth second through 112 feet, what is the acceleration per second? How far does it move in the second second and the third second? *Ans.* **32 feet per second.[2]**
48 feet 2d second.
80 feet 3d second.

Force.—The unit of force is that force which acting for one second on a free gram mass, will impart to it a velocity of one centimeter per second. The unit of force is called the **dyne**.

Force is that which produces or tends to produce motion or change of motion. When force acts on a free mass at rest, it imparts to it a certain velocity. Unit force acting upon a unit mass for unit time imparts to it unit velocity or, in other words, unit force acting upon unit mass produces unit acceleration. Force, mass and acceleration in the C. G. S. system are thus connected by the equation

$$F=ma.$$

There are many kinds of force, such as mechanical, physical, electrical, gravitational, etc. It has already been shown how the earth's attraction, or force of gravity, acts to produce acceleration, and the force with which any body is held to the earth depends upon its mass and the local value of the acceleration due to gravity.

The acceleration of gravity varies slightly in different localities, but its average value may be assumed to be 981 centimeters per second^2 or 32.2 feet per second^2. This acceleration due to gravity is designated by the symbol "g." The force of gravity acting on a body is called the weight of the body. The weight of a gram mass is thus equal to 981 dynes and the weight of a kilogram equal to $1000 \times 981 = 981{,}000$ dynes.

The unit of force used by engineers and practical men in this country is called a "standard pound force" or simply "a pound force." A standard pound force may be defined as the force which is numerically equal to the force of gravitation acting on a 1-pound mass at a standard fixed locality. Careful experiments were made in the chosen locality for the determination of the value of g. The value thus obtained was about 980.6 centimeters or 32.17 feet, and this value was fixed by law.

Unless otherwise stipulated the words "pound force" or "pound weight" will refer to the standard invariable value fixed by law. In order to facilitate the solution of numerical examples the approximate values for g of 980 or 981 centimeters or 32 or 32.2 feet are often used.

It is thus seen that a pound force is numerically equal to a pound weight. Force, however, is a vector quantity and may act in any direction while weight acts only in the direction of gravity.

The magnitude of forces may be compared by ascertaining the relative accelerations imparted to the same mass. Let F and F' represent two forces and m the given mass, and then if a and a' represent respective accelerations produced, we have the following equation:

$$\frac{F}{F'} = \frac{a}{a'}, \quad \text{or } F = \frac{F'}{a'} \cdot a.$$

Now let F' represent the weight of the body then $a' = g$ the acceleration of gravity and the equation becomes $F = \frac{w}{g} \cdot a$ which may be called the fundamental equation of force and should be used for the solution of all problems relating to force. This will be illustrated by several typical numerical examples.

1. What force acting on a 5-pound mass will produce an acceleration of 64 feet per second?

$$F = \frac{w}{g} \cdot a,\ w = 5,\ g = 32,\ a = 64,\ F = ?.$$

Substitute

$$F = \frac{5}{32} \cdot 64 = 10 \text{ pounds.}$$

2. A 10-pound force acting on a certain mass produces an acceleration of 128 feet per second. What is the magnitude of the mass?

$$F = \frac{w}{g} \cdot a = 10 = \frac{w}{32} \cdot 128;$$

$$4w = 10,\ w = \frac{5}{2} \text{ pounds.} \quad \therefore m = \frac{5}{2} \text{ pounds.}$$

3. If a force 1960 dynes acts on a 3-gram mass, what acceleration will be produced, assuming the value of g to be 980 centimeters per second per second?

In the C. G. S. system the weight of a 1-gram mass is 980 dynes.

$$F = \frac{w}{g} \cdot a,\ 1960 = \frac{3 \times 980}{980} \cdot a,$$

$$a = \frac{1960}{3} = 653\tfrac{1}{3} \text{ centimeters per second per second.}$$

It will be noted that in the C. G. S. system $w = mg$ and substituting in the fundamental equation, we have $F = ma$. This equation is very frequently employed, but the former equation $F = \frac{w}{g}a$ is preferred, as it is derived directly from Newton's law and is applicable to any system of units.

In many text-books an absolute unit of force called "a poundal" is defined as that force which acting on a free pound mass for one second will impart to it a velocity of one foot per second. This unit is rarely if ever employed in practical calculations.

Examples of Force.

1. A constant force acting upon a mass of 30 grams causes it to move through 10 meters in 3 seconds starting from rest. What is the value of the force in dynes? *Ans.* $6666\tfrac{2}{3}$ dynes.

2. Express the weight of 10 kilos in dynes, and the value of a dyne in terms of a grams weight. $g = 981$ dynes. *Ans.* 9,810,000 dynes. $\frac{1}{981}$ gram.

3. A spring balance is carried in a balloon which is ascending vertically. What is the acceleration of the balloon when an 8-ounce weight hung upon the spring balance is found to indicate 9 ounces? $g = 32$.

***Ans.* 4 feet per second.[2]**

4. A body of mass 4 pounds is moving at the rate of 8 feet per second. At this instant a constant force begins to act upon it in the direction of its motion, and after 20 seconds its velocity has increased to 24 feet per second. Determine the magnitude of the force.

***Ans.* 0.1 pound.**

Work.—The unit of work is the work done in overcoming unit force through unit distance, or the work done in overcoming one dyne through one centimeter, or the work done by one dyne working through one centimeter. It is called the **erg**.

Work is done on a body when a force causes it to move or to change its direction of motion. A body does work when it overcomes an opposing force through a certain distance. Thus a locomotive drawing a train of cars does work against the friction of the rails, resistance of the air, etc. If the force producing the work is removed, if steam is cut off, the train will be brought to rest in a certain distance by the force due to the resistances that were previously overcome. It is necessary to produce motion in some direction for work to be done, however great a force may be applied. A locomotive may exert considerable force but unless the train or itself is moved, it does no work.

The practical unit of work is the foot-pound, which is the work done in raising one pound one foot against gravity, or in other words when a force of one pound acts through the space of one foot.

Energy.—Energy is the power of doing work. A body may have the power to do work, but yet be restrained from doing it. Thus a body held at a given distance from the earth's surface has the power of doing work and can do so if the restraining force holding it is removed. It may fall and do work, as in the case of the hammer of a pile-driver. This energy due to its position is called **potential energy.**

The measure of its potential energy is the amount of work expended in putting it in position. Thus, to raise a certain mass m to a certain height h, requires work equal to wh when w is the weight of the mass m. Its potential energy is therefore equal to wh.

If the body falls, the potential energy is converted into energy in motion, or **kinetic energy,** and when it reaches the ground from which it was removed, the kinetic energy will be just equal to its potential energy at its highest point and will be again equal to the work required to raise it.

At the moment of striking the ground, it has a velocity V and its kinetic energy at that instant equals $\frac{1}{2}\frac{w}{g}V^2$. This may be derived as follows:

It has been shown that in the case of a falling body, $h=\frac{1}{2}gt^2$ and that $V=gt$ at any time t. Potential energy at the highest point which is equivalent to the kinetic energy just before reaching the ground is wh.

Substituting the values of h and t obtained from the equations above we have

$$wh = w \times \frac{1}{2}g \cdot \frac{V^2}{g^2} = \frac{1}{2}\frac{w}{g}V^2.$$

That is kinetic energy of a moving body equals $\frac{1}{2}\frac{w}{g}V^2$. In the C. G. S. system since $w=mg$ this reduces to $\frac{1}{2}mV^2$.

Examples of Work and Energy.

1. A body of mass, 3 pounds is projected vertically upwards with a velocity of 640 feet per second; how much work has been done against gravity when it has ascended to half its maximum height?

***Ans.* 9600 foot-pounds.**

2. An engine is running at the rate of 80 feet per second on level ground, when steam is shut off. Assuming that the frictional resistances are equivalent to a weight of 14 pounds per long ton, how far will the engine run and for how long? ***Ans.* 16,000 feet.**
400 seconds.

3. A 4-ounce bullet is projected vertically upwards with a velocity of 800 feet per second. What is its potential energy when it has reached its maximum height? ***Ans.* 2500 foot-pounds.**

4. A hammer moving at the rate of 12 feet per second hits a nail and drives one inch of its length into a board. The mass of the hammer is half a pound. Assuming it to be inelastic, and to come to rest; find the average resistance it encountered. ***Ans.* 13½ pounds.**

Power.—Power is the rate of doing work. The unit of power is the *erg per second.* It is connected with the unit of work by the element of time. Two forces may do the same amount of work in different times, and the one that does it in the shorter time is said to be the more powerful, that is, it can do more work in a given interval of time than the less powerful. If an electric motor can turn a turret once completely around in 10 minutes, and another motor can turn the same turret once in five minutes, the second one does as much work as the first in one-half the time, and it has therefore twice the power, though they each do the same amount of actual work; they have overcome the same force through the same distance.

The unit of power in the C. G. S. system has no distinctive name, being called the *unit of activity,* or the erg per second.

The practical unit of power in the English system is the horse-power, equal to work done at the rate of 33,000 foot-pounds per minute, or 550 foot-pounds per second.

The practical unit of power in the C. G. S. system is the **watt,** which is the power developed when work is done at the rate of $(10)^7$ ergs per second. A horse-power is equal to 746 watts (nearly).

Examples of Power.

1. Find the horse-power, H. P., of an engine which will in 9 hours empty a vertical shaft of water, whose section is 9 square feet and depth 400 feet. Density of water = 62.5 pounds per cubic foot.

Ans. 2.525 H. P.

2. An engine takes a train of 60 tons in all up an incline of 1 in 100 at a maximum speed of 30 miles per hour and it can take a train of 150 tons on the level at the same speed. Find the frictional resistances of the road in pounds per ton and the rate in H. P. at which the engine works at this speed.

Ans. 14.93 pounds per ton.
179.16 H. P.

Heat.—The unit of heat is the amount of heat required to raise the temperature of one gram of water 1° C. It is called the **calorie.***

The mechanical equivalent of one calorie is nearly 42,000,000 ergs.

The British thermal unit (B. T. U.) is the amount of heat necessary to raise the temperature of one pound of water 1° F.

* The heat required to raise the temperature of one gram of water 1° C. varies slightly with the temperature. The unit is indefinite unless the temperatures are stated. The interval from 15° to 16° C. is generally used.

The relation of these units is given under the unit of electrical work, the joule.

Units in the C. G. S. and Practical Systems.

Magnetic Units.

A **unit magnetic pole** is one of such strength that it will repel a like pole at a distance of one centimeter in air with a force of one dyne.

A **magnetic field** is any space near a magnet or a conductor carrying a current in which a magnet pole would be acted upon by a magnetic force tending to move it in one direction or another. The positive direction of the field is the direction in which a free north pole would tend to move. Unit strength of magnetic field is a field in which a unit magnetic pole would be acted upon by a force of one dyne.*

It is convenient to represent a magnetic field by so-called lines of force or lines of magnetic induction. According to this system a field of unit strength is represented by one line per square centimeter. This unit of field strength is called a **gauss**. Thus a field represented by 50 lines per square centimeter would have a field strength of 50 gausses. The total number of lines passing through a section of the field perpendicular to the direction of magnetic induction is called the magnetic flux and the number passing through each square centimeter is called the flux density. If the field is uniform the magnetic flux is equal to the product of the area of the section in square centimeters and the flux density.

Electromagnetic Units.

These units are derived units of the C. G. S. system based upon the foregoing magnetic units.

Unit of Current.

An electric current is not a tangible material substance; it cannot be seen; a conductor carrying a current looks to be in the same condition as one in which no current is flowing. A conductor has cer-

* Strictly speaking this is true only when the permeability $\mu = 1$.

tain properties; viz., resistance, inductance, and capacity. These depend upon the material, form, and dimensions of the conductors directing the current and upon their relative positions to each other. These properties only become manifest when the circuit is subjected to certain conditions. It will be shown later that electrical resistance is only evident when current is flowing; inductance when current is changing, and capacity when electromotive force is changing.

It has been determined experimentally that every conductor carrying a current is surrounded by a magnetic field and that the intensity of the field varies with the current.

Also if a conductor carrying a current is placed in a magnetic field, a reaction will take place between the two fields and the conductor will be acted upon by a force tending to move it.

We thus arrive at the definition of unit current.

Unit current is a current of such strength that when flowing in a conductor lying in and at right angles to the direction of a homogeneous magnetic field of unit strength, every centimeter length of the conductor will be acted upon by a force of one dyne tending to move the conductor sidewise out of the field.

A unit of one-tenth the value of this C. G. S. unit is the **practical unit of current,** and is called the **ampere,** being named for Andre Marie Ampere, a French physicist who lived from 1775 to 1836.

A **milliampere** is a unit one-thousandth of the value of the ampere.

Unit of Quantity of Electricity.

The unit quantity of electricity is that quantity which is conveyed by unit C. G. S. current in one second.

The **practical unit of quantity** is the quantity of electricity conveyed by an ampere in one second. It is equal in value to one-tenth the C. G. S. unit of quantity and is called the **coulomb,** being named for Charles Coulomb, a French mathematician, who lived from 1736 to 1806.

A microcoulomb is equal to one-millionth of a coulomb.

Difference of Potential.—If two bodies are in such an electrical condition in regard to each other that when joined by a conductor a current will flow, the bodies are said to be at a different potential.

The earth is arbitrarily assumed to be at zero potential and any body differing in potential from the earth is called a charged body. The difference of potential between any two bodies is measured by the amount of work in ergs required to move a positive unit of electricity (electrostatic) from one body to the other against the electric force. The difference of potential existing between the two bodies may have been caused by friction, contact of metals and electrolytes or by electromagnetic induction. The potential of a charged body is proportional to the quantity of the charge and inversely proportional to the capacity of the body. The analogy sometimes used of electric potential to the potential energy of a mass elevated above the earth is misleading. Potential energy represents the amount of work a body is capable of doing due to its mass and position. The energy of a charged body, however, depends not only on its potential, but also upon the quantity of the charge. The relation between the potential of a body and the amount of its charge may be compared with the relation between temperature of a body and the number of heat units contained therein. If an iron rod be heated to redness and plunged into a tub of warm water, the heat will flow from the rod to the water as the former is at the higher temperature, though the total number of heat units contained in the tub of warm water may have been greatly in excess of the number contained in the rod.

If a difference of potential exists between two points, a current will flow from one point to the other, if they are connected by a conducting medium. There will be a gradual *fall* of potential or fall of electric pressure from the one of higher potential to the lower. There is a constant endeavor to equalize the difference of potential and in doing so, electricity flows from one to the other and work is done. If the difference of potential be maintained constant by the continual expenditure of work there will be a constant endeavor to equalization which will result in a continuous flow of current of electricity and continuous electric work.

Electromotive Force.—A difference of potential tending to produce a current is called the electromotive force, E. M. F. The total E. M. F. is the potential difference between the terminals of any machine or device used to produce a current when no current is flowing. Between any two points in a closed circuit in which current is flowing a difference of potential exists. The sum of all these differences of potential around the circuit is equal to the total E. M. F.

Fall of potential and total E. M. F. have their analogy in the fall of pressure due to a head of water flowing through restricted pipes.

In Fig. 1 *C* represents a tank filled with water and connected by the column *CB* with a level pipe *AB,* to which are connected vertical pipes *D, E, F, G.* The end of the pipe *A* is fitted with a faucet

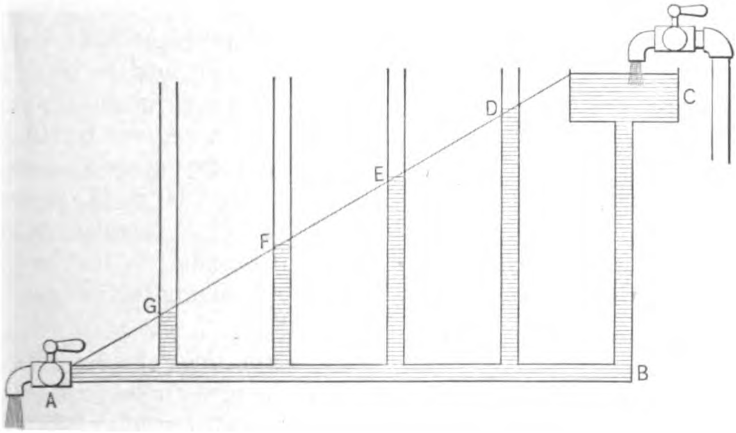


FIG. 1.—Illustrating Fall of Potential.

which may be opened or closed, and *C* is connected to a source of supply so that the level of water in *C* may be kept constant. If at first the faucet at *A* is closed, by a well-known hydrostatic principle, the water will rise in all the pipes until the height in each is on the same level and equal to the height in *C.* The pressure along each portion of *AB* is the same and there is no flow of water. This corresponds to an electric conductor *AB* whose ends are at the same potential; that is, there is the same pressure at each end and, consequently, there is no difference of potential and no movement of electricity.

If now the faucet at *A* is opened, then due to the consequent difference of water pressure produced between *C* and *A,* water will flow in *AB*. The water level in each tube will assume a height determined by the pressure at that point in *AB*. If now water is poured into *C* as fast as it flows out from *A*, the level of the water in the several tubes will remain stationary, while the flow of water through *BA* will be constant. Experiment will show that if the cross-section of *AB* is uniform and the tubes are equally spaced from each other there will be an equal difference in the levels of the tubes, and the fall of pressure may be shown by a straight line connecting the level of the water in *C* and end of tube *A*. The fall of water pressure is due to the friction of the sides of the pipe *BA* and the fall of pressure is expended in overcoming this resistance.

This is analogous to the case of a conductor whose ends are at different potentials. The level in *C* represents the total E. M. F. in the circuit and is maintained by the expenditure of the energy that is necessary to keep the height of the water at a constant level. In each section of *BA* there is a drop or fall in potential, and the sum of all the differences from *B* to *A* is equal to the total E. M. F., represented by the total head of water. The fall of potential is expended in overcoming the resistance of the conductor, just as the drop in water pressure was expended in overcoming the friction of the pipe.

If the cross-section of *AB* is not uniform, the water will stand at different heights such that the fall of the pressure between them will not be regular. The different sections will then offer different amounts of friction, so the fall in pressure will be greater or less. So in the case of the electric conductor, if the resistance through any one particular section is greater, the fall of potential will be greater. Further, the same amount of water will flow through each section regardless of the area of cross-section. It will therefore flow most rapidly in the sections having the smaller areas and the loss of head due to friction will be greater in these sections. So with an electric current; the same current flows in all parts of a series circuit, and the greatest drop of potential occurs in the sections having the smallest cross-sections, hence the greatest resistance.

C. G. S. Unit of E. M. F.—Of all the means available for generating E. M. F., magnetic induction seems the most logical one on which to base the definition of the unit E. M. F.

Faraday proved experimentally that when a conductor was moved across a magnetic field in such a direction as to cut the "lines of force" an E. M. F. was induced in it, and that the magnitude of this E. M. F. depended only upon the rate at which lines were cut. The induced E. M. F. does not depend upon the material or size of the conductor, nor is it necessary to have a closed circuit. If there is not a closed circuit no current will flow, but the E. M. F. will be induced and there will be a difference of potential between the terminals of the conductor. If Φ represents the total lines cut in time t and E the induced E. M. F. then $E = \frac{\Phi}{t}$.

The **C. G. S.** or **absolute unit of E. M. F.** is defined as the E. M. F. induced in a conductor when it moves at such a rate as to cut one line of magnetic flux per second. This unit is sometimes called an abvolt.

The **practical unit of E. M. F.** is the **volt** and is equal to $(10)^8$ absolute units.

A **millivolt** is a unit one-thousandth of the value of the volt.

Unit of Resistance.

The application of a steady E. M. F. to the ends of a conductor will produce in the conductor a current inversely proportional to the resistance the conductor offers to the flow of electricity. *A conductor has one electromagnetic unit of resistance when a steady E. M. F. of one electromagnetic unit applied to it produces one electromagnetic unit of current.* This definition is derived from a consideration of Ohm's law.

Ohm's Law.—This law expresses the relation between E. M. F., current and resistance in a closed circuit in which the current is continuous. It states that the current is directly proportional to the E. M. F. and inversely proportional to the resistance, or in symbols,

$$I = \frac{E}{R}$$

where

I = Current,
E = E. M. F.,
R = Resistance.

This relation holds in whatever system of units in which the quantities are expressed, provided they are all expressed in the same system. This law will be more fully dealt with later, and is only introduced here to help explain the unit of resistance. A consideration of the relation existing between the electromagnetic units of current and E. M. F. and the practical units shows that the ohm must be of a value 1,000,000,000 times as great as the electromagnetic unit of resistance. In both systems of units by Ohm's law

$$I = \frac{E}{R}$$

where I, E, and R represent current, electromotive force, and resistance in the two systems. If I', E', and R' represent the values in the practical system of units and I'', E'', and R'' the values in the electromagnetic system, we have

$$I' = 10^{-1} I'',$$
$$E' = 10^{8} E'',$$
$$R' = \frac{E'}{I'} \text{ and } R'' = \frac{E''}{I''},$$

whence

$$R' = \frac{10^8 E''}{10^{-1} I''} \text{ or } R' = \frac{10^8}{10^{-1}} R'' = 10^9 R'';$$

or, the value of the practical unit, the ohm, must be 10^9 times as great as the value of the electromagnet unit.

A unit 1,000,000,000 times the value of the C. G. S. unit of resistance is called the **practical unit of resistance** and is the **ohm,** being named for George Simon Ohm, a German mathematician who lived from 1789 to 1854, and who was the first to clearly enunciate Ohm's law.

A **megohm** is a unit one million times as great as the ohm.

A **microhm** is a unit one-millionth of the value of the ohm.

Unit of Power.

The C. G. S. unit of power is the power exerted when work is being done at the rate of one erg per second.

If a wire l centimeters long is caused to move across a magnetic field of intensity H at a velocity of v centimeters per second, Hlv

will be the rate of cutting lines and therefore the value of the induced E. M. F. If the ends of the wire be connected and a current I absolute units flows through the circuit, a force of HlI dynes will be exerted on the wire due to its position in the magnetic field (see definition of unit current). Power has to be exerted to make the wire move against this force. Since the wire is moved with a velocity v centimeters per second the following relation holds: $P=Fv=HlvI=EI$ ergs per second when E and I are given in absolute units. If E and I are given in volts and amperes the equation becomes

$$P=E(10)^8\times I(10)^{-1}=EI(10)^7 \text{ ergs per second.}$$

The practical unit of power is the power exerted when work is being done at the rate of $(10)^7$ ergs per second and is called a **watt.** The equation for power now becomes $P=EI$ watts when E is given in volts and I in amperes.

The relation between the watt and horse-power may be determined as follows:

$$1 \text{ pound}=453.6 \text{ grams.}$$
$$1 \text{ foot}= 30.48 \text{ centimeters.}$$
$$1 \text{ foot-pound}=453.6\times 30.48 \text{ gram centimeters.}$$

The weight of one gram is 981 dynes and the work done in lifting one gram against this force through the space of one centimeter equals 981 ergs. Hence,

$$1 \text{ foot-pound}=453.6\times 30.48\times 981 \text{ ergs.}$$

1 H. P. = 550 foot-pounds per second $=550\times 453.6\times 30.48\times 981$ ergs per second. 1 watt $=(10)^7$ ergs per second.

$$1 \text{ H. P.}=\frac{550\times 453.6\times 30.48\times 981}{(10)^7}=746 \text{ watts (nearly).}$$

The watt was named in honor of James Watt, an English physicist, the inventor of the steam-engine, who lived from 1736 to 1819.

A unit one thousand times as great as the watt is the **kilowatt.**

To convert			Multiply by	Divide by
Watts into		H. P.	.00134	746
"	"	ergs per sec.	10^7	
"	"	ft.-lbs. per min.	44.26	
"	"	ft.-lbs. per sec.	.7376	
"	"	kilogr.-meters per sec.	.102	9.81
H. P.	"	ft.-lbs. per min.	33,000	
"	"	ft.-lbs. per sec.	550	
"	"	kilowatts	.746	
"	"	watts	746	
"	"	ergs per sec.	7.46×10^9	

Unit of Work.

The C. G. S. unit of work has already been defined. The **practical unit of work** is a unit 10,000,000 times as great as the C. G. S. unit and is called the **joule,** being named for James Prescott Joule, an English physicist, who lived from 1818 to 1889. As heat and work are mutually convertible, it is sometimes referred to as the **electrical unit of heat** and is equal to 10,000,000 ergs. Remembering that the watt is the unit rate of doing work, the number of units of work, or joules, performed in a given time, must be equal to the number of watts multiplied by the number of seconds.

It has been shown that when an E. M. F. of one volt impressed on a circuit causes a current of one ampere to flow the power developed is one watt, or $P=EI$ watts when E is in volts and I in amperes. The work performed in one second is then $EI(10)^7$ ergs or EI joules. The general equation for work performed or energy expended in any time t is therefore $W=EIt$ joules. Since by Ohm's law $E=IR$ this may be written $W=I^2Rt$ joules. Where I is in amperes, R in ohms, and t in seconds. The joule is sometimes called the watt-second as it represents the energy expended in one second when the power developed is one watt.

A watt-hour represents the energy expended in one hour when the power developed is one watt. A watt-hour $=60\times 60=3600$ joules.

A kilowatt-hour is the unit used practically to represent electrical energy expended or absorbed and equals the energy expended in one hour when the power developed is one kilowatt on 1000 watts. A kilowatt-hour is equal to $1000 \times 3600 = 36(10)^5$ joules.

It has been determined experimentally that the mechanical equivalent of the energy for one calorie is about 4.186 joules. It is often desirable to transform the equation representing the energy absorbed into calories.

$$W = I^2Rt \text{ joules} = \frac{I^2Rt}{4.186} \text{ calories} = I^2Rt \times .239 \text{ calories}.$$

A British thermal unit (B. T. U.) is equal to 252 calories (nearly). The expression given above is useful in finding the increase of temperature in conductors, etc.

The temperature in degrees Centigrade, neglecting losses by radiation, etc., are given by the equation

$$\theta^\circ \text{(Cent.)} = \frac{I^2Rt \times .239}{ms},$$

when m equals mass in grams and s the specific heat or the heat in calories required to raise one gram of the substance 1° Centigrade.

To convert	Multiply by	Divide by
Watts into B. T. U. per sec.	.000948	1055
" " joules per sec.	1	
H. P. " calories per sec.	178.1	
" " B. T. U. per sec.	.707	

1 H. P. = 33,000 foot-pounds per minute, and is also equal to 746 watts; therefore,

$$1 \text{ watt} = \frac{33000}{746} = 44.26 \text{ foot-pounds per minute},$$

$$1 \text{ joule} = \frac{44.2}{60} = .7376 \text{ foot-pound}.$$

The work in foot-pounds done by a current of I amperes flowing through R ohms for t minutes is

$$W = 44.26 I^2Rt \text{ foot-pounds}.$$

The number of calories produced by a current I, in resistance R, in time t is

$$H = .239 I^2Rt.$$

1 calorie $=$ 4.186 joules
$= 4.186 \times 10^7$ ergs $=$ 3.088 foot-pounds
$=$ .00397 B. T. U.,
1 B. T. U. $=$ 252 calories
$=$ 1055 joules $= 1055 \times 10^7$ ergs
$=$ 778.1 foot-pounds,
1 joule $=$ .239 calorie.

Examples of Power, Work, and Heat.

1. If 20 amperes flow through a circuit of 10 ohms resistance for an hour, find (1) the heat generated, (2) work done in the circuit, (3) power absorbed. *Ans.* 3,441,600 calories.
14,400,000 joules.
5.362 H. P.

2. Find the potential difference at the terminals of a circuit in which 10 H. P. is absorbed, when a current of 37.3 amperes passes through it. *Ans.* 200 volts.

3. An incandescent lamp of 145 ohms resistance is placed under water in a pail containing 2 kilos of water at 18° C. How long must a current of 2 amperes flow through the lamp in order to raise the temperature of the water to 35° C., provided 98 per cent of the heat goes to raise the temperature of the water?

$$\text{Calories generated} = .24I^2Rt \times 0.98 \quad (1)$$
$$\text{Calories required} = (35\text{-}18) \times 2000 \quad (2)$$
$$(1) = (2) \text{ or } t = \frac{34000}{2^2 \times 145 \times .24 \times .98} = 249.2^s = 4.15 \text{ minutes.}$$

4. How much paraffin could be raised in temperature from 10° C. and melted in four minutes by a current of 3 amperes through a wire of 12 ohms resistance imbedded in the paraffin? Specific heat of paraffin $= .2$, latent heat $= 8$, melting point 54° C.

$$\text{Heat generated in calories} = I^2Rt \times .24$$
$$= 9 \times 12 \times 4 \times 60 \times .24 \quad (1)$$
$$\text{Heat necessary} = M \times .2 \times (54\text{-}10) + M \times 8 \quad (2)$$
$$(1) = (2) \text{ or } M = 370.3 \text{ grams.}$$

Unit of Capacity.

It has been noted that any conductor or group of conductors when insulated can hold a charge of electricity. This property of a conductor is called capacity. Capacity depends upon the size and form of the conductor, its proximity to other conductors, etc. When a conductor is given a charge of electricity, the potential to which it is raised is proportional to the magnitude of the charge and inversely proportional to the capacity, or if proper units are chosen

$$E = \frac{Q}{C} \text{ or } C = \frac{Q}{E}.$$

If two metal plates are brought close together but separated by a thin sheet of some dielectric, as glass, or mica, or even air, we have the simplest form of a condenser. If the two plates are connected to a source of E. M. F. so as to be at different potentials, the condenser stores a certain quantity of electricity. The quantity stored at any time depends upon E, the difference of potential at the terminals, and C the capacity of the condenser. It will be proved that the capacity is proportional to the area of the plates and to the dielectric constant of the material separating the plates and inversely proportional to the thickness of the dielectric

$$C \propto \frac{A\epsilon}{t}.$$

A conductor or condenser has one C. G. S. unit of capacity when it is charged to one C. G. S. unit of potential by one C. G. S. unit quantity of electricity, $E = \frac{Q}{C}$ where each is given in C. G. S. units.

The practical unit of capacity is called the farad. A conductor or condenser has a capacity of one farad when it is charged to a potential of one volt by one coulomb of electricity. To obtain the relation between a farad and a C. G. S. unit of capacity let C_1, E_1 and Q_1 represent the C. G. S. units and C_2, E_2 and Q_2 the corresponding practical units

$$C_1 = \frac{Q_1}{E_1},\ C_2 = \frac{Q_2}{E_2},\ Q_2 = (10)^{-1}Q_1,$$

$$E_2 = (10)^8 E_1,\ C_2 = \frac{(10)^{-1}Q_1}{(10)^8 E_1} = \frac{C_1}{(10)^9},$$

or the farad equals $(10)^{-9}$ C. G. S. units. The farad is too large for practical purposes and so the capacity of a condenser is given in microfarads. A microfarad is one-millionth part of a farad and is equal to $(10)^{-15}$ C. G. S. units.

Take the equation $Q=EC$ and differentiate it assuming C constant for same condenser we have

$$\frac{dQ}{dt}=C\frac{dE}{dt} \text{ or } i=C\frac{dE}{dt}.$$

That is, the rate of change of quantity or the current flowing in or out the condenser is proportional to the rate of change of E. M. F. applied at the terminals.

It is thus seen that a condenser has a capacity of one farad when a rate of change of E. M. F. of one volt per second at its terminals causes a current of one ampere to flow.

Example of Capacity.

The E. M. F. in a circuit alternates between 20,000 volts positive and negative, 40 times a second. What current will flow in a conductor if its capacity is 8 microfarads? *Ans.* 12.8 amperes.

Unit of Inductance.

It will be shown that every circuit carrying an electric current is surrounded by a magnetic field, which is brought into existence by the current. Any change in the current will produce a change in the magnetic field, and this field reacting on the conductor induces an E. M. F. which tends to prevent the change. If the current is increasing, the induced E. M. F. tends to prevent the increase, and similarly when the current is decreasing the induced E. M. F. tends to prevent the decrease.

The induced E. M. F. is directly proportional both to the rate of change of current and to the inductance. The induced E. M. F. acts as a counter E. M. F. to the applied E. M. F. If a certain current is flowing in a circuit of certain inductance, the E. M. F. required to reverse it in a given time may be calculated.

A circuit consisting of many turns has a large inductance.

When a rate of change of current of one C. G. S. unit per second induces one C. G. S. unit of E. M. F., the circuit has one C. G. S. unit of inductance. The inductance of a circuit is represented by the letter L. If E represents the counter E. M. F. induced and $\frac{di}{dt}$ the rate of change of current, we have $E=L\frac{di}{dt}$.

The practical unit of inductance is the henry and is the inductance of a circuit when a rate of change of current of one ampere per second induces an E. M. F. of one volt. In order for the above equation to be true the henry must be equal to $(10)^9$ C. G. S. units of inductance.

A millihenry is one-thousandth part of a henry and is equal to $(10)^6$ C. G. S. units of inductance.

Examples of Inductance.

1. The current in a circuit is changed from 0 to 50 amperes in .005 second. The average induced E. M. F. is 10 volts. What is the inductance of the circuit? *Ans.* 1 millihenry.

2. How many volts are required to reverse a current of 50 amperes in a circuit of 5 henries inductance in .5 of a second? *Ans.* 1000 volts.

International or Legal Units.

As a result of an International Congress of Electricians held in 1893, the following units were adopted, these being approved and adopted in June, 1894, by the United States Congress:

1. The **unit of resistance**, the international ohm, which is based upon the ohm equal to 10^9 units of resistance of the C. G. S. system of electromagnetic units, and is represented by the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 grams in mass, of a constant cross-sectional area, and of a length of 106.3 centimeters.

If the mass of one cubic centimeter of water at 4° C. is one gram, the area of cross-section of such a column will be one square millimeter.

2. The **unit of current**, the international ampere, which is 10^{-1} of the unit of current of the C. G. S. system of electromagnetic units, and which is represented sufficiently well for practical use by the unvarying current, which, when passed through a solution of nitrate of silver, in water, and in accordance with standard specifications, deposits silver at the rate of .001118 gram per second.

The anode in the solution is pure silver, the cathode pure platinum, and the liquid is a neutral solution of pure silver nitrate, containing about 15 parts by weight of the salt to 85 parts by weight of water.

3. The **unit of electromotive force,** the international volt, which is the E. M. F. that steadily applied to a conductor, whose resistance is one international ohm, will produce a current of one international ampere.

For all practical purposes this value is equivalent to $\frac{10000}{10183}$ times the E. M. F. of a Weston Normal cell at 20° C.

The **unit quantity of electricity** is the international coulomb and is the quantity flowing through a circuit in one second if the current is constant and equals one international ampere.

The **unit of capacity,** the international farad, is the capacity of a conductor which is charged to a potential of one international volt by one international coulomb of electricity.

The **unit of energy,** the joule, is equal to $(10)^7$ ergs and is the energy expended in one second when a constant current of one ampere flows through a constant resistance of one ohm.

The **unit of power,** the watt, is equal to $(10)^7$ units of power in the C. G. S. system and is the power developed when work is being done or energy expended at the rate of one joule per second.

The **unit of inductance,** the henry, is the inductance of a circuit when a rate of change of current of one ampere per second induces an E. M. F. of one volt.

CHAPTER II.

RESISTANCE.

All kinds of matter, whether solid, liquid, or gaseous, offer resistance to the passage of electricity. An electric current cannot flow unless a difference of electric potential exists, nor can a current flow without encountering some resistance. The definition of the International Unit of Resistance, the ohm, is based on the fact that a certain column of mercury at a certain temperature has a given definite resistance, or it offers at that temperature a certain obstruction to the passage of electricity.

Those substances which offer little resistance to electric currents are called **conductors**, and those which offer great resistance are called **insulators**. Between these extremes are certain substances which are partly conductors and partly insulators and which are called **partial conductors**.

Table of Conductors.

Good Conductors.

Silver,	Lead,	Manganin,
Copper,	Mercury,	Brass,
Aluminum,	Carbon,	Bronze,
Zinc,	Water,	Phosphor Bronze.
Platinum,	German Silver,	
Iron,	Platinum Silver,	

Partial Conductors.

The Body,	Cotton,	Dry wood,	Paper.

Uses of Conductors.

Most of these conductors find some use in the electrical apparatus and instruments installed on board ship.

Copper is used in the dynamo and motor windings, electric light and power mains, switchboards, bus bars, switches, interior communication circuits, and in general where high conductivity is required and where the allowable fall of potential small. It is particularly adapted for conductors on account of its high conductivity, its abundance, and the ease with which it is worked into various shapes. For conductors it is generally of the wire, ribbon, or bar shape.

Zinc finds its principal use in the anodes of electric batteries.

Platinum conductors are used in incandescent lamps as connecting wires between the copper leading wires and the carbon filaments. Alloys of platinum are used in some forms of rheostats.

Brass or **bronze** finds use for conductors on switchboards, and in the various terminals of dynamo leads on headboards and switchboards and as the interior fittings in water-tight appliances. The conductors, however, for these are copper.

Lead or an **alloy of lead** is used for conductors in the numerous fuses placed in different parts of dynamo or motor circuits to protect the circuits against excessive current.

Carbon is used for conductors in dynamo and motor brushes, in contact pieces for circuit breakers and in the searchlights and arc lamps.

Manganin is used in the resistances of voltmeters and ammeters.

German silver finds use in rheostats, resistance coils, and parts of apparatus where high resistance is required. Its general composition is:

Copper	4 parts.
Nickel	2 parts.
Zinc	1 part.

The variation of the resistance of German silver due to changes of temperature is very small, its coefficient per degree rise in temperature C.° being one-ninth that of copper. Strong currents continually used in German silver resistances tend to make the conductors brittle.

Phosphor bronze is used in the clips of switches to prevent blisters forming, due to the arc on opening the switch. In some cases it has been used for commutator segments, but now they are usually made of hard drawn copper.

Laws of Resistance.

Experiment shows that the two following laws hold in the case of conductors:

First Law.—The resistance of a given conductor of uniform section at a constant temperature is directly proportional to its length.

Thus if l represents length and R resistance, then R varies directly as l, or

$$R \propto l.$$

If a conductor of a certain length has a certain resistance, then a conductor twice as long, of the same area of cross-section, at the same temperature, will have a resistance twice as great; and if half as long, it will have a resistance half as great.

Second Law.—The resistance of a given conductor at constant temperature is inversely proportional to its sectional area.

If, as before, R represents resistance and a area of cross-section, then R varies *inversely* as a

$$\mathrm{R} \propto \frac{l}{a}.$$

If a conductor of a certain area of cross-section at a certain temperature has a certain resistance, then a conductor of twice the area of cross-section, at the same temperature, will have a resistance one-half as great; and if half its area of cross-section, it will have a resistance twice as great.

From a consideration of the above laws, it is seen that R varies directly as the length and inversely as the area of cross-section of the conductor, or

$$R \propto \frac{l}{a}.$$

In order that this equation may give the value of R in ohms and be a pure equation rather than a proportion, it is necessary to multiply it by a *constant* for the particular material of the conductor and temperature at the time.

This constant is called the resistivity or **specific resistance** of the conductor at the temperature and is defined as *the resistance in ohms of unit length of the conductor having unit cross-sectional area.*

The unit adopted is the centimeter, so that the specific resistance is the resistance in ohms between the opposite faces of a cube, one centimeter on the side.

Combining the laws of resistance with the definition of specific resistance, we have the fundamental equation of resistance

$$R=\rho\frac{l}{a} \qquad (1)$$

where ρ represents the specific resistance of the conductor at a certain temperature.

Thus the resistance of any conductor may be found if its specific resistance, length, and area of cross-section are known.

In cases where it is inconvenient to measure the length, as in a long coil, it may be weighed and l found from the expression

$$l=\frac{w}{ad}\text{ centimeters} \qquad (2)$$

where

w = weight in grams,
a = area in square centimeters,
d = density,

R then becomes, by substituting the value of l from (2) in (1)

$$R=\rho\frac{w}{a^2d}.$$

The specific resistance in this system is usually stated in microhms; thus, that of lead is 19.14 microhms, or .00001914 ohm.

Electrical engineers usually express the length of a conductor in feet and the area of the cross-section in circular mils. In this system ρ in the formula equals the resistance in ohms of a wire of the substance one foot in length and one mil or $\frac{1}{1000}$ inches in diameter. A circular mil is the area of a circle $\frac{1}{1000}$ inch in diameter. Since the areas of circles are proportional to the squares of their diameters, the area of any circle in circular mils is equal to the square of its diameter when the latter is expressed in mils. The formula now becomes

$$R=\rho\frac{l}{d^2},$$

where

R = resistance in ohms.

ρ = specific resistance or resistance of a wire of the substance one foot long and one mil or $\frac{1}{1000}$ inch in diameter.

l = length in feet.

d = diameter in mils.

For practical purposes where no particular refinement is necessary, the value of ρ for copper at ordinary room temperature is assumed to be 10.8 ohms.

TABLE OF SPECIFIC RESISTANCES OF METALLIC WIRES (SMITHSONIAN).

Substances.	Resistance in microhms at 0° C. of a wire one centimeter long and one square centimeter in section.	Resistance in ohms at 0° C. of a wire one foot long and $\frac{1}{1000}$ inches in diameter.
Copper (annealed).	1.584	9.529
Copper (hard drawn).	1.619	9.741
Silver (annealed).	1.46	8.781
Gold (annealed).	2.088	12.56
Zinc (pressed).	5.613	33.76
Aluminum.	2.906	17.48
Platinum.	9.035	54.35
Iron.	9.693	58.31
Nickel.	12.43	74.78
Lead.	19.14	115.1
Mercury.	94.07	565.9
German silver.	20.89	125.7

German silver, an alloy of copper, nickel, and zinc, combined with 1 to 2 per cent of tungsten is known as platinoid. The addition of tungsten gives the alloy greater density and reduces tendency to oxidation. The alloy takes a polish like silver.

Any foreign matter considerably reduces the conductivity of metals and alloys usually show higher resistances than any of their constituents. As a rough unit, a mile of copper wire, $\frac{1}{4}''$ diameter has a resistance slightly less than one ohm.

Relation of Heat and Resistance.

Generation of Heat.—One effect of a current of electricity on a conductor is to produce heat in the mass of the conductor, the number of joules developed being given by the equation I^2Rt. The greater the current, the higher the resistance, and the longer the time, the greater the increase of heat and consequent rise of temperature.

If the heat is carried away by conduction or radiation as fast as developed the temperature will not rise; or, if after a certain temperature has been attained, the heat is carried away as fast as developed, the conductor will remain at that temperature; but if the heat cannot be dissipated, the conductor will get hotter and hotter until its melting point is reached.

Table of Melting Points.—The melting point of some of the most important conductors in degrees C.

Alloy, 3 lead, 2 tin, 5 bismuth	93°
Alloy, 1½ tin, 1 lead	168°
Alloy, 1 tin, 1 lead	240°
Tin	232°
Lead	325°
Aluminum	656°
Bronze	922°
Silver	960°
Gold	1062°
Copper	1085°
Cast Iron	1375°
Steel	1360°
Steel, hard	1410°
Wrought Iron	1600°
Platinum	1775°

Variation of Resistance with Temperature.—It is to be noted that the table of specific resistances is for materials at a certain temperature, 0° C. This is necessary from the fact that the resistance of any substance, conductor or insulator, depends on its temperature at any given time.

A substance whose resistance increases with an increase of temperature is said to have a positive temperature coefficient. This class includes all pure metals and most of the alloys.

A substance whose resistance decreases with an increase of temperature is said to have a negative temperature coefficient. This class includes carbon, conducting solutions and liquids and insulators, such as marble, slate, glass, etc., which become partial conductors at high temperatures.

Resistance Temperature Coefficient.—The **resistance temperature coefficient** is defined to be *the amount of increase or decrease of resistance in ohms which one ohm in any substance would undergo for each degree Centigrade change of temperature.*

The resistance of conductors increases with temperature in accordance with the following formula:

$$R = r(1 + at \pm bt^2)$$

where

R = resistance at temperature t,
r = resistance at temperature 0° C.,
t = temperature in degrees C.,
a, b = temperature coefficients of the conductor.

It is usually sufficient to disregard the last term and use

$$R = r(1 + at). \qquad \text{(a)}$$

It is ordinarily sufficient to regard t as the difference between any two temperatures, and then r becomes the resistance at the lower and R at the higher temperature.

The temperature coefficient a is positive for all elementary metals except carbon and for most pure metals has an average = .004 between 0° C. and 100° C.

As a general rule, if two or more elements form an alloy, it has a higher specific resistance and lower temperature coefficient than any of its component elements.

The increase in temperature of copper conductors, apart from the increased resistance, is an important factor in calculating the size of conductors to carry certain currents, as they must be large enough to carry their currents without overheating.

Formula (a) may be used to determine the increase in temperature of conductors due to current, by measuring the resistance both when hot and cold. Then knowing the temperature coefficient, the increase in temperature t may be calculated.

The effect of a change in temperature shows that it is important to know the resistance of certain conductors when current is flowing, as the different windings of dynamos and motors, of rheostats, regulators and starting boxes, and particularly it is required to know the *hot* resistance of incandescent lamps, so that the current a lamp is absorbing when it is giving its rated candle-power may be known.

Problems on Resistance.

1. Find the resistance at 25° C. of a copper wire 10 meters long and 1 millimeter in diameter. The resistance of copper increases by .39 per cent for each degree rise of temperature. Specific resistance of copper = 1600 C. G. S. units.

$$R_0 = \rho \frac{l}{\pi r^2} = 1600 \times \frac{10 \times 100}{\pi} \times \frac{1}{(.05)^2} = 2.0378 \times 10^8 \text{ C. G. S. units}$$

or $R_0 = \frac{2.0378 \times 10^8}{10^9} = .2037$ ohm

$R_{25^\circ} = .2037\ (1 + 25 \times .0039) = .2236$ ohm.

2. A uniform glass tube 92.1 centimeters in length was filled with mercury and the resistance of the column of mercury was measured and found to be 1.059 ohms. The weight of the mercury contained in the tube was 10.15 grams. Calculate from this experiment the specific resistance of mercury, taking its specific gravity as 13.6.

Ans. 93.177 microhms.

3. The resistance of a bobbin of wire is measured and found to be 68 ohms; a portion of the wire 2 meters in length is now cut off and its resistance is found to be .75 ohm. What was the total length of wire on the bobbin? Resistance of one meter equals .375 ohm.

$$\therefore l = \frac{68}{.375} = 181.3 \text{ meters.}$$

4. The resistance at 0° C. of a column of mercury 1 meter in length and 1 square millimeter in cross-section is called a "Siemens unit." Find the value of this unit in terms of the ohm. Specific resistance of mercury = 94.340 microhms. *Ans.* .9434 ohm.

5. What length of platinum wire 1 millimeter in diameter is required to make a 1 ohm resistance coil? Specific resistance platinum = 9.0 microhms. *Ans.* 872.8 centimeters.

Problems on Heat and Resistance.

1. On a certain circuit on board ship there are 15 lamps each taking .7 ampere and a margin of 25 per cent excess of current is allowed. Find

the diameter of a lead safety fuse for this circuit. Specific resistance of lead = 19.85 microhms, melting point 335° C.; loss of heat by radiation and convection per square centimeter of surface .001 joule per second per degree rise of temperature. Initial temperature 18° C.

$$\text{Current allowed for} = 15 \times .7 + \frac{15 \times .7}{4} = 13.125 \text{ amperes.}$$

$$\text{Resistance of fuse} = \rho \times \frac{l}{\pi r^2} = \frac{19.85}{10^6} \times \frac{4l}{\pi d^2}.$$

Joules generated by current per second

$$= I^2R = (13.125)^2 \times \frac{19.85}{10^6} \times \frac{4l}{\pi d^2}. \qquad (1)$$

Joules carried away by radiation

$$= \frac{(335 - 18) \times \pi dl}{1000}. \qquad (2)$$

$$(1) = (2) \qquad \text{or } d^3 = \frac{(13.125)^2 \times 19.85 \times 4 \times 1000}{317 \times \pi^2 \times 10^6}$$

$$d = .1635 \text{ centimeters.}$$

2. A potential galvanometer has a resistance of 367 ohms and is graduated to show a difference of potential of 100 volts between the terminals. Find the diameter of a lead safety fuse which will melt if the potential difference rises above 100 volts. Temperature of room 20° C., other data as in example 1. *Ans.* $d = .01237$ centimeter.

3. On a circuit there are 65 incandescent lamps in parallel, each lamp requiring .6 ampere. If a margin of 30 per cent excess of current is allowed, find the diameter of a lead safety fuse to be inserted in the mains. Temperature of room 20° C., other data as in example 1. *Ans.* $d = .4034$ centimeter.

4. If a ward room is supplied with 30 lamps, each taking .8 ampere and a margin of 20 per cent is allowed for, what should be the diameter of a lead safety fuse to protect this circuit? Temperature of room 18° C., other data as in example 1. *Ans.* $d = .2761$ centimeter.

Conductance.

Conductance is the name given to express the ease with which substances conduct electricity. It is the reciprocal of resistance. The practical unit of conductance is called the mho. It is the conductance of a conductor whose resistance is 1 ohm. If the resistance of a circuit is 6 ohms its conductance will be $\frac{1}{6}$ mho, that is it will have $\frac{1}{6}$ the conductance of a circuit whose resistance is 1 ohm.

The specific conductance or conductivity of a substance is the conductance between opposite faces of a cube 1 centimeter on a side. Conductance is represented by the letter G and conductivity by g.

The conductance of a substance varies directly as its conductivity and area of cross-section and inversely as its length.

$$G = \frac{ga}{l}.$$

Resistance of Series and Parallel Circuits.

Electric circuits consist of conductors of various resistances connected in one or more ways to form one or more complete paths for the flow of the electric current, and the combined or total resistances of the various branches depend on the manner in which they are joined.

There are two main systems of arranging conductors, called **series system** and **parallel system**, and a complete circuit may be of a complex system of either or a combination of both.

Resistances in Series.—Conductors are joined in series, when the end of one is connected to the end of another, all in one line, or connected *end on* to one another, as indicated in Fig. 2.

FIG. 2.—Resistances in Series.

Any current that flows from A to B must flow through each of the several resistances in turn, and the same current must flow through them all. The resistances are additive and it is plainly evident that the total resistance of any number of separate resistances connected in series is equal to the sum of their separate resistances. Thus the resistance from A to B is

$$R_1 + R_2 + R_3 + R_4 + R_5.$$

It is also evident that it matters not in what order the resistances are joined, as the addition of each resistance is a positive increase to the total resistance.

Resistances in Parallel.—Resistances are connected in parallel when one or more branches of the circuit are connected to the same points of the circuit. This is illustrated in Fig. 3.

Three resistances R_1, R_2, and R_3 are connected to the same points of the circuit at A and B, and it is required to find the combined resistance of the three, or the resistance of a single conductor joining A and B that would allow the same current to flow in the circuit to which A and B are connected.

The *conductance* of R_1 is $\frac{1}{R_1}$ and similarly for R_2 and R_3, and it is evident that the conductance from A to B is the sum of the

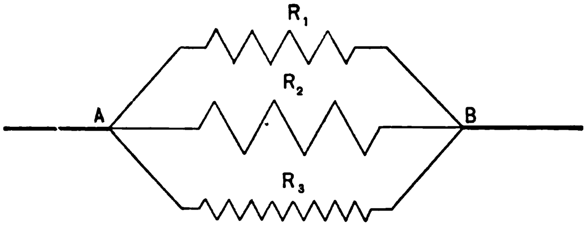


FIG. 3.—Resistances in Parallel.

conductances of the various branches, or the total conductance from A to B is

$$G=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3},$$

and as the total conductance is the reciprocal of the total R,

$$G=\frac{1}{R},$$

or

$$\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}$$

and

$$R=\frac{R_1R_2R_3}{R_1R_2+R_1R_3+R_2R_3}.$$

If

$$R_1=R_2=R_3$$

$$R=\frac{R_1}{3}=\frac{R_2}{3}=\frac{R_3}{3}.$$

As there are now three equal paths for the current to flow, it is the same as though the three resistances had been replaced by one of three times the cross-sectional area, and as it has been shown that resistance varies inversely as the area, and the area is three times as great as that of one conductor, the resistance will be one-third of that of one conductor.

Resistances in Series and Parallel.—The most common arrangement of conductors in an electrical circuit is a combination of the series and parallel systems as indicated in Fig. 4.

The resistance from *A* to *B* of such a circuit is the sum of all the resistances of the several parts, thus from *A* to *B* is equal to resist-

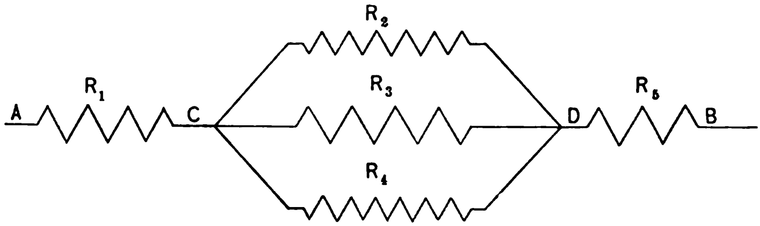


FIG. 4.—Combined Series and Parallel Resistances.

ance from *A* to *C* plus that from *C* to *D* plus that from *D* to *B*, and as above, total resistance is

$$R = R_1 + \frac{R_2R_3R_4}{R_2R_3 + R_2R_4 + R_3R_4} + R_5.$$

Resistance of Joints and Imperfect Contacts.

It is impossible to compute what is the extra resistance added to a circuit due to imperfect joints or contacts, the resistance varying with the goodness or poorness of contact. It should be seen that all joints and connections are perfectly tight, for the less nearly perfect they are, the greater the resistance, the more heat developed in them and consequently more energy wasted. Loose connections in an electric-light circuit will often cause a flickering of the lights.

One form of a rheostat is based on this contact resistance and is composed of carbon blocks. By varying the pressure on them the resistance of their contacts is altered.

Insulation.

Insulation is defined as the means adopted for preventing electric currents from acting along any other path than through the conductors provided for the purpose. Insulators are simply substances which are poor conductors of electricity, though even the best insulator has some conductance, just as the best conductors have some resistance.

The amount of electricity which insulators allow to pass through them is called the **leakage**, and this takes place through the whole cross-section of the insulation, and also along the film of moisture on the outside surface of the insulation.

Dirt and moisture act against good insulation, and whenever possible insulators should be highly polished to prevent dirt from sticking, and they should be coated with some form of non-absorbent to prevent the absorption of moisture.

The resistance to leakage is obviously the resistance of the insulator, and is given by the same formula as resistance of conductors,

$$R = \frac{\rho l}{a}.$$

Therefore, the longer the insulator and the smaller the area of cross-section, the greater the resistance, or the more efficient the insulator.

Properties of Insulators.—The first requisite of all insulators is of necessity high insulation resistance. This should be combined with waterproof and fireproof qualities, and with toughness and flexibility. For use with high potentials, insulators should have sufficient dielectric strength to prevent rupture from sparking.

Heat affects very materially the insulating properties of substances and in some cases it may alter the chemical composition of insulating compounds. In testing the insulation of electric conductors the resistance is measured after the current has been flowing through the conductor for at least one minute.

Table of Insulators.

Oils,	Wool,	Resin,	Glass,
Shellac,	Silks,	Mica,	Air.
Varnish,	Rubber,	Paraffin,	
Porcelain,	Cotton,	Ebonite,	

Uses of Insulators.

Rubber.—Some form of rubber, either gutta-percha, India rubber, pure rubber, or vulcanized rubber is universally used as the principal insulation for copper conductors. Hard rubber is used for washers in the disc or cylindrical form, for switch handles, rheostat arms, and the bases of instruments. The ease with which it can be pressed or molded into shape makes it particularly useful for many purposes. All bushings through bulkheads or beams are made of hard rubber.

Porcelain is used in certain forms of rheostats with the conductors imbedded in it, and for the bases on which rest interior fittings of wiring appliances. Many washers are made of porcelain or some form of earthenware and used under screw heads or bolts. Porcelain, marble, or slate is used for the foundation of switchboards and panel boards. It is also used for insulators to carry cables where conduit or molding is not used.

Mica is used for the insulation between segments of the commutator of dynamos and motors, in wiring appliances under the fittings, and for covers of fuse boxes.

This is an excellent insulator; does not deteriorate with high temperature and has a high resistance to sparking, and is also practically non-hygroscopic. It can be made in thin sheets or built up in layers of any desired thickness, and can be made pliable by interposing insulating varnish made from shellac or resin between sheets.

Cotton is used in the form of thread on conductors and in tape form for insulation of certain parts of armatures, particularly the conductors and on the core.

Shellac is used where a light insulation is required and in connection with other insulators. It is rarely used by itself and is generally used as an outside covering to prevent the accumulation of moisture. Armature laminations are insulated with shellac or lacquer.

Paraffin is used to cover the resistance coils in resistance boxes, offering at the same time good mechanical protection, as it is put on in the liquid state and covers all parts of the coils.

Glass is used as the dielectric for condensers used in wireless telegraphy sets.

Oils are used for insulation where high potentials are carried. The secondary coils of induction coils and certain glass-plate condensers used in wireless telegraphy outfits are often contained in receptacles which are filled with oil.

Different kinds of **paper, cardboard,** or **pressboard** are used for armature insulation.

Okonite or some form of rubber forms the base of many insulating tapes and is applied to cotton tape.

A very good flexible insulation, with fairly high resistance, can be made by heating fibrous material with linseed or other oil, drying and finally thoroughly baking it.

Vulcabeston, a mixture of rubber and asbestos, is a very good insulator and satisfies most of the requirements. It is unaffected by high temperatures, does not absorb moisture, is very hard and strong, and has high dielectric strength.

There are many other insulating materials on the market, but the above varieties include the majority of types.

CHAPTER III.

PRIMARY BATTERIES.

Batteries, defined as combinations of electric cells, are of two general classes, primary and secondary or storage batteries. Primary batteries were formerly used on board ships for bell work, telephone circuits, firing guns and exploding electric mines. The power for these purposes is now supplied by motor generators operated from the main electric plant. Primary batteries are still in use on some of the older ships for some of the purposes given above and on the newer ships to some extent as a reserve.

Primary Cells.

Electric cells all generate electricity by chemical action and the term cell is applied to an arrangement in which one or more substances forming a fluid or dry mixture act upon two different metals, or a metal and carbon placed in the mixture, whereby a difference of potential is produced between the metals.

If a piece of metal is placed in a fluid called an electrolyte, there is at once produced an electrical condition of such a kind that the metal either takes a higher or lower potential than the fluid. If two pieces of different metals are placed in the electrolyte, a condition may be produced of one metal assuming a higher potential than the liquid and the other a lower, in which case if the two metals are connected by a conductor, there will be a current of electricity established.

Simple contact of dissimilar metals will give rise to a difference of potential, and all substances may be arranged in a table so that any one element in the list will be electropositive to any one below it; or, in other words, will be of an absolute higher potential than any below it when they are placed in contact.

Table of Electrochemical Series.

1. Aluminum,	7. Tin,	13. Platinum,
2. Manganese,	8. Copper,	14. Carbon,
3. Zinc,	9. Hydrogen,	15. Chlorine,
4. Iron,	10. Mercury,	16. Oxygen.
5. Nickel,	11. Silver,	
6. Lead,	12. Gold,	

Electrolyte.—The electrolyte must be a substance that will act chemically upon at least one of the elements placed it it, and it may be either a chemical acid or a chemical salt. The object of the electrolyte is to increase the difference of potential between the elements placed in it, and by chemical action to keep the difference of potential constant, so that when the electric circuit is completed, a continuous current flows.

The real source of energy seems to be in the element that is acted upon most actively chemically. The electric energy is represented by the wasting away or the consumption of the electropositive element, and the real starting point of the current is at the surface of this element.

Simple Examples of Electrochemical Action.

An examination of the table of electrochemical series shows that iron is electropositive to copper, so that if these two metals are in direct contact, a difference of potential arises causing a current that will be represented by the wasting away or pitting of the more electropositive one, iron. If these two elements are brought in contact by salt water, we have all the elements for a simple galvanic cell, and the effects of this combination are plainly shown in some copper-sheathed ships, the iron near the sheathing becoming pitted and eaten away. The same effect is seen in the pittings of copper pipes in the salt-water system, the pitting of the copper being due to the fact that copper is electropositive to the chlorine in the salt water. Where copper pipes come through the side of iron ships, it is customary to use zinc rings, so that the zinc-copper combination will prevail over the iron-copper combination and the zinc will be consumed rather than the iron. These zinc plates may be renewed from time to time so as to protect the iron.

Definitions.

The following general definitions apply to all single cells:

The **cell** is the shell, cup or vessel that contains the elements and the electrolyte. It may be made of glass, porcelain, earthenware or metal.

The **plates** are the elements, metal or carbon pieces that dip into the electrolyte, and are generally referred to as the *electrodes.*

The **electrolyte** is the liquid or dry mixture which acts chemically on the electrodes. In general it is a liquid that is decomposed by a current passing through it.

The **poles** are the portions of the electrodes that project from the electrolyte.

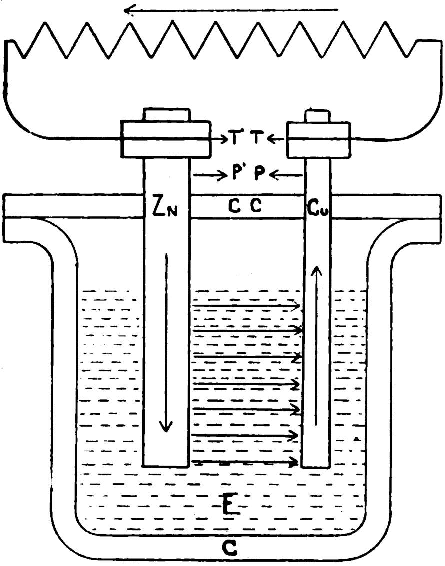


FIG. 5.—Typical Primary Cell.

T = + terminal,
T' = — terminal,
P = + pole,
P' = — pole,
CC = cell cover,
C = cell,
E = electrolyte (exciting fluid),

Zn = zinc strip,
= + plate,
= + electrode,
= anode,
Cu = copper strip,
= — plate,
= — electrode,
= cathode.

The **terminals** are mechanical devices by which conductors are secured to the poles.

The electrodes are distinguished by one being called positive +, the other negative —, the positive one being the one coming first in the Table of Electrochemical Series.

The **anode** is the positive electrode, the one at which the chemical action is the greater and is the plate by which the current enters the liquid.

The **cathode** is the negative electrode and is the one by which the current leaves the liquid.

It should be noted that the positive pole is part of the negative plate, and the positive terminal is on the positive pole, while the negative pole is part of the positive plate and the negative terminal is on the negative pole.

These definitions are illustrated in Fig. 5, showing a simple typical cell with its outside conductor.

The term *cell* is also applied to the whole combination, including the cell, electrolyte, electrodes and terminals.

Polarization.

This name is given to express the action which takes place in ordinary voltaic cells when the circuit is closed whereby the current rapidly diminishes and almost ceases to flow. As soon as the circuit is closed chemical action begins and hydrogen bubbles are carried over to the cathode. This causes the current to be diminished for two reasons: (1) The presence of the gas increases the resistance of the cell; (2) the copper plate becomes virtually a hydrogen plate and the resultant E. M. F. of the cell is greatly diminished.

Polarization is reduced in three different ways: (1) By mechanical, (2) by chemical, and (3) by electrochemical means: the latter preferably by using a second substance separated from the electrolyte, or by a solution in the electrolyte which will absorb or enter into chemical composition with the liberated gases.

The *depolarizer* is the substance used to prevent or counteract polarization and may be either a solid or a liquid.

Local Action.

This is a name given to the chemical action that goes on in a cell when the circuit is open, that is when the outside circuit is broken. This is a quiet action and is usually due to impurities in the electrodes. It ordinarily arises from particles of iron, arsenic or other foreign metals in the anode, which in most forms is zinc. These impurities being imbedded in the zinc and the zinc and impurities in contact with the electrolyte form little closed circuits which gradually waste away the zinc. It is obviated by using chemically pure zinc or, as this is very expensive, by amalgamating the zinc, that is by giving it a slight coating of mercury. The mercury covers up the impurities and seems to bring only the pure zinc to the surface.

Electromotive Force of Cells.

As has been stated, the E. M. F. of a cell depends entirely on the electrodes and the electrolyte used. In the contact of dissimilar metals, the difference of potential is due alone to the elements themselves, and not to their size, shape, or other characteristics, and this holds true in an electric cell as far as the E. M. F. is concerned, though the resulting current depends very much on the size, shape, and distance apart of the electrodes.

E. M. F. on Open Circuit.—When the circuit is open the difference of potential between the poles is always equal to the total E. M. F. developed within the cell; or, in other words, the E. M. F. of a cell is the difference of potential between its poles when no current is passing through or from it. When the circuit is closed, the E. M. F. at the poles is less than the total E. M. F. due to the volts lost in driving the current through the internal resistance of the cell, and this point must always be borne in mind in connecting up cells for any particular work.

By Ohm's law, the loss of potential in the cell itself is equal to the current flowing through the cell multiplied by the internal resistance. So if E is the total E. M. F. of a battery due to the battery itself, I the battery current, and r the internal resistance, then the loss of potential or lost volts in the cell is Ir and the available difference of potential at the terminals $E_x = E - Ir$.

To measure directly the total E. M. F. of a battery or cell, it must be compared with the E. M. F. of some standard cell, but to obtain the E. M. F. of this standard cell, it must be measured electrostatically by some means, for in all other ways, there must be current drawn from the cell and this will vitiate the result.

Methods of measuring accurately the E. M. F. of a cell are given later in the chapter on Measurements.

For all practical purposes, however, the E. M. F. of a cell is sufficiently determined by connecting its terminals to the binding posts of a low-reading portable voltmeter. The small current flowing from the cell is inappreciable owing to the high resistance of the voltmeter, so that the lost volts in the cell are extremely small and the E. M. F. as measured is very near the total E. M. F. of the cell.

Resistance of Cells.

By the resistance of a cell is meant the resistance it offers to the flow of electricity, measured from terminal to terminal, and is the sum of the resistances of the separate parts that go to make up the internal circuit. It is a physical characteristic depending on the elements of which the electrodes are made, of the electrolyte fluid, and of the depolarizing substance, solid or liquid. The resistance of the cell may be reduced by making the electrodes in the form of plates, by which a large surface is exposed to the electrolyte, and by shortening the path the current has to follow. This is done by bringing the electrodes close together, and in some forms, one electrode entirely surrounds the other. The resistance of liquids is high as compared with metals, and that of gases still higher. The resistance of the gases liberated by the chemical action is the chief cause of polarization in a cell, increasing the resistance to such an extent that the current rapidly falls off. This resistance due to the gases is not properly a part of the cell resistance, and being a variable quantity is not included in the internal resistance.

Methods of measuring the resistance of a cell are given later in the chapter on Measurements.

Resistance of a Working Battery.—When a battery is working through an external resistance and a certain current is being drawn from it, the internal resistance may and will probably be different from its resistance on open circuit, and it is frequently of importance to know what the working resistance is. A sufficiently accurate method for determining this is as follows: With a voltmeter (see later) measure the difference of potential between the terminals of the battery when on open circuit; call this E. Make the same measurement when working through the external resistance and call this E_x, and this should be made before polarization sets in.

When a current is flowing, part of the total E. M. F. is expended in sending current through the external resistance and part through the battery resistance, but only E_x, the fall of potential through the external circuit can be measured, and $E-E_x$ is the fall of potential through the battery; therefore, by Ohm's law, where r is the internal resistance of the battery,

$$I=\frac{E-E_x}{r} \text{ and } I=\frac{E_x}{R},$$

or

$$r=\frac{E-E_x}{E_x}R.$$

If an ammeter (see later) is connected in the circuit, it is not necessary that the value of R should be known, as

$$r=\frac{E-E_x}{I}.$$

When two resistances are available, r can be calculated as follows: With the resistance R_1 in circuit measure E_x and I, and with R_2 measure E'_x and I', then

$$Ir=E-E_x.$$
$$I'r=E-E'_x.$$
$$r(I-I')=E'_x-E_x, \text{ hence } r=\frac{E'_x-E_x}{I-I'}.$$

Grouping of Cells.

Knowing the E. M. F. and internal resistance of the cells that are available, and the character of the work to be performed it becomes important to know the method of grouping the cells in order to get the best results. It may be that either a high E. M. F., a large current, the greatest current, or the most economical operation may be desired. There are three principal ways of arranging cells, namely, in **series**, in **multiple** or **parallel**, and in **series parallel**.

Series Grouping.—Cells are connected in **series** when the positive electrode of one is connected with the negative electrode of another, and the positive one of this to the negative of the next and so on, the number so connected being referred to as so many in series. This arrangement is shown in Fig. 6.

FIG. 6.—Cells in Series.

The effect of such a grouping is to sum up all the electrical effects of each cell; that is, the total E. M. F. is the sum of the individual E. M. F.'s of each cell, and the total resistance is the sum of the internal resistances of each cell. If the cells have the same characteristics, then this total E. M. F. is the E. M. F. of one multiplied by the number of cells, and the total resistance, that of one multiplied by the number of cells.

By Ohm's law, for a single cell

$$I=\frac{E}{r+R}.$$

Where

I = current in circuit,
E = E. M. F. of the cell,
r = internal resistance of the cell,
R = external resistance in circuit.

With a number of cells m, connected in series,

$$I=\frac{mE}{mr+R}.$$

If there is no external resistance, that is, if the battery terminals are short-circuited, $R=0$ and

$$I=\frac{mE}{mr}=\frac{E}{r},$$

or the current is no more than if there was one cell with its terminals short-circuited.

If R is very small compared with mr, the current is practically that of a single cell.

If mr is small compared with R, $I=\frac{mE}{R}$ (nearly), or in this case the current increases with the number of cells.

Cells connected in series are used on work in which R is already large, so that any increase in the internal resistance is not of much moment, the increased E. M. F. producing increased current.

Multiple Grouping.—Cells are grouped in **multiple arc**, or **parallel**, when all the positive electrodes are connected, and all the negative electrodes connected, or all the positive electrodes are connected to one common conductor and all the negative electrodes to another common conductor. This arrangement is shown in Fig. 7.

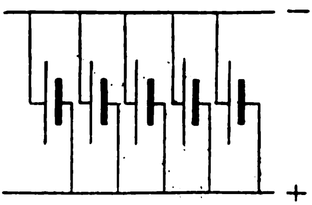


FIG. 7.—Cells in Parallel.

The effect of this grouping is to practically make one big cell, for as was shown under the electromotive force of batteries, the difference of potential is due to the electrodes themselves. In the case of the five cells shown, the effect is to make two electrodes each five times as large as that in a single cell and, therefore, the total E. M. F. due to these cells grouped in multiple arc is the same as that due to one cell. In this arrangement, there are now five paths for the current to follow in the battery; or, in other words, the total resistance of these five cells is only one-fifth that of each cell. Or, considering two electrodes each five times as large as that of a single cell, the resistance of each large electrode would be only one-fifth of that of each cell.

If there are n cells connected in multiple, and the resistance of each is r, the total resistance of the n cells is $\frac{r}{n}$, and the total current through the battery, neglecting the external resistance would be

$$I = \frac{E}{\frac{r}{n}} = \frac{nE}{r}.$$

This arrangement, therefore, increases the current, without increase of E. M. F. and is used where a strong current is required with low E. M. F. or for work in which the external resistance is low.

Multiple Series Grouping.—Cells are grouped in **series parallel** when some are connected in series, and the groups connected in series are grouped in multiple, as shown in Fig. 8.

Here are shown ten cells, groups of two being connected in series and five groups of two in series being connected in multiple arc. The effect of this grouping is to give an E. M. F. double that of one cell, with an internal resistance of one-fifth of the resistance of the two cells in series, or two-fifths the resistance of one cell, assuming they are all alike.

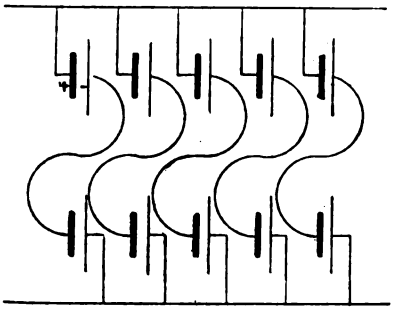


FIG. 8.—Cells in Multiple Series.

In general if there are *m* cells connected in series and *n* groups of *m* cells each connected in multiple arc, the resulting battery current, neglecting external resistance would be given by

$$I = \frac{mE}{\frac{mr}{n}},$$

where *I, E,* and *r* have the same significance as before. The total external current through a given resistance *R* would be

$$I = \frac{mE}{\frac{mr}{n} + R}.$$

It should be noted that the current through each group in series, and consequently through each cell, would be $\frac{I}{n}$.

For most battery work, some modification of this system is used, depending on the difference of potential and current required. It is used also when a higher E. M. F. and stronger current are required than any one cell would give.

Best Arrangement and Efficiency of Batteries.

a. To find the best arrangement of a given number of cells (N) to obtain the maximum current (I) through a given external resistance (R).

In addition to the symbols and significations already used, let

m = the number of cells in series in each group,
n = the number of series groups in multiple.

$$I = \frac{mE}{\frac{mr}{n} + R} = \frac{mnE}{mr + Rn}.$$

Since the total number of cells N equal to mn is fixed, this expression is one in which the numerator is constant and the denominator consists of the sum of two terms whose product is constant. It can easily be shown that the maximum value of the expression will occur when the two terms constituting the denominator are equal to each other, *i. e.*, $Rn = mr$ or $R = \frac{mr}{n}$. In other words the maximum current will flow when the cells are so arranged that the internal resistance of the battery is equal to the given external resistance. Assuming the two expressions $mn = N$ and $R = \frac{mr}{n}$, we have two simultaneous equations for solving for m and n. This will be illustrated by the solution of a numerical problem.

Example.—How should a battery of 32 cells be arranged in order to send the maximum current through an external resistance of 4 ohms; each cell having an E. M. F. of 1 volt and an internal resistance of 2 ohms? What is the value of the current?

$$mn = 32,\ 4 = \frac{m}{n}2,\ m = 2n,$$

$$2n^2 = 32,\ n^2 = 16,\ n = 4,\ m = 8,$$

$$I = \frac{mE}{\frac{m}{n}r + R} = \frac{8}{8} = 1 \text{ ampere.}$$

The battery should be arranged in 4 groups, 8 cells in series in each group. In solving problems if m and n should not have integral values, the nearest integers would have to be used.

b. To find the greatest current which can be obtained from a given number of cells (N) through a given external resistance (R).

Find the integral values of m and n which nearest satisfy the equations $mn=N$ and $R=\frac{m}{n}r$ and then substitute in the equation $I=\frac{mE}{\frac{m}{n}r+R}$ and the value of the current will be obtained.

c. To find the number of cells in series (m) and number in parallel (n) required to give a current (I) through an external resistance (R) and to have an efficiency (F).

By the *efficiency* of a battery is meant the ratio between the total power available in the external circuit and the total power developed by the battery. The total power developed by the battery is the product of the total E. M. F. and total current, and the total available power is the product of the total external current and the E. M. F. at the terminals.

Let E = E. M. F. of each cell.
E_x = terminal E. M. F. of battery.
I = current on external circuit.

The total power developed in battery $=mEI$

$$=I^2\left(R+\frac{m}{n}r\right), \quad (1)$$

since $I=\frac{mE}{R+\frac{m}{n}r}$.

The total power available in external circuit $=E_xI=I^2R$, (2)

since $E_x=IR$. Dividing (2) by (1) we have Efficiency $=\frac{R}{R+\frac{m}{n}r}$.

If the value of the current, external resistance and E. M. F. and internal resistance of each cell are known the values of m and n to satisfy the required efficiency may be found from the two equations

$$\text{Efficiency}=\frac{R}{R+\frac{m}{n}r} \text{ and } I=\frac{mE}{R+\frac{m}{n}r}.$$

d. To find the efficiency of a battery arranged (m) in series and (n) in parallel through an external resistance (R).

From above, Efficiency $= \dfrac{R}{R + \frac{m}{n} r}$. Knowing the values of R, r, m and n, the value of efficiency is obtained at once. It will be remembered that in finding the arrangement of the cells of a battery in order to produce the maximum current, it was shown that the cells should be so arranged that $\frac{m}{n} r$ the internal resistance of the battery should be equal to R, the external resistance. Substituting this value for $\frac{m}{n} r$ in the equation above, we have Efficiency $= \dfrac{R}{R+R} = \frac{1}{2}$. It is thus seen that when cells are arranged to produce the greatest current the efficiency is only 50 per cent.

It is well to consider the difference between maximum output and maximum efficiency. As noted above when a battery of cells is so arranged as to give the maximum output the efficiency is only 50 per cent. In other words one-half the total energy is wasted as heat in the battery.

e. To find the best arrangement of cells for most economical working.

The economy of working is proportional to the efficiency. If one has an efficiency of 100 per cent it means that all the energy developed is available for useful purposes. Take the equation Efficiency $= \dfrac{R}{R + \frac{m}{n} r}$. The only factor of this equation depending upon arrangement is $\frac{m}{n} r$. In order for the efficiency to be large, $\frac{m}{n} r$ the internal resistance must be made as small as possible. In order to do that n must be as great as possible and m as small as possible, that is all the cells must be in parallel.

Examples of Grouping of Cells.

1. What arrangement of 24 cells, each of E. M. F. 1.3 volts and resistance 2 ohms, will send the greatest current through an external resistance of 13 ohms?

For greatest current, the internal resistance must be equal to the external resistance.

Let $m =$ the number of cells to be grouped in series.
$n =$ the number of series groups to be placed in parallel.
$m \times n =$ whole number of cells.

$\frac{mr}{n} =$ internal resistance, $13 =$ external resistance,

or

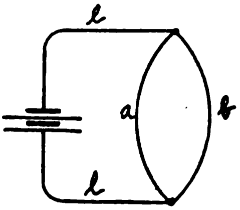
$$\frac{2m}{n} = 13 \qquad mn = 24.$$

$$\therefore \quad m = 12 \qquad n = 2.$$

2. What is the best arrangement to give the greatest current from 12 cells, E. M. F. of each 1.8 volts and resistance 5 ohms? The external resistance consists of an instrument .5 ohm resistance, of the leading wires .25 ohm resistance, and two electrolytic cells, one of 4 ohms resistance and the other of 3 ohms. *Ans.* $m = 4$.
$n = 3$.

3. A battery of 40 cells is to be so arranged that it will send the maximum current through an external resistance consisting of two branches, connected to the battery by two leading wires, one of resistance of 2 ohms, the other of 2.5 ohms. One branch has a resistance of $6\frac{2}{3}$ ohms and contains 4 fuses in series, each of 1 ohm resistance, and the other has a resistance of 11 ohms and contains 7 fuses in series, each of 3 ohms resistance. Each cell has a resistance of 5 ohms.
Ans. $m = 10$.
$n = 4$.

4. A circuit is arranged as in the figure. The branch *a* is composed of 10 fuses in series and *b* of 15, each fuse having a resistance of 1 ohm and requiring .75 ampere to fire it. The leading wires have a resistance of 3 ohms. How should a battery of 36 cells, each having an E. M. F. of 1 volt and resistance .25 ohm be arranged to give the maximum current through the fuses? *Ans.* All in series.



5. Twelve cells, each of which has an E. M. F. of 1.9 volts and resistance .28 ohm are to be coupled up so as to develop the greatest possible amount of heat in a copper wire of .21 ohm resistance. How must this be done? *Ans.* No. of groups in parallel, 4.
No. in series in each group, 3.

CHAPTER IV.

TYPES OF PRIMARY BATTERIES.

Batteries for use on board ship are generally confined to one or two classes, the Leclanché type being used for call, telephone, and alarm circuits, and some form of dry cell used for firing guns, torpedoes, or mines. The use of cells is being replaced by the dynamo current and an illustration of how this is accomplished will be given later, but the cells in ordinary use will be described.

Leclanché Cell.

There are several types of this cell to be found, but their general characteristics are the same, differences arising from the manner in which the electrodes and depolarizer are made up, this last making a difference in the resistance of the various types.

The positive electrode, or anode, is zinc, as near chemically pure as possible, and some forms being amalgamated. This is generally in the form of a round strip not unlike a lead pencil in shape. The negative electrode, the cathode, is carbon and in different types, this is made up in different shapes, and it is this difference that makes the various types of this cell. The electrolyte fluid is ordinary clean water in which is dissolved the chemical salt, ammonium chloride, or the sal ammoniac of commerce. The depolarizer is a paste made of peroxide of manganese, a black powder, mixed with powdered graphite. In the earlier forms, the carbon was imbedded in this paste which after treatment became hard, and the whole filled a porous earthenware cup that stood in the sal ammoniac solution. The porous cup was found to increase the resistance of the cell and another form was adopted. In this the depolarizer is in the form of hard blocks and these are secured to the carbon plate, one on each side, by rubber bands, and then the whole is placed in the electrolyte fluid, in which the zinc simply stands.

In another form of this battery, notably in the Samson and Hayden types, the carbon is made in the form of a hollow cylinder and the depolarizer is placed inside the cylinder. The cell is an ordinary glass jar, coated a short distance from the top with paraffin to prevent the salts that are formed from "creeping" over the top, and covered with a hard rubber top, through which the terminals of the electrodes project.

Chemical Action in the Cell.—The action that goes in the cell is represented by the following chemical formula:

$$2(MnO_2) + 2(NH_4Cl) + Zn = Mn_2O_3 + 2NH_3 + H_2O + ZnCl_2.$$

The current is primarily produced by the action of the ammonium chloride on the zinc, the zinc gradually wasting away as shown in the formula and the salt zinc chloride being formed. It is the double salt of this chloride that collects on the electrodes and on the sides of the cell and sometimes works its way over the edges of the cell. Free ammonia gas is evolved from the ammonium chloride which escapes or is dissolved in the liquid. Hydrogen is liberated from the ammonium chloride, and this would soon cause depolarization were it not for the manganese peroxide. Under the chemical action, this salt gradually gives up oxygen and part of it is converted into another manganese salt, Mn_2O_3. The oxygen thus liberated unites with the hydrogen freed from the ammonium chloride, to form water, thus getting rid of the chief cause of polarization. As shown by the formula, the zinc gradually wears away while the carbon remains unchanged.

In one form of this cell, the E. M. F. is about 1.48 volts with an internal resistance of 4 ohms, though these values vary in the different types. It gives a quick current for a short time, but its great advantage lies in the fact that on open circuit it recovers itself so quickly. It runs down quickly owing to the formation of the hydrogen bubbles, but part of the action goes on when the circuit is open, the hydrogen uniting with the oxygen. This quick recovery makes it particularly useful for bell work, where the current is not steady or continuous but intermittent.

With ordinary care a good Leclanché cell should last for years, and by this is meant keeping the cells clean, free from accumulation of salts on the electrodes, and taking precautions to keep the liquid from splashing over as the ship rolls. The battery locker should be kept free from dust and be in a cool, dry location. Above all, it should be seen that there are no short circuits when the circuit is open, as this would soon destroy the usefulness of any cell.

Sal Ammoniac Solution.—Different classes of cells of the Leclanché type require different strengths of solution to get the best results, but an average solution is about five ounces of dry ammonium chloride (sal ammoniac) to one quart of water. If the solution is too strong the double chlorides of zinc and ammonium are liable to crystallize and be deposited on the zinc, increasing the internal resistance and lowering the E. M. F.

Effect of Double Chlorides.—There is generally more or less of the double chloride of zinc and ammonium present in every sal ammoniac cell. This is heavier than the solution of zinc chloride and ammonium chloride and sinks to the bottom of the cell. Zinc in a zinc chloride solution is positive to zinc in a solution of the double salt, the result of which is a local action which tends to dissolve the zinc at the top and deposit it at the bottom. The cell is practically short-circuited on itself and this explains why almost all zincs in this class of cells grow thinner at the top first. Near the surface there is a slight oxidation process which also tends to thin the zincs.

Firing Batteries.

Different forms of batteries were used for firing guns, illuminating the night sights of guns, and for firing torpedoes and submarine mines. The general form adopted for firing guns and torpedoes is a dry cell similar in its electrical conditions to the Leclanché type. Some forms used are known commercially as "Roach Standard Dry Cell," "O. K. Cells," "Harrison Electrolyte Jelly Cells." The "Dry Cell" is furnished in two sizes, the small dry cell and the large dry cell.

In the dry cell, the cell itself forms the anode, being made of zinc to which is soldered the terminal. The cathode is a carbon slab imbedded in a paste which fills the whole cell. Next the zinc cup is a layer of powdered ammonium chloride mixed with lime, inside of which is a powdered mixture of graphite and manganese dioxide in which the carbon is imbedded in the center of the cell. The carbon projects over the top of the cup to which the terminal is secured. After the paste is packed in around the carbon and fills the cell, the whole is sealed with pitch to prevent the access of moisture and for mechanical protection. There is a small hole left in the pitch through which a small amount of water may be added if necessary and to allow the escape of gases.

The E. M. F. of the small cell, dry, is 1.5 volts with an internal resistance of not over .3 ohm, while the large cell has an E. M. F. of 1.5 volts and a resistance of not over .15 ohm.

Standard Cell.—The cell now used as a standard is one similar to the "Navy Reserve Cell," Type FFF, as manufactured by the National Electrical Supply Co., of Washington, D. C. This cell is entirely similar to other dry cells described above with the exception of the active material which is furnished in a perfectly dry state. The cell itself is of zinc which forms the anode and to which the terminal is secured. The cell is lined with an inactive material, and dry ammonium chloride and manganese dioxide in a powdered state fills the space in the cell between the zinc anode and the carbon cathode in the central portion. This latter is made in the form of a cylindrical tube perforated with holes. The upper portion of the carbon is fashioned like the neck and mouth of a bottle, to which the terminal is secured and in which fits a cork. The active material is kept intact by a layer of pitch, and the outer surface of this, as well as the neck of the carbon which protrudes through the pitch, are coated with a layer of paraffin.

In the dry state there is not intimate contact of the active materials and the cell is inert, but is rendered active by the addition of water through the mouth of the carbon. This makes a paste of the ammonium chloride, sal ammoniac, and of the depolarizer, manganese dioxide, and brings all into close contact. One cell requires about a gill of water. This cell should give about 1.5 volts and 10 amperes of current. The specifications for this cell require dimensions of $7\frac{1}{4}''$ high $\times 2\frac{1}{2}''$ diameter and when charged to show at least 1.45 volts at the terminal, measured with circuit closed through a resistance of 25 ohms at the end of 3 minutes.

Common Batteries.

Although the Leclanché type of cell is used almost to the exclusion of all others on shipboard, the following table may be useful as giving the characteristics of some of the standard common cells:

STATISTICS OF CELLS.

Class.	Name.	Anode.	Electrolyte.	Cathode.	Depolarizer.	E.M.F.	Remarks.
Mechanical depolarizer.	Volta.	Zinc.	Sulphuric acid (dilute).	Copper.	None.	.9	Polarizes rapidly.
Same.	Smee.	Zinc.	Sulphuric acid (dilute).	Platinized silver.	None.	1 to .5	Same.
Chemical depolarizer.	Bunsen.	Zinc.	Sulphuric acid (dilute).	Carbon.	Nitric acid.	1.9	Cathode and depolarizer in porous cup.
Same.	Grove.	Zinc.	Sulphuric acid (dilute).	Platinum.	Nitric acid.	1.9	Same.
Same.	Leclanché.	Zinc.	Ammonium chloride.	Carbon.	Peroxide of manganese.	1.48	High resistance about 4 ohms.
Electro-chemical depolarizer.	Daniell.	Zinc.	Zinc sulphate.	Copper.	Copper sulphate with crystals.	1.07	Cathode and depolarizer in porous cup.
Same.	Chloride of mercury.	Zinc.	Ammonium chloride.	Carbon.	Paste of mercurous paste.	1.45	Same. For small currents.
Same.	Chloride of silver.	Zinc.	Ammonium chloride.	Silver.	Silver chloride.	1.03	Used for testing.
Same.	Latimer Clark.	Zinc.	Paste of mercurous sulphate with zinc sulphate.	Mercury.	Electrolyte.	1.442	Standard cell for very small currents.

CHAPTER V.

SECONDARY BATTERIES.

There is no essential difference in principle between a secondary cell and a primary cell. A primary cell which is free from local action and which in operation retains in the cell the products of the electrical action is reversible and when the positive plate has wasted away, due to the chemical action required to supply the energy, it can be restored by passing a current through the cell from the opposite direction. This, of course, cannot be done in the case of those cells when some of the products of the chemical action are given off, as gas. A cell which is restored electrolytically by sending a current through it in an opposite direction and again used to supply electrical energy constitutes a secondary cell. Secondary batteries are combinations of such cells. Secondary cells are also called storage cells and accumulators. Cells of this class did not become of any commercial importance until after the experiments of M. Gaston Planté about 1860. Planté used a cell which was virtually a simple voltaic cell in which the zinc plate had been replaced by a plate of spongy lead and the copper plate by a plate covered with lead peroxide (PbO_2), the electrolyte being a solution of sulphuric acid. When this cell is supplying energy the acid is broken up into hydrogen (H) ions and sulphion (SO_4) ions. The hydrogen acts on the PbO_2, reducing it to PbO. This is then changed to $PbSO_4$ by the action of the acid. The (SO_4) ion acts on the spongy lead also forming $PbSO_4$. The result being that both plates are covered with a white film of lead sulphate ($PbSO_4$). If a current is now passed through the cell from the opposite direction the action is reversed, the anode or plate at which the current enters is oxidized and finally becomes covered with lead peroxide (PbO_2) while the H ions go to the cathode and unite with the (SO_4) ions of the lead sulphate to form sulphuric acid, leaving the cathode covered with pure spongy lead. When this operation known as charging is completed the cell is again in a condition to supply energy. The above description applies to any type of lead storage cell, the principle being the same, the cells differing of course in structural details.

In the Planté cell the process of "forming," which consisted in starting with two ordinary lead plates and changing the surface of one to PbO_2 and the other to a sponge-like form of pure lead, was very difficult. It required a long time and many reversals of current. In 1881 Faure suggested a type of pasted cell which would obviate this long "forming" process.

In the pasted cell, the active material usually in form of minium or red lead (Pb_3O_4) or litharge (PbO) is applied in the form of a paste (usually with some constituent to make it harden and adhere to the grid) and when the current passes through the cell the anode is oxidized, becoming (PbO_2), while the cathode is reduced first to PbO and then to spongy lead. The reactions that are usually considered to take place in the lead cell are as follows:

$$2PbSO_4 + 2H_2O = PbO_2 + Pb + 2H_2SO_4.$$

Reading from left to right represents the action on charging, and reading from right to left gives the reverse action upon discharge.

The capacity of a cell is the amount of energy in ampere hours that it is capable of delivering when fully charged. The output of a cell depends upon its rate of discharge and the capacity is usually based on an 8-hour discharge rate.

The capacity of cell varies with the amount of exposed surface of the active materials and great ingenuity is employed to have a large exposed surface of active materials without excessive weight. In all modern cells the plates consist of two parts, the grids or supporting forms and the active portions. As lead is the only commercial metal available that is not attacked by the acid practically all grids are made of lead, or of an alloy of lead containing a small amount of antimony to give stiffness. The active material is generally in the form of ribbons or corrugations in order to give a greater amount of exposed surface. Several positive plates and several negative plates may be used in each cell, all the positive plates being joined together by one bus and the negative by another. The outside plates are usually negative plates and hence the number of negative plates in a cell is one greater than the number of positive plates. It is necessary to use care to prevent contact of positive and negative plates and rubber or wood separators are used to keep the plates apart.

The container or the cell itself is usually made of glass for small batteries, while wood lined with lead is used for large batteries where glass would not be suitable. For portable batteries, jars made of hard rubber are used.

The relative advantages of the two types of plates are as follows: Planté are more durable and less liable to injury from abuse due to overcharging or overdischarging, but they are heavier, more costly, and occupy more space. Several manufacturers make the positive plates by some form of Planté process and use pasted negative plates. One disadvantage of the earlier forms of pasted plates was the liability of the active material becoming loosened and falling to the bottom of the cell. This defect has been overcome by skillful construction.

It is customary to call the plate which is anode while charging (the cathode on discharge) the positive plate or positive grid and the other plate the negative plate or negative grid.

Types of Plates.

Positive Plates.—The positive plates which are of a brownish color have lead peroxide PbO_2 for the active material.

The form of the Planté positive that has been most extensively used in this country is called the Manchester plate. (See Fig. 9.) Its construction consists of a grid of cast lead suitably alloyed for the purpose of making the plate rigid and to resist the forming effect of the electrolytic action. The grid contains a series of closely spaced circular openings about $\frac{1}{2}$ inch in diameter into which coils of pure, soft, corrugated lead ribbon are forced under pressure. By the "forming" process, the entire surface of these coils or buttons is formed into active material. The Planté positive is most suitable for batteries doing regular work; the all-lead form (see Fig. 10) where the service is mainly regulating and not otherwise too severe, and good attendance is given; the hardened grid form for irregular and trying operating conditions.

The Faure positive plate is constructed with a light alloy grid or ladder of lattice design into the interstices of which lead oxide in paste form is pressed to become the active material of the plate.

FIG. 9.—"Manchester" Positive Plate.

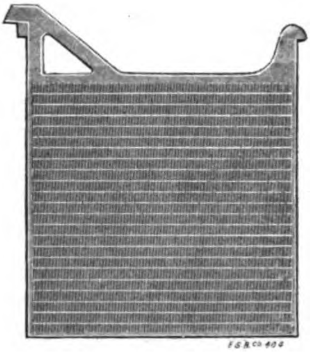


FIG. 10.—"Tudor" Positive Plate (all lead type).

FIG. 11.—"Exide" Positive Plate.

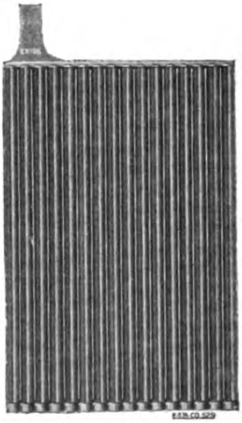


FIG. 12.—Exide Iron-clad Positive Plate.

This type allows a large amount of active material for a comparatively small space, hence it is possible to construct a sufficiently rugged plate of much less weight and size for unity capacity than a

Planté positive, better adapted for emergency service requirements where the demand is for high discharge rates of short duration occurring at infrequent intervals. The leading development of this type is called the Exide plate. (See Fig. 11.) A more rugged type of Exide positive plate is manufactured which permits of very trying service without injury. This is known as the Ironclad Exide and is illustrated in Fig. 12. From an ordinary cell of this type when fully charged as much as 1000 amperes of current can be taken for several minutes without damage to plates or excessive rise in temperature of cell.

FIG. 13.—Exide Negative Plate.

FIG. 14.—"Box" Negative Plate.

Negative Plates.

The negative plates, which are of grayish color, have spongy lead for their active material, and are also of both Planté and Faure types. Planté negatives are usually constructed in the same manner as the all-lead Planté positives.

Faure type negatives are mainly of two forms—those with ladder or lattice grids, similar to Faure positives (see Fig. 13), and another known as "Box" negatives. (Fig. 14.) The former are used in high capacity or emergency batteries. The "Box" negatives are so-called because the alloy grid is made up of a series of square pockets, with perforated sheet-lead covering, enclosing bricquettes of lead oxide which are formed into active material. Box negatives are used mainly in regularly worked batteries having Planté type positives.

Types of Secondary Cells.

Many patents have been taken out for secondary cells, but they may be generally classified in three classes:

1. Those in which the active element is formed from the substance of the plate itself, or from corrugated lead ribbons mounted in alloy grids.

2. Those in which the active element is formed from some reducible lead salt applied to the plate.

3. Those in which one element of class 1 is employed for one plate and an element of class 2 for the other.

The Electric Storage Battery Company of Philadelphia, the largest manufacturer of lead storage batteries in this country, make three general types of cells known as "The Chloride Accumulator," "The Tudor Accumulator" and the "Exide Cell." As this company has supplied the equipment for about 25 submarines and also many of the batteries used for gun firing and other purposes in the navy, a description of these cells should be of practical use and also give a good idea of lead storage battery construction.

In the "Chloride Accumulator," "Manchester" positive plates and Box negative plates are used. (See Figs. 9 and 14.)

In the "Tudor Accumulator" "Tudor" positives and "Box" negatives are used and in the "Exide" cell both positive and negative plates are constructed on the Faure principle as illustrated above. In the "Ironclad Exide" cell the positive plates, while constructed on the Faure principle, are very strong mechanically and capable of standing much abuse without injury.

The illustrations below show two standard types of the assembled cells of this company.

In Fig. 15 is shown the standard glass jar assembly. The positive and negative groups consisting of several plates each. In this figure is also shown one type of wood separator used to keep the plates apart. In other batteries a different type wood separator is used for this purpose. The glass sand tray generally used to insulate this type of cell is also shown. In Fig. 16 is shown the standard tank assembly illustrating the lead-lined wooden tanks used for large batteries. The tank is shown mounted on proper insulators.

Great care must be exercised in the manufacture of wooden tanks. The wood used must be well seasoned and strong enough to require

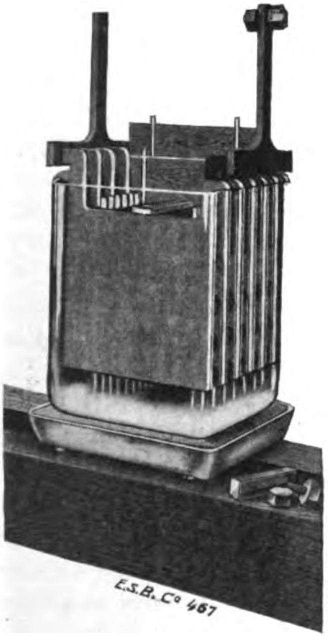


FIG. 15.—Glass Jar Assembly.

FIG. 16.—Tank Assembly.

no exterior bracing. The ends and side walls are joined with dovetail and dowel corners. The tanks are reinforced under the bottom with wooden strips. The lining is of sheet lead, all seams being burned together by flowing the lead with a non-oxidizing flame. Solder must never be used in making joints. The lining extends over the top of the tank projecting downward clear of the woodwork (see Fig. 16) and is shaped so that any electrolyte that may accumulate on the edges will drop clear of tanks and supports.

In Fig. 16 is shown a cell cover which consists of a piece of rough sheet glass about ¼ inch thick. The chief objects of this cover are to reduce the amount of acid spray given off while the cells are "gassing" and decrease the evaporation of the electrolyte. The spray condenses on the under side of the cover and drops back into the tank. The cover also assists in preventing impurities from dropping into the electrolyte.

The Battery.

A battery consists of a number of cells connected in series. The number depending upon the voltage to be supplied. At the normal discharge rate the voltage of each cell in operation varies from about 2.05 volts when fully charged to about 1.75 volts when requiring recharging. It is apparent, therefore, that a varying voltage will result from a battery consisting of a definite number of cells depending upon the state of charge.

For ordinary house batteries with a very low rate of discharge this may not be important, but where a steady voltage is desired some method of regulation must be devised.

Regulation of Voltage at Discharge.

The simplest method is to use a resistance in the battery circuit but this is objectionable because of the waste of energy.

A common method is to have in addition to the regular battery a number of extra cells so arranged that when on discharge the voltage of the battery falls, these cells may be switched in one at a time in series and in this way keep up the total electromotive force of the battery. These cells are called **end cells**. The terminals of these cells are connected to contact points arranged in a circle over which moves a contact arm, which by moving one way or the other acts to raise or lower the total voltage by varying the number of cells in series.

In switching from one point to the next, the circuit must not be opened, for the switch contacts would suffer by sparking, nor must the contact arm touch two adjacent contacts as this would short circuit the cell to which these terminals are connected. The end cell switches are provided with an auxiliary contact either on the movable arm or fixed near each main contact. The main and auxiliary contacts are joined by a resistance, and the auxiliary contact rests on one of the switch contacts while the main contact touches the adjoining point. By this means the circuit is not broken, being completed through the resistance which has too low a value to affect materially the line potential, but is sufficiently great to prevent the cell from being short circuited.

Battery Location.

Location.—The proper location of a battery is important. It should preferably be in a separate compartment well ventilated, dry, and of moderate temperature. The ventilation should be free not only to insure dryness, but to prevent a chance of an explosion, as the gases given off while charging form an explosive mixture if confined. For this reason never bring an open light near the battery when it is gassing. The jars should be arranged in tiers where each jar will be accessible. They should be in one tier if practicable and if not, overhead space as great as the height of a jar should be provided.

Electrolyte.—The electrolyte of a cell is a solution of sulphuric acid and water of from 1.240 to 1.300 specific gravity for batteries with Faure positive plates and approximately 1.210 for batteries with Planté positives. When making the solution care must be taken that the acid is poured gradually into the water and that the acid and water contain no elements that would injure the plates. The electrolyte should be tested for traces of iron, chlorine, nitrates, copper, mercury, arsenic and acetic acid. If the test shows the presence of any of the above in considerable quantities it should be replaced by fresh electrolyte free from these impurities.

Capacity and Output.

Practically the only limit to the current which a secondary cell will give is the resistance to which it is connected, as the internal resistance of the cell itself is very low, in some cells amounting to a few ten-thousandths of an ohm.

The current that can safely be taken from a cell depends on the type of cell and the total area of the positive plates, counting both sides, and is rated as so many amperes per square foot, and in different types and makes may vary from 5 to 100 amperes per square foot.

The capacity of a cell is rated in either **ampere hours** or **watt hours.**

The capacity of a cell depends upon several things, viz.: (1) Rate of discharge. (2) Porosity of active material. (3) Arrangement of active material. (4) Quantity of active material. (5) Strength of electrolyte. (6) Temperature of electrolyte.

As the rate of diffusion is practically independent of the current, the absorption of acid by the active material is not accelerated in proportion to the rate of discharge. It follows, therefore, that with increased rates of discharge the voltage of the cell must necessarily fall more rapidly and the limit of its capacity be reached at a lower ampere-hour output. This does not mean that all the active material has been sulphated, for, as a matter of fact, by lowering the rate the discharge can be continued for a considerable time.

The value of porosity to permit of sufficient and rapid supply of acid to the material throughout its mass while undergoing discharge is therefore apparent.

Where batteries are to be called upon principally for high rate of discharge, the arrangement of material should be such that it does not require great depth of penetration for the electrolyte. The material should therefore be more thinly distributed over a greater area of surface of exposure to the electrolyte. Depth of active material is therefore of no special value for the high rates of discharge used in stand-by practice, but is of value for medium and low rates of discharge where enough time elapses for acid diffusion.

Quantity of active material has no value as to capacity further than its ability to be acted upon by the electrolyte; in other words, if by reason of high rates of discharge, or lack of porosity or both, the active material underlying does not receive the needed supply of acid, it becomes incapable of giving out further discharge, and the fact that there is a large quantity of material is then of little moment.

The strength of the electrolyte has some influence on the capacity, in so far as the average voltage of a cell is somewhat higher if stronger electrolyte is used. But experience has shown that the life of the plates is materially shortened if they are worked in acid of higher specific gravity than that advised by the manufacturers.

The capacity also varies quite proportionately with changes of temperatures of the electrolyte, increasing with a rise and decreasing with a fall of temperature.

This accounts for the fact that better results are obtained by using electrolyte of somewhat lower specific gravity than normal in the batteries of submarines operating in tropical waters and subject to high temperatures.

Efficiency.—The efficiency is the ratio of output to input and

$$\text{Ampere-hour efficiency} = \frac{\text{ampere hours given out}}{\text{ampere hours put in}}, \text{ and}$$

$$\text{Energy efficiency} = \frac{\text{watt hours given out}}{\text{watt hours put in}}.$$

Local Action.—Even when a storage battery is on open circuit chemical changes slowly take place in its elements which affect the state of charge, reducing its immediate available capacity. This may be detected by a drop in the specific gravity of the electrolyte. This is called local action and causes a slow internal discharge, which corresponds to local action in a voltaic cell.

The local action in a lead cell in good condition is commercially negligible, since after several weeks standing, a battery will give from 90 to 100 per cent of its capacity without recharge.

Operation.

Initial Charge.—New battery plates as received from the factory are generally in a more or less sulphated condition, particularly the negative plates. When these plates are assembled in the cells and covered with electrolyte, the amount of sulphate increases somewhat on the positive and very considerably on the negative plates. This is evidenced by a drop in the specific gravity of the electrolyte, due to some of its sulphuric acid being extracted in the sulphating of the plates. The purpose of the initial charge, which is the last step in preparing the battery for service, is to completely convert this sulphated active material of the positive plates into peroxide of lead and of the negative plates into spongy lead.

The manner of giving the initial charge is described in a book of instructions issued by the manufacturer. The method of procedure and the duration of the charge depend upon the construction of the plates and therefore specific instructions are required for each type of cell.

Specific Gravity.—As the specific gravity of the electrolyte falls while discharging and rises while charging, it affords a convenient means of following the operation of the battery. Proper operation is very necessary, **as both overdischarging and excessive overcharging are very injurious to the plates and, if persisted in, will shorten their life.**

The specific gravity of all cells in a battery on discharge and charge falls and rises together, so that a reading of the electrolyte of one cell, termed the "Pilot Cell," will indicate quite accurately the state of discharge or charge of the battery as a whole at the time the reading was taken.

Pilot Cell.—For a pilot cell select an accessible cell about the middle of the battery and keep the level of the electrolyte at a fixed point ($\frac{1}{2}$ inch above the plates) by adding a little water at frequent intervals. The proper height for the electrolyte can be indicated by a paint line on the jar. As changes in the temperature affect the specific gravity the hydrometer readings should be corrected by adding one point for each three degrees of temperature above 70° F. and subtracting one point for each three degrees below. Compensated hydrometers are sometimes furnished which automatically correct for variations in temperature.

The proper variation in specific gravity of the electrolyte from the full-charged to the discharged condition of the battery is generally contained in the book of instruction furnished by the manufacturer. This variation differs for different types and rate of discharge. For cells using Planté positives the variation in specific gravity at normal discharge rate is from about 1.210 to 1.180. For some cells using Faure positives the variation may be from about 1.280 to 1.150.

Ampere Hour Meter.—A battery may be supplied with an ampere hour meter whose readings will show the output of the battery since charging.

The dial often contains the markings "full" and "empty" and as the hand approaches the latter it is time to recharge.

Discharging.—As previously stated the electrolyte in a cell is a solution of sulphuric acid (H_2SO_4) and distilled water (H_2O), and if the cell is fully charged the active material in its plates consists of lead peroxide (PbO_2) in the positives and of pure spongy lead (Pb) in the negatives. During a discharge a chemical reaction takes place according to the formula:

$$PbO_2 + Pb + 2H_2SO_4 = 2PbSO_4 + 2H_2O,$$

or, in other words, during the discharge the sulphur radical (SO_4) of the electrolyte unites with the lead peroxide of the positive plates and with the pure lead of the negative plates, forming in each of them lead sulphate ($PbSO_4$). The extraction of the sulphur radical from the electrolyte and the simultaneous combination of the oxygen and hydrogen forming water reduce the strength of the electrolyte, as may be noted by the decrease of its specific gravity.

The voltage of the cell falls during a discharge due, mainly, to the inadequate diffusion of the acid throughout the active material, to the increase of the internal resistance, and to the weakening of the electrolyte. The chemical changes which take place in a cell during discharge demand a constant renewal of acid in the plates by diffusion, to combine with the lead peroxide and pure lead, and the demand continues throughout the conversion of active material.

The internal resistance of a cell increases as the discharge progresses, mainly because of the formation of lead sulphate in the active material, which is of higher resistance. This, of course, reduces the terminal voltage of a cell depending upon the current output. It should be noted here that the principal reason for the large reduction in terminal voltage, when a high discharge rate is used, is that owing to the rapid extraction of acid from the electrolyte and imperfect diffusion, the portion of the electrolyte in contact with the active material is greatly reduced in strength. It is of vital importance not to continue the discharge beyond the legitimate working capacity of the battery. The specific gravity of the electrolyte, the individual voltage of the cells, the ampere hour meter, and terminal voltage of the battery at the known rate of discharge all serve to indicate the state of charge of battery. It is a good idea to recharge when about two-thirds or three-fourths of the capacity has been delivered. The *most fruitful source of injury to a storage battery is overdischarge.*

Charging.—To charge, a direct current is made to pass through the cells in a direction opposite to that of discharge. This current, passing through the cells in the reverse direction, will reverse the action which took place in the cells during discharge. It will be remembered that during discharge the acid of the electrolyte went into and combined with the active material, filling its pores with sulphate and causing the electrolyte to become weaker. Reversing the current through this sulphate in the plates restores the active material to its original condition and returns the acid to the electrolyte. Thus, during charge, the electrolyte gradually becomes stronger as the sulphate in the plates decreases, until no more sulphate remains and all the acid has been returned to the electrolyte, when it will be of the same strength as before the discharge and the same acid will be ready to be used over again during the next discharge. Since there is no loss of acid, none should ever be added to the electrolyte.

The acid absorbed by the plates during discharge is, during charge, driven from the plates by the charging current and restored to the electrolyte. This is the whole object of charging.

There are many different methods of charging a storage battery, but all methods are essentially the same in principle; that is, to pass direct current through the cells in the right direction. In the use of this current, there are only two points to be considered—rate in amperes and time.

The rate in amperes is limited by the state of discharge. When a battery is fully discharged, at which time the plates contain the greatest amount of sulphate, it can utilize current at the highest rate. As the charge progresses and the amount of sulphate in the plates decreases, they can no longer utilize current at the same rate and the current should be reduced. The time at which to reduce the current is when the cells begin to give off gas.

The gassing of a cell is a feature of charging which has been very little regarded, but is of great importance. Gassing shows at any time whether or not the charging rate is too high.

Current passing through an electrolyte will always do something. It will always do the easiest thing first. When a charging current is passing through a discharged cell, the easiest thing is to decompose sulphate. As there is a comparatively large amount of sulphate in a fully discharged cell, a high rate of current can be used; but as the amount of sulphate decreases a point will be reached at which there will not be sufficient sulphate remaining in the plates to utilize all the current passing through. The excess current will then begin to do the next easiest thing, which is to decompose the water of the electrolyte, producing gas and, therefore, when the cells begin to gas freely, it indicates that the current is being passed through the cells at too high a rate and the current should be lowered sufficiently to stop the gassing. As the charge is continued at the lower rate, the remaining sulphate will continue to decrease in amount until there is not sufficient left to utilize this rate of current and the cells will again begin to gas. The current should be lowered each time the gassing begins. When the cells begin to gas freely at a very low rate, it indicates that there is no sulphate remaining, so that even this very low rate of current cannot be utilized, and the charge is completed.

It is apparent from the above that when it is desired to charge a battery in a minimum time a high current rate may be used at first when the cell is in the fully discharged condition. This method, however, requires very careful supervision for if this high rate is continued too far violent gassing will take place and injury to the plates will result. Most manufacturers recommend using the normal rate for charging, but state that a rate about 40 per cent greater than the normal 8-hour discharge rate may be used at the beginning, but that the rate must be reduced to normal rate as soon as gassing commences.

In regular operation there are two kinds of charges to be given the battery as follows: The "regular charge" given as often as necessary in order to recharge the battery after discharge, and the "overcharge" which is merely a continuation of the "regular charge," and is given chiefly for the purpose of keeping the battery in good condition by equalizing any irregularities which may develop. An overcharge should be given at intervals of one or two weeks depending upon the use of the battery. If possible, the battery should be charged at regular periods. A little experience will soon show how often charging is necessary. The normal rate should be used throughout the regular charge when conditions permit; but if it is necessary to hasten the charge a high charging rate may be used during the first part of the charge, that is, until the cells begin to gas, when it should be reduced to normal. Do not charge at a higher rate than normal after the cells are gassing. Charge until the specific gravity of the pilot cell has reached a point which is about three to five points below the maximum reached on the preceding overcharge. Thus, if the gravity reached on the last preceding overcharge is 1.209, the regular charge for the next week should be cut off when the gravity has risen to about 1.204 to 1.206. The cells should all be gassing moderately at this time, that is, not quite so freely as on the overcharge.

If when the discharge limits are reached or approached there is not time to complete the charge, a partial charge may be given. Care should be taken, however, to complete the charge at the first opportunity.

For the "overcharge" continue the "regular charge" until the specific gravity of the pilot cell shows no rise over a period of one hour and all cells have been gassing freely for the same length of time. Keep a record of this maximum reading of the pilot cell specific gravity to be used as a guide in stopping subsequent regular charges.

To replace evaporation from the electrolyte use only pure water, this should be added often enough (preferably just before the overcharge) to keep the plates covered; do not, however, fill the cells too full.

"Sulphated" Battery.

During any discharge of a battery, there is being formed sulphate of lead, without which there would be no production of current. If, however, charging is neglected, the sulphate reaches a condition which tends to fill the pores of the plates and make the active material dense and hard. It is this condition which is ordinarily referred to as "sulphated."

The cause of this condition is some form of abuse, such as: standing discharged for some length of time; habitual undercharging; neglecting evidence of trouble in individual cells; replace evaporation with electrolyte, thereby restoring the specific gravity by adding acid to the cell instead of bringing it out of the plates by proper charging.

The lead sulphate formed in a normal discharge of a battery is in a form in which it absorbs the charge very readily. When a battery is "sulphated" as ordinarily expressed, the sulphate is then in a condition to absorb the charge with difficulty and the ordinary charge is not sufficient. Continued and persistent charging at a low rate will restore any condition of sulphate, the time being in proportion to the degree to which the condition has been allowed to extend. It is a question of time, since a higher rate will only produce gassing and high temperature, the low rate being all which the battery in this condition is capable of using.

If the sediment in a battery has not been allowed to reach the bottom of the plates and the level of the electrolyte has been properly maintained by replacing evaporation with pure water, the battery can be "sulphated" only because it has not been properly charged or because acid has been added to the electrolyte. An individual cell may become "sulphated" by an internal short circuit or by drying out such as might be caused by failure to replace evaporation with water or failure to promptly replace a broken jar.

To determine whether a battery is "sulphated," when it is known that it does not need cleaning, give it the ordinary overcharge and then discharge it at the normal rate.

If the rated capacity is not obtained, recharge the battery in the regular way at a rate as near one-half its normal rate as the charging apparatus will permit. If the temperature reaches 110° F., reduce the current or temporarily interrupt the charge so as not to exceed this temperature.

A battery is "sulphated" only when acid is tied up in the plates. When the specific gravity of the electrolyte has reached a maximum, it shows that there is no more sulphate to be acted upon, since during charging the electrolyte receives acid from no other source. Hydrometer readings should be recorded at regular intervals of one or two hours to determine if the specific gravity is rising or if it has reached its maximum. Continue the charge, recording the readings until there has been no further rise in any cell during a period of from 5 to 10 hours. Maintain the level of the electrolyte at a constant height by adding water. Hydrometer readings should be corrected for any considerable change in temperature. Should the gravity rise ten points above the normal in any cell, draw off its electrolyte down to the top of the plates and put in as much water as possible without overflowing. Continue the charge and if the gravity again goes up ten points above the normal it shows that acid has been added during the previous operation of the battery and some of the electrolyte should be emptied out, replaced with water and the charge continued.

The treatment can be considered complete only when there has been no rise in the gravity of the cell during a period of from 5 to 10 hours of continuous charging.

Upon completion of the treatment, the specific gravity of the electrolyte should be adjusted to its proper value using water or new electrolyte of normal specific gravity, as may be necessary.

If only a few individual cells have become "sulphated" while the balance of the battery is in good order it is better to remove such cells and treat separately.

The active material of "sulphated" negative plates is generally of light color, and either hard and dense or granular and gritty and easily disintegrated. It is the negative plates which require the prolonged charge necessary to restore a "sulphated" battery.

"Sulphated" positives, unless physically disintegrated or badly buckled, are but little changed in general appearance and can be restored to operative conditions, although their life will not be as great as if they had not been subjected to this abuse.

Care and Maintenance.

A battery should be completely charged, but excessive charging must be avoided. A cell must never be overdischarged or allowed to remain in a discharged condition.

The accumulation of sediment in the bottom of the jars must be watched and not allowed to get up to the plates, for if this occurs, serious injury will result, due to short circuits between plates. To remove the sediment proceed as follows: Fully charge the battery, lift out the plates from one cell, draw off the electrolyte into a glass jar or earthenware vessel, wash out the sediment; replace the plates and fill with electrolyte as quickly as possible, so that there will be no chance of the plates or separators drying out. As there will be some loss, new electrolyte of normal specific gravity will be required to complete the filling of the cell. Then in the same manner clean the next cell and so on throughout the battery. If gravity is then found to be low it should be restored to standard, by the addition of electrolyte instead of water to replace evaporation. When the work is completed, charge until all cells have been gassing freely for 10 hours.

Read the specific gravity of each cell with the hydrometer at the end of the overcharge and record the readings in a blank book.

Carefully look over all cells just before the overcharging and make sure that there are no short circuits, either between the plates or hanging lugs. Short circuits may be caused by positive and negative plates touching or by an accumulation of material lodging between them. Pay particular attention to cells which gas lower than surrounding cells at the end of the charge, and to cells which read lower than the others as shown by the cell readings. Any short circuits discovered must be removed at once with a wooden stick. Never use metal.

Indications of Trouble.—The following are indications of trouble which may occur in the cells:

(1) Falling off in specific gravity of a cell compared with surrounding cells.

(2) Lack or deficiency of gassing on regular charge or overcharge as compared with the rest of the cells.

(3) Color of plates markedly lighter or darker than in surrounding cells. If any of the above symptoms are noted, inspect the cells in question at once for short circuits.

Instruments.—The following instruments should be provided for the proper care of the battery:

(1) Voltmeters to give terminal voltage of battery and voltage of charging current.

(2) Ammeters to indicate charging current and discharge rate.

(3) Low reading portable voltmeter for ascertaining voltage of individual cells.

(4) Hydrometer with proper graduations to cover the variations in the specific gravity of the electrolyte.

(5) A mercurial thermometer, Fahrenheit scale, for taking the temperature of the electrolyte.

In addition to the above, the following instruments are of value in the care and operation of a battery:

(1) One ampere hour meter to show the condition of charge of the battery.

(2) A cadmium tester to ascertain the electrical condition of the individual plates.

The Cadmium Tester.

This instrument is used in the expert examination of a cell, which fails to give its rated capacity, to determine to which plate the cause may be attributed. It requires a great amount of experience in the use of a cadmium tester to render it of any value and for this reason it is seldom used. Not only do the readings have to be most carefully taken, but they must be correctly interpreted or they will be misleading. As the principle involved is of interest, the following explanation is given:

When a lead cell is discharged to the point that the voltage between plates is about 1.8 volts, it should be considered as fully discharged. This voltage is the difference of potential between the plates, and depends on the state of charge on both plates. Similarly when fully charged the voltage between plates should be from 2.5 to 2.7 volts. If one plate is fully charged and the other but imperfectly charged, the capacity of the cell is affected. Both plates should be fully charged, and while the difference of potential between them may be obtained by a voltmeter, this will not suffice to determine whether each is fully charged. To determine the state of charge on each plate, recourse is had to the cadmium tester. This consists of a stick of pure cadmium, which should be free from impurities and should never be scraped bright. It is well to have it protected by a hard rubber tube perforated with holes to avoid a short circuit by touching either of the plates when immersed in the electrolyte.

At the end of the charge the voltage between the cadmium electrode and the positive plate should be from 2.3 to 2.5 volts and between the cadmium electrode and the negative plate about .20 volt, the voltage reading being in an opposite direction to that between the cadmium and positive plate. This gives a voltage difference between the positive and negative plates of 2.5 to 2.7 volts. When fully discharged the voltage difference between cadmium and positive plate should be about 2.05 volts and between cadmium and negative plate about .25 volt, the voltage readings being in the same direction in both cases and hence the voltage difference between positive and negative plates when fully discharged will be $2.05 - .25 = 1.8$ volts.

Series and Parallel Charging.—The source of charging voltage must be at least slightly greater than the voltage of the whole battery, calculated on a basis of 2.7 volts per cell. Thus, if a battery of 50 cells is to be charged in series, a source of at least $50 \times 2.7 = 135$ volts must be available.

If the source of voltage is not sufficient to give the proper charging current against the counter E. M. F. of the battery, the battery may then be charged in parallel. Thus, suppose a 110-volt circuit was available to charge 50 cells and the desired charging current was 10 amperes; the 50 cells could be divided into two groups of 25 each, making a maximum counter E. M. F. of $25 \times 2.7 = 67.5$ volts. On first starting the charge, the counter E. M. F. would be $25 \times 2.1 = 52.5$ volts, and with a 10-ampere current, a resistance of $\frac{110 - 52.5}{10} = 5.75$ ohms would have to be inserted in each charging line. As the counter E. M. F. increased, the inserted resistance would have to be reduced to keep the charging current constant. After being charged in parallel, by a proper arrangement of switches, the battery can be discharged in series, and the full potential utilized. After charging, the voltage of each cell will fall to a little over 2 volts on open circuit, and to 2 volts or a little less on closed circuit at normal rate of discharge.

If a 220-volt circuit was available, the battery could be charged in series, and would require $\frac{220-135}{10}=8.5$ ohms in the line at the end of the charge.

It is customary to use a fixed resistance in the charging line which permits a charging current of about 40 per cent above the normal rate at the beginning of the charge. As the charging proceeds this rate is reduced, due to the increase in the counter E. M. F., and reaches the normal rate or perhaps a little less when the charge is completed. If a constant or reduced charging rate is desired, a rheostat or variable resistance may be used and adjusted from time to time so as to maintain the desired current reading as indicated by an ammeter placed in the circuit.

Boosters.—If the source of voltage is not sufficiently high to overcome the counter E. M. F. of the battery and it is not desired to charge in parallel, other means must be used to help the charging voltage, and machines for doing this are called **boosters.**

An ordinary form of booster for this purpose consists of a shunt generator with its voltage regulated by its field regulator. This may be run by any means available, preferably by a motor, and so arranged in the circuit as to add its voltage to that of the charging source. By varying the field of this booster generator, the charging current can be kept approximately constant.

The Use of Secondary Batteries.

The use of secondary batteries for commercial purposes is increasing rapidly. They are used in power stations for various purposes such as regulation of output, as an equalizer on the three-wire system, etc. Very large numbers are used for motor vehicles and to supply light and power at points not reached by the regular distribution circuits. They are used on board army transports, light-house tenders, cable ships and other vessels to supply the energy for operating radio transmitting sets.

In the vessels of the navy, secondary batteries are used for an auxiliary lighting system for dynamo rooms, central stations and substations and for gun firing and other important purposes. They are also used to supply the motor power for submarines when running submerged.

Gun-Firing and Sight-Lighting Batteries.—The batteries used for gun firing and sight lighting are of two classes, viz.: the Exide and the " Edison."

A description of the Edison battery is given in the latter part of this chapter. The Exide battery consists of five three-plate cells, rubber jars being used for containers. The five cells are placed in a

FIG. 17.—Gun-Firing and Sight-Lighting Battery.

wooden case with an alloy sheathing. The complete battery ready for use is shown in Fig. 17. The capacity of the battery is 20 ampere hours at a discharge rate of 1 ampere.

The general principles governing the care and operation of this battery are the same as outlined heretofore for large batteries. Specific instructions applicable to this type of battery are issued by the Bureau of Ordnance (Ordnance Pamphlet No. 347). These instructions should be carefully followed to insure satisfactory service.

Edison Storage Battery.

(NOTE.—All Edison storage cells for use in government service are manufactured especially for that service, and each is designated by the letters "ANS" stamped on the filler cap. Only such cells as are so designated are accepted by inspectors.)

The elements of a unit of the Edison storage battery consists of compounds of nickel and iron, the former being securely packed into and retained by reinforced perforated steel tubes: The latter, by perforated steel pockets. The tubes and pockets are mounted on steel grids, placed in an alkaline solution, and contained in a welded nickelled steel can.

The Edison storage battery is possessed of very rugged characteristics throughout.

There are four types—A, B, M and S.

The plates of Types A, B and M are thicker than those of the heavy duty, Type S. (Submarine.)

The A types are made up in six sizes (see table following), varying from 150 ampere-hour to 450 ampere-hour capacities, and are used principally for the propulsion of electric vehicles, electric locomotives, electric launches, wireless station reserve, isolated lighting, railway car lighting, telephone circuits aboard ship, etc.

The B types are of approximately half the height of the A types, and are made up in three sizes, the capacities varying from 40 ampere hours to 120 ampere hours. They are used principally for launch ignition and lighting, automobile lighting, isolated lighting plants, "cranking" internal combustion engines, sight lighting and gun firing, electric warning signals, etc.

When specified for use where only occasional opportunity is offered for replenishing solution with water, the A and B sizes can be secured in *high cans,* with an excess of solution, and without extra cost.

The M type is very small, and of relatively small capacity. Used principally in portable electric lanterns, etc.

The S types are designed especially for submarines, electric cranes, large electric locomotives, central station standby service, etc. They are made to order, to conform to specified conditions, and range in capacity from 900 A. H. to 10,000 A. H. and greater, if necessary.

TABLE OF DATA.

TYPES B, A AND M CELLS.

(NOTE.—The numeral following the Type letter indicates the number of positive plates in the various sizes of cells.)

	B-2.	B-4.	B-6.	A-4.	A-5.	A-6.	A-8.	A-10.	A-12.	M.
Normal ampere hour output.	40	80	120	150	187.5	225	300	375	450	4.5
Average discharge voltage per cell	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Rate of charge, amperes for 7 hours	8	16	24	30	37.5	45	60	75	90	1
Normal rate of discharge, amperes	8	16	24	30	37.5	45	60	75	90	.45
Length, per cell, inches	1.5	2.6	3.81	2.69	3.23	3.81	5.06	6.19	7.37	2.56
Width, per cell, not in tray, inches	5.12	5.12	5.12	5.12	5.12	5.12	5.25	5.5	5.5	1.34
Height of container, inches	7.81	7.81	7.75	12.37	12.5	12.37	12.62	12.62	12.75	5.87
Height of cell overall, not in tray, inches	8.75	8.75	8.87	13.44	13.57	13.44	14.00	14.00	14.62	6.5
Weight of complete cell in pounds	4.60	7.35	10.5	13.5	16.8	19.2	27.5	34.0	40.8	15 oz.

Fig. 18 shows a positive plate, and Fig. 19 a negative plate. Fig. 20 is an assembly, before being inserted in its can.

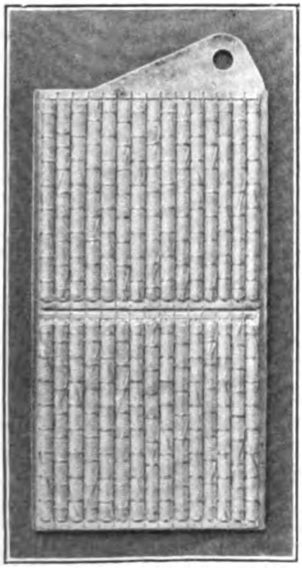


FIG. 18.—Positive Plate.

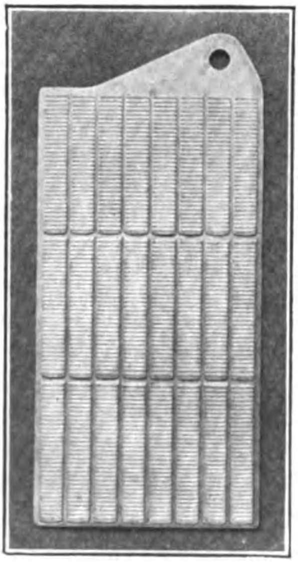


FIG. 19.—Negative Plate.

Each Type A-4 cell is composed of four positive and five negative plates. The plates are spaced at their edges, insulated from the container by slotted hard rubber insulators and supported by hard rubber insulators from the bottom of the can. The positives and

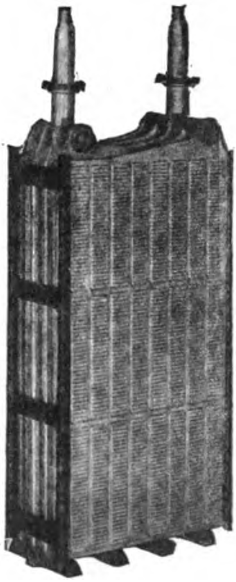


FIG. 20.—Type A-4, Cell Assembled but Entirely Removed from Container.

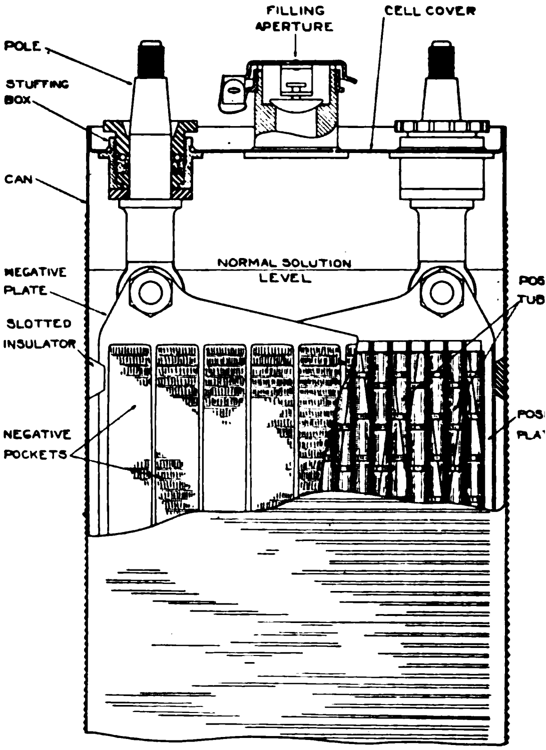


FIG. 21.—Section of an Edison Cell.

negatives are further insulated one from the other by vertical hard rubber pins, between plates of opposite polarity.

Fig. 21 shows a partial section through a cell.

The Positive Plate.—The positive plate (see Fig. 18) consists of 30 finely perforated reinforced steel tubes, supported by a sheet steel grid. The tubes are drawn from a perforated ribbon of nickelled steel, and have a spirally lapped seam. The active material, nickel hydrate, is loaded into each tube in 350 layers, the layers being separated by layers of pure metallic nickel in the form of very thin flakes. These layers of metallic nickel serve to increase the conductivity of the mass of active material. After being loaded, each tube is reinforced by eight steel rings, which are forced over and equidistantly spaced, thereby additionally strengthening the tube against expanding away from and breaking contact with the active material and metallic nickel layers.

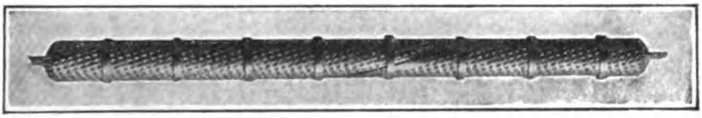


FIG. 22.—Positive Plate Tube.

The tubes are flattened at each end and clamped beneath the teeth of the supporting grid by hydraulic pressure, insuring excellent contact between tube and grid. Fig. 22 shows one of these positive tubes.

The Negative Plate.—The negative grid (see Fig. 19) consists of 24 flat, perforated, rectangular pockets, mounted in the sheet

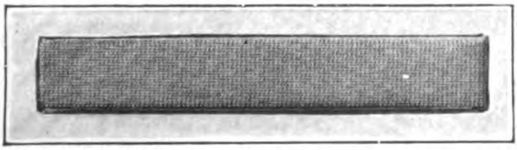


FIG. 23.—Pocket for Negative Plate.

steel supporting grid. These pockets are made up of very finely perforated nickelled steel and contain the active material, iron oxide, and a small amount of mercury to increase the conductivity of the oxide. After the pockets are filled and inserted into the grid, they are subjected to great pressure, between dies, which forces them into excellent contact with the active material, and clamps the edges around the supporting grid members. Fig. 23 illustrates a negative pocket.

The positive plates are assembled on a nickelled-steel rod, which supports the positive pole or terminal of the cell. The plates are properly spaced by suitable nickelled-steel washers, and are clamped in place by two nuts, one on each end of the rod.

The negative plates are similarly assembled, the slotted hard-

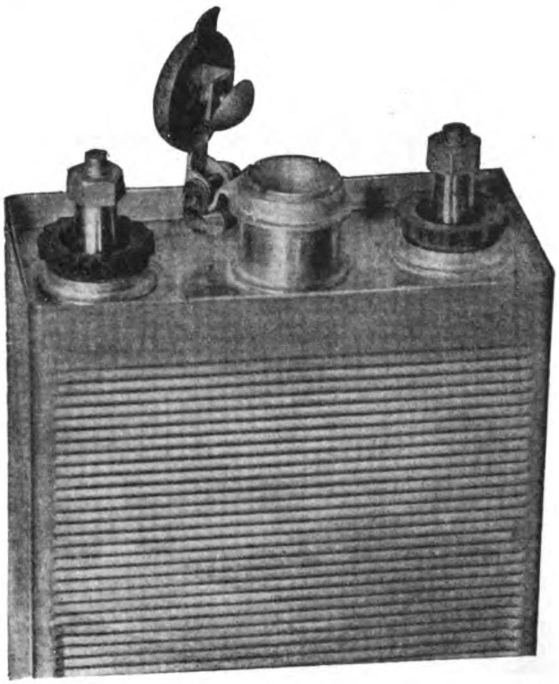


FIG. 24.—Top of A-4 Edison Cell with Gas Valve Open for Filling.

rubber side insulators are put into place, and the pocket and tube insulating pins inserted between the plates.

The complete group (see Fig. 20) is then ready to be placed into its can. The can is made from nickel-plated cold-rolled steel, with the bottom and side seams welded by the oxy-acetylene process.

Fig. 24 illustrates the top of a Type A-4 cell, with gas valve open for filling.

Fig. 25 shows four A-4 cells in tray. The number of cells assembled in a tray conforms to requirements.

All steel parts of the cell are nickel plated, the plating being *welded* to and amalgamated over the surface of the steel by intense heat in an atmosphere of hydrogen, thus precluding any possibility of porous plating or imperfect electrical contact.

The poles of the cell protrude through the stuffing boxes, and are insulated therefrom by hard-rubber washers (see Fig. 21). The

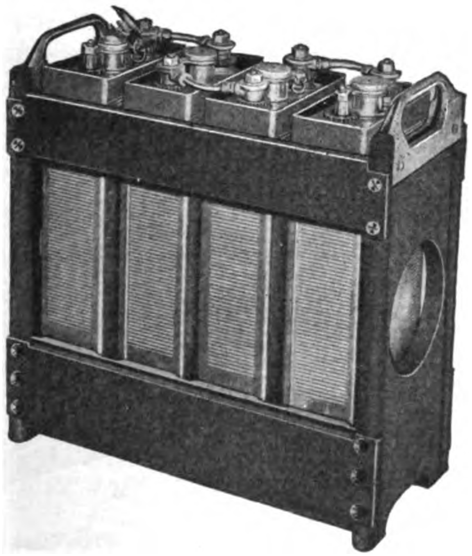


FIG. 25.—Four A-4 Cells in Tray.

soft-rubber packing around the pole effectually seals the cell against loss of electrolyte at these points.

The filling aperture provides a vent for the escape of the non-irritating, non-corrosive gas, and a convenient opening for replenishing of the electrolyte with water. It is provided with a hinged lid having a spring which holds it in an open or closed position. (See Fig. 24.)

The Electrolyte.—The electrolyte in which the cells are immersed consists of a 21 per cent solution of caustic potash (*KOH*) which contains a small amount of lithium ($LiOH$). The normal specific gravity of a 21 per cent solution of KOH is 1.200, and this does not change during charge or discharge. *Potash is a preservative of steel, and also of nickel and iron oxide.* As the Edison cell is composed entirely of nickel, iron oxide and steel, submerged in a solution of potash, there can be no undue deterioration in use or out of

FIG. 26.—Five-Type B-2, Cells Mounted on Tray and Placed in Steel Box.

FIG. 27.—Five-Type B-4, Cells Mounted Tray and Placed in Steel Box.

use. *It is for this reason that the Edison cell can be left in a charged, partly discharged, or wholly discharged condition indefinitely, without injury.*

Figs. 26 and 27 illustrate the commercial forms of the Types B-2 and B-4 ignition sets, respectively. Each consists of five cells placed in a suitable tray, said tray being placed in a steel box.

Chemical Reactions.—There are no complicated chemical changes within the cell. The positive active material, nickel hydrate, goes to an oxide on the first charge, in which the nickel has a higher valency and never reduces to its original state on future cycles. On every cycle, the negative plate changes to metallic iron on charge, and goes back to its original form, iron oxide, on discharge.

On first charge nickel hydroxide is converted to a high oxide, probably NiO_2, and the iron oxide or hydroxide is reduced to metallic iron.

On discharge the nickel oxide, NiO_2 of the positive is reduced to Ni_3O_4, and the iron of the negative is converted to Fe_3O_4. Upon recharging the products NiO_2 and Fe are again formed.

The electrolyte, potassium hydroxide, enters into the reaction, but in the end is regenerated and is undiminished in quantity. It is probably separated into the ions K and OH, which produce chemical change, after which the potassium hydroxide is again formed.

The chemical reactions for the above have been written as follows:

$$nKOH = nK + nOH \text{ (ions)}.$$

In first charge—

$$Fe_2O_3 + 6K + 3H_2O = 2Fe + 6KOH \text{ (negative)};$$
$$3Ni(OH)_2 + 6(OH) = 3NiO_2 + 6H_2O \text{ (positive)}.$$

In discharge—

$$3Fe + 8(OH) = Fe_3O_4 + 4H_2O \text{ (negative)};$$
$$6NiO_2 + 8K + 4H_2O = 2Ni_3O_4 + 8KOH \text{ (positive)}.$$

In recharging—

$$Fe_3O_4 + 8K + 4H_2O = 3Fe + 8KOH \text{ (negative)};$$
$$2Ni_3O_4 + 8(OH) = 6NiO_2 + 4H_2O.$$

Possibly a simpler way of representing the above changes is to consider that the current on charge in passing from the positive to the negative plate decomposes the KOH into the ions K and OH, K passing with the current and carrying a charge. On reaching the negative plate, the charge is given up to it, after which the atom of K unites with the water to form KOH and H is liberated, thus—

$$2H_2O + 2K = 2KOH + H_2.$$

The H liberated then acts on the negative plate to reduce it to metallic iron, thus—

$$Fe_2O_3+6H=2Fe+3H_2O \text{ (negative).}$$

The ion OH formed on charge passes to the positive plate and on reaching it gives up its charge to it, after which it unites with water to form H_2O and O is liberated, thus—

$$H_2O+2HO=2H_2O+O.$$

The O liberated then acts on the positive plate, thus—

$$Ni(OH)_2+O=NiO_2+H_2O \text{ (positive).}$$

On discharge, K goes to the positive plate, liberating H, which acts on it, thus—

$$6NiO_2+8H=2Ni_3O_4+4H_2O \text{ (positive).}$$

HO goes to the negative plate and O is liberated, which acts on it, thus—

$$3Fe+4O=Fe_3O_4 \text{ (negative).}$$

On subsequent charge, the H liberated at the negative plate acts on it, thus—

$$Fe_3O_4+8H=3Fe+4H_2O \text{ (negative).}$$

And the O liberated at the positive plate acts on it, thus—

$$2Ni_3O_4+4O=6NiO_2 \text{ (positive).}$$

There are probably other reactions that take place, as mercury is used in connection with the iron plate for the purpose of better contact, either to promote chemical action or to reduce internal resistance.

Charging.—The potential difference around the terminals of one cell, when on charge and fully charged, will vary somewhat with temperature and other conditions, but will usually be about 1.85 volts and may be 1.87 volts. The voltage available for charging must, therefore, be in the neighborhood of 1.85 volts times the number of cells in the battery. Thus, to charge 60 cells in series would require 60 times 1.85 volts, or 111 volts. If the line voltage be 2 per cent or 3 per cent lower than that required by calculation, there will be no material interference with charging, though the normal rate cannot be maintained near the end of the charge. If the normal rate cannot be maintained, the charging must continue for a longer period. When the state of full charge is reached, the voltage assumes a constant value, and it is possible, after some experience, to determine when a battery is fully charged, by careful observation of its voltage. The normal charging rate can be maintained throughout.

The Edison cell can be "boosted" at rates up to five times normal, when necessary, so long as the temperature of the cell does not exceed 115° F. Repeated short-time "boosting" under the above conditions will do no injury.

It is also possible to charge at constant potential, and in this case, a voltage of at least 1.70 per cell is required. If the line voltage be higher than this, a fixed resistance is required in series with the battery, such that with normal rate flowing, the voltage will be reduced to this value. When this method is employed, the battery is thrown on charge by simply closing a switch. The initial current may be as high as 50 per cent above normal, but it will taper down so that at the end of the normal period, the current may be at only half the normal rate. Care should be taken that the circuit be so proportioned that the *average* current value throughout the normal period of charge is not less than the normal rate.

Discharging.—The normal discharge rates are the same as the normal charge rates. The average discharge voltage, working at the normal rate, is 1.2 volts per cell, and the discharge is complete when an average of 1 volt per cell discharging at normal rate, is reached.

Temperatures.—The best results are obtained from a battery when the temperature is kept between 60° and 115° F. during charge. The temperature of the battery should not be allowed to go above 115° F. during charge, or 160° F. during discharge, and the lower the temperature is kept within the prescribed limits during *charging,* the longer will be the life of the battery.

The battery compartment should always be kept sufficiently open while the battery is charging, to provide ventilation and permit the hydrogen and oxygen gases to escape. All holes and openings in the battery compartment should be kept closed during cold weather, *during discharge* or while standing idle. If the electrolyte temperature falls below 50° F., either during charge or discharge, the output and efficiency will be lowered on the following discharge only.

Output and Efficiency.—The capacity of the Edison battery increases for some time after it has been put into service. It will give considerably above its rated output on normal charge when new, and after working some time, will give a greater output. The process of self-forming continues over a period of from one to three months of regular daily service.

A valuable feature is that the battery always has a reserve capacity which can be utilized by extending the length of charge. In a fully formed battery, charged for 10 hours at normal rate, the output may reach 30 per cent more than the rated output. In using this, the highest available capacity of a battery, some of the charging current is wasted and temporary efficiency is sacrificed. The wasted current tends to decompose the water which escapes as gas, and this evaporation must be made up by adding distilled water or rain water.

The so-called watt-hour efficiency (the percentage of the energy used in charging which is available on discharge), is about 60 per cent. The ampere hour efficiency is about 82 per cent.

The Type M Cell.—In the Type M cell, the positive tubes and negative pockets are placed horizontally in their container, and not vertically, as obtains in the A and B types. Furthermore, the plates of different polarity are not separated by hard-rubber pins placed between them, but they are fastened to steel rods and separated by hard-rubber bushings.

The cardinal feature of this Type M cell is the fact that it may be turned upside down or allowed to rest on its side, without a drop of the electrolyte being spilled. This is brought about by the valve, in the form of a tube (very small in diameter) which screws into the top of the container, and extends downward to about ½ inch above the top of the electrolyte. The tube also has a large hole at its end and several smaller holes around its circumference some distance above. Thus, when the cell is being charged, the gases evolved make their way to the tube and in passing through these small holes, the gas bubbles deposit a large percentage of the water of which they are composed, on this valve, and pass out, thus keeping the top of the

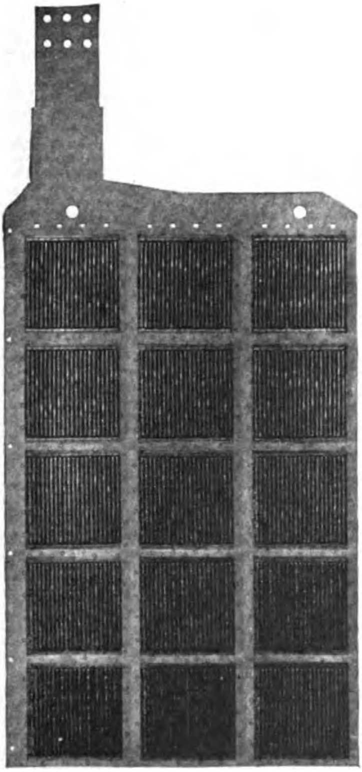


FIG. 28.—Plate for Type S Battery.

cell clean and dry. The water deposited on the valve again finds its way to the electrolyte.

The Type M cell is very light and compact.

The Type S Battery, for Heavy Duty.—The tubes of this battery are smaller in diameter ($\frac{3}{16}$ inch diameter) than the A, B and M ($\frac{1}{4}$ inch diameter) types.

The tubes and pockets are mounted on sub-grids, these sub-grids being electrically welded to the main grids, as shown. (See Fig. 28.)

The number of these sub-grids per plate depends upon the available height, etc., of the battery tank of the boat. A plate designated (5×3) specifies five sub-grids in height and three in width. (Fig. 28 shows a 5×3 plate.)

The positive plates are bolted together, and extend through a rectangular stuffing box in the cover (see Fig. 30).

The negative plates are similarly bolted together, and pass through a similar stuffing box.

The hard-rubber spacers between positive plates are milled on their inner edges to receive and retain the edges of the negative plates interposed, and vice versa.

The plates of opposite polarity are further insulated by hard-rubber vertical strips, secured to the positive plates.

The hard-rubber spacing blocks also insulate the edges of the plates from the steel containing can.

The plates rest upon a hard-rubber insulator in the bottom of the can.

The cover is welded on, when once placed in position. (The welded joint can be ground or filed off very quickly, should occasion require, and the grouped plates lifted from the can.)

Owing to the difficulty of adequately ventilating the battery tank of a submarine boat, sometimes the gases in pockets of the tanks' ventilation system become ignited. This is apt to cause considerable damage to the ordinary storage battery.

But in the top of each Edison cell (see Fig. 30) is a water trap, through which all gas which escapes from the cell must pass. Obviously, this water seal acts to prevent any external flame from entering the cell. Fig. 31 shows a cross-section of this water trap.

Should the electrolyte in any kind of storage battery get so low as to expose the plates to the action of the gases present, the rapid oxidation of the plates causes sufficient heat to ignite the gases within the cell.

Such an internal explosion in a Type S Edison cell cannot be communicated to the outside surrounding gases, and as the thick steel cans will stand a great many such internal explosions without rupture, this feature is very valuable.

FIG. 29.—Assembled Cell, Type S.

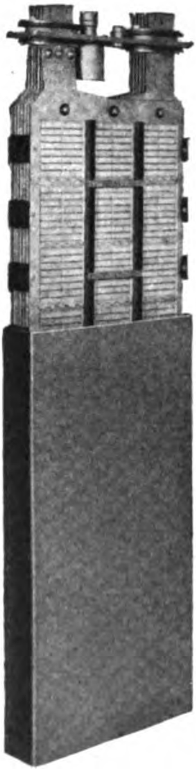


FIG. 30.—Type S. Cell Showing Plate Partly Removed.

It is not necessary to remove a Type S cell from the boat, to renew the electrolyte, and renewal is not necessary oftener than once every year or two, depending on the service. There is a drain tube passing through and attached to the cover, passing down one side of the can to within a short distance of the bottom. The top end of this tube, attached to a siphon or pump, will drain the cell.

One very strong feature which especially recommends the Edison battery for use on board ship is the fact that the electrolyte is an alkali; so also is sea-water. Therefore, in case the battery tank becomes flooded, or electrolyte leaks into the bilge of the boat, there is no deadly gas evolved, as occurs when sulphuric acid and sea-

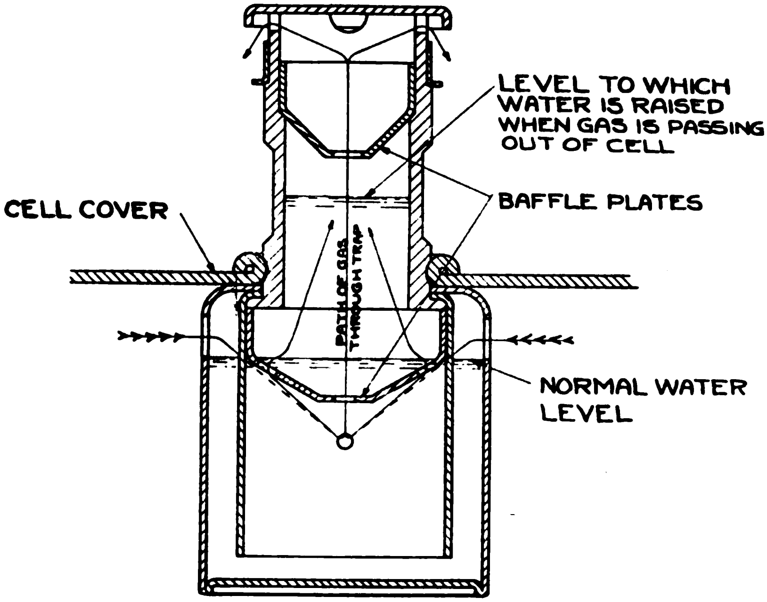


FIG. 31.—Water Trap for Edison Cell.

water become mixed and form hydrochloric acid, or when salt water enters a lead cell and forms chlorine gas.

The gases evolved by an Edison battery at any time do no harm to surrounding steel work or to the health of the crew.

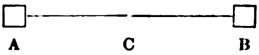
Cleaning.—The outside of the cans should be kept clean and dry. If dirt is allowed to accumulate between the cells, it is liable to become moist with water and potash, and an electrolytic action will result which, in time, may corrode the containing cans. If these become corroded or rusted, they should be given a coat of P. and B. compound or Esbalite, an insulating alkali-proof paint put up by the Edison Storage Battery Company. Cleaning is most easily accomplished by means of a steam or air blast, which can be directed over the tops of and down between the cells.

The Navy Department has arranged with the Edison Storage Battery Company to supply the electrolyte for Edison storage batteries in *dry form,* ready for mixing with distilled water, at destination. This prevents the payment of transportation charges on the large proportion of water in the liquid electrolyte.

CHAPTER VI.

OHM'S LAW AND ITS APPLICATION TO SIMPLE AND DIVIDED CIRCUITS.

Ohm's Law.—After conducting a series of experiments to find the relation existing between resistance, current, and difference of potential, Ohm deduced the following law: "In any wire at uniform temperature, the current is directly proportional to the difference of potential between its ends." This may be stated as follows: When an E. M. F. is applied to the terminals of a conductor, a current is produced which is directly proportional to the applied E. M. F. and inversely proportional to the resistance of the conductor. The units used in electricity have been so chosen that this law may be written $I=\frac{E}{R}$, where I, E and R represent the current, E. M. F., and resistance in the system of units employed. Ohm's law is applicable to an entire circuit or any part of a circuit. If an entire circuit is considered E represents the total E. M. F. of the circuit and R the total resistance. If a portion of a circuit is considered E represents the difference of potential between the ends of that part and R the resistance of the portion considered. This law and its applications are of the utmost importance and nearly all of the difficulties experienced in the solution of problems pertaining to continuous current circuits are due to a lack of facility in the use of this fundamental law.



A and B represent two bodies that are a part of an electric circuit. These two bodies are joined by a wire of uniform material and cross-section and a constant E. M. F. is maintained at the terminals of the wire. There will be a constant current flowing and a uniform drop of potential along the wire from A to B. Take a point C which is twice as far from B as from A, then the resistance from C to $B(R_2)$ is equal to twice the resistance from A to $C(R_1)$.

By Ohm's law the drop of potential from A to C will be $E_1 = IR_1$ and the drop from C to B will be $E_2 = IR_2 = 2IR_1$. In a like manner the drop of potential at any point along the wire may be determined. In any circuit whether the resistance is uniform or not, if the current flowing through any part and the resistance of that part is given, the drop of potential through that part $E = RI$.

This principle can best be illustrated by the solution of numerical examples.

Problems on Ohm's Law.

1. An arc lamp requires a current of 8 amperes at a difference of potential of 44 volts. What will be the value of an external resistance placed in series with the lamp to produce this voltage from a 100-volt main?

The fall of potential through resistance must be $100 - 44 = 56$ volts, and as 8 amperes flow through this resistance, the resistance must be

$$R = \frac{E}{I} = \frac{56}{8} = 7 \text{ ohms.}$$

2. An electric heater is connected by means of a cable to constant potential mains. When 4 amperes are flowing in the circuit the difference of potential across the heater is 98 volts, and when 6.5 amperes are flowing, it falls to 93 volts. Find the resistance of the cable.

If x = resistance of cable, $4x$ is the drop of potential in the cable and $98 + 4x$ = potential of the mains.

Similarly $\quad 93 + 6.5x$ = potential of the mains,

or $\quad 98 + 4x = 93 + 6.5x,$

or $\quad x = 2$ ohms.

3. A number of 100-volt incandescent lamps are connected at the end of a pair of mains connected to a dynamo. If the resistance of each main is .37 ohm, and the current is 14.6 amperes, what voltage must the dynamo produce at its terminals?

$$\begin{aligned}
\text{Resistance of cables} &= 2 \times .37 = .74 \text{ ohm.}\\
\text{Drop in cables} &= .74 \times 14.6 = 10.8 \text{ volts.}\\
\text{Potential at dynamo} &= 100 + 10.8 = 110.8 \text{ volts.}
\end{aligned}$$

4. The resistance of the filament of an incandescent lamp when cold is 220 ohms. If this value decreases 35 per cent when hot, what current will a pressure of 110 volts send through the filament?

Ans. .769 ampere.

5. A resistance of 20 ohms, on being added to a certain circuit caused the current flowing to be reduced from 13 to 9 amperes. What was the original resistance of the circuit? *Ans.* 45 ohms.

6. An ammeter connected in series with a standard resistance of .1 ohm indicates a current of 23 amperes. The difference of potential across the standard resistance is found to be 2.28 volts. Determine the error in the ammeter reading. *Ans.* + .2 ampere.

7. One end (*A*) of a wire *ABC* is connected to earth, the other end (*C*) is kept at a constant potential of 100 volts. If the resistance of the portion *AB* is 9.6 ohms and that of *BC* 2.4 ohms, what current will flow along the wire and what will be the potential at the point *B*?

Ans. 8⅓ amperes.
80 volts.

8. A primary cell, E. M. F., 1.8 volts, and a secondary cell are connected up in opposition with a resistance of 400 ohms and the strength of the current is observed. On rearranging the cells to send currents in the same direction, it is found that the resistance has to be increased to 4000 ohms in order to reduce the current to its former value. Neglecting the resistance of the cells, find the E. M. F. of the secondary cell, and the current produced. *Ans.* E. M. F. = 2.2 volts.
Current = .001 ampere.

Simple Circuits.

So far only the difference of potential between two points with the relation existing between that difference of potential and the current and resistance have been considered. The next step is to consider the total E. M. F. in a circuit and the relation between E. M. F. current and resistance.

In considering the total E. M. F. Ohm's law may be thus stated: **The current produced by a source of E. M. F. is dependent directly on the E. M. F. and inversely on the resistance.**

In symbols as before

$$I = \frac{E}{R}$$

where E = total E. M. F.

This means that the total current flowing through every point in a simple circuit depends directly on the *total* E. M. F. and inversely on the *total* resistance in circuit. The fall of potential around the whole circuit is equal to the total E. M. F. or the difference or sum of the individual E. M. F.'s, and is also equal to the sum of all the differences of potential from one point to another continuously around the circuit.

By **a simple circuit** is meant one in which the current follows but one path both in its internal and external parts. In other words, it is a circuit in which everything that goes to make up the circuit is in series. The circuit may be made up of cells, leading wires, instruments of different kinds or any electrical apparatus, provided that everything is connected so that the same current traverses every portion of the circuit.

Fig. 32 represents a typical simple circuit; the battery B composed of four cells in series, an instrument G, a resistance R_1, and an electrolytic cell C_1, all in series. The same current will traverse every part of this circuit including the connecting wires 1-2, 3-4, etc.

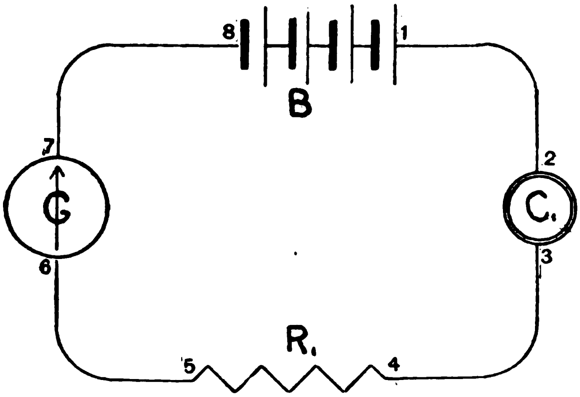


FIG. 32.—Simple Typical Circuit.

If E represents the total E. M. F. of the four cells and I the current, r' the resistance of all the connecting and leading wires, and r the total internal battery resistance, then

$$I = \frac{E}{r + r' + G + R_1 + C_1}, \tag{a}$$

G, R_1, and C_1 representing the resistances of the parts so lettered.

The fall of potential from 1 to $2 = I \times$ resistance of $1-2$
" " " " 3 to $4 = I \times$ " " $3-4$, etc.
" " " through $C_1 = I \times C_1$
" " " " $R_1 = I \times R_1$
" " " " $G = I \times G$
" " " " the battery $= I \times r$.

The fall of potential all around the circuit from 1 around again to 1 is,

$$Ir' + IC_1 + IR_1 + IG + Ir,$$

and this must equal E, the total E. M. F. of the battery; this corresponding to equation (a).

Problems as Applied to Simple Circuits.

1. A circuit consists of a dynamo of .5 ohm resistance and four separate resistances of 2, 6, 20, and 1.5 ohms respectively. If the total E. M. F. of the dynamo is 120 volts, find the value of the current flowing and the drop or fall of potential in each resistance.

$$I = \frac{E}{R} = \frac{120}{.5 + 2 + 6 + 20 + 1.5} = 4 \text{ amperes.}$$

Drop in separate parts =

$$\begin{aligned} 4 \times 2 &= 8 \text{ volts.} \\ 4 \times 6 &= 24 \quad " \\ 4 \times 20 &= 80 \quad " \\ 4 \times 1.5 &= 6 \quad " \\ 4 \times .5 &= 2 \quad " \end{aligned}$$

Total drop = total E = 120 volts.

2. A battery produces a difference of potential at its terminals of 1.8 volts when sending a current of 2.2 amperes through an external resistance. Assuming the internal resistance of the battery to be .74 ohm, what is the total E. M. F. of the battery?

The fall of potential through battery or lost volts is

$$2.2 \times .74 = 1.63 \text{ volts.}$$

$$\text{Total E. M. F.} = 1.8 + 1.63 = 3.43 \text{ volts.}$$

3. A battery of 20 similar secondary cells sends a current of 6 amperes through the coils of an electromagnet having a resistance of 4 ohms. Determine the internal resistance of each cell, assuming each to have an E. M. F. of 2 volts.

$$I = \frac{E}{R} = \frac{40}{r' + 4} = 6$$

$$6r' = 16 \quad r' = 2.7$$

$$\therefore \text{resistance of each cell} = \frac{2.7}{20} = .135 \text{ ohm,}$$

or the drop in potential through electromagnet = $6 \times 4 = 24$ volts.

$\therefore$ drop in battery = $40 - 24 = 16$ volts,

and $$r' = \frac{16}{6} = 2.7.$$

4. A battery consisting of 20 cells in series, each cell having an E. M. F. of 2 volts and an internal resistance 0.1 ohm is connected to two resistances in series, one of 3 ohms and one of 5 ohms. (1) What is the value of the current? (2) What is the terminal voltage of battery? (3) What is the P. D. across 3-ohm resistance? (4) The 5-ohm resistance?

$$I = \frac{20 \times 2}{20 \times .1 + 3 + 5} = \frac{40}{10} = 4 \text{ amperes.} \qquad (1)$$

$$E_x = E - rI = 40 - (2 \times 4) = 32 \text{ volts.} \qquad (2)$$

$$\text{P. D.} = 3 \times 4 = 12 \text{ volts.} \qquad (3)$$

$$\text{P. D.} = 5 \times 4 = 20 \text{ volts.} \qquad (4)$$

Counter E. M. F. in a Circuit.—If there are one or more sources of E. M. F. in a circuit, the total is either the sum or the difference of the individual E. M. F.'s. Where one E. M. F. acts against the source of supply it is said to be a counter E. M. F. and one of the best examples of this counter E. M. F. in a circuit is that of a battery of secondary cells being charged from a dynamo. The E. M. F. of the battery acts against the E. M. F. of the dynamo, and current will only flow from the dynamo if its E. M. F. is the greater. Having found the E. M. F. required to exactly balance the counter E. M. F. of a battery, the additional E. M. F. required to send a charging current through the battery may be found by multiplying the total resistance of the battery by the current required.

Problems on Counter E. M. F.

1. A battery of 50 secondary cells is to be charged from a 125-volt main, the current not to exceed 15 amperes. Assuming each cell to have an E. M. F. of 1.8 volts and an internal resistance of .004 ohm; determine the value of a resistance that will have to be put in series to accomplish the desired result.

Counter E. M. F. of battery	$= 50 \times 1.8$	$= 90$ volts.
Total internal resist.	$= 50 \times .004$	$= .2$ ohm.
Additional E. M. F. to force 15 amperes through battery	$= 15 \times .2$	$= 3$ volts.
Total E. M. F. required at terminals	$= 90 + 3$	$= 93$ volts.
Drop of potential in resistance	$= 125 - 93$	$= 32$ volts.
$\therefore$ resistance $= \frac{32}{15}$	$= 2.13$ ohms.	

2. Two cells of E. M. F. 1.8 volts and 1.08 respectively are placed in a certain circuit in opposition. The current is found to be .4 ampere. What current will be produced if the cells are properly placed in series?

$$I = \frac{E}{R} \text{ or } .4 = \frac{1.8 - 1.08}{R},$$

$$R = 1.8 \qquad I' = \frac{1.8 + 1.08}{1.8} = 1.6 \text{ amperes.}$$

3. A battery of 50 storage cells is connected up with 5 connected the wrong way. Assuming the E. M. F. and internal resistance of each cell to be respectively 2 volts and .02 ohm, determine what voltage lamps in circuit would get (1) with the faulty connection, (2) if they were connected up properly. Resistance of leading wires to lamps .2 ohm and of the lamps 4 ohms. *Ans.* (1) 61.5 volts.
(2) 76.9 volts.

Divided Circuits.

By a **divided circuit** is meant one in which the current does not follow one continuous path from the source of E. M. F., to its return, but two or more paths either in its external or internal parts, or both.

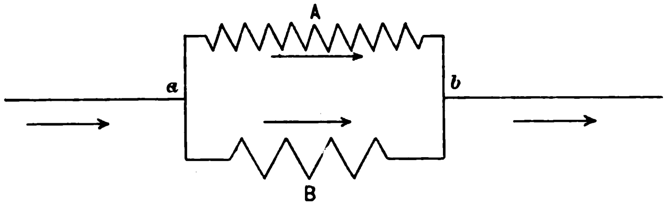


FIG. 33.—Resistance in Parallel.

In order that the currents in the separate branches that go to make up a divided circuit may be calculated, it is necessary to know the resistances of these branches.

A and *B*, Fig. 33, are two conductors, joined at *a* and *b* and it is required to know the combined resistance of *A* and *B*. These two conductors offer two paths for the flow of current, so the sum of the currents in *A* and *B* must equal the total current flowing from *a* towards *b*.

Let I = total current flowing from *a* to *b*.
I_1 = current in *A*.
I_2 = current in *B*.
R_1 = resistance of *A*.
R_2 = resistance of *B*.
R = total resistance of *A* and *B* together.

Then the drop of potential from A to B by Ohm's law $E=I_1R_1$ $=I_2R_2$ and $I_1=\frac{E}{R_1}$, $I_2=\frac{E}{R_2}$ and $I=\frac{E}{R}$, but $I=I_1+I_2$, hence

$$\frac{E}{R}=\frac{E}{R_1}+\frac{E}{R_2} \text{ or } \frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}$$

which is the expression for two resistances in parallel previously obtained in Chapter II.

Divided Circuits—Kirchoff's Laws.

Any combination of conductors making up a complete circuit as in Fig. 34 is spoken of as a network of conductors. Any part of this

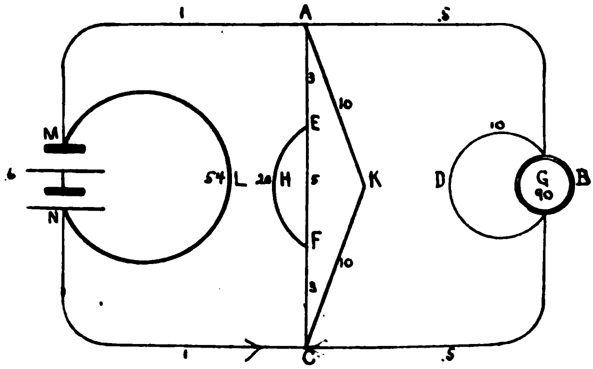


FIG. 34.—Illustration of Divided Circuits.

network as $NLMN$ which makes a continuous path for a current is called a closed circuit or a mesh.

Kirchoff enunciated two laws which are of the greatest value in determining the distribution of current in a network of conductors.

First Law.—The algebraic sum of the currents meeting at any point or junction in a network of conductors is zero; or in other words, the sum of the currents flowing to a point is equal to the sum of the currents flowing away from the point. $\Sigma I=0$.

That is, referring to Fig. 34, the current in conductor marked (1) flowing toward the junction marked C is equal to the sum of the currents in the three branches leading away from this point.

Second Law.—In any mesh of a network of conductors or in any closed loop the algebraic sum of the electromotive forces is equal to the algebraic sum of the products of all the resistances into the respective currents flowing through them. In other words, the algebraic sum of the E. M. F.'s of any mesh is equal to the sum of the *RI* drops.

It is of such vital importance to know these laws and the correct method of applying them that this subject will be discussed in detail and illustrated by the solution of many numerical problems.

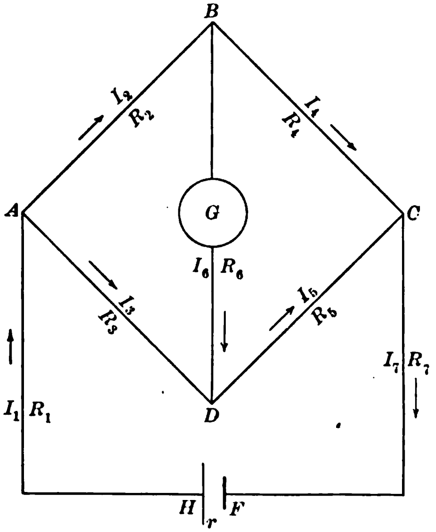


FIG. 35.—The Wheatstone Net.

The network given in Fig. 35 is called the wheatstone net and shows the combination of conductors required to illustrate the principle of the wheatstone bridge. It will be used to illustrate these laws. Take any point or junction *A*, then by the first law $I_1 = I_2 + I_3$. If *B* is taken $I_2 = I_4 + I_6$. If junction *D* is taken $I_3 + I_6 = I_5$, etc. This law is very simple and seems self-evident, but its accuracy was proved experimentally by Kirchoff.

To illustrate the principle of the second law, take the mesh or closed circuit *HADCFH* with currents and resistances of the various conductors as given, then the drop of potential from point to point will be as follows:

Drop of potential from H to $A=R_1I_1$.
" " " " A to $D=R_3I_3$.
" " " " D to $C=R_5I_5$.
" " " " C to $F=R_7I_1$.

The total drop of potential or difference of potential between H and F is then equal to $R_1I_1+R_3I_3+R_5I_5+R_7I$. But H and F are the positive and negative poles of the battery of internal resistance r and therefore their difference of potential is the terminal E. M. F. of

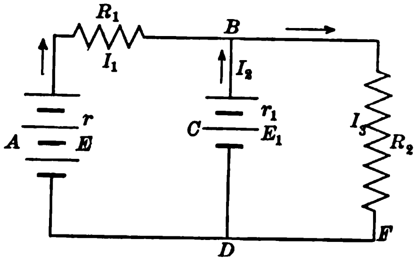


FIG. 36.

the battery which is given by the equation $E_x=E-rI_1$ where E is the total E. M. F. of the battery. Hence,

$$E-rI_1=R_1I_1+R_3I_3+R_5I_5+R_7I_1, \text{ or}$$
$$E=rI_1+R_1I_1+R_3I_3+R_5I_5+R_7I_1,$$

which demonstrates the accuracy of the second law $\Sigma E=\Sigma RI$.

There should not be any difficulty in the application of the first law, but unless some system is carefully followed in applying the second law, confusion will result in regard to signs.

The network shown in Fig. 36 represents two batteries in parallel with known external resistances R_1 and R_2 as shown and it is required to know the distribution of the current through the conductors of the network, E, E_1 and r, r_1, the E. M. F.'s and resistances of the two batteries being given. Arrows are drawn to indicate the assumed direction of the currents. The current is shown as flowing from D to B through battery C, but if the E. M. F. of battery A is much higher than that of battery C the point B may be at a higher potential than the positive pole of battery C, and in that case current would flow through C in the opposite direction.

In solving problems no difficulty arises on this score; for, if the wrong direction is assumed, the solution of the equations derived under this hypothesis will give a negative value for the current. This value will indicate its correct magnitude, but the negative sign will show that the current is flowing in a direction opposite to the assumed direction.

Take the mesh $ABCD$ and follow it around in a clockwise direction and there will be a drop of potential through battery $A = rI_1$ and a drop through $R_1 = R_1I_1$, but as the arrows are drawn it will be noted that there is an increase of potential at battery C as the current is flowing counter-clockwise and hence there will be an increase of potential or negative drop after leaving B. The E. M. F. of battery C in this mesh is opposed to the E. M. F. of battery A and is also negative. The equation then becomes

$$E - E_1 = rI_1 + R_1I_1 - r_1I_2. \qquad (1)$$

Now take mesh $DCBF$ and following the same rule, we have

$$E_1 = r_1I_2 + R_2I_3, \qquad (2)$$

and for mesh $ABFDA$ we have

$$E = rI_1 + R_1I_1 + R_2I_3. \qquad (3)$$

Subtracting (2) from (3) we have

$$E - E_1 = rI_1 + R_1I_1 - r_1I_2,$$

which is the same as equation (1). In writing down the equations, it will always happen that superfluous equations are obtained in this way. It will be noted that by applying Kirchoff's second law to this network only two distinct equations were obtained. This is not sufficient to afford a solution as the equations contain three unknown quantities. By applying Kirchoff's first law to any junction as B, another equation is obtained as follows:

$$I_1 + I_2 = I_3. \qquad (4)$$

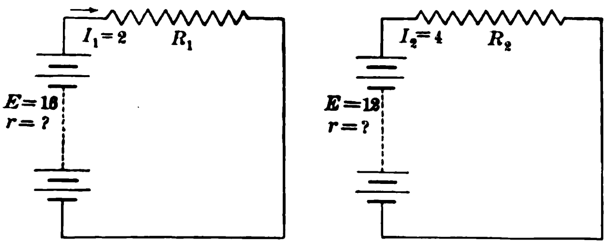
Thus, by applying both laws sufficient equations are always available for finding the various values of the currents.

In solving problems involving Kirchoff's laws, the following procedure will be followed:

1. Make a line sketch showing the conditions of the problem.
2. Assign the letter I with a suffix to represent the current flowing through each conductor and indicate with arrows the assumed direction of the flow of current in each part. Call the E. M. F., E, or if more than one call them E, E_1, E_2, etc. In a like manner designate the internal resistances of the batteries by r, r_1, etc., and external resistances by R, R_1, etc.
3. In writing the equation for any mesh, assume a clockwise flow of current as positive. Any E. M. F. which acts in a direction to oppose this flow is negative and any product of a resistance by its current where the direction of the current is counter-clockwise is considered a negative RI drop and is subtractive.
4. Insert known values in diagram abreast their respective parts and with these and symbols to represent the unknown values write equations and solve.

Examples Illustrating the Application of Kirchoff's Laws.

1. The potential differences between the terminals of a battery of 20 cells in series is 16 volts when a current of two amperes is flowing, and 12 volts when the external resistance is so reduced that 4 amperes flows in the circuit. Find the E. M. F. and internal resistance of each cell.

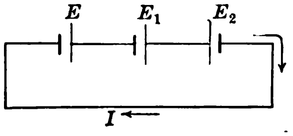


$$E - rI_1 = 16$$
$$E_1 - rI_2 = 12$$
$$r(I_2 - I_1) = 4$$

$2r = 4$, $r = 2$. Resistance of each cell $= \frac{2}{20} = .1$.

$E - (2 \times 2) = 16$, $E = 20$.

2. Three cells, each of an E. M. F. of 2 volts and a resistance of 3 ohms are connected in series by wires of negligible resistances, but one cell is reversed and acts in opposition to the others. Find the current in the circuit and the potential difference between the terminals of the reversed cell.



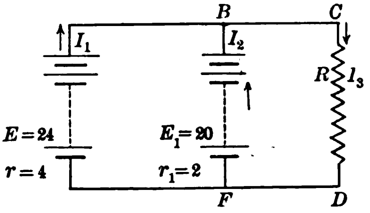
$$E + E_1 - E_2 = 2rI + rI.$$

Since E. M. F. and r of cells are equal

$$E = 3rI,\ 2 = 9I,\ I = \tfrac{2}{9} \text{ ampere.}$$

$rI = \frac{2}{9} \times 3 = \frac{2}{3}$ volt. Since this opposed to the direction of the E. M. F. of the cell the potential difference at the terminals must be $2 + \frac{2}{3} = 2\frac{2}{3}$ volts.

3. Two batteries, one of E. M. F. of 24 volts and internal resistance of 4 ohms and the other E. M. F. 20 volts and internal resistance 2 ohms, are joined up in parallel to an external circuit containing a resistance of 4 ohms. What is the current through each battery and through the external resistance?



$$E = rI_1 + RI_3 \text{ (mesh } ECD). \quad (1)$$
$$E_1 = r_1I_2 + RI_3 \text{ (mesh } BCDF). \quad (2)$$
$$I_1 + I_2 = I_3. \quad (3)$$

Subtracting (2) from (1) we have

$$E - E_1 = rI_1 - rI_2.$$

Substituting we have

$$24 - 20 = 4I_1 - 2I_2,\ 4 = 4I_1 - 2I_2.$$
$$I_2 = 2I_1 - 2. \quad (4)$$

Substituting in (3) we have $3I_1 - 2 = I_3$, substituting this in (1) we have $24 = 4I_1 + 4\ (3I_1 - 2)$, or $24 = 16I_1 - 8$, $I_1 = 2$, and from (4) $I_2 = 4 - 2 = 2$, and from (3) $I_3 = 2 + 2 = 4$. In this case each battery supplies 2 amperes.

4. Data same as in (3) except that the external resistance is assumed to be 20 ohms.

Substituting in equations of (3)

$$24 = 4I_1 + 20I_3. \qquad (1)$$
$$20 = 2I_2 + 20I_3. \qquad (2)$$
$$I_1 + I_2 = I_3. \qquad (3)$$

Subtracting (2) from (1) we have $4 = 4I_1 - 2I_2$, $2 = 2I_1 - I_2$, $I_2 = 2I_1 - 2$, and from (3) $I_3 = 3I_1 - 2$. Substitute in (1) $24 = 4I_1 + 20\,(3I_1 - 2)$, or $64I_1 = 64I_1 = 1$, hence $I_2 = 2 - 2 = 0$, $I_3 = 1 + 0 = 1$.

In this case the second battery is supplying no current and is what is technically called "floating on the line." Its maximum E. M. F. being just equal to line voltage at that point.

5. Data same as in (3) excepting that external resistance is assumed to be 84 ohms, as before:

$$24 = 4I_1 + 84I_3. \qquad (1)$$
$$20 = 2I_2 + 84I_3. \qquad (2)$$
$$I_3 = I_1 + I_2. \qquad (3)$$

Subtracting (2) from (1) we have

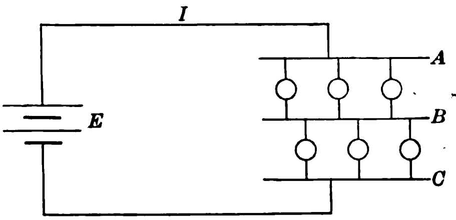
$$I_2 = 2I_1 - 2 \text{ and from (3) } I_3 = 3I_1 - 2,$$

substitute in (1)

$$24 = 4I_1 + 84\,(3I_1 - 2), \text{ or } 256I_1 = 192,\ I_1 = \tfrac{3}{4},$$
$$I_2 = 2\,(\tfrac{3}{4}) - 2 = \tfrac{3}{2} - 2 = -\tfrac{1}{2},\ I_3 = I_1 + I_2 = \tfrac{3}{4} - \tfrac{1}{2} = \tfrac{1}{4}.$$

In this case the first battery is actually sending current through the second in a direction opposed to the direction of its E. M. F.

6. A battery consists of 15 cells in series. The E. M. F. of each cell is 2 volts and the total internal resistance of the battery is 1 ohm. The battery supplies power for 6 lamps connected as shown. Each lamp takes two amperes when 12 volts are impressed upon its terminals. Find (1) the current through each lamp; (2) the voltage at the terminals of each lamp; (3) the current delivered by the battery; (4) the terminal voltage of the battery.



Resistance of each lamp $= \frac{12}{2} = 6$ ohms.
Resistance from A to $B = \frac{6}{3} = 2$ ohms.
Resistance from B to $C = \frac{6}{3} = 2$ ohms.

$$I = \frac{15 \times 2}{1 + 4} = 6 \text{ amperes.} \qquad (3)$$

$$I_1 \text{ for each lamp} = \tfrac{6}{3} = 2 \text{ amperes.} \qquad (1)$$

$$E_1 \text{ for each lamp } 6 \times 2 = 12 \text{ volts.} \qquad (2)$$

$$E_x = E - 6 \times 1 = 30 - 6 = 24 \text{ volts.} \qquad (4)$$

7. Same as (5) excepting that there are only 5 lamps, three in upper row and two in lower.

Resistance of each lamp = 6 ohms. Resistance from A to $B = \frac{6}{3} = 2$ ohms. Resistance B to $C = \frac{6}{2} = 3$ ohms.

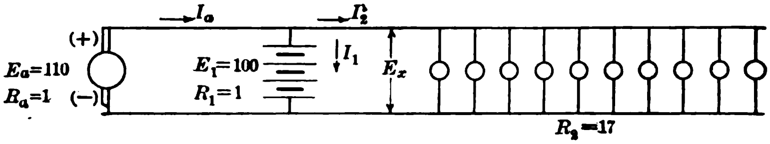
$$I = \tfrac{30}{6} = 5 \text{ amperes.} \qquad (3)$$

I_1 for each lamp from A to $B = \frac{5}{3}$ amperes and from B to $C = \frac{5}{2}$ amperes. (1)

E_1 for each lamp from A to $B = \frac{5}{3} \times 6 = 10$ volts and from B to $C = \frac{5}{2} \times 6 = 15$ volts. (2)

$$E_x = 30 - 5 \times 1 = 25 \text{ volts.} \qquad (3)$$

8. A separately excited generator has a constant induced E. M. F. of 110 volts and an internal resistance of 1 ohm. This generator is connected as shown to a lamp bank consisting of 10 lamps, each having a resistance of 170 ohms, and to a storage battery of 50 cells each having a constant E. M. F. of 2 volts and an internal resistance of .02 ohm. (a) What is the direction and value of the current in each part of this circuit, and what is the value of the terminal voltage of the generator?



$$E_1 = 50 \times 2 = 100 \text{ volts.}$$

$$R_1 = 50 \times .02 = 1 \text{ ohm.}$$

$$R_2 = \tfrac{170}{10} = 17 \text{ ohms.}$$

Hence

$$I_a = I_1 + I_2. \qquad (1)$$

$$110 = I_a \times 1 + I_2 \times 17 = I_a + 17I_2. \qquad (2)$$

$$100 = -1 \times I_1 + I_2 \times 17 = -I_1 + 17I_2. \qquad (3)$$

Subtract (3) from (2)

$$10 = I_a + I_1, \text{ or } I_1 = 10 - I_a. \qquad (4)$$

Substitute in (1)

$$I_a = 10 - I_a + I_2, \text{ or } I_2 = 2I_a - 10. \qquad (5)$$

Substitute in (2)

$$110 = I_a + 17\,(2I_a - 10) = 35I_a - 170, \text{ or } 35I_a = 280. \qquad (6)$$

$$35I_a = 280,\ I_a = 8. \qquad (7)$$

From (5)

$$I_2 = 16 - 10 = 6. \qquad (8)$$

From (4)

$$10 = 8 + I_1 \text{ or } I_1 = 2. \qquad (9)$$

$$E_x = E_a - R_a I_a = 110 - 8 \times 1 = 102 \text{ volts.} \qquad (10)$$

(b) If seven more lamps should be turned on what would then be the current through the different parts of the circuit and the terminal voltage of the generator?

$$E_1 = 100 \text{ volts as before.}$$

$$R_1 = 50 \times .02 = 1 \text{ ohm.}$$

$$R_2 = \tfrac{170}{17} = 10 \text{ ohms.}$$

Hence, equations (1), (4), (5) as before.

$$110 = I_a + 10I_2. \qquad (2)$$

$$100 = -I_1 + 10I_2. \qquad (3)$$

$$110 = I_a + 10\,(2I_a - 10),\ 21I_a = 210,\ \ I_a = 10. \qquad (6)$$

$$I_2 = 20 - 10 = 10. \qquad (9)$$

From (1)

$$10 = I_1 + 10 \text{ or } I_1 = 0. \qquad (10)$$

$$E_x = E_a - R_a I_a = 110 - 10 = 100. \qquad (11)$$

In this case the terminal voltage of the generator is equal to E. M. F. of the battery and the battery does not take or give current and is "floating on the line."

(c) If 34 lamps were used in parallel on this circuit, what would then be the various currents and the terminal voltage.

$$E_1 = 100,\ R_1 = 1 \text{ ohm},\ R_2 = \tfrac{170}{34} = 5 \text{ ohms.}$$

$$I_a = I_1 + I_2. \qquad (1)$$

$$110 = I_a + 5I_2. \qquad (2)$$

$$100 = -I_1 + 5I_2. \qquad (3)$$

$$10 = I_a + I_1,\ I_1 = 10 - I_a. \qquad (4)$$

$$I_a = 10 - I_a + I_2,\ I_2 = 2I_a - 10. \qquad (5)$$

$$110 = I_a + 5\,(2I_a - 10). \qquad (6)$$

$$11I_a = 160,\ I_a = \tfrac{160}{11} = 14\tfrac{6}{11}. \qquad (7)$$

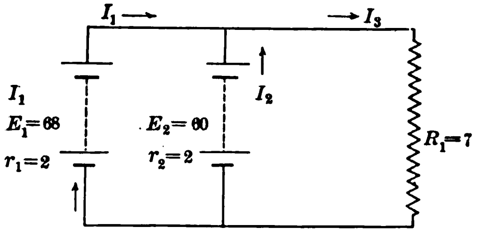
$$I_2 = 29\tfrac{1}{11} - 10 = 19\tfrac{1}{11}. \qquad (8)$$

$$I_1 = 10 - I_a = 10 - 14\tfrac{6}{11} = -4\tfrac{6}{11} \text{ amperes.} \qquad (9)$$

$$E_x = E_a - R_a I_a = 110 - 14\tfrac{6}{11} = 95\tfrac{5}{11} \text{ volts.} \qquad (10)$$

In this case the actual direction of the current through the storage battery is the reverse of that shown by the arrow, and the battery is now supplying energy to the lamps. This method is often used in power stations. The generator charges the storage battery in the day time when not many lights are used and the battery gives up its energy to assist the generator during the heavy load period at night.

9. Two storage batteries of 68 and 60 volts, respectively, are connected in parallel to an external resistance of 7 ohms. The internal resistance of each battery is 2 ohms. Find the value of (1) the current through each battery. (2) The current in external circuit. (3) The terminal voltage of each battery. (4) What is the direction and magnitude of currents when external circuit is open? (5) What is then the terminal voltages?



$$I_1 + I_2 = I_3. \quad (1)$$
$$68 = 2I_1 + 7I_3. \quad (2)$$
$$60 = 2I_2 + 7I_3. \quad (3)$$

Subtract

$$8 = 2I_1 - 2I_2, \text{ or } 4 = I_1 - I_2, I_2 = I_1 - 4. \quad (4)$$

From (1)

$$2I_1 - 4 = I_3. \quad (5)$$

Substitute in (2)

$$68 = 2I_1 + 7(2I_1 - 4), \text{ or } 16I_1 = 96, I_1 = 6. \quad (6)$$
$$I_2 = 6 - 4 = 2, \ I_3 = 2 + 6 = 8.$$

For 68-volt battery $E_x = E_a - r_1 I_1 = 68 - 12 = 56.$

For 60-volt battery $E_x = E_a - r_2 I_2 = 60 - 4 = 56.$

If external circuit is open $I = \frac{68 - 60}{4} = 2.$ $E_x = 68 - 2 \times 2 = 64.$

For second battery $E_x = 60 + 2 \times 2 = 64.$

10. (a) A slide wire 100 centimeters long has a resistance of 10 ohms. Its ends are connected to the terminals of a 24-volt battery. The positive terminal of a 12-volt battery is connected to the same end of the wire as the positive terminal of the 24-volt battery. How far from this end of the wire should the negative terminal of the 12-volt battery be secured in order that no current will flow through that battery? The

internal resistance of the 24-volt battery is 2 ohms and that of the 12-volt battery is 4 ohms.

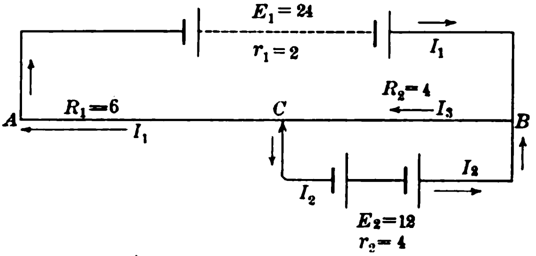


FIG. 37.

$$I_1 = \frac{24}{12} = 2 \text{ amperes.}$$

The resistance of one centimeter of slide wire is equal to $\frac{10}{100} = .1$ ohm.

The drop of potential per centimeter is equal to $.1 \times 2 = .2$ volts.

Since no current is to flow through the 12-volt battery the difference of potentials between its terminals must be 12 volts, and the distance BC which will correspond to a drop of 12 volts equal to $\frac{12}{.2} = 60$ centimeters. This problem illustrates the principle of the potentiometer.

(b) Same problem excepting that the distance CB is assumed to be 40 centimeters and it is desired to know the resulting currents.

The resistance of $CB = R_2 = 40 \times .1 = 4$ ohms.

$$I_3 = I_1 + I_2. \qquad (1)$$
$$24 = 2I_1 + 4I_3 + 6I_1 = 8I_1 + 4I_3. \qquad (2)$$
$$12 = 4I_2 + 4I_3.$$

Subtract

$$12 = 8I_1 - 4I_2, \text{ or } 3 = 2I_1 - I_2, \; I_2 = 2I_1 - 3.$$

Substitute in (1)

$$I_3 = I_1 + 2I_1 - 3 = 3I_1 - 3.$$

Substitute in (2)

$$24 = 8I_1 + 4\,(3I_1 - 3), \text{ or } 20I_1 = 36, \; I_1 = 1.8.$$
$$I_2 = 2 \times 1.8 - 3 = .6, \; I_3 = 1.8 + .6 = 2.4.$$

(c) Same excepting that the distance CB is assumed to be 80 centimeters.

$R_2 = 8$ ohms. With this value the equations become

$$I_3 = I_1 + I_2. \qquad (1)$$
$$24 = 2I_1 + 8I_3 + 2I_1 = 4I_1 + 8I_3. \qquad (2)$$
$$12 = 4I_2 + 8I_3.$$

Subtract

$$12 = 4I_1 - 4I_2, \; I_2 = I_1 - 3, \text{ or } I_3 = 2I_1 - 3.$$

Substitute in (2)

$$24 = 4I_1 + 8\,(2I_1 - 3), \text{ or } 20I_1 = 48,\ I_1 = 2.4.$$
$$I_2 = I_1 - 3 = 2.4 - 3 = -.6.$$
$$I_3 = I_1 + I_2 = 2.4 - 6 = 1.8.$$

The current is flowing in the opposite direction through the battery of 12 volts.

11. Two torpedo circuits (Fig. 38) *A* and *B*, are connected to a battery of E. M. F. of 17.5 volts and a total resistance of 3 ohms. The leading wires *C*, *D*, *A*, and *B* have a resistance of 1 ohm each. In *A* are 4 fuses in series. How many in series in *B* can be inserted, so that all will ignite simultaneously? Each fuse has a resistance of .5 ohm and requires .5 ampere to ignite it.

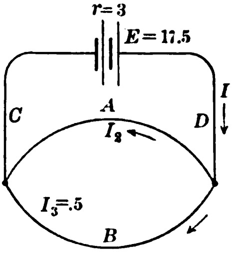


FIG. 38.

To insure ignition it must be assumed that .5 ampere flows in *B*. for *A*'s resistance being less, there will be more than .5 ampere in that branch, and how much more flows in that branch is a matter of indifference, for if each branch has .5 ampere or over, the fuses will all ignite together.

x = No. of fuses required,
I = Current in battery,
I_A = " " branch *A*,
I_B = " " " *B*,

$$\text{then } 17.5 = 3 \times I + I \times 1 + (4 \times .5 + 1)\, I_A + I \times 1,$$
$$17.5 = 3 \times I + I \times 1 + (x \times .5 + 1)\, I_B + I \times 1,$$
$$I = I_A + I_B \qquad I_A + .5 = I$$
$$17.5 = 5I_A + 2.5 + 3I_A \qquad \text{or } I_A = \frac{15}{8}$$
$$3I_A = (.5x + 1)\, .5, \qquad \text{or } x = 4 \times \frac{41}{8} = 20.$$

12. A battery (Fig. 39) of 15 volts E. M. F. and 6 ohms resistance has its poles connected by three circuits in multiple arc. Two of these contain fuses and their resistances with the fuses are 2 and 3 ohms respectively. What is the greatest resistance that can be given the third circuit without igniting the fuses, if $\frac{1}{2}$ ampere be required to ignite a fuse?

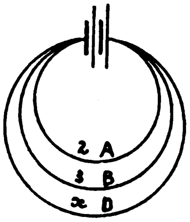


FIG. 39.

The current of $\frac{1}{2}$ ampere must be in the circuit of smallest resistance. Solve as preceding problem. *Ans.* $x = \frac{2}{3}$ ohm.

13. With a constant E. M. F. of 5 volts at *E* (Fig. 40), what is the current through *h*, *a*, *b*, and

c. the resistance of the parts *FhG*, *FaG*, *FbG*, and *FcG* being 8, 4, 3, and 6 ohms respectively?

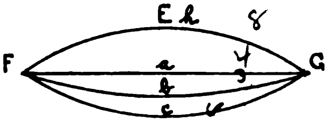


FIG. 40.

$$5 = 8I_h + 4I_a,$$
$$4I_a = 3I_b = 6I_c,$$
$$I_h = I_a + I_b + I_c,$$

or $$5 = 8I_a + \frac{8 \times 4I_a}{3} + \frac{8 \times 4I_a}{6} + 4I_a \qquad \text{or } I_a = .1785 \text{ amp.}$$

$$I_b = \frac{4}{3} I_a = .238 \qquad I_c = \frac{4}{6} \times I_a = .119,$$
$$I_h = .1785 + .238 + .119 = .5355,$$

or the total external resistance $= \frac{1}{\frac{1}{4} + \frac{1}{3} + \frac{1}{6}} = \frac{12}{9}$

$$I_h = \frac{5}{8 + \frac{12}{9}} = \frac{45}{84} = .5356 \text{ as before.}$$

14. A battery of 4 cells is arranged as in the diagram (Fig. 41). Required, the current through the battery and the wire *E*, and the difference of potential between *B* and *C*. The E. M. F. of each cell is 1.8 volts, resistance of each cell .5 ohm, resistance of $AB = 2$ ohms, of $CD = 3$ ohms, $E = 4$ ohms, $F = 6$ ohms, $G = 7$ ohms.

If the wire *G* were cut, would the current through the battery be increased or decreased; would it be increased or decreased through *E*?

$$E = 7.2, \quad r = 2,$$
$$7.2 = 2I + 4I_E + 5I = 7I + 4I_E,$$
$$4I_E = 6I_F = 7I_G. \quad I_F = \frac{4I_E}{6}, \quad I_G = \frac{4I_E}{7},$$
$$I = I_E + I_F + I_G = I_E + \frac{4I_E}{6} + \frac{4I_E}{7},$$
$$7.2 = 7\left(I_E + \frac{2I_E}{3} + \frac{4I_E}{7}\right) + 4I_E = \frac{59I_E}{3},$$
$$I_E = \frac{3 \times 7.2}{59} = .366, \quad 7.2 = 7I + 4 \times .366,$$
$$I = \frac{7.2 - 1.464}{7} = .819 \text{ amp.}$$

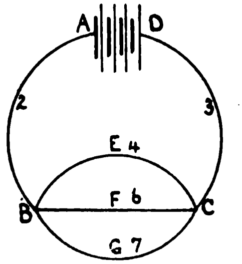


FIG. 41.

If *G* were cut, the resistance would be increased, and the battery current would be decreased.

The difference of potential between *B* and *C* is equal to $4I_E$ and $E = 7I + 4I_E$, or $4I_E = E - 7I$. If *I* is decreased, $4I_E$ will be increased and since the difference of potential between the points is increased while resistance of *E* remains the same, the current through *E* must now increase.

15. Suppose that a battery and wires are connected as in the diagram, Fig. 42.

Resistance of $ADB = 50$ ohms, $ACB = 30$ ohms and EB an unknown resistance. A volt-meter connected at E and B shows the same reading as when connected at A and C. The resistance of AC being $\frac{1}{3}$ of ACB, find the resistance of EB.

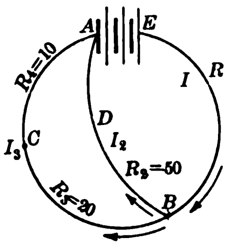


FIG. 42.

$$I = I_2 + I_3,$$

$$50I_2 = 30I_3,\ I_2 = \tfrac{3}{5} I_3,$$

$$10I_3 = RI,$$

$$I = \tfrac{3}{5} I_3 + I_3 = \frac{8I_3}{5},$$

$$\frac{8RI_3}{5} = 10I_3,\ 8R = 50,\ R = 6.25 \text{ ohms.}$$

16. The interpolar portion of a voltaic circuit consists of three separate wires in multiple, their resistances being 30, 50, and 70 ohms. If the E. M. F. of the battery is 5 volts and internal resistance 6 ohms, find the current in battery and through wire of greatest resistance.

Ans. Battery current .24 ampere.
Current through greatest resistance .0508 ampere.

17. Three parallel circuits contain 14, 10, and 4 torpedoes, respectively, and resistance of leading wires in each circuit is 1 ohm. What is the smallest number of cells (E. M. F. of each 1 volt and internal resistance of each .6 ohm) required to explode all the torpedoes simultaneously and how must the cells be arranged? Resistance of each fuse .5 ohm and requires 1 ampere to fire it.

Assumption necessary: that the current in the greatest resistance must = 1 ampere. *Ans.* 96 cells required; 6 groups in parallel, and 16 cells in series in each group.

18. A battery of E. M. F. of 36 volts and internal resistance 9 ohms is connected as shown to a divided circuit a and b; a has a resistance of 10 ohms and b a resistance of 15 ohms. (1) What is the magnitude of the current in a and b? (2) What resistance must be added at R to reduce the current flowing through a to $\frac{3}{4}$ ampere? (3) If this resistance is not used what must be resistance of a shunt circuit x to reduce the current in a to $\frac{3}{4}$ ampere?

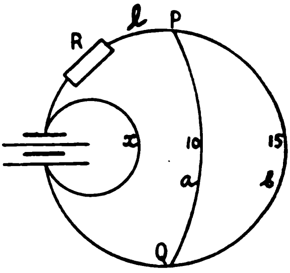


FIG. 43.

Resistance of leading wires neglected.

$$I = I_a + I_b,$$

$$36 = 9I + 10I_a,$$

$$10I_a = 15I_b,\ I_b = \tfrac{2}{3}I_a,$$

$$I = I_a + \tfrac{2}{3}I_a = \tfrac{5}{3}I_a,$$

$$36 = 9 \times \tfrac{5}{3} I_a + 10I_a,\ I_a = \tfrac{36}{25},\ I_b = \tfrac{2}{3} \times \tfrac{36}{25} = \tfrac{24}{25} \text{ ampere.}$$

(2) **If a is to have $\frac{3}{4}$ ampere, then b would have $\frac{2}{3} \times \frac{3}{4} = \frac{1}{2}$ ampere, and I would equal $\frac{5}{4}$ amperes. In order for a to have $\frac{3}{4}$ ampere the difference of potential between P and Q must be $10 \times \frac{3}{4} = 7.5$ volts.**

$$\therefore 36 - \frac{5}{4}(9 + R) = 7.5, \quad \frac{5R}{4} = \frac{69}{4}, \quad R = 13.8.$$

(3) **Current in $a = \frac{3}{4}$, in $b = \frac{1}{2}$, total $= \frac{5}{4}$. Current through battery $= I_x + \frac{5}{4}$. Since the resistance of leads is neglected $I_x x = I_a R_a = \frac{3}{4} \times 10 = 7\frac{1}{2}$.**

$$36 = 9\left(\frac{5}{4} + I_x\right) + I_x x = 9\left(\frac{5}{4} + I_x\right) + \frac{15}{2}, \quad I_x = \frac{69}{36} = \frac{23}{12},$$
$$x = \frac{15}{2} \div \frac{23}{12} = \frac{15}{2} \times \frac{12}{23} = \frac{90}{23} \text{ ohms.}$$

Shunts.

In measuring currents with a galvanometer it is sometimes necessary to connect a resistance in parallel with the galvanometer in

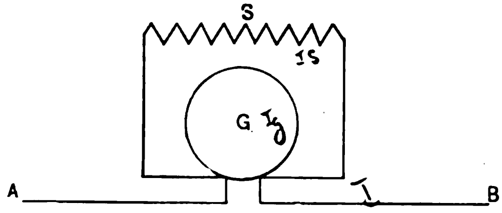


FIG. 44.—Illustrating Use of Shunts.

order that only a fraction of the total current will pass through the instrument. A resistance of this nature is called a shunt. Sometimes galvanometers are provided with a shunt box and by plugging in the proper shunt resistance the current through the galvanometer will indicate $\frac{1}{10}$, $\frac{1}{100}$ or $\frac{1}{1000}$ of the total current flowing.

In Fig. 44, let G equal resistance of galvanometer, S resistance of shunt, I the total current, I_s current through shunt and I_g current through galvanometer.

$$I = I_s + I_g, \quad I_s S = I_g G, \quad I_s = \frac{I_g G}{S},$$

$$I = \frac{I_g G}{S} + I_g = I_g\left(\frac{G+S}{S}\right), \text{ or } I_g = I\left(\frac{S}{G+S}\right).$$

The term $\left(\frac{G+S}{S}\right)$ is sometimes called the multiplier as the current shown by the galvanometer has to be multiplied by this number to equal the total current. Assume $I_g = \frac{1}{n} I$, then $\frac{1}{n} I = I\left(\frac{S}{G+S}\right)$; $nS = G + S$, $S(n-1) = G$, $S = \frac{G}{n-1}$. If $n = 10$, $S = \frac{1}{9} G$. If $n = 100$, $S = \frac{1}{99} G$, etc.

The shunt will, of course, decrease the resistance of the external circuit. If the external resistance is small the indication of the instrument after being shunted may be nearly as large as before. Sometimes it is desired to know the magnitude of the resistance which placed in series will cause the external resistance to remain the same. This may be called the compensating resistance.

An ammeter is a galvanometer calibrated so that the reading of its scale gives the magnitude of the current in amperes.

In most ammeters only a definite fraction of the current passes through the instrument, the larger part flowing through a low resistance shunt. Sometimes two shunts of different resistances are provided and the ammeter has two scales corresponding to the two shunts. This gives the instrument a greater range. Several shunts may be provided with an instrument with a single scale and if the resistances of the shunts bear a fixed ratio to one another the correct value of the current can be obtained by multiplying the scale reading by the ratio of these resistances.

A voltmeter is a galvanometer calibrated so that its scale reading gives the potential between its terminals in volts. The range of a voltmeter may be increased by putting resistance in series with it.

The following problems will illustrate the use of shunts and series resistances:

Examples of Shunts and Resistances.

1. A galvanometer of 198 ohms resistance requires a shunt to reduce the current traversing the coils to one-tenth the original amount. What must be the resistance of the shunt? What additional external resistance must be added in order that the total resistance remains unchanged?

$$S = \frac{G}{n-1}, \quad n = 10, \quad S = \frac{198}{9} = 22 \text{ ohms.}$$

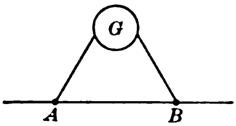
Combined resistance R is obtained as follows $\frac{1}{R} = \frac{1}{198} + \frac{1}{22} = \frac{10}{198}$ = 19.8 ohms. Resistance to be added = 198 — 19.8 = 178.2. This may be obtained by Kirchoff's laws direct.

$$I = I_S + I_G,\ 10 I_G = I_S + I_G,\ I_S = 9 I_G,$$

$$I_G G = I_S S,\ S = \frac{I_G \times 198}{I_S} = \frac{I_G \times 198}{9 I_G} = 22.$$

2. A certain galvanometer of 4 ohms resistance requires a current of .01 ampere to produce a full scale deflection. Calculate the resistance of a shunt which, when used in conjunction with the galvanometer, will give a full scale deflection for 100 amperes. What resistance must be inserted in series with the galvanometer in order that a full scale deflection may be obtained for 100 volts?

(a) Let G be the galvanometer and AB the shunt. The voltage drop from A to B when galvanometer produces full scale deflection is $4 \times .01 = .04$ volt. This must be equal to SI_s, where I_s is the current flowing through the shunt and S the resistance of the shunt.



$S \times 100 = .04$, $S = .0004$ ohm. The total current flowing will be 100.01 but the small amount flowing through the instrument in this case may be neglected.

(b) The drop of potential across the instrument will be .04 volt and the drop through the resistance must be 100 — .04 = 99.96. The current equals .01 ampere. Hence, $R = \frac{E}{I} = \frac{99.96}{.01} = 9996$ ohms.

3. A millivoltmeter with 100 scale divisions has a resistance of 1.5 ohms. Calculate the resistance to be put in series with the instrument in order that the full scale deflection shall represent 100 volts; also calculate the resistance of a shunt in order that the full scale deflection shall represent 10 amperes.

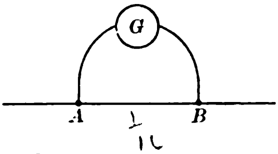
The full deflection of the scale will be equal to $100 \times \frac{1}{1000}$ volt $= \frac{1}{10}$ volt. $E = \frac{1}{10}$, $R = 1.5$, $I = \frac{1}{10} \div \frac{3}{2} = \frac{1}{15}$ ampere.

The drop of potential through the resistance will be 99.9 volts.

Resistance equals $\dfrac{99.9}{\frac{1}{15}} = 1498.5$ ohms.

Drop of potential from A to $B = \frac{1}{10}$ volt, $I_s = 10$, $R = \frac{1}{10} \div 10 = \frac{1}{100}$ ohm. (Neglecting current through instrument.)

A more accurate solution is obtained by taking the current through the shunt $10 - \frac{1}{15} = \frac{149}{15}$. Hence,



$$R = \frac{1}{10} \div \frac{149}{15} = \frac{15}{1490} = .01007 \text{ ohm.}$$

4. When measuring the value of a certain resistance, the voltmeter was connected up so as to measure the voltage, not only across the resistance, but also across the ammeter. The resistance of the voltmeter was 200 ohms, and of the ammeter .005 ohm. The ammeter reading was 25 amperes, and the voltmeter reading was 4.8 volts. Calculate the true value of the resistance. *Ans.* .187 ohm.

5. A direct reading millivoltmeter has 100 scale divisions. Each scale division corresponds to 1 millivolt impressed at the terminals of the instrument. When this instrument is connected to the terminals of a low resistance shunt, each scale division corresponds to a current of .5 ampere flowing through the shunt. What is the resistance of the shunt? *Ans.* .002 ohm.

CHAPTER VII.

ELECTROSTATICS.

Electrostatics is that branch of electricity which treats of charges of electricity at rest and of the stresses existing in the surrounding medium.

The early investigations were confined to this branch of the study and it is a matter of record that about 600 B. C. a Greek philosopher described the peculiar properties exhibited by amber when rubbed. This property being its power of attracting light bodies like small pieces of pith. The word "electricity" is derived from the Greek word "electron," meaning amber.

In later investigations it was discovered that there were apparently two kinds of electrification, for experiments showed that a glass rod after being rubbed with silk was repelled by another glass rod similarly electrified but was attracted by an ebonite rod which had been rubbed with flannel.

The kind of electricity represented by the glass rod was called positive and the other negative. From experiments of this nature the fluid theories of electricity were evolved and the amount of the charge was supposed to depend upon the amount of the so-called electric fluid present. With the development of the electron theory this idea has been exploded.

In the older method of treating this subject all deductions were based upon the repulsion and attraction existing between point charges. In the modern method the stress in the medium surrounding a charge is given the primary consideration as it is believed that this method, which is analogous to the method used for the electric circuit and magnetic circuit, presents the principles in a way more easily understood.

Laws of Electrostatics.

First Law.—Like charges of electricity repel one another and unlike charges attract one another.

Second Law.—The force existing between two point charges is directly proportional to the product of the strength of the two charges and inversely proportional to the square of the distance between them.

The force is also inversely proportional to the specific inductive capacity or dielectric constant of the medium separating the two charges.

These laws proved experimentally by Coulomb using the torsion balance may be written $F=\frac{qq'}{\epsilon d^2}$, where q and q' are the magnitude of the charges, d the distance between them and ϵ the dielectric constant of the intervening medium.

By taking the unit of distance as a centimeter and the unit of force as a dyne and considering the dielectric constant of air equal to unity the definition for unit quantity of electricity or unit charge follows:

A unit quantity of electricity (electrostatic) is that quantity which when concentrated into a point charge will repel a like charge at a distance of 1 centimeter in air with a force of 1 dyne.

The practical unit of quantity, the coulomb, is equal to $3\times(10)^9$ electrostatic units.

Electrostatic Field.—When a body is charged and another charged body is brought near it there exists between the two bodies a force of attraction or repulsion. This is caused by the electrostatic force action between the bodies. A space in which electrostatic force acts is called an electrostatic field. Every charged body is thus surrounded by such a field.

This field is usually represented by so-called lines of electric force or dielectric flux in an analogous manner to the representation of a magnetic field by lines of magnetic force or magnetic flux. These lines by their direction indicate the resultant direction of the electrostatic force and by their density the relative magnitude of the force. The positive direction of a field is assumed as the direction a positive unit charge would tend to move if placed in the field.

A unit field is a field that contains one line per square centimeter. That is, if a section of a homogeneous field is made perpendicular to its direction, each square centimeter would contain one line of flux. This notation of lines per square centimeter does not mean that the force exists only along the lines, but means that there is a uniform force everywhere in the section and its intensity is measured by the density of the lines.

If the medium is air whose value of $\epsilon=1$, the force exerted in a unit field on a unit charge is equal to 1 dyne and since the electrostatic force is proportional to the flux density and inversely proportional to the dielectric constant, the value of the force in dynes in any electrostatic field is given by the equation $F=\frac{D}{\epsilon}$, where D is the flux density or the number of lines per square centimeter and ϵ is the dielectric constant. If a point charge is isolated its field will

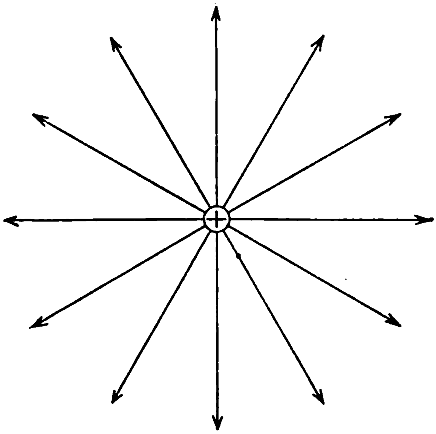


FIG. 45.—Electrostatic Field.

be represented by symmetrically spaced radial lines of flux as represented in Fig. 45.

If the charge consists of m positive units, the positive direction of the lines would be away from the body, the other ends of lines terminating in the walls and ceiling of the room in a negative charge of equal magnitude. At a distance r centimeters in air from this charged body the force acting on a unit point charge would be $F=\frac{m}{r^2}$. A force of this magnitude would act at every part of the surface of a sphere whose radius is r having the charge m at the center. Such a force at the surface of the sphere would be represented by $\frac{m}{r^2}$ lines of dielectric flux per square centimeter. Since the area of the sphere is $4\pi r^2$ the total flux $\psi = 4\pi r^2 \times \frac{m}{r^2} = 4\pi m$. Since the charge is m units each unit charge produces 4π lines of dielectric flux. These lines of dielectric flux extend from a body of high potential to one of lower potential and end at the surfaces

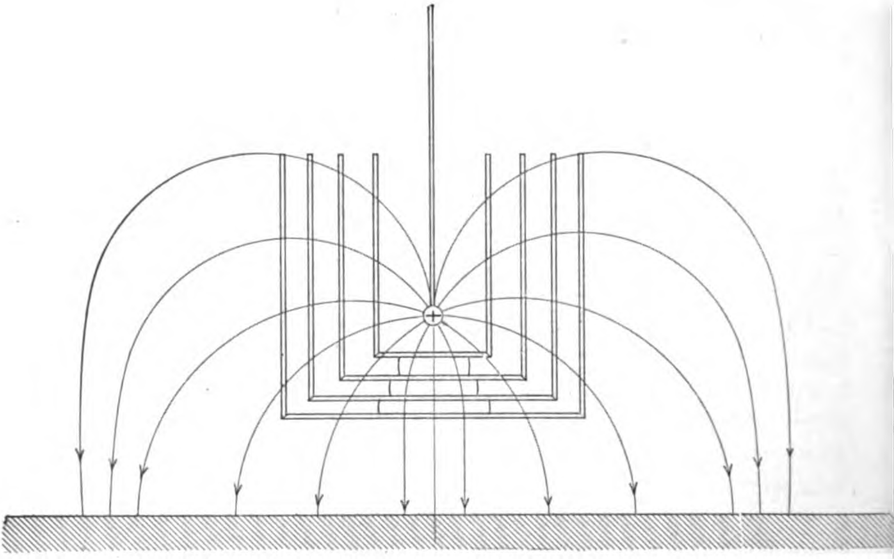


FIG. 46.—Illustrating Faraday's Ice-Pail Experiment.

of the charged bodies. Where 4π lines leave a body they represent a charge of one positive unit and where 4π lines enter a body they represent a charge of one negative unit. A positive charge is always linked with a negative charge of equal magnitude. There is a tension along these lines as represented by the force tending to draw the bodies together, and a tension between the lines tending to cause them to diverge laterally. This conception of dielectric flux simplifies many of the principles of electrostatics derived experimentally by the early investigators. Among these are "electrification by induction" and the principles demonstrated by Faraday in his ice pail experiment.

In the figure there are three metal pails insulated from each other and from earth by cakes of ebonite. A positive charge is introduced as shown and it is desired to ascertain the nature of the charge on the inside and outside of each pail and to prove that the magnitudes of the charges are equal to the original charge.

It is assumed that the pails are so deep that all the lines of dielectric flux pass through the pails. The electrostatic field is then represented by a system of lines emanating at the + charge and proceeding to earth, it will be noted that these lines pass through the series of pails and are then linked to earth. The charge on any side of any pail is equal to $\frac{\psi}{4\pi}$ where ψ is the total flux. The positive direction of the lines is toward the earth; where entering a conductor the charge is negative and where leaving it is positive. It is thus seen that a negative charge will exist on the inside of each pail and a positive charge on the outside of each pail. Since the total flux passes through each pail, the magnitude of the charges will be equal to each other and to the original charge. If the operator touches the inside pail with his finger thus making an electrical connection with the earth the lines will terminate on the inside of that pail in a negative charge, there will be no charge on the outside of this pail or on either side of the outer pails.

Quantity, Potential and Capacity.*—In Chapter I the relation existing between potential, capacity and quantity of a charge was explained and it was shown that by choosing proper values for the units, this relation is expressed by the equation $Q=EC$. In electrostatic units the difference of potential between two points is equal to the amount of energy in ergs that must be expended to bring a unit charge from one point to the other against the electrostatic force. The potential of any charged body is equal to the amount of energy that must be expended to bring a unit charge from infinity

* The word "capacity" as referred to electricity has several distinct meanings. To avoid confusion the American Institute of Electrical Engineers has adopted the word "capacitance" to replace the word "capacity" when used in this connection.

to that body. The potential of any point at a distance r from a point charge may be determined as follows:

Assume an isolated point charge of Q units. The force acting on a unit positive charge at P is $\frac{Q}{\epsilon r^2}$ dynes, where r is the distance from

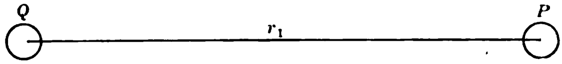


FIG. 47.—Potential of a Point Due to Isolated Charge.

Q in centimeters and ϵ the dielectric constant. The work required to bring this unit + charge from infinity to P will be

$$\int_r^\infty \frac{Q}{\epsilon r^2}\, dr = -\frac{Q}{\epsilon}\left.\frac{1}{r}\right]_r^\infty = \frac{Q}{\epsilon r} \text{ ergs},$$

which represents the potential of point P.

In Fig. 48 B is a battery and A and C are metallic plates connected to the poles of the battery. When these two plates are placed together the electric circuit is completed and current will flow. If these two plates are separated the current will cease to flow and the plates will remain at the potential of the poles of the battery. In this position the two plates will be connected by lines of dielectric flux and a force will be exerted between them. These two plates represent the simplest idea of a condenser. The total flux will depend upon the potential difference between the plates and what corresponds to the conductance in an electric circuit, that is, the relative ease of the medium in permitting the flow of flux. For want of a better name we will call this property electric permeance, and designate it by the symbol $\mathcal{P}$, permeance being the term applied to the same property in the magnetic circuit. This permeance is evidently directly proportional to the area of the plates and to the inductive capacity of the medium, and inversely proportional to the

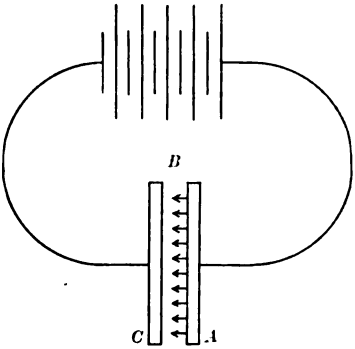


FIG. 48.—Illustrating a Condenser.

distance between the plates. By assuming a proper value for the units employed this relation is given by the equation

$$\psi = E\mathcal{P}. \tag{1}$$

Dividing this equation by (4) it becomes $\frac{\psi}{4\pi} = \frac{E\mathcal{P}}{4\pi}$

or

$$Q = E\frac{\mathcal{P}}{4\pi}, \tag{2}$$

since $\frac{\psi}{4\pi} = Q$. The fundamental equation referring to quantity potential and capacity is

$$Q = EC. \tag{3}$$

Then from equations (2) and (3) $EC = E\frac{\mathcal{P}}{4\pi}$ and $C = \frac{\mathcal{P}}{4\pi}$. It is thus seen that C is in the nature of a permeance for the dielectric flux. The constant 4π is due to the system of units chosen. In order for the equation $Q = EC$ to be a true one the unit of capacity must be chosen so that unit quantity will raise the body to unit potential, or unit charge for a condenser will give a unit difference of potential at its terminals. The practical unit of capacity is the farad and is the capacity of a condenser which will be raised to a potential of 1 volt by 1 coulomb of electricity. The farad is equal to $9 \times (10)^{11}$ electrostatic units.

Fig. 49 represents a plate condenser formed by two metal coverings and an intervening dielectric whose inductive capacity is equal to ϵ. Since the metal coverings are very close together it can be assumed that the field between the coverings is homogeneous and the lines of dielectric flux are straight and perpendicular to the two surfaces. If Q represents the charge on one plate, and A the area of plate in square centimeters, then $4\pi Q$ will be the total flux ψ and $\frac{4\pi Q}{A} = D$, the flux density. As explained above the electrostatic force or field intensity F is equal to $\frac{D}{\epsilon}$, and hence $F = \frac{4\pi Q}{A\epsilon}$. Since the field between the plates is assumed to be uniform, the difference of potential E is equal to Fd

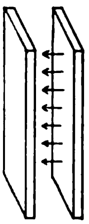


FIG. 49. A Plate Condenser.

where F = the field intensity and d the distance between the plates. Hence $Fd = E = \frac{4\pi Qd}{A\epsilon}$. Substitute this value for E in the formula $C = \frac{Q}{E}$ and we have $C = \frac{A\epsilon}{4\pi d}$ electrostatic units, where A = area in square centimeters and d the thickness of the dielectric in centimeters.

Though this equation is derived for a plate condenser it is practically true for all condensers in which the thickness of the dielectric is very small compared with the area of the metal coatings of the condenser. When it is used to find the capacity of a Leyden jar, A in the formula is equal to $\pi r^2 + 2\pi rh$, where r is the radius of the jar and h is the height of the metal coverings. The correct

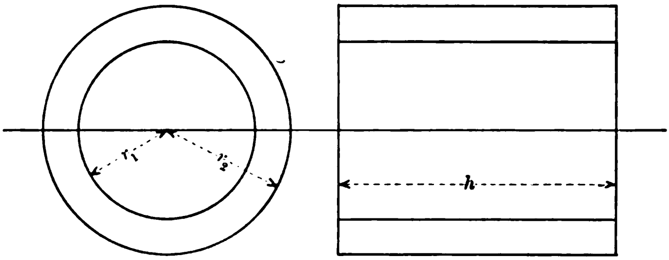


FIG. 50.—The Capacity of a Cylindrical Condenser.

expression for the capacity of a condenser of any symmetrical shape can be found by the aid of calculus.

Fig. 50 represents a cylindrical condenser, r_1, r_2 the radii of the metal coatings, and h the height and Q the charge. ψ the total flux $= 4\pi Q$. The surface of a cylinder with any radius $r = 2\pi rh$ and hence D the flux density at any distance r from the center $= \frac{4\pi Q}{2\pi rh}$ $= \frac{2Q}{rh}$. Since $F = \frac{D}{\epsilon}$ we have

$$F = \frac{2Q}{\epsilon rh}, \text{ and } E = \int F dr = \frac{2Q}{\epsilon h}\int_{r_1}^{r_2}\frac{dr}{r} = \frac{2Q}{\epsilon h}\log_\epsilon\frac{r_2}{r_1}.$$

Therefore,

$$C = \frac{Q}{E} = \frac{\epsilon h}{2\log_\epsilon\frac{r_2}{r_1}}.$$

A similar method may be used to find the capacity of a spherical condenser. However, as mentioned above, the formula for plate condenser $C=\frac{A\epsilon}{4\pi d}$ can be applied to any practical form of condenser by letting A be equal to the area of the surface. If, however, it is desired to find the capacity of a lead-covered cable where the thickness of the dielectric is relatively large the more exact equation derived above for a cylindrical condenser would have to be used.

The Energy of a Charged Body or Condenser.—In order to charge a body or a condenser to a certain potential requires an expenditure of energy. If a charge of Q units is carried from a place of zero potential to place of potential E it is evident that the energy expended will be EQ ergs. However, when charging a body or a condenser the problem is different for the potential is supposed to be zero at the beginning and E at the end, and hence the mean potential will be $\frac{E}{2}$ and the work required will be $\frac{QE}{2}$. This can be derived more easily as follows:

$$W=\int_0^E QdE \text{ or as } Q=CE,\ W=C\int_0^E EdE=\tfrac{1}{2}CE^2.$$

This may be written in various ways by substituting the values from the formula $Q=CE$, *i. e.*, $W=\frac{1}{2}QE=\frac{Q^2}{2C}$. This energy is contained in the electrostatic field and it is sometimes convenient to ascertain its value per cubic centimeter of field. In a plate condenser where the field may be considered as homogeneous this may be done as follows: It has been shown that

$$W=\tfrac{1}{2}CE^2,\ C=\frac{A\epsilon}{4\pi d},\text{ and } E=Fd=\frac{Dd}{\epsilon}.$$

Substitute

$$W=\frac{1}{2}\,\frac{A\epsilon}{4\pi d}\cdot\left(\frac{Dd}{\epsilon}\right)^2=Ad\cdot\frac{D^2}{8\pi\epsilon}.$$

Since Ad represents the volume of the electrostatic field, the energy per cubic centimeter equals $\frac{D^2}{8\pi\epsilon}$. The energy per cubic centimeter is thus proportional to the square of the flux density and since $D = F\epsilon$ it is also proportional to the square of the electrostatic force.

Force Exerted Between Parallel Plates.—In the plate condenser the dielectric flux is uniform and the flux density $D = \frac{4\pi Q}{A}$ and the electrostatic force, or $F = \frac{4\pi Q}{A\epsilon}$. This represents the force in dynes acting on a unit charge when taken from one plate to the other. In this case the force on unit charge is due to the combined action of both plates, one attracting and the other repelling, and is twice as great as the force acting per unit charge on a plate bounding the electrostatic field. Hence the attraction between the plates F' will be $\frac{2\pi Q}{A\epsilon} \times Q = \frac{2\pi Q^2}{A\epsilon}$ dynes. That is $F' = \frac{2\pi Q^2}{A\epsilon}$. Since $D = \frac{4\pi Q}{A}$, $Q = \frac{DA}{4\pi}$, and $Q^2 = \frac{D^2A^2}{16\pi^2}$. Substituting this value of Q^2 in the equation above gives

$$F = \frac{2\pi D^2A^2}{16\pi^2 A\epsilon} = \frac{D^2A}{8\pi\epsilon} \text{ dynes.}$$

The attracted disc electrometer is an electrostatic measuring instrument by means of which potential is measured by ascertaining the attraction between two parallel plates which are kept at the respective potential of the bodies whose difference of potential is to be measured. The force of this attraction is measured in dynes. In the equation $F' = \frac{D^2A}{8\pi\epsilon}$ substitute $E = \frac{Dd}{\epsilon}$ or $D = \frac{\epsilon E}{d}$ and we have $F' = \frac{\epsilon^2E^2A}{8\pi\epsilon d^2}$. This may be written

$$E^2 = \frac{8\pi d^2F'}{A\epsilon} \text{ or } E = d\sqrt{\frac{8\pi F'}{A\epsilon}} \text{ electrostatic units,}$$

where d is the distance between the plates in centimeters.

Ohm's Law for the Electrostatic Circuit.—Referring to the equation $E = \frac{Q}{C}$ and considering it in reference to a plate condenser, if we substitute $\frac{A\epsilon}{4\pi d}$ for C it becomes $E = 4\pi Q \cdot \frac{d}{A\epsilon}$, or $E = \psi \cdot \frac{D}{A\epsilon}$

where ψ is the total dielectric flux, and $\frac{d}{A\epsilon}$ is the dielectric reluctance. The equation now takes a form analogous to Ohm's law for electric circuits. It may be used to represent the entire electrostatic circuit or any part of it. If it represents the whole circuit E represents the E. M. F. at the terminals of the circuit. If it represents a part of a circuit E represents the drop of potential due to that part.

To illustrate this point take a condenser whose dielectric consists of two parallel sheets of different thickness and different dielectric constants as shown in Fig. 51.

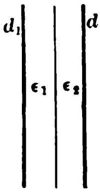


FIG. 51.

Let E represent the potential of the condenser and $d_1 d_2$ and $\epsilon_1 \epsilon_2$ their respective thicknesses and dielectric constants. The reluctance of the circuit will then be equal to $\frac{d_1}{A\epsilon_1} + \frac{d_2}{A\epsilon_2}$ and if E_1 and E_2 represent the drop of potential through the respective dielectric sheets then $E_1 = \psi \frac{d_1}{A\epsilon_1}$ and $E_2 = \psi \frac{d_2}{A\epsilon_2}$ and $E = E_1 + E_2$.

Condensers in Series and in Parallel.—Fig. 52 represents three condensers in parallel whose respective capacities and charges are

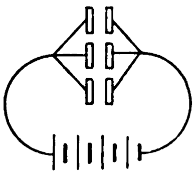


FIG. 52.—Condensers in Parallel.

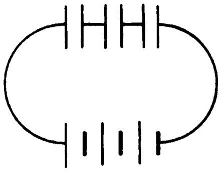


FIG. 53.—Condensers in Series.

C_1, C_2 and C_3 and Q_1, Q_2 and Q_3. Find the value of the capacity of a condenser whose capacity is equal to the combined capacity of the three. It is apparent that the potential of each condenser is the same, hence E being the potential $Q_1 = C_1 E$, $Q_2 = C_2 E$, $Q_3 = C_3 E$ and $Q = CE$. Where Q and C represent the charge and capacity of the three. However,

$$Q = Q_1 + Q_2 + Q_3 = E(C_1 + C_2 + C_3) = EC. \quad \therefore C = C_1 + C_2 + C_3.$$

That is, when condensers are connected in parallel the resultant capacity is equal to the sum of the individual capacities.

In Fig. 53 the three condensers are in series. In this case E, the total potential difference, is equal to $E_1+E_2+E_3$, or the sum of the potential difference of the condensers. Since the same dielectric flux passes through all the condensers the charge of each is the same. Therefore, $E_1=\frac{Q}{C_1}$, $E_2=\frac{Q}{C_2}$, $E_3=\frac{Q}{C_3}$ where E_1, E_2, E_3 and C_1, C_2, C_3 represent the respective potential and capacity of the different condensers.

Let E and C represent the potential and capacity respectively of a condenser equivalent to the three condensers given, then $E=\frac{Q}{C}$ and $E=E_1+E_2+E_3$, or $\frac{Q}{C}=\frac{Q}{C_1}+\frac{Q}{C_2}+\frac{Q}{C_3}$, or $\frac{1}{C}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}$.

It is thus seen that putting condensers in parallel increases the capacity, but in putting them in series the resulting capacity is less than that of any of the individual condensers. In high potential circuits it is often necessary to put them in series as they may not be designed to stand such a high E. M. F. By putting them in series the total potential difference will be equal to the sum of the terminal potentials of the condensers.

If the two plates of an air condenser be connected to the two knobs of an electric machine, a discharge will take place between the plates after they have reached a certain potential difference. All dielectrics possess what is called dielectric strength or ability to resist rupture by the stress in the dielectric. This property of dielectrics is an important consideration in the design of condensers. If the dielectric is air or oil and a rupture takes place, due to a high difference of potential, the rupture may be repaired by circulation in the medium. If the dielectric is glass or mica its usefulness is destroyed by the rupture. The dielectric strength is usually given in volts per millimeter and volts per mil (0.001 inch), and the values for the different substances can be found in the Standard Handbook for Electrical Engineers. Differentiate the equation $Q=EC$ and we have $\frac{dQ}{dt}=C\cdot\frac{dE}{dt}$. This shows that the rate of change of quantity or the current flowing in or out of the condenser at any instant is proportional to the rate of change of the impressed E. M. F. If the E. M. F. applied to a circuit containing a condenser is constantly changing a current will flow through the circuit depending upon the rate of change of E. M. F.

Problems in Electrostatics.

1. To what voltage will 2 coulombs of electricity charge a condenser whose capacity is 5 microfarads? What is the energy of the charge?

$$Q = CE, \; E = \frac{Q}{C} = \frac{2}{5(10)^{-6}} = 4(10)^5 \text{ volts.}$$

$$W = \frac{Q^2}{2C} = \frac{2^2}{5(10)^{-6}} = 4(10)^5 \text{ joules.}$$

2. The terminal voltage of a 100-microfarad condenser in a circuit varies from 4000 to 1000 volts in .02 second. What is the average current flowing in the circuit? $\frac{dQ}{dt} = I = C\frac{dE}{dt} = \frac{100}{(10)^6} \times \frac{3000}{2(10)^{-2}}$ or $\frac{(10)^2 \times 3(10)^3}{2(10)^4} = 15$ amperes.

3. Three condensers have capacities of 20, 30 and 40 microfarads respectively. What is the combined capacity, (1) when in parallel, (2) when in series?

$$C = C_1 + C_2 + C_3 = 20 + 30 + 40 = 90 \text{ microfarads.} \quad (1)$$

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} = \frac{1}{20} + \frac{1}{30} + \frac{1}{40} = \frac{6+4+3}{120} = \frac{13}{120};$$

$$C = \frac{120}{13} = 9\frac{3}{13} \text{ microfarads.} \quad (2)$$

4. If the above condensers are placed in 30,000 volt-circuit what will be the terminal E. M. F. of each condenser for both arrangements?

In parallel the terminal E. M. F. of each condenser equals 30,000 volts. In series, let E_1, E_2, E_3 be the respective terminal E. M. F.'s of the condensers, then $E_1 + E_2 + E_3 = 30{,}000$, $E_1 = \frac{Q}{C_1}$, $E_2 = \frac{Q}{C_2}$, $E_3 = \frac{Q}{C_3}$; therefore, $E_1 : E_2 : E_3 :: \frac{1}{C_1} : \frac{1}{C_2} : \frac{1}{C_3} :: \frac{1}{20} : \frac{1}{30} : \frac{1}{40} :: 6 : 4 : 3$. $\therefore E_1 = \frac{6}{13} \times 30{,}000$ volts, $E_2 = \frac{4}{13} \times 30{,}000$, $E_3 = \frac{3}{13} \times 30{,}000$ volts. This may be also solved as follows: Find value of C as in example (3), then $Q = CE$ where $E = 30{,}000$. Therefore, $Q = \frac{120 \times 3(10)^4}{13 \times (10)^6} = \frac{36}{130}$. However,

$$E_1 = \frac{Q}{C_1}, \; E_2 = \frac{Q}{C_2} \text{ and } E_3 = \frac{Q}{C_3}.$$

Substituting:

$$E_1 = \frac{36 \times (10)^6}{130 \times 20} = \frac{6 \times 3(10)^4}{13} \text{ volts.}$$

$$E_2 = \frac{36 \times (10)^6}{130 \times 30} = \frac{4 \times 3(10)^4}{13} \text{ volts.}$$

$$E_3 = \frac{36 \times (10)^6}{130 \times 40} = \frac{3 \times 3(10)^4}{13} \text{ volts.}$$

5. How many square meters of glass 2 millimeters thick with copper foil on both sides would be required to provide a .035 microfarad plate condenser for use with a radio transmitting set? Dielectric constant of the glass 6.6, take $\pi = 22/7$. One farad $= 9 \times (10)^{11}$ electrostatic units $\therefore$ .035 microfarad $= .035 \times 9 \times (10)^5$ electrostatic units. For a plate condenser, $C = \frac{A\epsilon}{4\pi d}$. Therefore,

$$A = \frac{4\pi dC}{\epsilon} \text{ sq. cm.} = \frac{4 \times 22 \times 2(10)^{-1} \times 9 \times (10)^5 \times .035}{7 \times 6.6 \times (10)^2} \text{ square meters}$$

$$= 4 \times 2(10)^{-1} \times 30 \times (10)^3 \times 5(10)^{-3} = 120 \text{ square meters.}$$

6. What is the height of a standard .002 microfarad Leyden jar if the dielectric is glass 3 millimeters thick, and the diameter of the jar is 12 centimeters, dielectric constant 6?

$$C = .002 \times 9 \times (10)^5 \text{ electrostatic units.}$$

$$C = \frac{A\epsilon}{4\pi d} = .002 \times 9 \times (10)^5 = \frac{\pi(36 + 12h)6}{4\pi \times 3 \times (10)^{-1}},$$

or

$$2 \times (10)^{-3} \times 9 \times (10)^5 \times 2 \times (10)^{-1} = 36 + 12h.$$

$$h = \frac{324}{12} = 27 \text{ cm.}$$

CHAPTER VIII.

MAGNETISM AND ELECTROMAGNETISM.

Magnetism.

Magnetism is the science that teaches of the properties of magnets. The name *magnet* was originally applied to a mineral known as *magnetite,* an oxide of iron of the chemical composition Fe_3O_4, which in its native state has the power of attracting iron. *Magnetite* has the power of imparting its magnetic properties to pieces of iron or steel brought near it, and such pieces of iron or steel are then said to be *magnetized* and are then called *magnets.* Iron or steel may be magnetized in other ways, the principal method being by means of an electric current.

Substances which have the property of being attracted by a magnet are called magnetic substances. These are iron, steel, cobalt, nickel, chromium and manganese, but iron and steel are vastly superior to the others in this respect.

A piece of magnetite which possesses inherent magnetism is called a *natural magnet.* A piece of steel or a magnetic substance which has been magnetized is called an *artificial magnet.*

The Compass.—One of the most common examples of a magnet is the ordinary mariner's compass needle, a pivoted needle, highly magnetized, which, when at rest and undisturbed by local magnetism, takes a position that indicates the magnetic north and south. The end of the needle that points towards magnetic north is called the *north-seeking pole,* or briefly the **north pole** of the needle, and similarly the other end is called the **south pole** of the needle.

This action of the needle is due to the fact that the earth itself may be considered as a magnet having its magnetic poles near the geographical poles. Since like poles repel and unlike poles attract it is evident that, according to our definition of poles of a magnet, the north pole of the earth possesses south magnetism, that is, acts like the south pole of an ordinary magnet while the south pole of the earth acts like a north pole of a magnet.

Recent investigations seem to indicate that there is only one north magnetic pole but one or more south magnetic poles. Emanating and radiating from these poles, there may be considered an indefinite number of lines, the direction of which at any place represents the direction of the resulting forces due to the opposite poles of the earth. The positive direction of these lines in space is assumed to be the direction which a free north pole would tend to move.

These imaginary lines may be considered as forming closed curves,

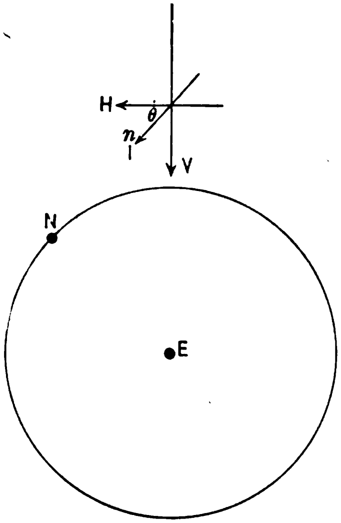


FIG. 54.—Illustrating Earth's Magnetic Force.

running through the earth from the north to the south pole, and through the space surrounding the earth, from the south to the north pole.

At any place on the earth's surface, the direction of one of these imaginary lines would be that which a freely suspended magnetic needle would take; the north pole of the needle pointing in the positive direction of the lines of force.

In Fig. 54, let the circle E represent the cross-section of the earth and N the north magnetic pole. A freely suspended magnetic needle n, will turn so as to place itself in the direction of the magnetic lines at the place of suspension, and its north end will point towards the north magnetic pole. The force which causes the needle to assume this direction is called the earth's total force and is designated by the letter T.

This force may be resolved into two forces, one parallel to the earth's surface, called H and the other vertical to the earth and called V.

If θ = the angle the needle makes with the horizontal then

$$H = T \cos \theta$$
$$V = T \sin \theta$$

and

$$T = \sqrt{H^2 + V^2}.$$

As the point of suspension of the needle approaches the poles, the angle θ will increase, and when $\theta = 90°$

$$V = T \sin 90° = T.$$

At the pole then the horizontal force is zero, the vertical force is equal to the total force, and the needle points vertically up and down.

When θ becomes zero,

$$H = T \cos 0° = T,$$

and at that place the needle is parallel to the earth's surface and there is no vertical force. The locus of all the places where the earth's vertical force is zero is called the **magnetic equator.**

The angle θ that the needle makes with the horizontal at any point on the earth's surface is called the **dip.**

Magnetic Field.

All the space surrounding the earth which is subject to the forces due to the poles is called the earth's magnetic field, and in general a magnetic field may be defined as **a space in which magnetic action takes place, or a region in which a magnet pole is acted on by a force tending to move it in one direction or another.** Magnetic fields may be produced by the earth, by magnets or by electric currents. The magnetic field of a magnet is similar to that produced by the earth, and all magnets may be considered as small imitations of the earth, regarded as one huge magnet. For instance, an ordinary bar magnet has its poles and its magnetic equator or neutral line and its magnetic field surrounding it, represented by a number of lines forming curves through the magnet and the space surrounding it.

The poles of an ordinary bar magnet are close to the ends of the magnetic axis; they are of equal strength and opposite sign. In a very long thin bar, uniformly magnetized, the poles are at the

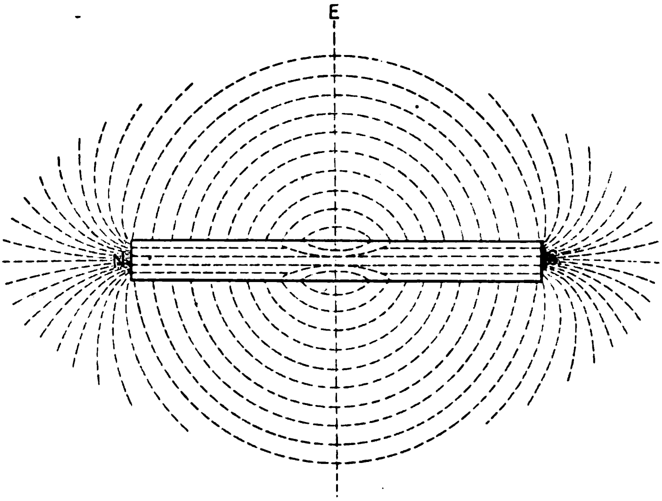


FIG. 55.—Magnetic Field Due to the Bar Magnet.

extremities of the magnet, and at these points the magnetic force is greatest.

In Fig. 55 is shown the magnetic field due to a bar magnet. The dotted lines represent the directions in which the forces due to the poles at *N* and *S* act, while the number of lines is a measure of the strength of the field. All the lines pass through the central portion of the magnet, the *equator,* but begin to emerge from the sides of the magnet as the poles are approached on either side of the equator. Most of the lines pass through the interior of the magnet and emerge from the poles, and each line is continuous and completes its path in the region outside the magnet.

Lines of Magnetic Force.—The subject of magnetism may be considered in two distinct ways. In one method the action of the poles of the magnet is considered and as it is impossible to obtain a magnet with only one pole, the hypothetical isolated pole is introduced. This method was used by the early investigators and many correct and valuable deductions were made in this way. The second method was originated by Faraday who realized that the most important function of the magnet was the surrounding space in which magnetic action takes place. He introduced the idea of representing this magnetic action by lines of magnetic force, the direction of which would indicate the direction of the force at any point and their ensity, that is the number of lines per square centimeter would dicate the magnitude of the magnetic force. This second method is the one employed in nearly all electrical engineering calculations and will be used in this book. This method permits of an easy demonstration of the magnetic circuit on account of its analogy to the electric circuit and the electrostatic circuit. The magnetic force existing at any point in a magnetic field may be measured in several ways but is defined by its action on a unit pole.

Laws of Magnetic Force.

First Law.—Like magnetic poles repel one another; unlike magnetic poles attract one another.

Second Law.—The force exerted between two magnetic poles is proportional to the product of their strengths and is inversely proportional to the square of the distance between them.

If the two magnetic poles are unit poles and are 1 centimeter apart in air, the force exerted between them is

$$f=\frac{mm'}{d^2}=\frac{1\times 1}{1^2}=1 \text{ dyne.}$$

The magnetic force or field intensity at any point in a magnetic field represents the force in dynes acting on a unit magnetic pole at that point. It is designated by the letter H. It will be remembered that in the electrostatic circuit it was necessary to distinguish between the electric force at any point in an electrostatic field and the flux density or the number of lines per square centimeter at this point. The same distinctions should be observed here, though of course it is simply an analogy as the lines of dielectric flux have no connection with lines of magnetic flux. The letter B is used to represent the magnetic flux density, that is the number of lines per square centimeter, and μ represents the permeability of the medium compared with air which is assumed to be unity.

As μ is always practically unity except inside substances like iron and steel the value of H and B are usually numerically equal and are often used indiscriminately one for the other. It is better, however, to keep in mind that H represents the magnetic force while B represents the magnetic flux density, and that $B = \mu H$. Unit magnetic force is that force which would cause one line of magnetic flux per square centimeter in air. This unit is called a gilbert. Unit magnetic field is a field that contains one line of magnetic flux per square centimeter of cross-section. These lines of magnetic flux have the following properties:

1. They are continuous throughout the circuit and form closed curves.

2. A tension exists along the lines tending to shorten them and also a lateral stress tending to cause them to diverge from each other.

3. The total flux at any part of a magnetic circuit is the same. The total flux depends upon the total magnetomotive force and the permeance of the circuit.

The total number of lines through any section of a magnetic circuit is called the total magnetic flux and is designated by the symbol Φ.

Unit field intensity is defined as that intensity which will exert a force of 1 dyne upon a unit pole placed in the field.

At a distance r from a magnetic pole of strength m in air the magnetic force acting on a unit test pole by formula equals $\frac{m \times 1}{r^2}$. If this pole be surrounded by a sphere of radius r, having an area of $4\pi r^2$ square centimeters, Φ the total flux would be equal to $4\pi r^2 \times \frac{m}{r^2} = 4\pi m$ lines. The total flux for each unit of pole strength, therefore, is equal to $4\pi m \div m = 4\pi$ lines. Hence every unit pole is represented by 4π lines, or for every 4π lines leaving a magnet we have a unit north pole, and for every 4π lines entering we have a unit south pole.

The magnetic potential at any point is measured by the amount of work required to bring a unit north pole from infinity to that point. Difference of magnetic potential between two points in a magnetic field is equal to the amount of energy in ergs that would have to be expended to bring a unit north pole from one point to the other against the magnetic force. If the field is uniform and has a magnetic force equal to H and the points are l centimeters apart the difference of potential will be Hl. If the field is not uniform the potential difference would be ΣHl, where the variable forces are each multiplied by the distance through which it remains constant and the sum of the products obtained.

In a magnetic circuit the sum of all the differences of potential around the circuit is equal to magnetomotive force (M. M. F.) which is thus analogous to the E. M. F. of the electric circuit.

Reluctance is that property of a magnetic circuit by which it resists the flow of the magnetic flux. A circuit has unit reluctance when unit M. M. F. causes a flux of one line through the circuit. The unit of reluctance, the oersted, is the reluctance of a centimeter cube of air.

Reluctance varies as the length and inversely as the area of cross-section and the permeability. In the units adopted, $\mathfrak{R} = \frac{l}{A\mu}$, where l equals length of flux path in centimeters, A its area of cross-section in square centimeters, and μ its permeability assuming the permeability of air as unity.

Permeance is the reciprocal of reluctance and is that property of a magnetic circuit which permits the flow of the magnetic flux. A circuit has unit permeance when one unit of M. M. F. permits the flow of one line of magnetic flux.

Reluctivity of a substance is the reluctance existing between the opposite faces of a cube of the substance each side of which is 1 centimeter in length. The reluctivity of air is assumed to be unity.

Permeability of a substance is the permeance existing between the opposite faces of a cube of the substance each side of which is 1 centimeter in length. Since the permeability of air is assumed to be unity the permeability of a substance is the ratio of the flux that passes through it to the flux that would exist in air if the magnetomotive force and flux path remained unchanged. The following equations then follow:

$$\Phi = \frac{M}{\mathfrak{R}}, \Phi = M\mathfrak{P}, \mathfrak{R} = \frac{l}{A\mu}, \mathfrak{P} = \frac{A\mu}{l}.$$

Where M represents M. M. F., $\mathfrak{R}$ the reluctance and $\mathfrak{P}$ the permeance, A the cross-section in square centimeters, and l the length in centimeters. Since B represents the flux density or lines per square centimeter, $\Phi = BA$. The above equations may be put in several forms as follows:

$$M = \Phi\mathfrak{R}, M = \frac{\Phi}{\mathfrak{P}}, \mathfrak{R} = \frac{M}{\Phi}, \mathfrak{P} = \frac{\Phi}{M}.$$

The magnetic circuit may be entirely in air, entirely in iron, or partly in each.

Diamagnetic Substances.—Some substances, as bismuth and antimony, have a value for μ slightly less than unity and are called diamagnetic substances, but for all practical calculations the value of μ for all substances excepting iron or steel or their alloys may be assumed as unity.

Electromagnetism.

Electromagnetism treats of the relation existing between electric currents and magnetic fields.

Magnetic Field Due to Current in a Straight Conductor.

If a straight conductor is held over and parallel to a small pivoted magnetic needle which is pointing towards magnetic north, and an electric current is passed through the conductor, the needle will be deflected one way or another out of the magnetic meridian. This experiment shows that there must have been some force brought into existence by the current in the conductor that was not present when the current did not flow.

This deflection of the magnetic needle is not due directly to the electric current, as the conductor does not touch the needle in any way, but it is due to a condition established by the current, the setting up of a magnetic field around the conductor. It is the reaction of the two magnetic fields, that due to the magnet and that due to the current, which causes the needle to take a position dependent on the resultant of the two forces. It has been proved experimentally that a straight conductor carrying a current has set up around it a magnetic field which is dependent for its intensity upon the current strength and the distance from the conductor. This magnetic field may be represented by a series of concentric curves, or rings, surrounding the conductor, the lines representing the lines of force of the magnetic field. These lines are brought into existence by the current, and increase with the current and die out with it, seeming to collapse like rubber bands that have been stretched, when the current has faded to zero, and spreading out as the current is increased. An idea is given of their form and direction in Fig. 56.

In Fig. 56, the lines of force are drawn as concentric circles around the conductor, but as a matter of fact they may or may not

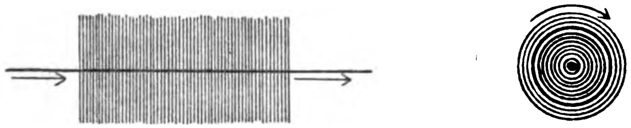


FIG. 56.—Magnetic Field due to Straight Current.

have a symmetrical form. In the right-hand sketch, the central dot represents the conductor, with the current flowing away from the observer. In this case the positive direction of the lines of force is clockwise or right-handed and the heavy circle has been drawn to represent the resultant of all the lines of force due to the current. This field will remain of constant intensity as long as the current remains steady, but will change in strength as the current starts, stops, or changes its rate of flow.

Knowing now the character of the field set up around a conductor carrying a current and the field of the magnetic needle, it is easy to account for the deflection of the needle under the influence of a current of electricity.

The upper figure in Fig. 57 represents the cross-section of the conductor with the current flowing away from the observer and marked *IN*, and the circle represents the resultant of the lines of force. Under the conductor and parallel to it is shown the cross-section of the needle, the north end marked *N*. The positive direction of the magnetic whirls is clockwise, and these whirls, apparently striking the north end of the needle, cause a reaction between the two magnetic fields. There is mutual repulsion, the field of the current being pushed out of its natural path, and the north end of the needle being repelled to the left. There is also attraction between the field of the current and the south pole of the needle, tending still more to deflect the north end of the needle to the left. If the needle were placed over the current, the north pole would be pushed to the right and opposite deflection would be the result.

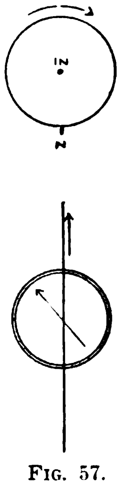


FIG. 57.

The resultant action of the two fields is also explained by the following general principle: **Whenever two different magnetic fields are near one another and capable of influencing one another, and one is fixed while the other is movable, the movable one will always tend to move to such a position that will cause the two fields to have one common path in one direction.**

In the above illustration, in order that the two fields may have one common path in one direction, the needle will have to turn at right angles to the conductor, when the magnetic lines due to the current would run through the needle from the south pole to the north, and from the north pole of the needle around the conductor in air to the south pole of the needle.

Rules for Remembering Direction of Field and Current.

Amperes' Rule.—Suppose a man to be swimming in the wire in the same direction as the current and with his face toward the needle then the north pole of the needle is deflected towards his left hand.

Hand Rule.—Another simple rule for remembering the direction of the lines of force due to a current is that known as the **Hand Rule.** *Grasp the conductor with the right hand with the thumb turned away from the hand and pointing in the direction in which the current is flowing. The direction in which the finger tips point is then the positive direction of the lines of force.*

Corkscrew Rule.—The best rule for the determination of the relative direction of magnetic field and current is called **Maxwell's** Corkscrew Rule and is as follows: The direction of the current and that of the resultant magnetic force are related to each other as the forward travel and direction of rotation of an ordinary corkscrew.

In other words, if the current is " in " as in the figure the positive direction of the lines of force will be clockwise.

Laws of Parallel Currents.

These laws may be stated here as they are so readily explained by a consideration of the magnetic fields surrounding conductors

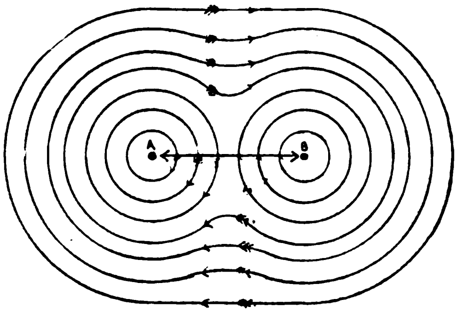


FIG. 58.—Magnetic Field of Parallel Conductors in Same Direction.

carrying currents, and illustrate so well the resultant action of those fields.

Parallel conductors carrying currents of electricity are mutually attracted if the current is flowing in each in the same direction, and are mutually repelled if the currents are flowing in opposite directions.

Fig. 58 shows two parallel conductors *A* and *B*, the current in each flowing away from the observer, and each surrounded by its own magnetic field, which is indicated by a few representative lines. The arrows show the positive direction of the lines of force, the same in both cases, each being right-handed or clockwise as viewed in the direction the current is flowing. The lines near the conductors are closed on themselves, but where they meet, they seem to absorb one another and each takes the path and continues the course of the other, which is the resultant path due to the forces exerted by the separate fields. In the region between the conductors, it is seen that though the positive direction of the lines of force is in the same direction, at this point they are opposite, and each path by itself represents the direction a free north pole would move. Here then is like magnetism, and by the principle of resolution of forces, it is seen that the resultant will be something similar to the curves above.

In this illustration is seen the analogy of the lines of force to stretched rubber bands, there being a tension along the lines tending to draw the conductors together. The lines could be imagined

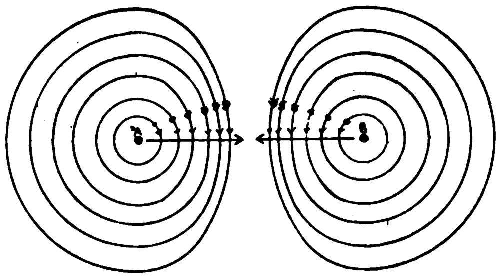


FIG. 59.—Magnetic Field of Parallel Conductors in Opposite Directions.

to be replaced by one line joining *A* and *B* such that if all resistance to motion was overcome the conductors would be drawn together.

Fig. 59 shows two parallel conductors *A* and *B,* the current in *A* flowing away from the observer with its right-handed or clockwise field as viewed in the direction the current is flowing, and the current in *B* flowing towards the observer with its left-handed or anti-clockwise field as viewed in the direction opposite to that in which the current is flowing.

By the resolution of forces, it is seen that there is mutual repulsion between the fields in the region between the conductors, each field being compressed on its own conductor. The action of the two fields is such that there is compression across the lines of force while yet tension in the direction of their length.

As in the above case, the fields could be imagined to be replaced by a band in a state of compression which would cause the conductors to be pushed apart if the resistance to compression was overcome.

From this another simple rule may be formulated: A magnetic circuit tends to change its conformation so that its reluctance is a minimum, or so that it embraces the maximum possible lines of force. Referring to Fig. 58, very little flux flows in the space between the two walls. By closing up this idle space the permeance of the mag-

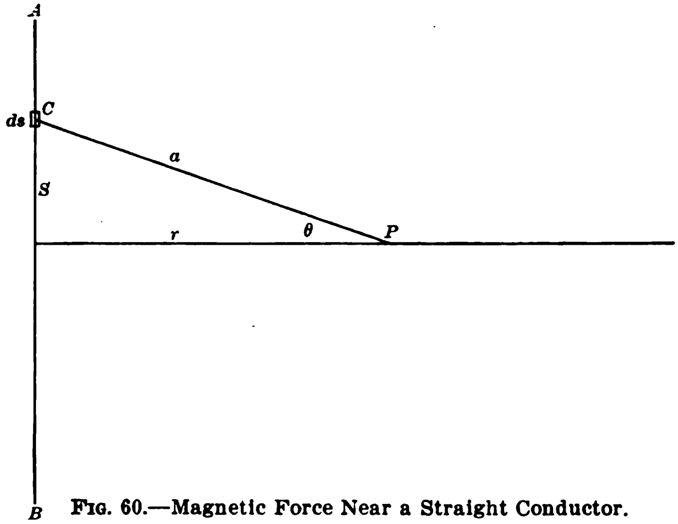


FIG. 60.—Magnetic Force Near a Straight Conductor.

netic path is increased. On the other hand, Fig. 59, the conductors by separating, increase the area, hence the permeance of the flux path, so the tendency is to make the flux a maximum.

It now becomes necessary to find the magnetic force produced by current flowing in conductors under certain conditions.

(1) To find the magnetic force at a distance r from a straight conductor of infinite length in which a current is flowing. In Fig. 60 AB is the conductor and I the current in absolute units. P is a test pole. The magnetic force at any point C on the conductor, due to the pole P, equals $\frac{1}{a^2}$. The magnetic field at the point C has the

direction of the line PC and an intensity equal to $\frac{1}{a^2}$. This may be resolved into two components; viz., $\frac{1}{a^2}\cos\theta$ perpendicular to the conductor and $\frac{1}{a^2}\sin\theta$ parallel to it. The first component (see definition of unit current, Chapter I) will exert a force on a small length ds of the conductor equal to $\frac{Ids\cos\theta}{a^2}$ dynes. The other component being parallel to the conductor will exert no force upon it. Then $\int_{-\infty}^{+\infty}\frac{Ids\cos\theta}{a^2}$ will represent the total force in dynes acting on conductor due to magnetic field of P and this is therefore equal to the magnetic force at P due to the conductor. To integrate, put $s=r\tan\theta$ and $a=r\sec\theta$. $\therefore ds=r\sec^2\theta\, d\theta$. Substituting, we have,

$$H=\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\frac{I\cos\theta\, d\theta}{r}=\frac{I}{r}\sin\theta\Big]_{-\frac{\pi}{2}}^{\frac{\pi}{2}}=\frac{2I}{r}\text{ gilberts.}$$

If I is in amperes this formula becomes $H=\frac{2I}{10r}$.

(2) Find the magnetic force at the center of a circular loop of wire carrying a current. The force will tend to move the test pole perpendicular to the plane of the paper. The force acting on each element of the conductor as before $=\frac{Ids}{r^2}$. The entire force then equals $\int_0^{2\pi r} Ids$, but the integral of $ds=2\pi r$, hence $H=\frac{2\pi rI}{r^2}=\frac{2\pi I}{r}$. The force on the conductor equals the force on the test pole and the magnetic force at center, $H=B=\frac{2\pi I}{r}$. I being in absolute units.

(3) To find the magnetic force at a perpendicular distance a from the center of a circular loop carrying current.

The magnetic force acting on any small portion of the loop ds due to field of $P=\frac{Ids}{a^2+r^2}$. The unbalanced component of this which tends to cause relative motion is

$\frac{Ids \sin\theta}{a^2+r^2}$. $\therefore H=\int_0^{2\pi r}\frac{Ids \sin\theta}{a^2+r^2}$. Referring to Fig. 61, it is seen that $\sin\theta=\frac{r}{\sqrt{a^2+r^2}}$.

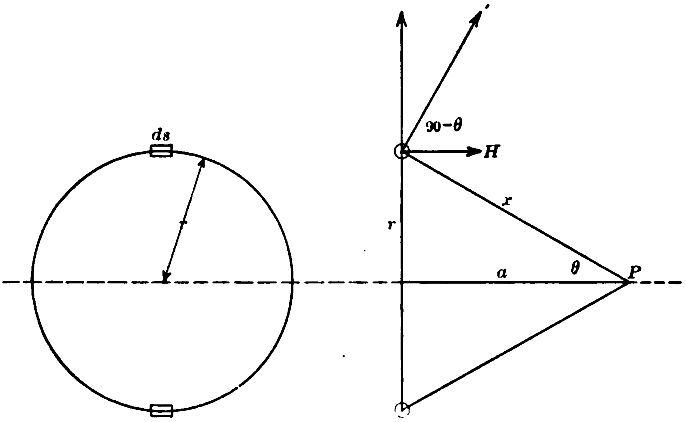


FIG. 61.—Magnetic Force at a Point on the Axis of a Circular Conductor.

Substitute this value and integrate and we have

$$H=\frac{2\pi r^2 I}{(a^2+r^2)^{\frac{3}{2}}}.$$

(4) To find the magnetic force inside a long solenoid. Let AB represent a unit section of the solenoid 1 centimeter in width. We

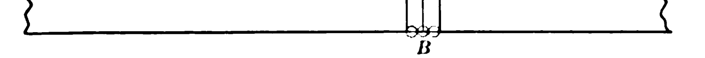


FIG. 62.—Magnetic Force Inside a Long Solenoid.

will assume that it contains n turns, then the force exerted by it at P by the preceding problem will be $\frac{2\pi r^2 nI}{(a^2+r^2)^{\frac{3}{2}}}$. The resultant force at P will be the sum of the magnetic forces exerted at P by every unit element of the solenoid. The sum of all these forces is $H=\int_{-\infty}^{+\infty}\frac{2n\pi r^2 I da}{(a^2+r^2)^{\frac{3}{2}}}$. To integrate this take $\frac{a}{r}=\cot\theta$, $\therefore a=r\cot\theta$, $da=-r\operatorname{cosec}^2\theta$, $\frac{r}{(a^2+r^2)^{\frac{1}{2}}}=\sin\theta$. Substitute and

$$H=-\int_{\pi}^{0} 2n\pi I\sin\theta\, d\theta = 2n\pi I\cos\theta\Big]_{\pi}^{0}=4\pi nI.$$

The limits 0 and π may be used if the solenoid is long in comparison with its cross-section.

It will be noted that the force is entirely independent of the size of the solenoid and though worked out above for cylindrical coil it is independent of the form of cross-section and depends only upon the product of the number of turns and the current.

If N represents the total number of turns of a solenoid whose length is l, then $n=\frac{N}{l}$ and the equation becomes $H=\frac{4\pi NI}{l}$ gilberts. If I is given in amperes the equation becomes $H=\frac{4\pi NI}{10l}$ gilberts. $H\times l=$ magnetomotive force $=\frac{4\pi NI}{10}$.

This expression, $\frac{4\pi NI}{10}$, gives the value of the magnetomotive force in gilberts. The expression NI the product of the number of turns and the current in amperes is called "ampere turns." Attention has been called to the fact that the magnetomotive force does not depend upon the size or material of the coil or upon anything excepting this current and number of turns. It is very often desired to know the number of ampere turns required to produce a certain flux. The following relation exists between gilbert and ampere turns: One ampere turn $=\frac{4\pi}{10}$ gilberts. In a long solenoid with a core of uniform permeability the magnetic field is assumed to be uniform, and to have the same flux density at every point inside of the solenoid and the direction of the field at any point is assumed to be parallel to the axis. As the field of the solenoid is represented by lines of magnetic flux parallel to the axis it is evident that the solenoid will behave as a magnet. As noted before where the lines of force enter will be a south pole and where they leave will be a north pole.

To find the positive direction of the lines it is only necessary to apply Maxwell's Corkscrew Rule which is applicable to all cases of

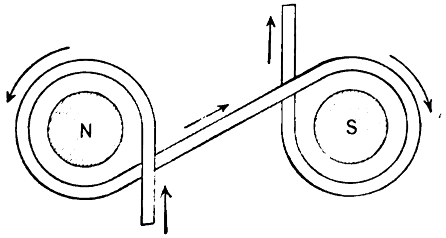


FIG. 63.—End View of Horseshoe Electromagnet, Showing Direction of Current and Resulting Polarity.

interlinkage of flux and current. In case of the solenoid, if the current flows around the solenoid in the direction of rotation of the corkscrew the direction of the flux will be in the direction of the resulting forward travel. In other words, if looking at the end of a solenoid the direction of the flow of current is clockwise, the direction of the flux will be away from the observer and *vice versa.*

This rule is a convenient one to remember as it not only gives the relation between the current in a straight wire and the resulting field, but also is applicable to the solenoid as described above.

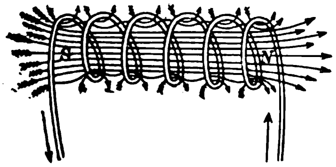


FIG. 64.—The Magnetic Field Inside a Solenoid.

Fig. 63 illustrates the polarity resulting from a flow of current around an iron core as in the case of an electromagnet. Figs. 64 and 65 are reproduced from lantern slides prepared by the Central Scientific Company showing the magnetic field inside a long solenoid. Fig. 64 shows the relative directions of the current and flux.

Fig. 65 is a magnetic figure made by using iron filings to produce a physical conception of the lines of magnetic flux.

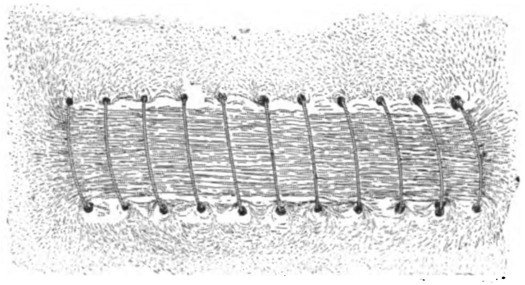


FIG. 65.—Magnetic Figure Showing Field of Solenoid.

Magnetic Circuit.

By a magnetic circuit is meant the path of the magnetic lines of force, and it has been shown that these lines tend to make closed curves, either passing entirely through magnetic substances or partly through them and partly through air. Whatever the form of the magnetic circuit, its function is to direct the lines of force and the material of the circuit governs the resistance offered to the flow of the magnetic lines. Although these lines have no material existence, yet they can best be explained by their analogy to the electric current and considered as actually *flowing* in the magnetic circuit. In the magnetic circuit there is a leakage of the lines of force just as in the electric circuit there is a leakage of current.

The *total number of lines* in a magnetic circuit is generally referred to as the **magnetic flux.**

Open and Closed Magnetic Circuits.

A **closed magnetic circuit** is one in which the lines of force due to the magnet flow around a *complete* iron path; an **open magnetic circuit** is one in which the paths of the lines of force are broken by one or more air gaps. The *open* circuit exhibits *free* magnetism, produces and can induce definite polarity and is sometimes called a *polar* circuit, while the *closed* circuit possesses practically no free magnetism and produces induction in neighboring magnetic substances only by the *leakage* of magnetic lines from it.

The ordinary bar magnet and the solenoid are examples of open magnetic circuits, and forms of open circuits are extensively used with continuous currents while closed circuits find their greatest uses in alternating current apparatus.

In practically all magnetic circuits used in electrical engineering the magnetomotive force required to produce the flux is obtained by placing coils of wire carrying current around one or more parts of the circuit. These coils acting as solenoids supply the magneto-

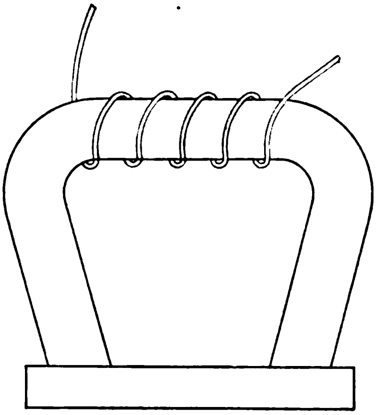


FIG. 66.—Electromagnet.

motive force. In circuits of this nature it has been shown that the magnetomotive force $=\frac{4\pi NI}{10}$, and the equation for all practical magnetic circuits will be $\Phi=\frac{4\pi NI}{10\mathfrak{R}}$. When the coil is of uniform cross-section and permeability this becomes $\Phi=\frac{4\pi NIA\mu}{10l}$, where I is in amperes.

The Electromagnet.

An electromagnet is a device consisting of an iron core surrounded by a coil of wire through which a current of electricity may be passed. A simple form of electromagnet is shown in Fig. 66. It consists of a horseshoe-shaped piece of soft iron upon which are placed coils of wire forming virtually a solenoid with an iron core. The magnetic circuit is completed through a bar of soft iron, *AB*. When a current is flowing, this bar or armature is attracted to the magnet, as will be shown later, by a force which is proportional to the square of the flux density. Hence, in order to make the pull great, it is necessary to have a large M. M. F. and small reluctance. If the cross-section of the armature and magnet are the same and the armature fits snugly over the poles this device constitutes practically a closed magnetic circuit. Hence, $\Phi = \frac{4\pi NIA\mu}{10l}$, where

Φ = total flux.
N = number of turns.
I = current in amperes.
A = area of cross-section in square centimeters.
μ = permeability of the core and armature.
l = length of the circuit in centimeters (mean path of the flux).

It has been previously noted that every electric circuit has inductance. That is, when the current changes the magnetic field changes also and this change of flux causes a cutting of the lines by the conductor and thus induces an E. M. F. in the circuit which is opposed to the change. The product of this back E. M. F. and current represents the power required to change the magnetic field to correspond with the change of current. When no current is flowing there will be no magnetic field, and when an E. M. F. is applied to the terminals of the conductor the current does not immediately rise to its value as given by Ohm's law due to the inductance, and this apparent loss of energy represents the energy of the magnetic field. If $d\Phi$ represents the change of flux and N represents the number of turns then $N\frac{d\Phi}{dt}$ will be the induced E. M. F. If I represents the current flowing then $NI\frac{d\Phi}{at}$ will represent the change of energy in the magnetic field. In a magnetic circuit

$$\Phi = \frac{4\pi NI}{\mathfrak{R}}, \therefore \frac{d\Phi}{dt} = \frac{4\pi N}{\mathfrak{R}}\frac{dI}{dt}, \therefore \frac{Nd\Phi}{dt} = E = \frac{4\pi N^2}{\mathfrak{R}}\frac{dI}{dt}.$$

Hence,

$$EI = NI\frac{d\Phi}{dt} = \frac{4\pi N^2 I}{\mathfrak{R}}\frac{dI}{dt},$$

and the total energy stored up in the magnetic field when the current changes from

$$0 \text{ to } I = W = \frac{4\pi N^2}{\mathfrak{R}}\int_0^I I\,dI = \frac{4\pi N^2}{\mathfrak{R}} \cdot \frac{I^2}{2}.$$

If the magnetic circuit is of uniform cross-section and permeability

$$\mathfrak{R} = \frac{l}{A\mu}.$$

Therefore, $W = \frac{2\pi N^2 I^2 A\mu}{l}$. Multiply numerator and denominator by $\frac{8\pi}{l}$ this equation becomes $W = \frac{16\pi^2 N^2 I^2 l A\mu}{l^2 \cdot 8\pi}$, but $H = \frac{4\pi NI}{l}$ and hence $W = \frac{H^2\mu \cdot Al}{8\pi}$. By substituting $B = H\mu$ this equation becomes $W = \frac{B^2}{8\pi\mu} \cdot Al$ and since Al represents the volume of the core, the energy per cubic centimeter contained in the field equals $\frac{B^2}{8\pi\mu}$. If the field is air this equals $\frac{B^2}{8\pi}$.

This last expression is often used to calculate the force required to remove the armature from an electromagnet, or, in other words, to ascertain the lifting power of a magnet.

At the instant of separation of armature and magnet the energy stored in the field of air gaps would be equal to Fdl, where F represents the pull or force and dl the length of the small air gap. The volume of this field will be Adl, where A is the cross-section of the poles of the magnet. The energy therefore is $Adl \cdot \frac{B^2}{8\pi}$. Hence,

$$Fdl = Adl \cdot \frac{B^2}{8\pi}.$$

$F = \frac{B^2 A}{8\pi}$ dynes, where B is in lines of magnetic flux and A in square centimeters.

Examples of Electromagnets.—A very common and typical form of electromagnet is shown in Fig. 67.

This consists of two coils of fine wire, *C,* wound oppositely on two bobbins which are slipped over the iron cores, *D,* which are secured to the base of magnetic material, *Y,* called the *yoke.* When current is sent through the coils, poles of opposite polarity are produced in the ends of the cores, *D,* the open magnetic circuit being through the two cores and the yoke. Above the upper ends of the cores is secured the *armature, A,* of soft iron, and so pivoted that it can approach the cores. It is made large enough to project slightly over the whole area of the cores which are usually circular. The free poles in the ends of the cores induce opposite polarity

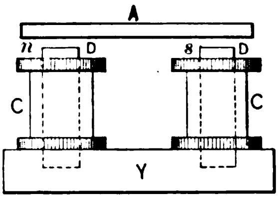


FIG. 67.—Typical Double-Coil Electromagnet.

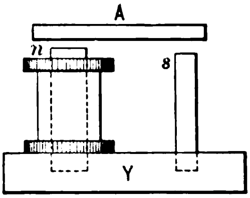


FIG. 68.—Club-Foot Electromagnet.

in the ends of the armature, after which attraction takes place and the armature moves towards the cores and brings up against them, forming a closed magnetic circuit. The armature will remain attracted as long as current flows, but when it is broken, the magnetic field is dissipated and the armature is usually provided with some arrangement by which it is returned to its original position.

This form of electromagnet is very common and is used largely in vibrating bells, relays and like appliances.

Fig. 68 shows a one-coil electromagnet, known as a **club-foot** electromagnet.

This differs from the two-coil electromagnet in that it only has one coil, the magnetic circuit being completed through the other core which is unwound, and which has the same polarity as the lower end of the wound core and the yoke. Its action is the same as the two-coil type.

This saves the winding of one magnet but diminishes the pull on the armature.

Fig. 69 shows another and very common form of a **one-coil electromagnet.**

In this form the core forms the yoke and is fitted with two end plates, *B* and *B,* secured to it, in which opposite poles are produced.

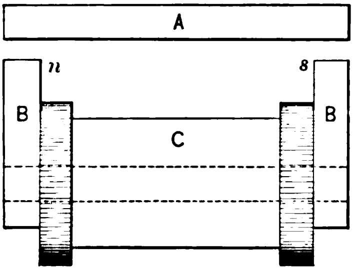


FIG. 69.—One-Coil Electromagnet.

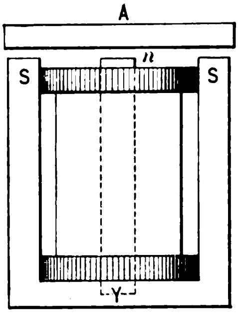


FIG. 70.—Ironclad Electromagnet.

These poles in turn induce opposite polarity in A and the armature is attracted. This is a very compact form and is used largely in resistances for starting motors and other appliances.

Fig. 70 shows another form of one-coil electromagnet, known as the **ironclad** type.

In this form the iron core is secured to and inside the bottom of a pot, and on the core is slipped the bobbin containing the winding. The upper end of the core forms one pole while the whole upper rim of the pot forms the other, and the armature consists of a disc or lid of the same diameter as the pot.

All the foregoing types of electromagnets are examples of forms capable of exercising a strong pull over a short range.

For a weak pull over a long range, the ordinary solenoid with a movable core is used, as shown in Fig. 71.

When current is sent through the coils of this electromagnet, the core is sucked into the coil and the pull increases as the entering end approaches the further end of the coil. The pull in this form is not nearly as great as the form of Fig. 67, but the range of motion is very much increased.

Double Magnetic Circuit.—A modification of the above is shown in Fig. 72.

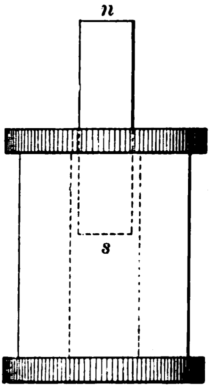


FIG. 71.—Long-Range Electromagnet.

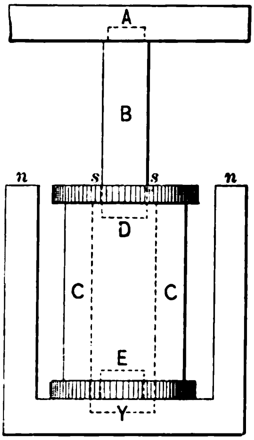


FIG. 72.—Stopped Solenoid.

In this the magnetizing coil is slipped over a short core, *E,* which is secured to the yoke, *Y,* which is also provided with two limbs, *n* and *n*. The armature, *A,* is of the ordinary shape and is secured to a core *B,* which is sucked into the coil when current is turned on. The dimensions are such that the bottom of *D* comes up against the top of *E* just when the armature brings up against the limbs *n* and *n*. This arrangement therefore produces a double pull.

Typical Magnetic Circuits.

The simplest form of a magnetic circuit is a solenoidal ring as shown in Fig. 73. The core may be of air or some magnetic substance. In this circuit the core is of uniform cross-section and permeability and $\mathcal{R} = \frac{l}{A\mu}$.

Hence, $\Phi = \frac{4\pi NIA\mu}{10l}$ lines, where I is the current in amperes. If the solenoid had an air core the value of μ would be unity.

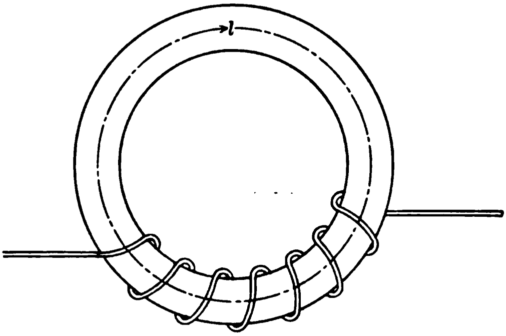


FIG. 73.—A Closed Magnetic Circuit.

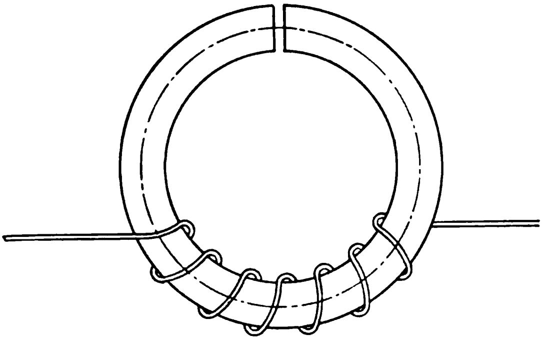


FIG. 74.—Magnetic Circuit with Air Gap.

Fig. 74 represents an open magnetic circuit having an air gap. If A_1, μ_1, l_1 represent the cross-section, permeability and mean length of the iron core, its reluctance will be $\mathcal{R}_1 = \frac{l_1}{A_1\mu_1}$. If A_2 and l_2 represent the area of cross-section and mean length of the air gap its reluctance will be $\mathcal{R}_2 = \frac{l_2}{A_2}$, μ for air being equal to unity. The total reluctance is then equal to $\mathcal{R}_1 + \mathcal{R}_2$ and the flux,

$$\Phi = \frac{4\pi NI}{10(\mathcal{R}_1 + \mathcal{R}_2)} = \frac{4\pi NI}{10\left(\frac{l_1}{A_1\mu_1} + \frac{l_2}{A_2}\right)}.$$

Fig. 75 represents the field of a bipolar dynamo. The dotted line is supposed to represent the mean path of the magnetic flux.

In this case, all the reluctances are in series and consist of the reluctance of yoke, field cores, pole pieces, armature and air gaps. Each one of these has to be calculated separately from the formula,

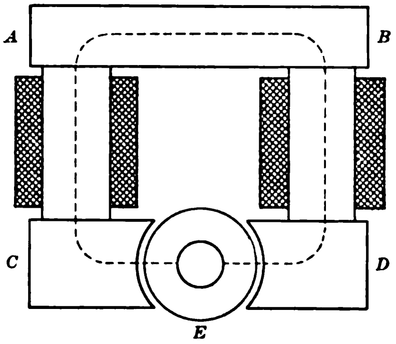


FIG. 75.—Magnetic Circuit of Bipolar Dynamo.

$\mathcal{R} = \frac{l}{A\mu}$, where A the area of cross-section in square centimeters, μ the permeability and l the mean path of the flux for that particular part. If $\mathcal{R}_1, \mathcal{R}_2, \mathcal{R}_3, \mathcal{R}_4, \mathcal{R}_5$, represent the reluctances of the various parts then $\Phi = \frac{4\pi NI}{10(\mathcal{R}_1 + \mathcal{R}_2 + \mathcal{R}_3 + \mathcal{R}_4 + \mathcal{R}_5)}$. If in a magnetic circuit there are two or more paths between two points differing in magnetic potential the reluctance between these points has to be found in a manner analogous to finding the combined resistance of two conductors in parallel in an electric circuit.

Fig. 76 illustrates a rectangular circuit made up of two concentric cores of different cross-sections and permeabilities. Find the reluctance of each part separately, then the permeance of each part would be equal to the reciprocal of its reluctance and the permeance of the entire core would be the sum of the permeances of the com-

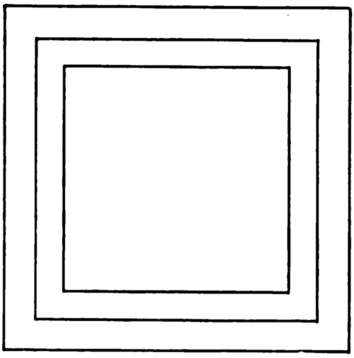


FIG. 76.—Magnetic Circuit Consisting of Different Materials in Parallel.

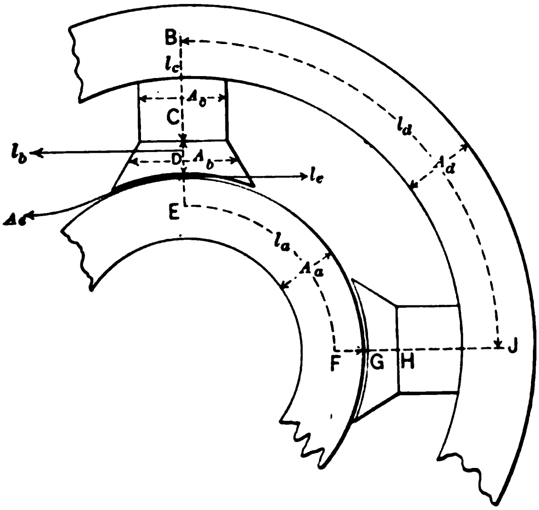


FIG. 77.—Typical Magnetic Circuit of a Multipolar Dynamo.

ponents parts. If R_1 and R_2 are the separate reluctances and P_1 and P_2 the corresponding permeances, then $P=P_1+P_2$ or $\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}$.

Fig. 77 shows a typical four-pole magnet frame, in which there are four closed magnetic circuits. One of these circuits is represented by the dotted line, through the magnet frame, the core pieces, the pole pieces, the air gaps and the armature.

If A = area of cross-section of the different parts shown,
l = length of corresponding parts,
μ = coefficient of permeability of the corresponding parts,
then the reluctance

from J to B $= \dfrac{l_d}{\mu_d A_d}$,

B to C and J to $H = \dfrac{l_c}{\mu_c A_c}$,

C to D and H to $G = \dfrac{l_b}{\mu_b A_b}$,

D to E and G to $F = \dfrac{l_e}{\mu_e A_e}$, $\mu = 1$ for air.

E to F $= \dfrac{l_a}{\mu_a A_a}$.

If all the magnetic parts of the circuit are of the same material $\mu_a = \mu_b = \mu_c = \mu_d$.

If the magnetic field is due to a current of I amperes with N turns, then the full expression giving the relation between the magnetomotive force, the reluctance, and the total number of lines Φ is, assuming the same material,

$$\Phi = \frac{4\pi NI}{10\left(\dfrac{l_a}{\mu A_a} + \dfrac{2l_e}{A_e} + \dfrac{2l_b}{\mu A_b} + \dfrac{2l_c}{\mu A_c} + \dfrac{l_d}{\mu A_d}\right)}.$$

To this denominator should be added the reluctance of the joints, which being known by experiment Φ can be calculated for a given number of ampere turns, or Φ being known from the E. M. F. to be generated, NI the necessary number of ampere turns can be calculated.

In most practical cases either the flux or the flux density is known, and the problem is to determine the ampere turns necessary to produce such flux. The method generally employed is to determine the number of ampere turns required to produce the desired flux in each part of the circuit. The sum of the ampere turns required for the different parts of the circuit is the total magnetomotive force.

It has been shown that $B=\mu H$ or $H=\frac{B}{\mu}$ and that B the flux density in any part is equal to the total flux divided by the area of the cross-section of that part, that is $B=\frac{\Phi}{A}$.

The M. M. F. required for any part of the circuit $=Hl=\frac{Bl}{\mu}$ gilberts where B, l and μ are the flux density, length and permeability of the part in question.

Since 1 ampere turn is equal to $\frac{4\pi}{10}$ gilberts, the M. M. F. is equal to $\frac{Bl}{\mu}\times\frac{10}{4\pi}$ ampere turns. Hence the equation,

$$\text{M. M. F.}=\frac{Bl}{\mu}\times\frac{10}{4\pi}=\frac{.796Bl}{\mu}\text{ ampere turns.}$$

For practical purposes the following approximate equation is generally used: M. M. F. $=\frac{.8Bl}{\mu}$ ampere turns. This method is best illustrated by the solution of a numerical problem.

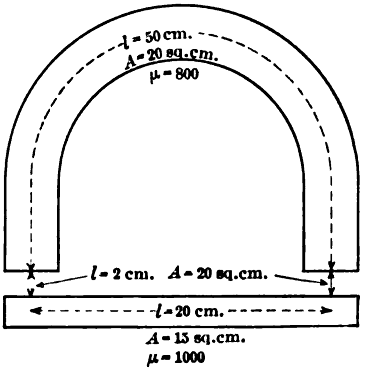


FIG. 78.—Illustrating Magnetic Calculations.

Example.—Required to find the ampere turns necessary to send a flux of 200,000 lines through the horseshoe magnet shown in Fig. 78.

Consider first the iron core,

$$B=\frac{200{,}000}{20}=10{,}000\text{ gausses.}$$

$$NI=\frac{0.8\times 10{,}000\times 50}{800}=500\text{ ampere turns.}$$

The air gaps,

$$B = \frac{200{,}000}{20} = 10{,}000 \text{ gausses.}$$

$$NI = 0.8 \times 10{,}000 \times 2 \times 2 = 32{,}000 \text{ ampere turns.}$$

The yoke,

$$B = \frac{200{,}000}{15} = 13{,}300 \text{ gausses.}$$

$$NI = \frac{0.8 \times 13{,}300 \times 20}{1000} = 213 \text{ ampere turns.}$$

Total ampere turns,

$$500 + 32{,}000 + 213 = 32{,}713.$$

Magnetic Leakage.—In the discussion of the foregoing magnetic circuits, no allowance was made for leakage. It was assumed that all the flux passes entirely through the circuit, but this is never the case and an allowance has to be made for leakage in practical calculations. The total flux Φ is divided into two parts, Φ_u the useful flux and Φ_c the leakage flux. Referring to Fig. 77 the useful flux will be the flux that flows from one pole piece to the other through the armature core. A portion of the flux will pass through the air from one pole tip to another, and this flux is not cut by the conductors on the armature and therefore is wasted so far as the electromagnetic action of the dynamo is concerned. $\frac{\Phi_u + \Phi_c}{\Phi_u}$ is called the leakage coefficient. Its average value is about 1.25, but varies with the type of the machine. It will be noted that the ratio of useful flux to leakage flux depends upon the relative permeance of the magnetic path through the core, and the path through the air and most leakage calculations are based upon this method.

Magnetic Saturation.—The attention of the reader has been invited to the analogy between the magnetic circuit and the electric circuit. The equation for the magnetic circuit is $\Phi = \frac{4\pi NI}{\mathfrak{R}} = \frac{M}{\mathfrak{R}}$. The analogy, however, is not complete as the value of $\mathfrak{R}$ in the magnetic circuit varies with a change of flux density while the resistance of the electric circuit remains the same regardless of the value of the current, provided of course that the temperature remains constant. The increase in the reluctance of a magnetic circuit is due to the fact that μ, the relation between H and B, is not constant for the iron core. If the magnetic force is increased the flux density will increase, but after a certain value of B has been obtained a further increase in H causes a very small increase in B and the iron is then said to be saturated. Normal B and H curves are curves showing the value of B that correspond to values of H. The curve is plotted using values of H for abscissæ, and corresponding values of B for ordinates. The value of μ for any degree of saturation may be obtained by taking from the curve the corresponding values of B and H and then $\mu = \frac{B}{H}$. Unless care is taken in obtaining the data for a

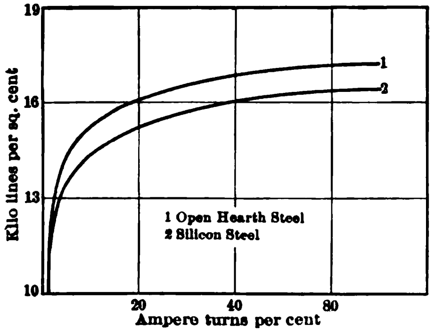


FIG. 79.—Normal B and H Curves.

magnetization curve, erratic results may be obtained due to residual magnetism.

If, however, the rod being tested is given mechanical shocks and the magnetizing current is made to pulsate with diminishing amplitude before settling down to a steady value this residual effect is eliminated and a normal value of B is obtained to correspond with a value of H. Such curves for two grades of steel are shown in Fig. 79.

Residual Magnetism.

Suppose a piece of soft iron which exhibits no, or practically no, magnetism is made the core of a solenoid. When current is sent through the solenoid, the core at once evinces strong magnetic properties, due to its permeability. If the solenoid current is turned off, it is found that the soft iron will now show magnetic properties, although in all other respects it is the same as before. The magnetization that is left in the iron is called **residual magnetism,** and the property of acquiring residual magnetism is called **retentivity.** If the magnetizing current is reversed, the residual magnetism disappears and if the current is the same as before, the core will be as highly magnetized with the opposite polarity. The force necessary to reduce the residual magnetism to zero is called the **coercive force,** being a fraction of the total magnetizing force.

Certain substances show more residual magnetism than others. Soft annealed iron shows more than hard iron or steel, though the latter substances will hold their magnetism longer than the former, requiring a greater coercive force. In view of the above, permanent magnets made of specially treated hard steel are used for the magnetic circuits of voltmeters and ammeters where an unchanging magnetic field is required.

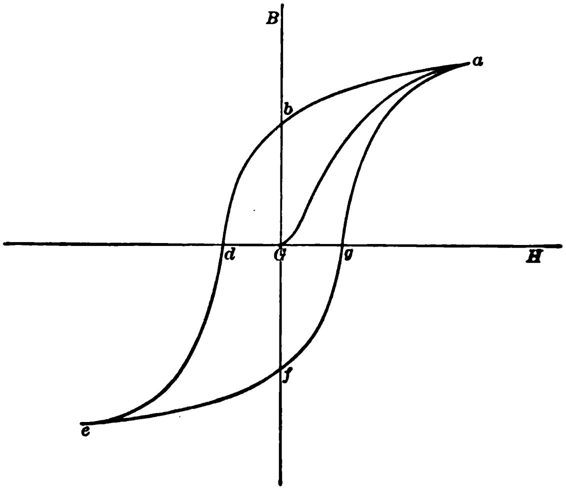


FIG. 80.—The Hysteresis Loop.

Hysteresis. Magnetic Cycle.—The curve shown in Fig. 80 is known as the hysteresis loop and represents what occurs during the magnetization of a piece of iron throughout a complete cycle. Beginning with a specimen containing no magnetism a magnetic force H is applied and the line Ga is drawn with the abscissæ of any point as the value of H and the ordinate as the corresponding value of B. After reaching a representing the maximum value, the value of H is gradually reduced and it is found that some of the magnetism remains even when H is reduced to zero. Gb represents the residual magnetism. By applying a force H in the opposite direction this residual magnetism disappears at d. The force Gd required to dissipate the residual magnetism is called the coercive force. By continuing to increase H until its value becomes as great as before and then reducing it to zero and applying an opposite force to overcome residual magnetism and allowing this force to again reach the maximum, a magnetic cycle is completed. An amount of energy proportional to the area of the hysteresis loop is the loss per cycle and appears as heat in the iron. It has been shown in the first part of this chapter how a change of current causes a change of flux which in turn induces a counter E. M. F. and that the energy expended by the current flowing against this counter E. M. F. represents the change of energy in the magnetic field. If $d\phi$ represents a change of flux and N represents the number of turns in the coil and i the instantaneous current flowing, then the work required to produce the change of flux, $d\omega = \frac{Ni}{10}\, d\phi$ ergs where the current is given in amperes. Let A equal the area of cross-section and l the length of the magnetic circuit. Then $\phi = AB$ or $d\phi = AdB$. The magnetic force is given by the equation,

$$H = \frac{4\pi Ni}{10l}\ ; \quad \therefore \frac{Ni}{10} = \frac{Hl}{4\pi}.$$

Substituting these values in the equation above gives $d\omega = \frac{Al}{4\pi}\, HdB$. Then the total work required for a complete cycle would be

$$W = \int d\omega = \frac{Al}{4\pi} \int HdB \text{ ergs}$$

where Al is the volume of the core and $\int HdB$ is proportional to the area of the loop. The actual area of the loop can be found by means of a planimeter and the value of $\int HdB$ can be determined from the scale of ordinates and abscissæ used.

Steinmetz gives the following formula for the hysteresis loss per cycle:

$$W = \nu V B^{1.6} \text{ ergs.}$$

Where

V = volume of core.
B = maximum flux density.
ν = a constant depending upon the material.

For the iron usually used for armature cores $\nu = .003$.

When a piece of iron as an armature core is rapidly rotated in a magnetic field frequent reversals of magnetism take place and although it has been advanced that the action in this case is quite different from that which takes place when the magnetic force is reversed and the core remain stationary, experiments show that the hysteresis loss is practically the same.

Measurement of Magnetic Fields.

It is not necessary to make an exact measurement of the magnetic fields of dynamos on board ship, but it may be of importance to know how far the action of a magnetic field of a dynamo is felt from the machine, or to investigate the stray field of a generator. This may readily be done by the vibration of an ordinary horizontal compass needle.

A compass needle when at rest, and only under the action of the earth's force, will point to magnetic north and if drawn aside from that position will vibrate from one side of north to the other, the arc of the angle described gradually lessening until the needle is again at rest and points north. During this time, the needle will make a number of vibrations depending upon the strength of the earth's horizontal force at that place. If now this same needle is made to vibrate in some other magnetic field, as the stray field of a dynamo, it will vibrate under the combined action of two forces, that of the stray field in addition to the earth's field. The square of the number of vibrations is proportional to the force under which the needle vibrates, and if the number of vibrations is counted for the same interval of time in the two cases, the forces are proportional to the squares of the number of vibrations in that time.

If n is the number of vibrations due to H, the earth's horizontal force, and n' the number due to the combined forces H' then $H' = \frac{Hn'^2}{n^2}$. The nearer n' approaches n the nearer H' approaches H. The needle may be vibrated at different distances from the dynamo or motor, and the combined forces of the earth and machine may be calculated in terms of H, and the point noted where n' becomes equal to n, when $H' = H$, or the influence of the field has disappeared. This will give the distance in one direction where the stray field is zero, and the operation can be repeated in different directions. In making these experiments, the field of the machine should be excited to its fullest magnetization so the extreme distance will be known at which the effect of the stray field can be detected.

Problems Relating to Magnetic Circuits.

1. The mean circumference of a cast iron ring is 100 centimeters, required the gilberts and turns necessary to produce a flux density of 6500 lines if $\mu = 217$ and the current is 5 amperes. $H = \frac{B}{\mu} = \frac{6500}{217} = 30$.

$$\text{M. M. F.} = Hl = 30 \times 100 = 3000 \text{ gilberts.}$$

$$NI \text{ (ampere turns)} = 3000 \div \frac{4\pi}{10} = \frac{3(10)^4}{4\pi}.$$

Since $I = 5$,

$$N = \frac{3(10)^4}{4\pi \times 5} = 477.5.$$

2. If the above ring be cut and forced open so as to leave an air gap of $\frac{1}{4}$ centimeter, what will be the total number of turns required to produce the same flux, the current remaining the same?

For air gap

$$H_1 = B_1 = 6500, \text{ M. M. F.} = Hl = \tfrac{1}{4} \times 6500 = 1625 \text{ gilberts.}$$

$$N_1 I = 1625 \div \frac{4\pi}{10} = \frac{16{,}250}{4\pi}. \quad N_1 = \frac{16{,}250}{20\pi} = 258.6.$$

Total $N = N_1 + N_2 = 258.6 + 477.5 = 736.1$.

3. An iron ring has a mean diameter of 90 centimeters and an area of 30 square centimeters. If a total flux 450,000 lines is required what will be the value of the M. M. F. in gilberts and ampere turns?

$$\mu = 600, \Phi = 450{,}000, B = \frac{450{,}000}{30} = 15{,}000,$$

$$H = \frac{15{,}000}{600} = 25, \text{ M. M. F.} = 25 \times \pi \times 90 = 2250\pi \text{ gilberts}$$

$$= 2250\pi \div \frac{4\pi}{10} = \frac{22{,}500}{4} = 5625 \text{ ampere turns.}$$

4. What is the reluctance of an iron ring of the same dimension as previous problems when $\mu = 200$? If the total flux is 180,000 lines what is the M. M. F. in gilberts and in ampere turns?

$$\mathcal{R} = \frac{l}{A\mu} = \frac{90 \times \pi}{30 \times 200} = \frac{3\pi}{200} \text{ oersteds.}$$

$$\Phi = \frac{\text{M. M. F.}}{\mathcal{R}} \therefore \text{M. M. F.} = \mathcal{R}\Phi = 180{,}000 \times \frac{3\pi}{200} = 2700\pi \text{ gilberts}$$

$$= 2700\pi \div \frac{4\pi}{10} = 6750 \text{ ampere turns.}$$

5. A bipolar dynamo magnetic circuit is made up as follows: Yoke $l = 60$ cm., $A = 100$ sq. cm., $\mu = 400$; magnet cores $l = 100$ cm., $A = 80$ sq. cm., $\mu = 500$; pole pieces $l = 40$ cm., $A = 120$ sq. cm., $\mu = 500$; air gaps $l = 5$ mm., $A = 120$ sq. cm. Armature core $l = 20$ cm., $A = 100$ sq. cm., $\mu = 600$. Find the reluctance of each part and total reluctance. What will be the resulting flux for 1400 ampere turns?

Take $\pi = \frac{22}{7}$. Let $\mathcal{R}_1, \mathcal{R}_2, \mathcal{R}_3, \mathcal{R}_4, \mathcal{R}_5$, represent the reluctances of the various parts in the order given. Then

$$\mathcal{R}_1 = \frac{60}{100 \times 400} = \frac{6}{4(10)^3}, \quad \mathcal{R}_2 = \frac{100}{80 \times 500} = \frac{10}{4(10)^3}, \quad \mathcal{R}_3 = \frac{40}{120 \times 500}$$

$$= \frac{4}{6(10)^3}, \quad \mathcal{R}_4 = \frac{1}{240}, \quad \mathcal{R}_5 = \frac{20}{600 \times 100} = \frac{2}{6(10)^3}.$$

$$\mathcal{R} = \Sigma\mathcal{R} = \frac{6}{4(10)^3} + \frac{10}{4(10)^3} + \frac{4}{6(10)^3} + \frac{1}{240} + \frac{2}{6(10)^3}$$

$$= \frac{18 + 30 + 8 + 50 + 4}{12(10)^3} = \frac{11}{1200}, \quad \Phi = \frac{4 \times 22 \times 1400 \times 1200}{10 \times 7 \times 11}$$

$$= 192{,}000 \text{ lines.}$$

6. In order to lift a certain weight by a horseshoe-shaped electromagnet a flux density of 22,000 gausses is required. Assuming the magnetic path to be of symmetrical cross-section and the length of the iron circuits to be 100 centimeters and μ for iron 500, how far away from the magnet must the armature be before the weight would be lifted if M. M. F. = 7000 ampere turns?

This circuit consists of the iron path and two air gaps the length of one air gap is the distance required.

Let x = length of one air gap.
Then $2x$ = total length of air gap.

$$\Phi = \frac{4\pi NI}{10\left(\frac{l}{A\mu} + \frac{2x}{A}\right)}. \quad B = \frac{\Phi}{A} = \frac{4\pi NI}{10\left(\frac{l}{\mu} + 2x\right)}.$$

Therefore,

$$22{,}000 = \frac{4 \times 22 \times 7000}{7 \times 10(\frac{1}{5} + 2x)}. \quad \frac{1}{5} + 2x = \frac{4 \times 22 \times 7000}{7 \times 10 \times 22{,}000}.$$

$$\frac{1}{5} + 2x = \frac{2}{5}, \quad x = \frac{1}{10} = 1 \text{ mm.}$$

7. A circular ring is made of three concentric rings of different qualities of iron, the cross-section of each ring is 25 centimeters and the mean diameters of 40, 45 and 50 centimeters, the permeabilities are 400, 500 and 600. What is the combined reluctance and how many ampere turns would be required to give a total flux of $149(10)^3$ lines?

Let P_1, P_2 and P_3 represent the respective permeances of the rings. Then,

$$\mathcal{P}_1 = \frac{25 \times 400}{40\pi} = \frac{250}{\pi}, \quad \mathcal{P}_2 = \frac{25 \times 500}{45\pi} = \frac{2500}{9\pi}, \quad \mathcal{P}_3 = \frac{25 \times 600}{50\pi} = \frac{300}{\pi}.$$

$$\mathcal{P} = \mathcal{P}_1 + \mathcal{P}_2 + \mathcal{P}_3 = \frac{2250 + 2500 + 2700}{9\pi} = \frac{7450}{9\pi}. \quad \therefore \mathcal{R} = \frac{9\pi}{7450}.$$

$$\Phi = \mathcal{P}M = \frac{7450(4\pi NI)}{10 \times 9\pi} = 149(10)^3 \text{ lines.}$$

$$NI = \frac{149{,}000 \times 10 \times 9}{7450 \times 4} = 450 \text{ ampere turns.}$$

8. The flux in the armature of a bipolar dynamo is equal to $44(10)^6$ lines while the total flux is $55(10)^6$ lines, what is the leakage coefficient?

$$\frac{\Phi_u + \Phi_e}{\Phi_u} = \text{leakage coefficient} = \frac{55(10)^6}{44(10)^6} = \frac{5}{4} = 1.25.$$

9. Given the leakage coefficient equal 1.28 and an armature flux required $(10)^6$ lines. What should be the cross-sectional area of yoke if flux density is to be 6400?

Total flux, $\Phi = (10)^6 \times 1.28 = 128\ (10)^4$.

$$A = \frac{\Phi}{B} = \frac{128(10)^4}{64(10)^2} = 200 \text{ sq. cm.}$$

10. Using the data of problem 5, and the flux of 192,000 lines, determine the total ampere turns required, by finding the ampere turns for each portion of the circuit.

Yoke,

$$l = 60 \text{ cm.}, A = 100 \text{ sq. cm.}, \mu = 400;$$

$$B = \frac{192{,}000}{100} = 1920 \text{ gausses;}$$

$$NI = \frac{0.8 \times 1920 \times 60}{400} = 230 \textit{ ampere turns.}$$

Magnetic cores,

$$l = 100 \text{ cm.}, A = 80 \text{ sq. cm.}, \mu = 500;$$

$$B = \frac{192{,}000}{80} = 2400 \text{ gausses;}$$

$$NI = \frac{0.8 \times 2400 \times 100}{500} = 384 \textit{ ampere turns.}$$

Pole pieces,

$$l = 40 \text{ cm.}, \; A = 120 \text{ sq. cm.}, \; \mu = 500;$$

$$B = \frac{192{,}000}{120} = 1600 \text{ gausses};$$

$$NI = \frac{0.8 \times 1600 \times 40}{500} = \textit{102 ampere turns.}$$

Air gap,

$$l = 5 \text{ mm.}, \; A = 120 \text{ sq. cm.};$$

$$B = \frac{192{,}000}{120} = 1600 \text{ gausses};$$

$$NI = 0.8 \times 1600 \times 0.5 = \textit{640 ampere turns.}$$

Armature core,

$$l = 20 \text{ cm.}, \; A = 100 \text{ sq. cm.}, \; \mu = 600;$$

$$B = \frac{192{,}000}{100} = 1920 \text{ gausses};$$

$$NI = \frac{0.8 \times 1920 \times 20}{600} = \textit{51 ampere turns.}$$

Total ampere turns, $NI = 230 + 384 + 102 + 640 + 51 =$ *1407 ampere turns.*

This checks problem 5 very closely, the difference being due to the fact that 0.8 was used instead of 0.796. This is well within the precision with which magnetic calculations can be made.

CHAPTER IX.

ELECTROMAGNETIC INDUCTION.

In the preceding chapter the results of Oersted's experiments were described and it was shown that there exists a magnetic field around a conductor carrying a current. It was further shown that where the conductor formed a closed circuit a certain magnetic flux threaded through the circuit which was proportional to the current, provided that the permeability of the circuit was constant.

Faraday conducted a series of experiments to ascertain the effects of changing the magnetic flux threading through a circuit and found that while the flux was changing an induced E. M. F. was produced. He experimented with two coils near each other. In one coil he placed a galvanometer and in the other a battery and found that when the battery circuit was broken the galvanometer needle was deflected indicating a current in the other coil. When the battery circuit was closed the galvanometer needle gave another deflection. There was no indication in the galvanometer circuit excepting when the current in the battery circuit and consequently the magnetic fields were changing. He further experimented with a magnet and a coil containing a galvanometer in circuit and obtained analogous results. From these experiments were deduced the laws of induction.

Laws of Induction.

(1) When the number of lines of force threading through a closed circuit are changing an induced E. M. F. is set up which is proportional to the rate of change.

(2) An increase in the number of lines threading through a coil induces an inverse E. M. F. which, as one looks in the positive direction of the lines of force, tends to produce a counter-clockwise current.

(3) A decrease in the number of lines threading through a coil induces a direct E. M. F. which, if one looks along the positive direction of the lines of force, tends to produce a clockwise current.

If there exists a closed conductor without current, and by any means external to the conductor, a magnetic field is set up around it, it will be found that there is indication of current in the conductor as long as there is any change in the intensity of the field around the conductor. When once the field around the conductor is constant, then indication of current in the conductor ceases, although the field still surrounds it.

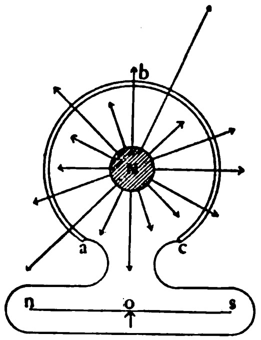


FIG. 81.—Electromagnetic Induction.

Suppose we have a closed conductor *a, b, c,* of the shape shown in Fig. 81, the circuit being completed around a small compass needle *ns,* pivoted at *O,* the whole so arranged that the conductor and connecting wires are parallel to the needle. If a pole of a permanent magnet *N* is thrust into the ring formed by the conductor, the magnetic lines due to this magnet spread out as shown in the figure, some passing through the space enclosed by the conductor. This changing magnetic field reacts on the conductor, inducing an E.M.F. which in turn produces a current in the conductor. This process is called **induction,** and the current is manifested by the needle, *ns,* being deflected. This current is only noticed during the time that there is relative motion between the field of the magnet and the conductor, for as soon as the magnet is held steady in any one position, and the intensity of the field remains constant, there is no induced E. M. F. and therefore no manifestation of current. The energy of pushing the magnet towards the conductor has been converted into electric current and when the magnet is at rest, there is no energy expended and no current.

If the magnet were held steady and the conductor pulled away from it, there would be the same phenomenon exhibited, except that the needle would be deflected in the other direction. Inserting the south pole would produce a current in the opposite direction from that produced by the approach of the north pole.

The magnitude of the deflection in every case is proportional to the rate of change of lines threading through the coil.

If the *N* pole of the magnet referred to above is thrust into the ring at right angles to the plane of the paper from the near side of the paper, there is an increase in the number of the lines that pass through the coil and the observer is looking along the positive direction of the lines of force, and therefore the E. M. F. induced causes a counter-clockwise current.

The effect of this current is to make the near side of the coil a magnetic shell of north polarity. We then have the effect of a north pole approaching a north pole, which produces repulsion between them and which is manifested by its requiring greater force to thrust in the magnet as it approaches the coil.

In pulling away the magnet (*N* pole) from the coil or the coil from the magnet (*N* pole), there is a decrease in the number of lines of force that pass through the coil, and still looking along the positive direction of the lines of force from the same side, the resulting current is direct, or clockwise, tending to make the near side of the coil a shell of south polarity. We have now the effect of a north pole being pulled away from a south pole or vice versa, causing an attractive force between them, which is manifested in the greater force required to separate them.

Lenz's Law.—This phenomenon of induced currents is summed up in Lenz's law, which states that "**in all cases of electromagnetic induction, the induced currents have such a direction that by their reaction, they tend to stop the motion or change which produces them.**"

Illustration of Induction.

As a further illustration of the laws of induction suppose we had a circular closed coil lying in a magnetic field, the plane of the coil being at right angles to the lines of force and so arranged that the coil could be revolved about the extremities of one of its diameters.

In Fig. 82 the lines of force are represented by the dots running through the paper, the observer is looking along the positive direction of the lines. As long as there is no movement of the coil, there is no induced E. M. F. Imagine the coil to be revolved on the axis *ab*, the upper half turning into the paper, then there is a decrease in the number of lines that pass through the coil, and from the law

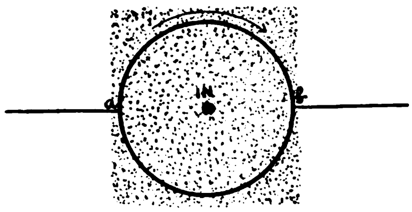


FIG. 82.—Illustration of Induction.

of induction, the induced E. M. F. would produce a current in the direction shown by the arrow.

If, instead of approaching a magnet with its lines of force issuir in all directions to our closed coil, suppose we imagine this coil to be thrust into a uniform magnetic field as represented in Fig. 83.

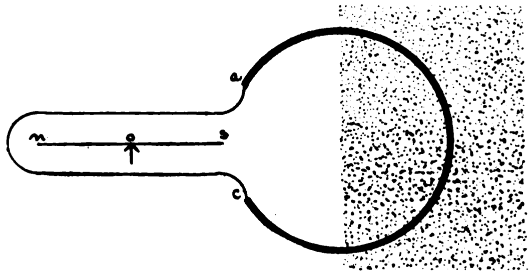


FIG. 83.—Illustration of Induction.

The magnetic field is represented as before by the dots, and the observer is looking along the positive direction of the lines of force. As the closed coil *ac* is moved from left to right into and at right angles to the magnetic field, there is an induced E. M. F. in *ac* due to the change in the number of lines that pass through the coil. It has already been noted that to induce an E. M. F. there must be a *change* in the number of lines passing through the coil. If the coil is moved up and down the plane of the paper while lying in the field, there will be as many lines entering the coil on one side as are leaving it on the other, so there will be no change and no induced E. M. F. Similarly, if the coil, while parallel to the plane of the paper, is moved up and down through the paper, there will be no induction. The above phenomenon is true only when the field is homogeneous, for if the flux density at any portion is greater than at another, there will be a change in the number of lines passing through the coil, and therefore an induced E. M. F.

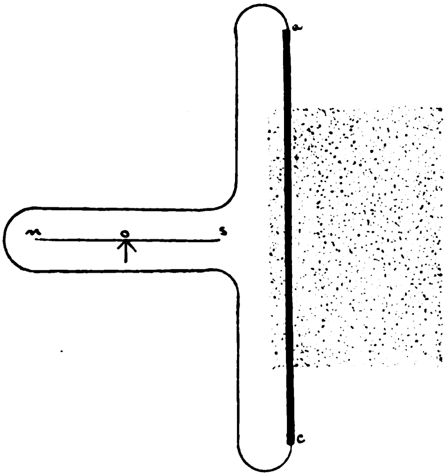


FIG. 84.—Illustration of Induction.

If the coil while lying at right angles to the lines were revolved about one of its diameters, there would be induction, for the number of lines that passed through the coil would then vary from a maximum to a minimum.

Suppose now the conductor *ac* instead of forming a closed coil is straightened out and forms a long straight conductor, so in the sense we have been speaking, there is no closed coil. This is represented in Fig. 84.

If this straight conductor *ac* is moved from left to right at right angles to the magnetic field and into it, it will be found that there is an induced E. M. F. precisely as in the case where the conductor was bent into a circular coil. In this case the E. M. F. may be considered as induced by the conductor *cutting* the lines of force, although the lines threading the coil must also change when this conductor moves. If the conductor is moved parallel to the lines there will be no cutting and no induced E. M. F.

This illustrates the principle of induction that when **a conductor is moved across a magnetic field so as to cut the lines of force, there is an E. M. F. induced which tends to produce a current in the conductor.** If the rate of cutting be made constant a steady induced E. M. F. will result.

The distinction between the E. M. F. induced in a conductor by a change in the number of lines that pass through the coil and by a conductor cutting across lines of force is not so sharp as it might appear. The induced E. M. F. in either case is due to the same movement, and every conductor carrying a current forms part of a closed circuit, and the lines are passing into and out of the coil at the exact rate that the conductor is cutting them.

This method of treating the subject is therefore a special adaptation of Faraday's laws which is convenient in application to many problems in electrical engineering. If the conductor does not constitute a part of a closed circuit, no current will flow, but a difference of potential will exist between the ends of the conductor due to the cutting of the lines of magnetic flux.

In either case, it is not a current that is induced, but an E. M. F. If, initially, there is no current flowing in a coil in which an E. M. F. is induced a resulting current will flow depending upon the value of the induced E. M. F. and the resistance. If current is already flowing in a circuit, the induced E. M. F. may increase or decrease the original E. M. F. and the resulting current will equal the algebraic sum of the two E. M. F.'s divided by the resistance.

Rule for Determining the Direction of Induced E. M. F.

Probably the simplest rule for determining the direction of the E. M. F. induced in a conductor by cutting lines of force is the hand rule, which is as follows:

Place the *right* hand with thumb and fingers at right angles and extended in the magnetic field so that the positive direction of lines of force will strike the palm of the hand and then if the thumb indicates the direction of motion of the conductor, the direction of the finger tips will indicate the direction of the induced E. M. F. This will be understood more easily by reference to Fig. 85.

Generator Action.—In the preceding pages it has been shown that when a conductor is moved across a magnetic field so as to cut the lines of magnetic flux an E. M. F. is induced, and if the conductor forms a part of a closed circuit a current will flow. In such case

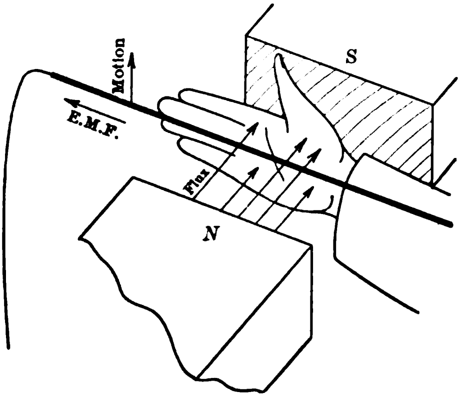


FIG. 85.—Illustrating Hand Rule for Determining Direction of E. M. F. Induced by a Conductor Cutting Lines of Magnetic Flux.

mechanical force has to be applied to the conductor to cause it to move across the field and the mechanical energy thus expended appears as electric energy in the circuit. This is the principle of the electric generator which will be explained fully in the succeeding chapters.

Motor Action.—It will be remembered that the definition of unit current was based upon the experimental fact, that when a conductor in which a current was flowing was placed in a magnetic field it was acted upon by a force tending to move it sidewise out of the field.

If *A* is a battery whose terminals are connected to two straight parallel metal bars enclosing a homogeneous magnetic field as shown in Fig. 86 and *CD* is a conductor resting on the bars and completing the circuit, a force will be exerted on *CD* tending to move

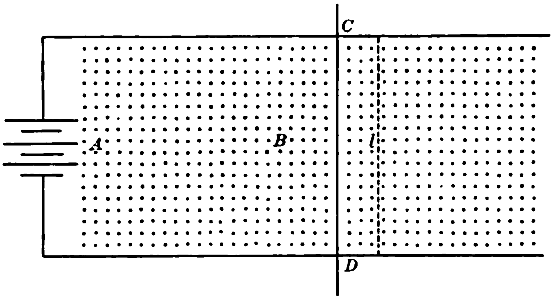


FIG. 86.

it to the right or left depending upon the direction of the magnetic field. The magnitude of this force in dynes will depend upon the length l in centimeters of the cutting portion of the conductor, B the flux density of the magnetic field in gausses and I the strength of the current in abamperes flowing through the conductor. The force acting is therefore given by the equation $F = BlI$ dynes.

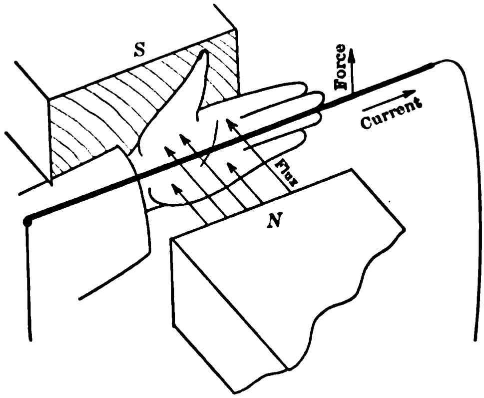


FIG. 87.—Illustrating Hand Rule for Determining the Direction of the Force Acting on a Conductor Lying in a Magnetic Field.

If a group of such conductors are suitably arranged on the periphery of a drum rotary motion can be produced. This action of a magnetic field upon a conductor carrying a current is called motor action. This is the principle of the electric motor of which the reader will be given a full description later. The simplest rule for determining the direction of the force acting on a conductor carrying a current when placed in a magnetic field is a hand rule similar to the one given for induced E. M. F.

The Left-Hand Rule.—Place the left hand, with thumb and fingers at right angles and extended, in the magnetic field so that the positive direction of lines of force enter the palm of the hand, and then if the direction of the finger tips indicate the direction of flow of current the direction of thumb will indicate the direction of the resulting force acting on the conductor. This will be understood by reference to Fig. 87.

Self-Induction.

As we have seen before, when a straight conductor or a coil carries a current, a magnetic field, which depends upon the current strength, is set up. When the current increases the flux also increases, and as this changing flux cuts the conductor or coil, an E. M. F. is induced, which by Lenz's law opposes the increase of current. On the other hand, when the current is decreased there is a collapse of the lines of force and this must also induce an E. M. F., which, by Lenz's law, is in such a direction that it tends to prolong the flow of current. For these reasons and also because the flux, in each of the two above cases, cuts the conductors in opposite directions, the induced E. M. F., when the current is decreasing, will be opposite to what it was when the current was increasing.

So long as the current is rising the lines of force are increasing and the current is being retarded by this counter E. M. F. When the current finally reaches a steady value there is no further increase of flux, and the retarding action ceases. When, for any reason, the current decreases, the lines of force must necessarily decrease, and they act in such a direction as to oppose the decrease of current. If the current is suddenly interrupted, this induced E. M. F. may have an instantaneous value many times the circuit E. M. F. This is the E. M. F. which produces the sparks or arcs noticed when a circuit linking with considerable flux is interrupted, as, for instance, a field circuit. The high E. M. F. tends to bridge over the circuit at the point of interruption and will volatilize metal contacts and an arc may be maintained for some time. This induced E. M. F. becomes so great in the case of the fields of large generators that special provision is made to limit its magnitude, for the insulation of the windings has in many instances been punctured. When the change of flux causing an induced E. M. F. in a conductor is due to a change of current in the conductor itself, it is called self-induction.

Forms of Inductive Circuits.—The amount of self-induction of an electrical circuit depends on its geometrical form. Fig. 88 shows some forms of typical circuits.

Type 1 shows that a current entering one of the terminals flows as many times around the helix in one direction as it does in the

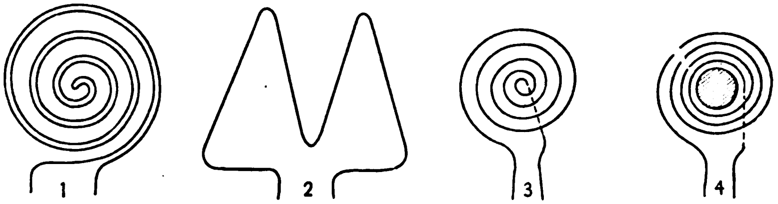


FIG. 88.—Forms of Self-Induction Circuits.

opposite direction, and in consequence the magnetic field set up by one series of convolutions is practically counteracted by that of the other series and there is practically no self-induction. This is known as a non-inductive resistance and this *double winding* is used for the coils of standard resistances.

Type 2 shows very little self-induction, but type 3 shows more. If the conductor of type 3 be made of many turns of wire close together, the effect of self-induction may be very marked. It will be still more marked if these turns are wound on an iron core, as type 4, as in the case of an ordinary electromagnet, for then there are many more lines of force due to the permeability of the metal.

The coefficient of self-induction or the inductance of a circuit is the ratio of the change of interlinkages of flux and circuit to the change of current producing it. It is represented by L.

If a change dI in the current causes a change $d\Phi$ in the flux and the circuit has N turns then the change of interlinkages will be $Nd\Phi$.

In a circuit of constant permeability the change of flux is proportional to the change of current, and the ratio of the change of interlinkages to change of current is constant. Hence,

$$L = \frac{Nd\Phi}{dI}. \tag{1}$$

This may be written

$$L = \frac{Nd\Phi}{dt} \div \frac{dI}{dt}. \tag{2}$$

$N\frac{d\Phi}{dt}$ is the rate of change of interlinkages and therefore represents the induced E. M. F. Hence the inductance of a circuit may be defined as the ratio of the induced E. M. F. to the rate of change of current in the circuit. Multiplying both sides of equation (2) by $\frac{dI}{dt}$ we have $L\frac{dI}{dt} = N\frac{d\Phi}{dt}$. This equation is usually written $e = -L\frac{dI}{dt}$, where e is the induced E. M. F. The negative sign being used to indicate that the induced E. M. F. is opposed to the change of current.

The C. G. S. unit of inductance has been defined as the inductance of a circuit when a change of one C. G. S. unit of current per second will induce one C. G. S. unit of E. M. F. The practical unit of inductance is the henry and is the inductance of a circuit where a change of current of one ampere per second induces an E. M. F. of one volt. A henry is equal to $(10)^9$ C. G. S. units.

When an electromotive force E is suddenly impressed upon a circuit, the current does not immediately attain normal value on account of the inductance of the circuit.

The value of the resultant current in a continuous current circuit at any time after the circuit is closed can be determined as follows:

Let E = the impressed E. M. F. and R the resistance of the circuit, and I the instantaneous value of the current. The instantaneous value of the induced E. M. F. will then be given by the equation

$e=-L\frac{dI}{dt}$. The instantaneous value of the resulting E. M. F. will then be equal to $E-L\frac{dI}{dt}$. Hence $I=\frac{E-L\frac{dI}{dt}}{R}$, where I is the instantaneous value of the current. Therefore, $I-\frac{E}{R}=-\frac{LdI}{Rdt}$, or $\frac{dI}{I-\frac{E}{R}}=-\frac{Rdt}{L}$. Integrating this we have $I=\frac{E}{R}\left(1-\epsilon^{-\frac{Rt}{L}}\right)$.

This expression is known as Hemholz's law and gives the instantaneous value of the current t seconds after the circuit is closed

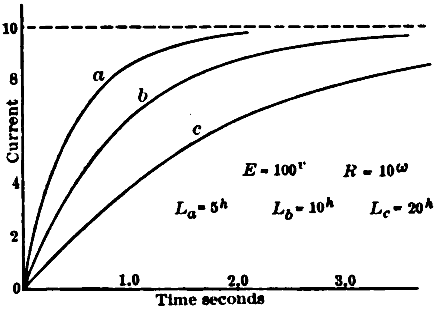


FIG. 89.—Rise of Current in an Inductive Circuit.

and the current begins to build up. ϵ is the base of the Naperian system of logarithms and equals 2.71828. It will be noted that theoretically $I=\frac{E}{R}$ only when t is infinite. In practical cases, however, the current reaches the Ohm's law value within a second or so. Fig. 89 shows the rise of current in circuits whose resistances are 10 ohms, and where the values of inductance are 5, 10 and 20 henries, respectively.

The factor $\frac{L}{R}$ is called the time constant of the circuit. When the time t in seconds is equal to the ratio $\frac{L}{R}$ the current equation becomes $I=\frac{E}{R}\left(1-\frac{1}{\epsilon}\right)=\frac{E}{R}\left(\frac{2.71828-1}{2.71828}\right)=.632\frac{E}{R}$. The time constant of the circuit is then the time required by the current to rise to 63.2 per cent of its ultimate value, as given by Ohm's law.

If the current in a circuit is changing, the relation between current and E. M. F. is not given by the equation $E=RI$, for the effects of inductance are introduced. In the case of a varying current the relation is given by the equation $E=RI+L\frac{di}{dt}$ where E and I are the instantaneous values of the impressed E. M. F. and current and L the inductance. When the current is increasing, the rate of change is positive and the impressed E. M. F. is equal to the arithmetical sum of the induced E. M. F. and the RI drop. When the current is decreasing, its rate of change is negative and the impressed E. M. F. is equal to the arithmetical difference between the induced E. M. F. and the RI drop. If the impressed E. M. F. is suddenly reduced to zero and the circuit completed through a negligible resistance the current will therefore continue to flow. To find the value of this current at any instant proceed as follows:

If, in the expression, $E=RI+L\frac{dI}{dt}$, E is made zero, and the circuit be short-circuited, when the current I_0 is flowing, then

$$0=RI+L\frac{dI}{dt},$$

$$\frac{dI}{I}=-\frac{R}{L}dt,$$

$$\log I=-\frac{R}{L}t+K,$$

where K is a constant of integration.

When

$$t=0,\ I=I_0,\ K=\log I_0.$$

$$\text{Then } \log\frac{I}{I_0}=\frac{-Rt}{L},$$

or

$$I=I_0\epsilon^{-\frac{Rt}{L}}.$$

The current then drops logarithmically as shown in the three curves of Fig. 90, in which $I_0=10$ amperes.

If i represents the instantaneous value of the current at any instant and E the impressed E. M. F. and R the resistance of a circuit then Ei will be the instantaneous value of the power expended. A portion of E is expended in sending a current i through a resistance R and is equal to Ri. The remaining part of E is expended in overcoming the E. M. F. of self-inductance and is equal to $L\frac{di}{dt}$. Therefore $E=Ri+L\frac{di}{dt}$ and $Ei=i\left(Ri+L\frac{di}{dt}\right)$, or $Eidt=Ri^2dt+Lidi$. Hence,

$$\int_0^t Eidt=W=\int_0^t Ri^2dt+\int_0^I Lidi.$$

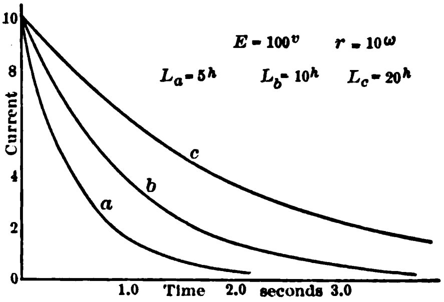


FIG. 90.—Decay of Current in an Inductive Circuit.

The term $\int_0^t Ri^2dt$ represents the energy spent in heat and

$$\int_0^I Lidi=\frac{LI^2}{2},$$

represents the energy stored up in the magnetic field while the current increases from 0 to I. If the current is gradually decreased the energy $\frac{LI^2}{2}$ is returned to the circuit due to its action in tending to prevent the decrease, but if the circuit is suddenly broken a very high induced E. M. F. is created and the energy is expended in sparking across and volatilizing the metal contacts.

If a circuit contains no iron the value of L is constant but often hard to calculate, due to the unequal distribution of flux. If the circuit has a closed iron core the value of L then depends upon μ and is not constant, for as we have seen the value of μ varies with the degree of magnetic saturation of the iron. In a circuit consisting of a long solenoid or of a solenoidal ring the value of the flux is given by the equation

$$\Phi = \frac{4\pi NI}{\mathfrak{R}} \text{ or } \frac{4\pi NIA\mu}{l}.$$

Hence, assuming that μ is constant

$$\frac{d\Phi}{dt} = \frac{4\pi NA\mu}{l} \frac{dI}{dt}$$

and

$$N\frac{d\Phi}{dt} = \frac{4\pi N^2 A\mu}{l} \frac{dI}{dt};$$

and when the current is changing at the rate of one C. G. S. unit per second

$$L = N\frac{d\Phi}{dt} = \frac{4\pi N^2 A\mu}{l} \text{ C. G. S. units.}$$

One henry equals $(10)^9$ C. G. S. units and therefore

$$L = \frac{4\pi N^2 A\mu}{(10)^9 l} \text{ henries.}$$

Mutual Induction.

If the change in the magnetic field of one conductor is due to a change of current in a second conductor then the induced E. M. F. of the first conductor is said to be due to mutual induction.

The coefficient of mutual induction or the mutual inductance of two circuits is the change in the interlinkage of flux that takes place in one circuit for a change of unit current in the other. It is designated by M. If N_1 and N_2 represent the number of turns in the first and second circuit, respectively, Φ_1 and Φ_2 their respective flux, and $d\Phi_2$ the change of flux in second circuit due to a change of unit current in that circuit, and if all the flux of the second circuit cuts the first, the change of interlinkages will be $N_1 \frac{d\Phi_2}{dt}$.

For a solenoid

$$\Phi_2 = \frac{4\pi N_2 I}{\mathcal{R}},$$

$$\frac{d\Phi_2}{dt} = \frac{4\pi N_2}{\mathcal{R}} \frac{dI}{dt}.$$

Then the induced E. M. F. in coil (1) due to the flux of coil (2)

$$= \frac{4\pi N_2 N_1}{\mathcal{R}_2} \frac{dI}{dt}.$$

The total E. M. F. in coil (1)

$$e_1 = \mathcal{R}_1 i_1 + \frac{4\pi N_1^2}{\mathcal{R}_1} \frac{di_1}{dt} + \frac{4\pi N_2 N_1}{\mathcal{R}_2} \frac{di_2}{dt},$$

and in (2)

$$e_2 = \mathcal{R}_2 i_2 + \frac{4\pi N_2^2}{\mathcal{R}_2} \frac{di_2}{dt} = \frac{4\pi N_2 N_1}{\mathcal{R}_1} \frac{di_1}{dt}.$$

If all the flux of circuit (2) links circuit (1) and all the flux of (1) links (2), then $\mathcal{R}_1 = \mathcal{R}_2$; for both coils have a common magnetic circuit.

The term $\frac{4\pi N_2 N_1}{\mathcal{R}}$ is called the mutual inductance of the circuit, and

$$M = \sqrt{L_1 L_2},$$

where

$$L_1 = \frac{4\pi N_1^2}{\mathcal{R}}, \text{ and } L_2 = \frac{4\pi N_2^2}{\mathcal{R}}.$$

Then the total E. M. F. in each circuit becomes

$$e_1 = \mathcal{R}_1 i_1 + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt},$$

$$e_2 = \mathcal{R}_2 i_2 + L_2 \frac{di_2}{dt} + M \frac{di_1}{dt}.$$

The units employed in mutual inductance are the same as in self-inductance. Two circuits are said to have a mutual inductance of 1 henry when a rate of change of current of 1 ampere per second in one will induce an E. M. F. of 1 volt in the other.

Principle of Transformers.

The elementary form of transformer consists of a closed magnetic circuit on which are wound the two coils, one called the primary, the other, the secondary, as shown in Fig. 91.

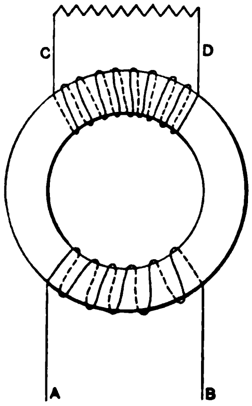


FIG. 91.—Typical Transformer.

The primary and secondary are arranged, as far as possible, so that all the flux produced by primary will cut the secondary, the path of the flux is supposed to be wholly within the iron ring.

If a steady E. M. F. is applied to the terminals of the primary there will be an induced E. M. F. in the secondary only when making and breaking the circuit. If, however, a source of alternating E. M. F. be applied to the terminals, an alternating current will flow in the primary and will cause a varying or changing flux through the magnetic circuit, and a varying E. M. F. will be induced in the secondary. The principle of the transformer will be explained later under alternating currents, but it is easy to see that as long as the same flux passes through both coils the rate of change $d\Phi$ is the same. The induced E. M. F. in the two coils will then be $N_1 \frac{d\Phi}{dt}$ and $N_2 \frac{d\Phi}{dt}$, when N_1 and N_2 are the respective number of turns in primary and secondary. The induced E. M. F. of the primary is nearly equal to the impressed E. M. F. and opposite to it. Hence, if E_1 and E_2 represent the terminal E. M. F. of the primary and secondary respectively, neglecting losses, we have $\frac{E_1}{E_2} = \frac{N_1}{N_2}$.

In the transmission of electric power to a distant point it is very economical to have a high voltage to avoid excessive loss in heating of the transmission line. For delivery to the customer it is desired to reduce the high voltage down to 100 or 200 volts. With alternating current this is done by means of transformers. In a step-up transformer the primary has few turns and the secondary many, and a low voltage applied to the primary gives a high voltage in the secondary. In a step-down transformer the reverse action takes place. The power delivered by the secondary will always be less than the power delivered to the primary on account of the copper losses in both coils and the eddy currents and hysteresis in the core, but the efficiency of a well-designed transformer at full load is seldom below 95 per cent and may run as high as 98 per cent. Neglecting this loss we have $E_1I_1=E_2I_2$ or $\frac{E_1}{E_2}=\frac{I_2}{I_1}=\frac{N_1}{N_2}$ as the relations that hold for an ideal transformer.

Induction Coils.

In the ordinary induction coil a source of constant E. M. F. is used and the induced E. M. F. in the secondary is caused by "making" and "breaking" the primary circuit. Induction coils were used in the navy to produce the high potential required for radio telegraphy, but alternating current supplied by motor generators is now used. The induction coil is used extensively to induce the high E. M. F. required in X-ray work.

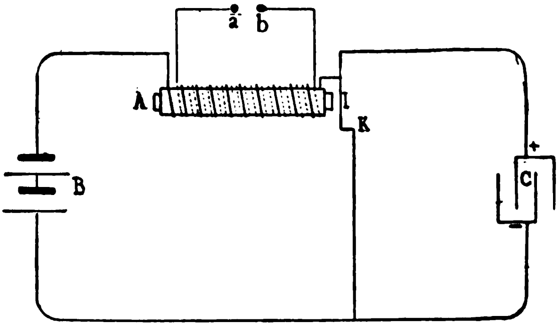


FIG. 92.—Circuit of Induction Coil.

As the value of the secondary E. M. F. depends upon the rate of change of flux it is necessary that the make and break, especially the latter, be done as quickly as possible. In order to accomplish this some form of interrupter is installed in the primary circuit and this device automatically makes and breaks the circuit many times in a second.

The connections of a simple induction coil circuit are shown in Fig. 92.

A represents the magnetic core around which are wound the two coils, the primary from the battery *B*; the secondary being wound over it, and carefully insulated. The terminals of the secondary coil are shown at *a*, *b*. The continuous current from the battery is interrupted by *I*, a pivoted conductor, which makes contact either with *K* or is drawn away from it towards the core *A*. When *I* makes contact with *K*, the current from the battery flows around the primary coil, and *I* is attracted to the core against the action of a spring, breaking the circuit at *K*. As soon as the circuit is broken, the core ceases to be magnetic and *I* makes contact again with *K*, when the circuit is re-established. This constitutes the make and break, and the varying flux produced in the core induces a high E. M. F. in the secondary coil, which may be manifested by a spark jumping from *a* to *b*.

The Use of the Condenser.

If a condenser was not used every time that the circuit was broken an arc would be formed at *K*. In addition to wasting the energy stored in the magnetic field this would soon result in the burning away of the platinum contact points. Furthermore, since the induced E. M. F. depends upon the rate of change of current it is advisable to make the break as sharp and quick as possible and delay the make. Thus, in using a spark coil across the terminals of the secondary, it may be arranged so that the spark will jump across at break but not at make, and the sparks will all be in one direction. With a condenser in the circuit as shown the energy stored up in the magnetic field at break goes to charge the condenser, which immediately discharges through the battery in such a direction as to oppose the ordinary flow of current and delay the time of make; and also this sudden rush of current in the primary is from the proper direction to add to the induced E. M. F. of the secondary at break.

Induction Coils for Creating Electric Oscillations.—In some systems of radio telegraphy an induction coil is used in the creation of electric oscillations necessary for the formation of electromagnetic waves, and the following description is of a type suitable for such work:

Induction coils are known by the length of spark. Thus a 10-inch coil means that it will produce in air a spark 10 inches long between the terminals of the secondary coil. A coil of the above size would consist of 300 to 400 feet of insulated copper wire, wound around an iron core consisting of a bundle of soft iron wires about 2 inches in diameter. The secondary would consist of 12 to 15 miles of very fine double-covered silk copper wire, depending on the diameter, making 45,000 to 50,000 turns, wound over the primary. The winding of the secondary is made in a large number of sections, each section prepared separately and each carefully insulated with paraffin and discs of shellaced paper. A large number of such sections varying from 100 to 500 are slipped over a thick ebonite tube, inside of which are the primary coil and iron core.

When the coil is in operation great differences of potential exist in the coils of the secondary and this must be so wound that no two parts, which are a great difference of potential, are near together. There must also be perfect insulation between the primary and secondary coils, and it is usual to have them separated by a tube of ebonite at least half an inch thick covered with a layer of paraffin an inch thick.

When the sections of the secondary coil are assembled on the insulating tube they are compressed and immersed in molten paraffin. This is done on a former, after which the whole secondary winding is enclosed in a cylinder of ebonite and thick ebonite cheeks are fitted on the ends of the ebonite tube on which the secondary is wound.

The completed coil may be then enclosed in a wooden box which is filled with insulating oil or filled in solid with paraffin, the ends of the secondary being brought out through ebonite tubes.

If the coil is to be used with an interrupted continuous primary current, a condenser is placed across the point of rupture of the primary current, its action being previously described.

In some forms of induction coils, the primary is wound in sections and the ends of each brought out in such a manner that the various sections can be joined in series or in parallel so as to vary the resistance and inductance of the coil, as well as the effective number of turns.

Problems on Inductance.

1. Find the inductance of a primary coil of 100 turns and secondary of 10 turns, wound on an iron ring of 20 centimeters mean diameter and 10 square centimeters section, the permeability of the iron being 700.

Ans. 14 millihenries.
.14 millihenry.

2. A transformer is wound with 50 turns in the primary coil and 1000 in the secondary. The magnetic circuit has a mean length of 50 inches and an area of 12 square inches. Assuming a permeability of 1800, what are the inductances of the two coils? What is the mutual inductance?

Ans. .0345 henry.
13.8 henries.
.691 henry.

3. If 1000 volts are impressed on a circuit of 10 henries inductance and 4 ohms resistance, what will be the value of the current at the end of $\frac{1}{120}$ second, at the end of 1 second? What the final value?

Ans. 7.5 amperes.
82.3 amperes.
250 amperes.

4. A coil of wire has an inductance of .025 henry and a resistance of 25 ohms, and a current of 25 amperes is flowing in it. The current is suddenly stopped and dies to zero in .005 second. What is the momentary value of the induced E. M. F.? *Ans.* 125 volts.

5. A coil of wire has a resistance of 4.5 ohms and an inductance of 0.01 henry. An E. M. F. of 38 volts is suddenly impressed upon the coil. In $\frac{1}{450}$ second, what will the current be? What is the time constant of the current?

Ans. 5.34 amperes.
$\frac{1}{450}$ second.

6. In problem 5, the resistance is doubled. How does this affect the time constant? Will this current have reached the same value as in problem 5, in $\frac{1}{450}$ second?

Ans. $\frac{1}{900}$ second.
3.66 amperes.

CHAPTER X.

THE THEORY OF THE GENERATION OF ELECTROMOTIVE FORCE.

SYMBOLS USED IN CHAPTERS X AND XI.

A, armature power loss.
e, instantaneous value of electromotive force.
E, maximum value of electromotive force.
E_a, average value of electromotive force.
E_x, terminal voltage of generator or motor.
f, rotational force, frequency.
F, magnetic force.
F_c, series field power loss.
F_s, shunt field power loss.
H, magnetic field intensity.
I, current.
I_a, armature current.
I_c, series field current.
I_s, shunt field current.
I_x, current in external circuit.
n, revolutions per second.
ω, angular velocity.
P, power.
P_a, armature power.
P_m, mechanical power, input of generator, output of motor.
p, number of field poles.
p', number of armature circuits in parallel between terminals.
Φ, magnetic flux.
ϕ, angle of phase displacement.
r_a, armature resistance.
r_c, series field resistance.
r_s, shunt field resistance.
r_x, resistance of external circuit.
S, stray power loss.
T, torque, period.
T_a, armature torque.
T_m, torque developed by driving engine or mechanical load.
T_s, stray loss torque.
v, velocity in a direction perpendicular to magnetic field.
V, linear velocity of rotating conductor.
Z, number of armature inductors.

Fundamentals.

The electric dynamo * is, fundamentally, simply a machine designed to move a conductor across a magnetic field, thereby producing or generating in the conductor a difference of potential or electromotive force.

Whenever a conductor is moved so as to "cut" the lines of force of a magnetic field an electromotive force is set up in the conductor. The medium surrounding a magnet is in a condition of stress. For convenience the direction of this stress is represented conventionally by the direction of imaginary lines, called lines of force, emanating from the magnets' poles, and the magnitude of the stress is indicated by the number of such lines per square centimeter of cross-sectional area of the field; *i. e.*, per square centimeter in a plane at right angles to the lines. When a conductor is so moved in the field that a component of its direction of motion is perpendicular to the direction of the magnetic stress, or, in other words, when the conductor, in moving, breaks or "cuts" the lines of force, a difference of potential, or electromotive force, is set up in the conductor. It appears as if the process of cutting the lines of force caused the stress of the medium to be imparted to the molecules of the conductor, and as if such resultant molecular stress in the conductor were difference of potential or electromotive force. When the conductor moves parallel to the lines of force or remains stationary, no lines are cut and no electromotive force is induced.

The amount of the electromotive force so created depends solely upon and varies directly as the rate at which the conductor cuts the lines of the field. The absolute or C. G. S. unit of electromotive force may be defined as the electromotive force generated when a conductor cuts one line of force per second. This definition is predicated on the assumption that a line of force represents a magnetic stress of 1 dyne. Similarly, the volt may be defined as the electromotive force generated when a conductor cuts 10^8 lines of force per second.

* A dynamo may be either a generator or a motor. The contents of this chapter apply equally well to both. See under "Generator Action," Chapter XI, p. 236.

Referring to Fig. 93: Assume the existence of a uniform magnetic field H whose lines of force lie parallel to the plane of the paper and whose positive direction is from left to right. Let A be the cross-section of a straight wire placed perpendicular to the plane of the paper and so held while being moved with a uniform velocity of V centimeters per second in the direction indicated, making any angle ϕ with the direction of the field. Let v be the component of V at right angles to the field; H the intensity or the number of lines per square centimeter of cross-sectional area of the field, and l the length of the wire in centimeters. Then the number of lines cut per second by the conductor is $Hlv = HlV \cos(90-\phi) = HlV \sin \phi$. Consequently, from the two foregoing definitions, the electromotive force generated is $HlV \sin \phi$ absolute units (abvolts) or $\frac{HlV \sin \phi}{10^8}$ volts.

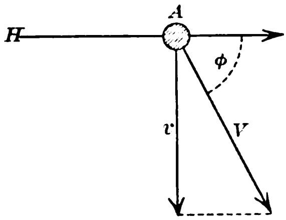


FIG. 93.

If ϕ be considered as a variable angle, and H, l and V as constants, it is evident that the electromotive force induced in the conductor varies directly as $\sin \phi$ or as v, the component of V at right angles to the field. Therefore the electromotive force is zero when ϕ is zero and a maximum when ϕ is 90°. In the former case the conductor, since it is then moving parallel to the field, cuts no lines of force, and hence no electromotive is induced. In the latter case the conductor moves at right angles to the field, and therefore the rate of cutting and the electromotive force are a maximum. For values of ϕ intermediate between 0° and 90° the rate of cutting and the electromotive force are dependent upon v, which, in turn, is proportional to $\sin \phi$.

The Rotating Conductor.

Any device whereby a conductor could be moved in any manner through a magnetic field would accomplish the generation of electromotive force, but mechanical limitations require that such movement of a conductor shall be rotational.

Let it be considered that the conductor A of Fig. 93 is rotated at a uniform tangential velocity V instead of being moved in a straight line at that velocity. Fig. 94 represents the conditions intended. Let the straight wire whose cross-section is A and which as before maintains continuously its length perpendicular to the paper, be rotated clockwise in the uniform magnetic field H at a uniform tangential velocity V about a center C, and let A be the position of the conductor at the instant under consideration. As in Fig. 93 the electromotive force generated at this instant is $Hlv = HlV \sin \phi$. [It is to be noted that the angle ϕ between the direction of the tangential movement of the conductor and the direction of the field is equal to the angle A_0CA, where A_0 is the position of the conductor when its tangential movement is parallel to the field. During a complete revolution of the conductor this angle varies from 0° to 360°.] As from the position A the conductor continues in its rotary path, v and $\sin \phi$ and, consequently, the electromotive force increase, until when the conductor reaches the position A_1, ϕ is 90° and v, $\sin \phi$, and the electromotive force are a maximum. From the position A_1 all three decrease until at A_2, where ϕ is 180°, they are zero. From A_2 they begin to increase again, until at A_3, where ϕ is 270°, they become a maximum for the second time. From A_3 once more they decrease, until at A_0, where ϕ is 360° or 0°, they are again zero. It is therefore evident that in one complete revolution of the conductor the electromotive force twice reaches its maximum and twice its zero value, and that at any given instant the electromotive force induced is proportional to the sine of the angle through which the conductor then has moved, reckoned from the position of zero electromotive force.

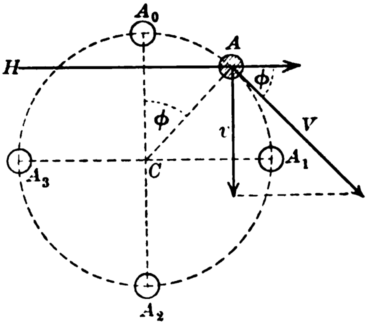


FIG. 94.

The electromotive force existing in the conductor at any given instant is known as the **instantaneous** value of the electromotive force, and is denoted by the symbol e. When e is expressed in absolute units we may write

$$e = HlV \sin \phi, \text{ abvolts.} \tag{1}$$

In this expression H, l and V are constants and only $\sin \phi$ is variable. e attains its maximum value when $\sin \phi$ is unity, and this maximum electromotive force is denoted by the symbol E. $E = HlV$, a constant, and we may rewrite equation (1) as follows:

$$e = E \sin \phi. \tag{2}$$

When the value of ϕ lies between 180° and 360° the sine of ϕ and consequently e are negative. Such negative value of e is due to a reversal of the movement of the conductor relative to the direction of the field. **The direction of the electromotive force induced in the conductor depends solely upon the direction of the motion of the conductor relative to the field.** Applying to Fig. 94 any of the various rules for determining the direction of an induced electromotive force, it will be seen that when ϕ lies in the first or second quadrants; *i. e.,* when the conductor is rotating in the right-hand hemisphere, the positive direction of the electromotive force will be towards the observer; whereas, when ϕ lies in the third or fourth quadrants, or the conductor is rotating in the left-hand hemisphere, and hence has its direction of movement relative to the field reversed, the positive direction of the electromotive force will be away from the observer. If we determine arbitrarily that in the conductor the electromotive force is to be considered as setting in its positive direction when that direction is towards the observer, then the direction of the electromotive force will be always positive when the conductor is in the right-hand hemisphere and negative when the conductor is in the left-hand hemisphere. The opposite assumption could be made with equal accuracy. Positive and negative are merely relative terms.

It follows, therefore, that in one complete revolution of the conductor, starting from the position of zero electromotive force at A_0, the electromotive force first rises to a maximum positive value at A_1, decreases to zero at A_2, rises to a maximum negative value at A_3, and decreases again to zero at A_0. The process of passing through these successive values is called a **cycle**. The time required for the consummation of the cycle is the **period.** The number of cycles occurring per second is the **frequency.**

The angle ϕ through which the conductor has moved since the electromotive force last changed its sign from negative to positive is the **phase.**

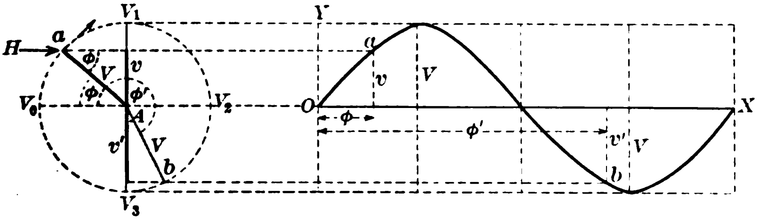
If ω be the angular velocity in radians of the rotating conductor and f the frequency, then, since there are 2π radians in each revolution, $\omega=2\pi f$. If, further, t be the time in seconds elapsed at any instant since the conductor last passed through the position of zero electromotive force, A_0, it is seen that at that instant $\phi=\omega t=2\pi ft$. Accordingly, equation (2) may be rewritten:

$$e=E \sin 2\pi ft, \qquad (3)$$

in which expression t is the only variable.

The Curve of Sines.

The successive values of the instantaneous electromotive force throughout a complete cycle may be represented graphically by the curve of sines.



Velocity	V_0	V_1	V_2	V_3	V_0
E. M. F.	A_0	A_1	A_2	A_3	A_0
Degrees	0	90°	180°	270°	360°
Radians	0	$\frac{\pi}{2}$	π	$\frac{3\pi}{2}$	2π
Seconds	0	$\frac{T}{4}$	$\frac{T}{2}$	$\frac{3T}{4}$	T

FIG. 95.—Sine Curve of Alternating Electromotive Force.

In Fig. 94 v is obtained by projecting V on a line perpendicular to the field. Since in one revolution of the conductor A the line V also makes a complete revolution about A as a center, the successive values of v for a cycle could be obtained by considering A stationary, revolving V about it as a center through 360°, and obtaining the various projections of V on a line at right angles to the field. Such process is followed in Fig. 95. The line V, the radius of a circle whose center is A, rotates in the same direction and at the same angular velocity as the conductor in Fig. 94. As in Fig. 94, ϕ is the angle made by V with the direction of the field, and it is measured from the line V_0AV_2, parallel to the field. An inspection of Figs. 94 and 95 will show that at the instant when the conductor of Fig. 94 is in the position A, making an angle ϕ with A_0C, in Fig. 95 the peripherical extremity of V is at a, making the same angle ϕ with V_0A; that when the conductor is at A_0, V is at V_0; when the conductor is at A_1, V is at V_1, etc.

It is clear that if, as V rotates through 360°, it be successively projected on the line V_1AV_3, at right angles to the field, such projections will be the various values of v for a cycle. Using these values as ordinates and the corresponding values of ϕ as abscissæ a curve may be constructed as in Fig. 95. As there shown but six points of the curve have been determined, those for the positions V_0, a, V_1, V_2, b, and V_3, but any desired number of points may be fixed.

Since $v = V \sin \phi$, such is the equation of the curve, and, because its ordinates are proportional to the sines of its abscissæ, the curve is known as the curve of sines. For v may be substituted e, and for V, E, since these factors are directly proportional to each other. The equation of the curve then becomes:

$$e = E \sin \phi = E \sin \omega t = E \sin 2\pi f t.$$

The ordinates of the curve now show the instantaneous values of the electromotive force generated throughout a cycle; the maximum ordinates, the maximum electromotive force. The portion of the curve above the line OX represents positive values of the electromotive force; the portion below, negative values. It is to be noted that the degrees in which the abscissæ are expressed may be converted into radians. The abscissæ may also be expressed in the fractional parts of the period, T, in seconds: hence, the line OX may be regarded as an axis of time. This is indicated by the presence of the factor t in the equation of the curve.

Average and Maximum Electromotive Force.

The average electromotive force is the average of the instantaneous values of the electromotive force. For a complete cycle this is zero, since the aggregate positive ordinates of the sine curve equal the aggregate negative ordinates. For a half cycle, however, reckoned from the instant of zero electromotive force, the average electromotive force is the average of the ordinates of the curve comprised between V_0 and V_2, and may be determined as follows:

The conductor A (Fig. 94) in making a half revolution, starting from the position A_0, sweeps out a rectangular area perpendicular to the field equal to $2rl$ square centimeters, where r is the radius of rotation of the conductor. The total number of lines of force cut by the conductor in one-half revolution is therefore $2rlH$. If n be the number of revolutions * per second of the conductor, the time required for one-half revolution is $\frac{1}{2n}$ seconds. Hence the **average** rate of cutting, which is the average electromotive force, for the half revolution is:

$$\frac{2rlH}{\frac{1}{2n}} = 4rlHn. \qquad (4)$$

Such average electromotive force is denoted by E_a.

The maximum electromotive is induced when the conductor is moving at right angles to the field. At that instant each centimeter of the conductor's length cuts H lines of force in moving through 1 centimeter, and the linear velocity of the conductor is $2\pi rn$. Therefore the **maximum** rate of cutting, or maximum electromotive force is:

$$2\pi rn \times lH = 2\pi rlHn. \qquad (5)$$

Equations (4) and (5) establish the following ratio:

$$\frac{E_a, \text{ Average E. M. F.}}{E, \text{ Maximum E. M. F.}} = \frac{4rlHn}{2\pi rlHn} = \frac{2}{\pi}. \qquad (6)$$

Since this ratio is a constant it holds good in all cases.

The total number of lines cut by the conductor in the half cycle is the **flux**, denoted by the symbol Φ. Φ equals $2rlH$, and equation (4) may be written:

$$E_a = 2\Phi n. \qquad (7)$$

* **The number of revolutions of a conductor per second, n, should not be confused with the frequency, f. See equation (11), p. 209.**

The Rotating Coil.

Let it be imagined that in Fig. 94 a second conductor *B*, of length equal to *A*, is placed parallel to and at the opposite end of a diameter of rotation from *A* (Fig. 96); that the ends of the two conductors are joined by metallic connections, *g*, *h*, so as to form the rectangular loop shown in perspective in Fig. 97; and that this loop is rotated about its axis *CC* in a clockwise direction.

The connections *g* and *h* will at all times be moving in a plane parallel to the direction of the field. They will therefore cut no

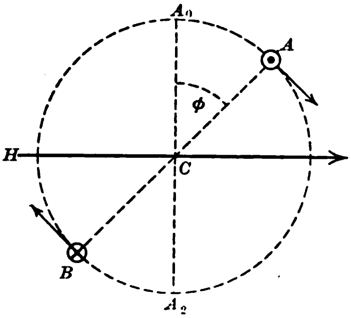


FIG. 96.

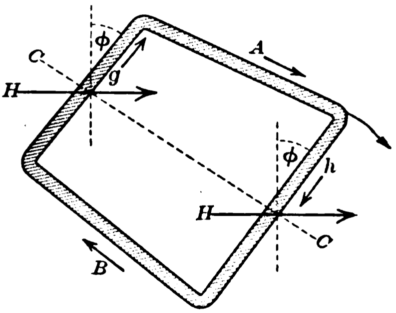


FIG. 97.

lines of force, and hence will play no part in the generation of electromotive force. Their function is solely to connect *A* and *B*, the cutting conductors, electrically.

As the loop revolves the electromotive force generated at any instant in *A* will be equal and of opposite sign to the electromotive generated in *B* at that instant. For, since both conductors are of the same length and revolve at the same velocity in the same field, the maximum electromotive forces generated in each are equal, and

$$\therefore E = \frac{e_A}{\sin\phi} = \frac{e_B}{\sin(\phi + 180^\circ)} = \frac{-e_B}{\sin\phi}, \text{ or } e_A = -e_B.$$

Also, since $E_a = E \times \frac{2}{\pi}$, the average electromotive forces of the two conductors are equal.

As in the case of the single rotating conductor the rules governing the direction of an induced electromotive force, as well as the sign of sin Φ, make it plain that whenever either A or B is rotating in the right-hand hemisphere the electromotive force sets toward the observer, while when the conductor is in the left-hand hemisphere it sets in the opposite direction. When the loop is in the position indicated in Fig. 96 for example, the electromotive force in A sets up and in B down, whereas in Fig. 98 the opposite holds.* The electromotive force reverses its direction in each conductor when the conductor passes through the position of zero electromotive force, A_0 or A_2.

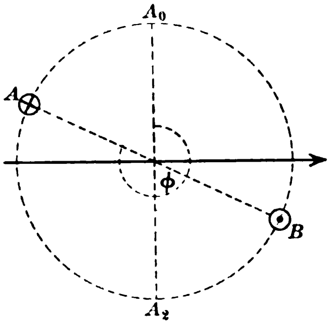


FIG. 98.

Although the electromotive force has opposite directions in the two conductors when looked at from end-on, yet with reference to the closed circuit $AhBg$ it is to be regarded as having the same direction in both—that is, it has but one direction around that circuit. With the loop in the position of Fig. 97, for example, the direction of the electromotive force around the loop will be $AhBg$, as indicated by the arrows. As long as A is in the right-hand hemisphere this direction of the electromotive force will be maintained. When A passes through A_2 and, simultaneously, B passes through A_0, the direction of the electromotive force in the loop is reversed and continues reversed until A reaches A_0 and B, A_2. Two reversals of the electromotive force therefore occur in each cycle. An electromotive force which thus periodically changes its sign is an **alternating** electromotive force.

Since around the loop the electromotive force generated in A has the same direction as that generated in B, and since A and B are in series, the total electromotive force of the loop is the sum of the electromotive forces of A and B. Or, since the electromotive force of A equals that of B, the electromotive force generated by the loop is double the electromotive force generated by either conductor, or

* A dot, symbolizing an arrow-head, denotes an approaching E. M. F. or current; a cross, symbolizing the tail of an arrow, denotes a receding E. M. F. or current.

equal to the electromotive force of a single conductor multiplied by the number of conductors in series.

Let it now be supposed that for the single loop of Figs. 96, 97 and 98 is substituted a coil consisting of several rectangular loops of insulated wire, equal in dimensions and connected in series (Fig. 99). These loops should be regarded as being so close together as to be practically coincident, although the figure, for clearness, shows them separated considerably. A and B represent the cutting conductors of the coil; h and g the connections. Assume that the coil is rotated about its axis CC in the same fashion as the single loop, and that the number of its cutting conductors, A and B combined, is Z. (The figure shows $Z=6$.) If l be the length and r the

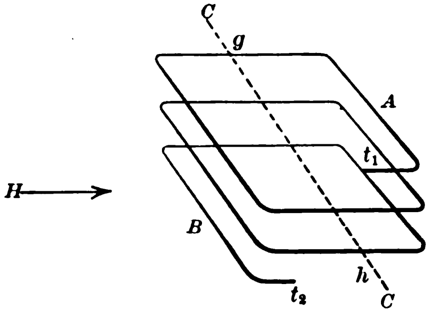


FIG. 99.

radius of rotation of each cutting conductor—or l the length of the coil measured parallel to the axis of rotation and $2r$ its width measured at right angles to that axis—and if the coil make n revolutions per second, then, by equations (4) and (7) the average electromotive induced in each conductor during a half cycle, reckoned from the position of zero electromotive force, is:

$$4rlHn = 2\Phi n.$$

The average electromotive force generated by the coil during the half cycle, therefore, is given by the equation:

$$E_a = 2\Phi n Z, \qquad (8)$$

since the coil carries Z conductors in series. It is to be noted that Φ, equal to $2rlH$, is the total number of lines that thread through the coil when it is in the position of zero electromotive force.

The expression for the maximum value of the electromotive force generated by the coil may be obtained similarly from equation (5), as follows:

$$E = 2\pi rlHnZ; \qquad (9)$$

or E may be found by multiplying expression (8) by $\frac{\pi}{2}$.

Since the conductors are so close together as to be practically coincident, at any given instant each will have the same phase. Consequently the simultaneous values of the electromotive force in the various conductors will be equal to each other and to $\frac{1}{Z} \times$ the instantaneous electromotive force of the coil. The electromotive force generated by the coil throughout a cycle will follow the law of the curve of sines, and its instantaneous values may be obtained from the equation of that curve.

If to the terminals, t_1 and t_2, of the coil of Fig. 99 are connected the corresponding terminals of several similar coils, the whole will form a coil whose constituent sub-coils or sections are in parallel.

Fig. 100 represents such a coil. Here four sections, each formed by two loops of insulated wire in series, are connected in parallel. As before, the conductors of each section should be regarded as being so close together as to be practically coincident, but the sections may be separated. Since the sections are in parallel the average electromotive force generated in the whole coil is the average electromotive force generated in each section. Let p' represent the number of sections so connected in parallel (here $p'=4$), and let Z be the number of cutting conductors of the whole coil. (For Fig. 100, $Z=16$.) Then the number of cutting conductors for each section is $\frac{Z}{p'}$. Since these are in series, the average electromotive force generated by each section, and, hence, by the entire coil, may be determined from equation (7) as follows:

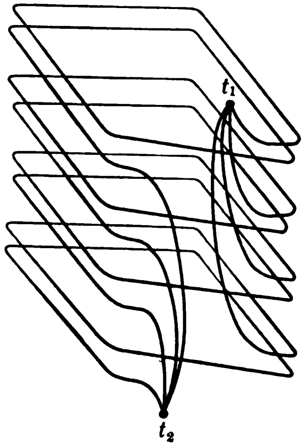


FIG. 100.

$$E_a = \frac{2\Phi nZ}{p'}. \qquad (10)$$

Multipolar Fields.

Hitherto it has been considered that the cutting conductor, loop, or coil rotated in a magnetic field of parallel or nearly parallel lines of force, such as would be formed by a single pair of magnet poles, as in Fig. 101, where the coil *AB,* whose cutting conductors are shown in cross-section at *A* and at *B,* rotates about the center *C* in the field created by the magnetic poles *N* and *S*. In conjunction with this figure it is to be noted that the symbol Φ does not necessarily represent all the lines of force of the field, but only those lines that thread through the coil when it is in the position of zero electromotive force, perpendicular to the general direction of the field.

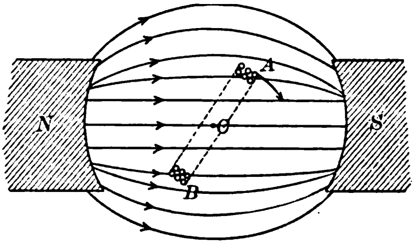


FIG. 101.

Fig. 101 depicts some of the lines as passing outside the circle described by the rotating conductors. These lines will not be cut by the conductors and hence will play no part in the induction of electromotive force. The symbol Φ denotes only those lines which are cut, or, which amounts to the same thing, those that pass through the coil in its zero position. In other words, Φ is the **effective** flux.

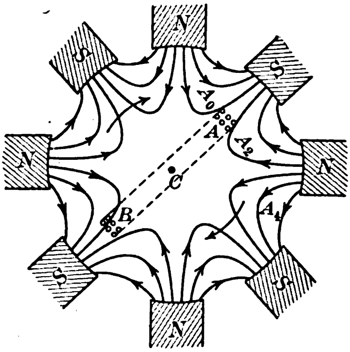


FIG. 102.

Instead of rotating in the field of a single pair of poles the coil may, and in practice usually does, rotate in the field created by several pairs of poles placed symmetrically about the circumference of a circle, as in Fig. 102.

Let *p* be the number of such poles, counted **individually,** not in pairs; n, as before, the number of revolutions made per second by the coil, and Φ the number of lines emanating from or entering each pole which are cut by conductors—in other words, the effective flux **per pole.**

As in the case of the conductor rotating in the field of a single pair of poles, when the conductors of Fig. 102 occupy a position midway between any two adjacent poles they will be moving parallel to the lines of the field and be in the position of zero electromotive force, as at A_0. They will next again be in the position of zero electromotive force when they occupy the next adjacent position midway between two poles, A_2. Between A_0 and A_2 the electromotive force will be of one sign and at its maximum when the conductors are at A, halfway between A_0 and A_2. As the conductors move from A_2 to A_4 the sign of the electromotive force will be reversed, the electromotive force will reach its maximum value of opposite sign when the conductors are midway between A_2 and A_4, and will decrease thence to zero once more at A_4, halfway between the next two poles. In other words, it is apparent that the value of the electromotive force passes through a cycle as the conductors progress from A_0 to A_4, or as they sweep past any adjacent pair of poles. The number of cycles occurring in one revolution of the coil is therefore $\frac{p}{2}$, and consequently the frequency, f, of the electromotive force, or the number of cycles per second, is:

$$f=\frac{pn}{2}. \tag{11}$$

The value of the electromotive force undergoes a half cycle, reckoned from zero, as the conductors sweep past a single pole. In so sweeping each conductor cuts Φ lines of force in $\frac{1}{pn}$ seconds, and consequently the average electromotive force induced in each conductor is:

$$E_a=pn\Phi. \tag{12}$$

If the coil consists of Z conductors in series, we have, for the coil:

$$E_a=pn\Phi Z. \tag{13}$$

If the coil is formed of p' sections in parallel, each section having

$\frac{Z}{p'}$ conductors in series, we have for each section and therefore for the entire coil:

$$E_a = \frac{pn\Phi Z}{p'}. \qquad (14)$$

Equation (14) is the **fundamental equation of the dynamo** and is the general expression governing the value of the electromotive force generated in dynamo electric machines, whose cutting conductors usually have the series-parallel connection and rotate in a multipolar field.

By comparing equations (7), (8) and (10) with equations (12), (13) and (14) it will be seen that the former are the latter applied to 2-pole machines.

Commutation.

If the terminals of a generating conductor, open loop or coil (the terminals t_1 and t_2 of the coils of Figs. 99 and 100, for example, or the ends of a break in one of the connections h or g of the loop of Fig. 97) are so connected electrically to the terminals of an external electrical circuit as to maintain the original terminal contacts despite the rotary motion of the conductor, loop, or coil, then the whole will form one circuit, and the alternating electromotive force induced in the revolving part of such circuit will be impressed on the stationary part.

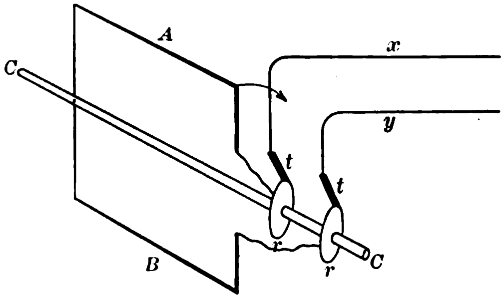


FIG. 103.

The alternating current dynamo makes such a connection with its external or **receiving** circuit by means of sliding contacts, whose elementary principle is shown by Fig. 103. Centered on but insulated from the shaft *CC* which carries the rotating loop *AB* are two revolving metal rings *rr,* called collecting rings. On these rings press metal brushes, *tt,* forming the terminals of the receiving circuit, *xy.* The conductor *A* of the loop is connected to one of the rings; the conductor *B* to the other. It is evident that the conductor *A* will be continuously in direct connection with the leg *x* of the receiving circuit, and the conductor *B* in direct connection with the leg *y,* despite the rotary motion of *AB.* Consequently, the electromotive force in the receiving circuit will reverse in synchronism with the electromotive force in the loop.

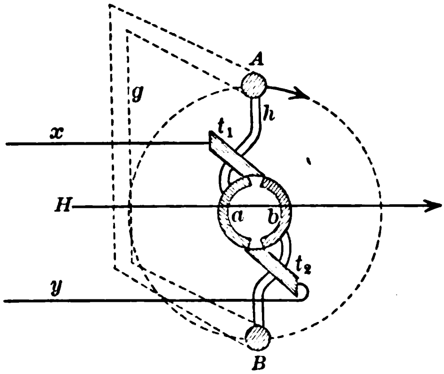


FIG. 104.

An alternating electromotive force, though having an extensive application, is undesirable for some forms of electrical work, such as operating certain kinds of motors or lights, and for these forms it is necessary that the electromotive force in the receiving circuit shall set in one direction only around that circuit—that it shall be a **direct** electromotive force. A direct electromotive force is obtained from the alternating electromotive force of the rotating coil by means of a device known as the **rectifying commutator,** or, simply, as the commutator.

In Fig. 104 let *A* and *B* be the cross-sections of the cutting conductors *A* and *B* of the rotating loop *AhBg.* Let the front connection *h* of the loop be broken and to the ends of the break be soldered the metallic sectors *a* and *b* concentric with the axis of rotation of the loop. Assume that against these sectors press two metal brushes, t_1 and t_2, in such positions that they make contact with both sectors at the instant when the loop is in the position of zero electromotive force, and of such width that each loses contact with one of the two

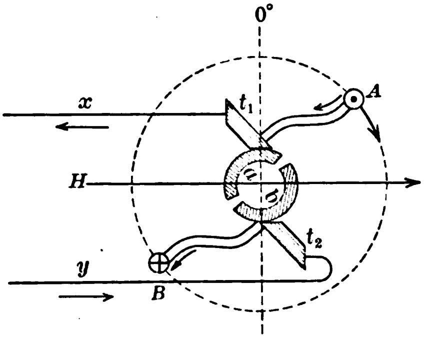


FIG. 105.

sectors immediately upon the departure of the loop from the zero position. Let the terminals of the receiving circuit, *xy*, be connected to the brushes.

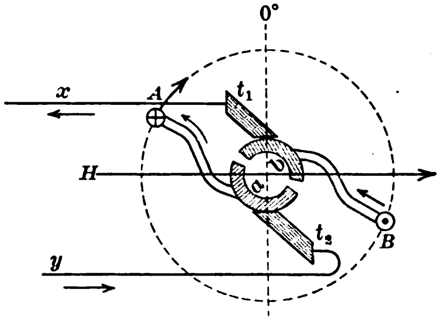


FIG. 106.

An inspection of the figure and of Figs. 105 and 106 makes it plain that, except when the loop is in the zero position, the brush t_1 is always in contact with the sector of the conductor which is moving in the right-hand hemisphere, and similarly, that the brush t_2 is always in contact with the sector of the conductor which is moving in the left-hand hemisphere. Consequently the electromotive force in the receiving circuit will have but one direction irrespective of the position of the loop; it will be a direct electromotive force. With the connections and the direction of field and rotation as depicted in the figures the electromotive force in the receiving circuit will set from t_1 towards t_2.

The sectors *a* and *b* form the commutator for the loop. An open coil, such as that of Fig. 99, could be substituted for the loop without impairing the commutation, provided the conductors of the coil were close enough together to have practically the same phase at any given instant.

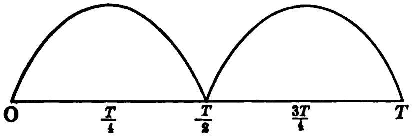


FIG. 107.—Curve of Rectified Electromotive Force, Single Coil.

Such a commutator is known as a "two-part" commutator, and the loop *AB* is an example of a type of winding designated as "open-coil." Both of these have little practical use. The action of the actual multipart commutator, having many segments and connected to a "closed-coil" winding, is somewhat different. It is explained under the heading "Armature Winding," this chapter.

Although the electromotive force, when thus rectified, will set continuously in one direction in the receiving circuit, it will, nevertheless, follow the law of the curve of sines for the half cycle. For a full cycle of the alternating electromotive force of the generating coil the various values of the electromotive force in the receiving circuit may, since they are of the same sign throughout the cycle, be represented by the sine curve with its negative half transferred to the positive side of the axis of time, as in Fig. 107.

The Generation of a Steady Electromotive Force.

Fig. 107 shows that the rectified electromotive force of a single coil fluctuates continuously between its zero and maximum values, and for that reason it would fail to operate satisfactorily most electrical appliances. A steady as well as a direct electromotive force is needed.

Let it be imagined (Fig. 108) that in place of one loop we have four similar and separate loops, *AB, FG, DL* and *JK,* rotating in a magnetic field about a common axis *C*. Let *A, B, F, G, D, L, J* and *K* be the cross-sections of the conductors of these loops. Let the angular distances between loops be fixed and equal. Suppose each

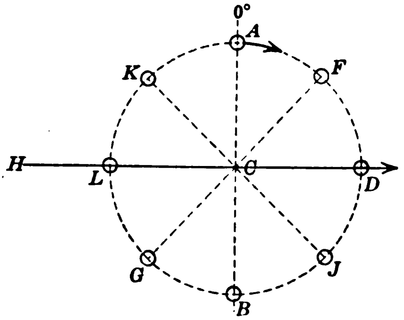


FIG. 108.

loop to be fitted with its individual commutator, connecting it, through an individual pair of brushes, to a common receiving circuit.

If the curve of the rectified electromotive force impressed on the receiving circuit by each loop during one revolution be constructed, and the four curves so obtained be superimposed on each other with proper regard to their phase relations, the result will be as in Fig. 109.

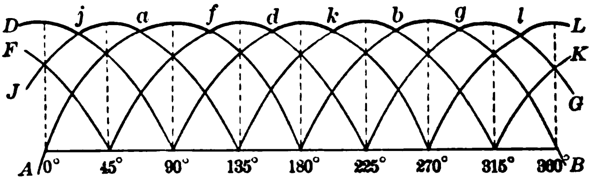


FIG. 109.—Curve of Rectified Electromotive Force, Four Separate Coils.

The phase displacement of any point in any of the four curves as drawn is measured from the zero position of *A*. Such selection of the zero point is purely arbitrary; any position of any loop might have been chosen as a point of reference without impairing the result. The curves are lettered to correspond with the lettering of Fig. 108;

thus *AB* is the curve of the electromotive impressed on the receiving circuit by the loop *AB*, etc. Fig. 109 will be found to check with Fig. 108 by inspection. For example, from Fig. 108 it is apparent that when *AB* is generating no electromotive force, *DL* is generating its maximum amount, *FG* an increasing electromotive somewhat greater than half the maximum $\left(E \sin 45° = \frac{E}{\sqrt{2}}\right)$, and *JK* an electromotive force equal in value to that being generated by *FG*, but decreasing. In Fig. 109, at the 0° position, the lengths of the ordinates of the various curves and the directions of the curves check with these observations. At any point along the axis of phase displacement, *AB*, the ordinates of the several curves indicate the simultaneous values of the electromotive force impressed by the corresponding loops on the receiving circuit at the instant when the loop *AB* has the phase displacement, measured from the position of zero electromotive force, of the point in question.

Since each loop has its individual connection direct to the terminals of the receiving circuit it is in series with that circuit and in parallel with the other loops. The instantaneous value of the electromotive force in the receiving circuit at any instant is therefore the instantaneous electromotive force of the loop which at that instant is generating the greatest electromotive force. In other words, the varying values of the electromotive force in the receiving circuit are represented by the ordinates of the curve *DjafdkbglL.*

The fluctuations of this curve are of small amplitude; consequently, the external electromotive force is comparatively steady. Had a greater number of loops or coils been utilized the amplitude of the fluctuations would have been correspondingly less, until finally, with a sufficient number of coils the curve of the receiving circuit electromotive force would have become approximately a straight line and the electromotive force of practically uniform value. Hence it is seen that **a steady electromotive force may be obtained by the use of a large number of coils equally spaced around a common axis.**

For the purpose of illustration it has been supposed that the loops are joined in parallel to the receiving circuit. However, so connected, no increase in the electromotive force generated by the machine would be obtained by enlarging their number. In practice, therefore, usually connections are made between the loops themselves in such manner that **all cutting conductors are in series, forming a single closed coil.** [How this is effected will be explained shortly.] Furthermore, were each loop to have a separate connection to the receiving circuit many brushes and a cumbersome construction of the commutator would be necessitated. With the conductors joined in series but one pair of brushes (for bipolar generators) is needed and the commutator is simplified.

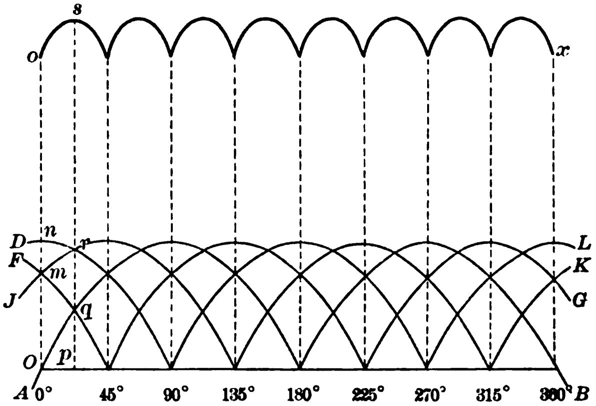


FIG. 110.—Curve of Rectified Electromotive Force, Four Coils in Series.

Connecting the conductors in series does not affect their phase relations, and the curves of Fig. 109 will show the simultaneous values of the electromotive force generated in four loops whose cutting limbs are thus joined. But since the conductors are in series the instantaneous value of the external electromotive force is to be found by adding the simultaneous values of the electromotive force of the several loops, and the curve of the external electromotive force is formed by adding the ordinates representing those simultaneous values. In Fig. 110 ox is the curve, so constructed, of the external electromotive force delivered by four loops in series. Here $Oo = On + 2Om$, $ps = 2pr + 2pq$, etc. The increased lengths of the ordinates indicate the increased voltage obtained.

Had eight loops instead of four been considered operative the shape of the curve of external electromotive force would have become as shown in Fig. 111, approximating more closely to a straight line than *ox*, and the ordinates of the curve of Fig. 111 would have been double those of *ox*.

It is apparent, therefore, that **by the use of many coils in series the electromotive force generated is increased** as well as made uniform.

FIG. 111.—Shape of Curve of Rectified Electromotive Force, Eight Coils in Series.

Armature Winding.

In direct current dynamo-electric machinery the armature is the rotating part. It consists of the armature winding, formed by the generating conductors and their connections, and an iron core carrying the winding. Armatures may be wound in a great many ways. No attempt will be made here to discuss more than the elementary principle underlying the construction of the various kinds of windings.

Armature windings may be divided into two general classes: open-coil and closed-coil windings. The former have a specific and limited use; they will not be considered. The loop of Fig. 104 is an example of an open-coil winding.

A **closed-coil** winding is one such that if it were removed from the core and stretched out it would form one or more **closed loops.** It is designated as simplex, duplex, triplex, or quadruplex according as to whether the number of loops are one, two, three or four, respectively. Multiplex winding, designed for machines carrying heavy currents, is not often used and in the essentials does not differ from simplex winding. Only the latter will be dealt with.

Closed-coil windings are of two general types: the **ring** winding and the **drum** winding. The former is so called because its core has the shape of a ring; the latter, because its core has the shape of a cylinder or drum. The drum winding has supplanted the ring winding in general use, but by the ring winding the generating action of a closed coil is more easily illustrated.

The portion of an armature winding comprised between two commutator segments is called an **element.** Thus the loop of Fig. 104 is, and the open coil of Fig. 99 would be, if its terminations were commutator segments, an element. As far as the connections of the winding are concerned the number of turns of wiring in an element is a matter of indifference. The cutting or generating conductors are termed **inductors.**

Fig. 112 depicts a ring-wound armature for a bipolar dynamo. The winding has eight elements or coils, each of three turns, connected in series and wound in a left-handed spiral about a ring-shaped iron core. It will be seen that if this winding were removed

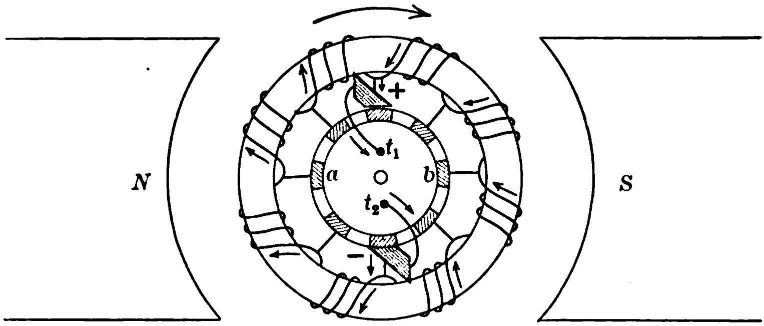


FIG. 112.—Ring-Wound Armature Bipolar Dynamo.

from the core and straightened out it would form a closed loop; hence it is of the closed-coil type. The terminations of each element are connected to segments of the commutator, *ab*. The latter consists of metal bars (shown in cross-section) insulated from each other and set parallel to the axis of rotation about the periphery of a circle whose center is that axis. The brushes, two in number, are placed at the positions of zero electromotive force,* and connected to t_1 and t_2, the terminals of the receiving circuit. It is evident that the commutator is merely a device for obtaining a sliding contact between the brushes and the winding. The same end would be served if the insulation were removed from the outer parts of the coils and the

* For reasons hereafter to be explained, in practice the brushes are somewhat removed from the positions shown.

brushes allowed to press against the wires so exposed. Each inductor itself would then be a commutator bar.

With the direction of field and rotation as shown the electromotive force induced in the several coils will set as indicated by the arrows. When a coil is moving in the right-hand hemisphere the direction of its electromotive force is, in the spiral, counter to the direction of rotation; in the left-hand hemisphere the reverse holds. With reference to the circuit formed by the winding itself the electromotive forces generated in the two hemispheres are opposed and in series, and the total electromotive force around the winding is therefore zero; but with reference to the receiving circuit the two electromotive forces have the same direction, from t_2 to t_1, and are in parallel. Hence the electromotive in the receiving circuit is rectified, and its strength and degree of uniformity are proportional to the number of elements in series between the terminals t_1 and t_2, or to one-half the total number of elements in the armature winding.

Referring to the deduction of the general expression for the value of the electromotive force generated by dynamo-electric machines, $E_a = \frac{pn\Phi Z}{p'}$, in which p' was said to be the number of coils in parallel, it is now evident that in an armature winding p' is the number of circuits in parallel between the terminals of the receiving circuit. In this case $p'=2$, since the windings of each hemisphere form a separate circuit between t_1 and t_2. Had the coil of Fig. 100 but two sections instead of four, and were its terminals the terminals of the receiving circuit, its circuits would be identical with those of the ring-winding under consideration. p' is also to be defined as the number of paths by which current may flow through the armature winding.

In a ring-winding the number of inductors, *Z*, is equal to the number of turns in the winding. Only that portion of each turn lying on the outer surface of the ring is an inductor. The magnetic flux is concentrated in the iron core; practically no lines of force penetrate the region inside the ring, and hence the inner portions of the conductors have no inductive action.

In a ring-wound dynamo, *p*, the number of poles, equals the number of brushes. This is evident from the fact that the brushes are placed at the positions of minimum electromotive force, which are equal in number to the number of poles. If the brushes were not placed at the zero positions a decrease in the external electromotive would result, such decrease increasing with the angular distance of the brushes from the zero points, until, when they were 90° in phase removed, no electromotive force would be delivered. Fig. 113 illustrates this.

Let the circle *mn* represent the winding of a bipolar ring armature, and let the arrows, *c, d, f, g,* by their direction and length

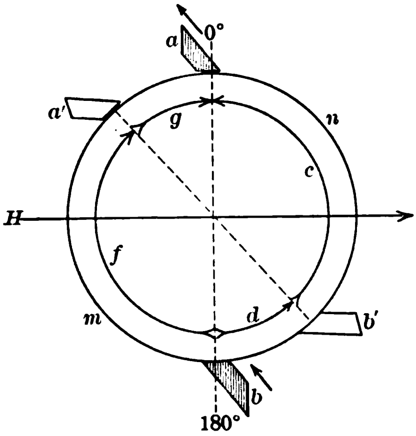


FIG. 113.

indicate the electromotive forces induced in the corresponding portions of the windings. Then, assuming the brushes *a, b,* to be set at the points of zero induction the electromotive force between brushes would be $c+d=f+g$. Next, assume the brushes to be shifted to any other positions, such as *a', b'*. The electromotive force between brushes now is $c-g=f-d$. The greater the angular displacement from the zero point the greater becomes the value of *g* and *d* and the less the electromotive force between brushes, until, when the displacement is a right angle, $c=g=f=d$, and the external electromotive force is zero.

If the number of pairs of brushes is less than the number of pairs of poles the electromotive force will not be altered, but the resistance

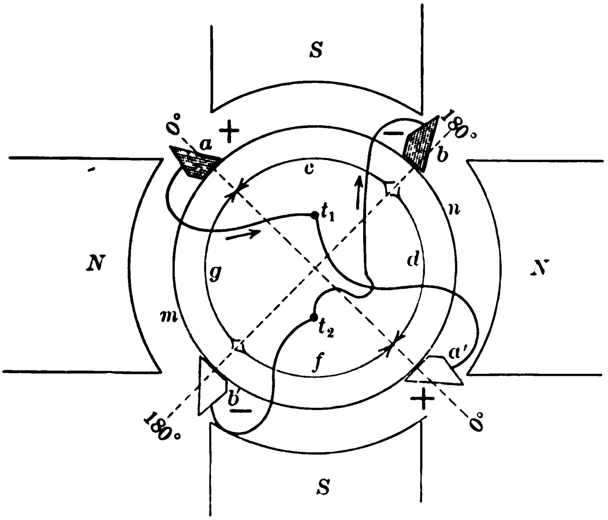


FIG. 114.

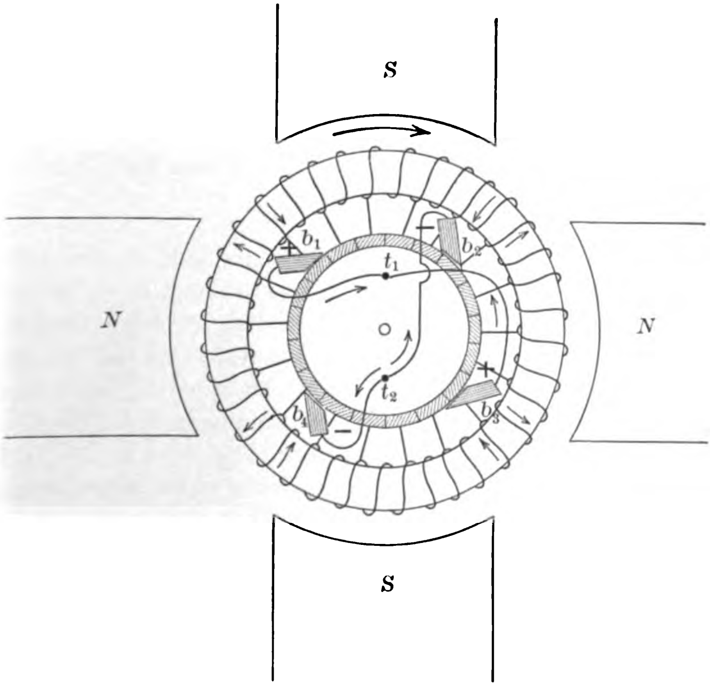


FIG. 115.—Ring-Wound Armature, Four-Pole Dynamo.

of the armature circuit will be increased, decreasing the efficiency of the machine. Fig. 114 represents a four-pole ring-wound armature supplied with the proper number of brushes. Let the arrows, by their length, indicate the resistances of the corresponding portions of the windings as well as the electromotive forces generated therein. With four brushes the electromotive force between any pair $=c=d=f=g$, and the resistance of the winding from terminal to terminal $=\frac{c}{4}$. With one pair of brushes (say $a'b'$) removed, the electromotive force between the remaining pair $=c=g-f+d=f=g=d$, as before, but the resistance of the winding now is $\frac{3c}{4}$.

Fig. 115 shows a four-pole ring-wound armature, and Fig. 116 is an elementary diagram of the winding. The positive brushes are

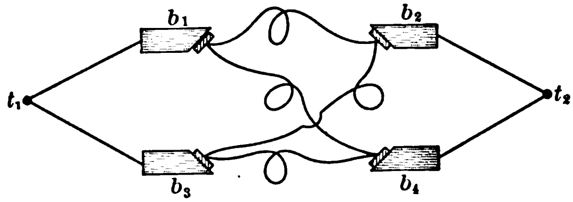


FIG. 116.—Elementary Diagram of Winding of Four-Pole Ring-Wound Armature.

b_1, b_3; the negative, b_2, b_4. Brushes of the same sign are connected together directly. It is evident that in this winding, as in the coil of Fig. 100, there are four circuits in parallel between terminals, and, furthermore, that their number is determined by and is equal to the number of brushes, which is the number of poles. Therefore, for a **ring-wound dynamo,** $p=p'$. In this winding, $p'=4$. Had the generator had six poles, p' would have been 6, etc.

Since the wires which lie on the inner surface of the ring have no inductive action, one-half of the winding generates no electromotive force. This ineffective half increases the resistance of the winding and the weight and cost of the machine. Furthermore, in a ring winding it is difficult to replace an injured coil. The drum winding does not possess these disadvantages.

In the drum winding the elements are formed by loops or coils, approximately rectangular in shape, joined in series and carried on the surface of a cylindrical core, the inductors lying parallel to the

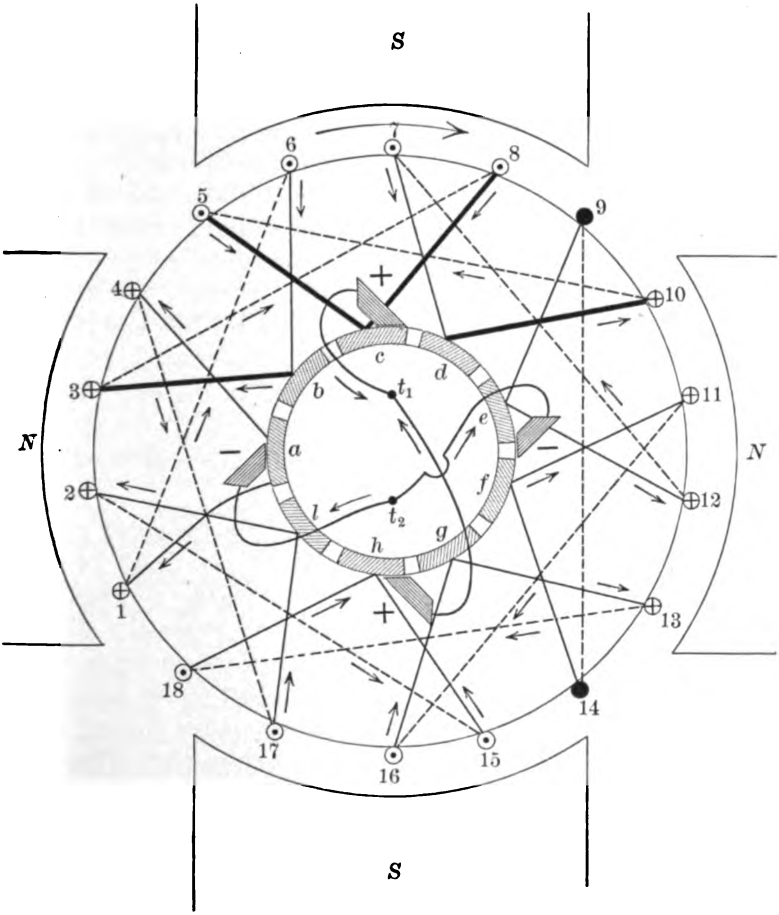


Fig. 117.—Simplex Lap-Winding Drum Armature, Four-Pole Dynamo.

axis of the core. The windings are of two types; namely, **multiple circuit** or **lap** windings, and **two circuit** or **wave windings.** Both are closed-coil windings.

Fig. 117 shows a simplex lap winding for the drum armature of a four-pole dynamo. The winding is viewed from a point on the prolongation of the axis of the core. Each element of the winding is a single rectangular loop or turn. There are nine such loops, or 18 inductors, in series in the winding. The inductors are shown in cross-section and numbered. Their front connections are shown by full lines; the back connections by broken lines. The directions of the instantaneous electromotive forces are indicated.

Each element has for its terminations adjacent commutator bars, and is formed by two inductors and their connections, as, $b-3-8-c$ or $c-5-10-d$. Starting at any commutator bar, such as a, and tracing the winding around the core back to a, it will be seen that the elements are in series, forming a closed coil, thus: $a-1-6-b-3-8-c-5-10-d-7-12-e-9-14-f-11-16-g-13-18-h-15-2-l-17-4-a$. In so tracing the winding and in passing through any one element we progress consecutively from one commutator bar to the bar next adjacent, as in the ring winding. Hence the lap winding may be represented by Fig. 114, and therefore the number of brushes required for it is equal to the number of poles, similarly to the ring winding.

It is also evident that there are two paths from the upper positive brush ($c-8-3-b-6-1-a$ and $c-5-10-d-7-12-e$) and two paths from the lower positive brush ($h-18-13-g-16-11-f$ and $h-15-2-l-17-4-a$) to the negative terminal. (In the position shown the element $e-9-14-f$ is short-circuited by the brush; otherwise its conductors would form part of the paths mentioned.) The circuits of this winding are therefore similar to the circuits of a four-pole ring winding, and the elementary diagram of the latter (Fig. 116) will serve for both windings. Hence **in the lap-wound dynamo**, as in the ring-wound, **the number of brushes equals the number of armature circuits in parallel equals the number of poles, or $p = p'$.**

In the **drum-wound dynamo,** however, whether lap or wave wound, ***Z*, the number of inductors, is double the number of turns in the armature winding,** since each turn or loop has two inductors; whereas, in the ring armature, as previously explained, each turn has but one inductor.

The number of inductors can be increased without altering the connections of the winding by increasing the number of turns in each element. If it were desired to effect this in the case of the winding of Fig. 117, it would be done in the following manner: Consider each inductor as there shown a slot in the core. Then starting from any commutator bar, say *a*, wind a wire down slot 1, and up slot 6, thence down 1 again, as many times as desired, finally connecting to *b*. An element which thus consists of two or more turns is known as an armature **coil** or **section.**

In the ring winding each inductor may be a commutator bar or be connected to a commutator bar, but in a drum winding the number of commutator bars cannot exceed one-half the number of inductors. Were each inductor to be connected to an individual bar, the bars of the two conductors of an element would be nearly 180° apart in phase and would pass under opposing brushes nearly simultaneously. Consequently the armature winding would be continuously short-circuited through one or two of its elements.

The lap winding is so designated because of the manner in which its conductors overlap; it is called also a multiple circuit winding because it has several circuits from terminal to terminal in parallel. Because of its multiple circuits the lap-wound dynamo is adapted to heavy currents at low voltage. The wave-wound dynamo, however, has but two circuits in parallel between terminals, and it is used when a small current at high voltage is required. From the fundamental equation of the dynamo (14) it is evident that, other factors being equal, the electromotive force of a wave-wound armature, having $p'=2$, is greater, if the machines are multipolar, than that of a lap-wound armature, having $p'=p$. It is also evident that the multiple connections of the lap winding reduce the armature resistance, rendering the machine more efficient under heavy load than the wave-sound dynamo.

Fig. 118 shows a simplex wave winding for a four-pole dynamo in which, as in the lap winding of Fig. 117, there are 18 inductors connected to nine commutator bars and each element is formed by a single turn. By tracing the winding around the core it will be seen that all elements are in series, forming, like the lap winding, a closed coil; thus: $a-1-6-f-11-16-b-3-8-g-13-18-c-5-10-h-15-2-d-7-12-l-17-4-e-9-14-a$.

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By considering any two adjacent elements, such as $c-5-10-h$ and $d-2-15-h$ the manner of winding will be made clear.

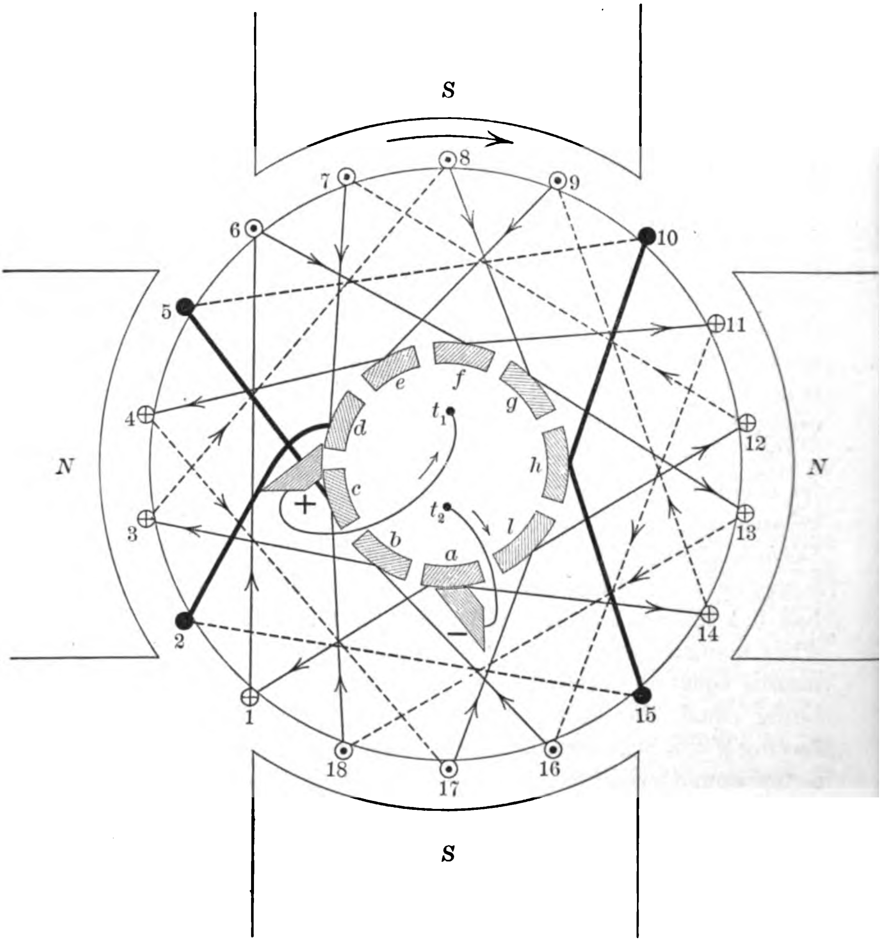


FIG. 118.—Simplex Wave-Winding Drum Armature, Four-Pole Dynamo.

Whereas, in the lap winding the terminations of each element are adjacent commutator bars, in the wave winding an element has for its terminations opposite commutator bars.* Such a method of winding necessitates the use of but one pair of brushes, because the positions of zero electromotive force are cross-connected.

Let it be supposed (Fig. 119) that the winding is supplied with four brushes set at the positions of minimum electromotive force. Then, with the armature in the position shown in Fig. 118, both positive brushes will be cross-connected by the element $c-5-10-h$, and both negative brushes will be cross-connected by the element

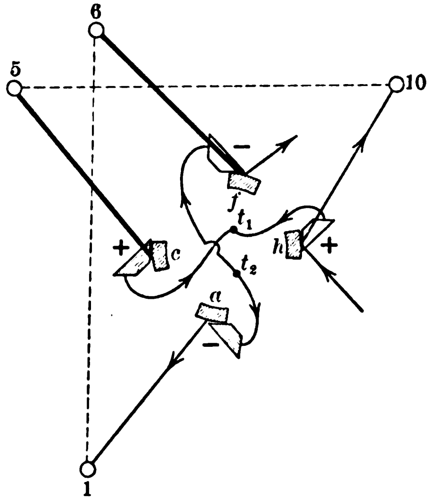


FIG. 119.

$a-1-6-f$. Inductors 5 and 10 and 1 and 6 are in the position of minimum electromotive force; hence they are ineffective inductively and may be regarded as merely electrical connections between brushes of the same sign. In consequence the second pair of brushes serves no purpose other than to aid the first pair in collecting current from and delivering it to the armature winding, without in any way altering the path of the current through the winding. For example, current flowing through the winding to the segment h would, if the brush were not there, continue on through inductors 10 and 5 to the other positive brush and the positive terminal. When a brush, con-

* In a four-pole dynamo.

nected to t_1 is placed at h a part of the current flows direct to t_1, but the path of the current through the winding is not changed.

Between any pair of brushes there are two paths through the armature winding, as will be seen by following the connections of Fig. 118. Since the use of additional brushes will not alter this number, **in the wave-wound dynamo p' is always 2.** Hence the wave winding is sometimes designated as a "two-circuit" winding.

Although but one pair of brushes is requisite, any number of pairs, not to exceed $\frac{p}{2}$, may be used.

The wave winding is so called because of the wave-like form given to it by the leads of its end connections. This is more easily seen on a developed diagram of the winding.

Problems.

1. A straight conductor 2 meters long, lying at right angles to the lines of force of a uniform magnetic field of intensity 8000, is moved across the field in a direction perpendicular to its length and to the field at a uniform velocity of 30 meters per second. Find the E. M. F. generated.

Solution.

Rate of cutting $= 200 \times 8000 \times 3000 = 48 \times 10^8$ lines per second.

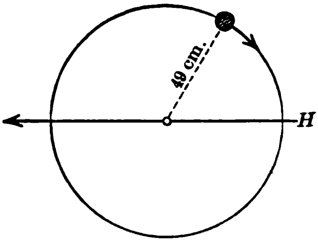
$\therefore E_a = 48 \times 10^8$ abvolts $= 48$ volts.

2. A straight conductor, 1 meter long, lies at right angles to the lines of force of a uniform magnetic field of intensity 5000, and is moved across the field in a direction perpendicular to its length and to the field with an acceleration of 10 centimeters per second², starting from rest. Find the instantaneous value of the electromotive force induced at the expiration of the first minute of the conductor's motion, and the average E. M. F. induced during that period.

Ans. Instantaneous value, 3 volts.
Average value, 1½ volts.

3. Consider that the direction of the motion of the conductor in problem 2 is inclined, first, 60°, second, 90°, to a direction perpendicular to the lines of force, other features remaining unchanged. Obtain the instantaneous and average values of the electromotive force under the conditions specified.

Ans. 60° { Instantaneous E. M. F. 1½ volts. Average E. M. F. ¾ volt.
90° { Instantaneous E. M. F. 0. Average E. M. F. 0.



4. A straight conductor 1 meter long, perpendicular to the plane of the paper, rotates in a uniform magnetic field of intensity 5000 as indicated. Find the E. M. F. induced and state its positive direction when the conductor is in (a) the 12 o'clock position; (b) the 3 o'clock; (c) the 6 o'clock; (d) the 9 o'clock. Calculate the average value of the E. M. F. for one-half revolution of the conductor, starting from (e) the 12 o'clock position, (f) the 3 o'clock.

Ans. (a) 0. (b) 30.8 volts, down. (c) 0. (d) 30.8 volts, up. (e) 19.6 volts. (f) 0.

5. A rectangular coil of copper wire has 50 complete turns in series, each 70 × 20 centimeters. Its longer axis lies parallel to the upper edge of the paper and it revolves about that axis at 1800 R. P. M. in a uniform magnetic field of intensity 5000 whose direction is perpendicular to the plane of the paper. Calculate (a) the E. M. F. generated when the coil lies in the plane of the paper; (b) when it has turned 60° therefrom; (c) when it is at right angles to the paper; (d) the average E. M. F. for one-half revolution, starting with the coil in the plane of the paper.

Solution.

(a) Zero. By inspection. $e = E \sin 0° = 0$.

(c) Linear velocity coil $= \frac{22}{7} \times 20 \times \frac{1800}{60}$.

Lines cut per inductor per second when motion is perpendicular to field $= \frac{22}{7} \times 20 \times \frac{1800}{60} \times 70 \times 5000$.

Number of inductors $= 2 \times 50$.

Coil's rate of cutting = number abvolts $= \frac{22}{7} \times 20 \times \frac{1800}{60} \times 70 \times 5000 \times 2 \times 50 = 660 \times 10^8 = 660$ volts. (Maximum E. M. F.)

(b) $e = 660 \sin 60° = 660 \times \frac{\sqrt{3}}{2} = 330\sqrt{3}$ volts.

(d) Number lines embraced by coil in zero position $= 70 \times 20 \times 5000$ = number of lines cut by inductor per half revolution. Number lines cut by inductor per second $= 70 \times 20 \times 5000 \times 2 \times \frac{1800}{60}$. Number lines cut by coil per second $= 70 \times 20 \times 5000 \times 2 \times \frac{1800}{60} \times 2 \times 50 = 420 \times 10^8$ abvolts = 420 volts, average E. M. F. Or, $E_a = E \times \frac{2}{\pi} = 660 \times \frac{14}{22} = 420$ volts.

6. A rectangular coil, 60 by 30 centimeters has 100 turns in series and revolves at 1200 R. P. M. about its longer axis, which is perpendicular to the plane of the paper, in a uniform magnetic field of intensity 7000 whose direction is parallel to the right-hand edge of the paper. Calculate (a) the maximum E. M. F. generated; (b) the average E. M. F. generated in one-half a revolution, starting with the coil's plane parallel to the upper edge of the paper; (c) the E. M. F. generated when the plane of the coil is inclined 60° to the right-hand edge of the paper.

Ans. (a) 1584 volts. (b) 1008 volts. (c) 792 volts.

7. A rectangular loop revolving in a uniform magnetic field at 1200 R. P. M. generates a maximum E. M. F. of 220 volts. Calculate (a) the average E. M. F. for one-half revolution, starting from the position of zero E. M. F.; (b) the E. M. F. generated $\frac{1}{240}$ second after the coil has left that position. *Ans.* (a) 140 volts. (b) 110 volts.

8. The equation of a curve of sines representing the varying values of an alternating electromotive force is $e = 100 \sin 44t$. What is (a) the frequency of the electromotive force? (b) Its average value if rectified?

Solution.

(a) $2\pi f = \omega. \quad 2 \times \frac{22}{7} \times f = 44. \quad f = 10.$

(b) $E_a = E \times \frac{2}{\pi} = 100 \times \frac{14}{22} = 63.6.$

9. The equation of a curve of sines representing the varying values of an alternating electromotive force is $e = 110 \sin 880t$. What is (a) the maximum value of the E. M. F.? (b) The average value for a half cycle, starting from zero E. M. F.? (c) The average value for a complete cycle? (d) The frequency of the alternating E. M. F.?

Ans. (a) 110. (b) 70. (c) 0. (d) 140.

10. Four rectangular coils, each having 40 inductors in series, are connected in parallel, and they revolve at 1200 R. P. M. in a magnetic field whose flux is 2×10^7 lines. Find (a) the maximum induced E. M. F., (b) the average rectified E. M. F.

Ans. (a) 502.7 volts. (b) 320 volts.

11. Six rectangular coils, each having the same number of turns in series are joined in parallel to form the winding of an armature having 180 inductors which revolves at 1800 R. P. M. in the magnetic field created by 3 pairs of poles, flux per pole 10,000,000 lines. Calculate the armature E. M. F. *Ans.* 540 volts.

12. An eight-pole generator has a lap-wound drum armature, 160 inductors, speed 600 R. P. M. Area of pole faces, 140 square centimeters, flux intensity, 10^5 lines. Calculate the armature E. M. F.

Solution.

$$E_a = \frac{pn\Phi Z}{p'} \text{ abvolts} = \frac{pn\Phi Z}{p' \times 10^8} \text{ volts.}$$

$$p = p'. \quad n = \frac{600}{60} = 10. \quad \Phi = 140 \times 10^5. \quad Z = 160.$$

$$E_a = \frac{10 \times 140 \times 10^5 \times 160}{10^8} = 224 \text{ volts.}$$

13. An eight-pole generator has a lap-wound drum armature winding each of whose circuits, from brush to brush, has 10 complete turns in series. Speed of revolution, 600 R. P. M. Flux per pole, 14×10^6 lines. Find the armature E. M. F. *Ans.* 224 volts.

14. An eight-pole generator has a wave-wound drum armature winding, total number of turns, 80. Flux per pole, 14×10^6 lines; speed of revolution, 600 R. P. M. Find the armature E. M. F.

Ans. 896 volts.

15. An eight-pole generator has a ring-wound armature winding, total number of turns, 80. Flux per pole, 14×10^6 lines; speed of revolution, 600 R. P. M. Find the armature E. M. F. *Ans.* 112 volts.

16. A six-pole generator has a lap-wound drum armature carrying 240 inductors. The flux per pole is 3×10^6 lines and the E. M. F. generated is 144 volts. Find the speed of revolution. *Ans.* 1200 R. P. M.

17. A lap-wound drum armature generates 100 volts at the terminals, carries 100 inductors, and revolves at 1200 R. P. M. Find the magnetic flux. *Ans.* 5×10^6 lines.

CHAPTER XI.

THE THEORY OF THE CONVERSION OF POWER.

Magnetic Reaction.—A current of electricity flowing in a conductor creates a magnetic field whose lines form circles concentric with the conductor. The directions of current and field bear to each other the same relation as that which exists between the directions of travel and rotation of a right-hand screw. If a conductor carrying current be placed near the poles of a magnet the field of the current will be superimposed upon the field of the magnet, and the resultant magnetic field will be a combination of the two individual fields.

In Fig. 120 such a combination is analyzed. For simplicity but two lines (dotted) of the magnet's field and one line (broken) of the conductor's field are shown. *A* is the cross-section of a conductor carrying current placed perpendicular to the magnet's field. The current in the conductor flows away from the observer. The arrowheads indicate the positive directions of the lines. In (a) the two fields are shown superimposed but undistorted. In (b) the circular field of *A* has been resolved into its rectangular components. If we let the lengths * of the dotted and broken lines indicate the strengths of the magnetic forces it is evident from (b) that it may be considered that two pairs of forces, 1, 2 and 3, 4, meet at a point directly above *A*, and that two other pairs, 5, 6 and 7, 8, meet directly below *A*. The resultants of the four pairs of forces are shown by the full lines of (c), which, by their lengths and directions, represent the strength and direction of the magnetic field produced by the combination of the two separate fields.†

From (c) it is seen that in the region above *A* the field is strengthened, while below *A* it is weakened. [An inspection of (a) would

* Contrary to the usual convention, by which one line, regardless of its length, indicates a force of 1 dyne.

† That magnetic forces can be treated with reference to their components and resultants in the same manner as mechanical forces is evident when it is remembered that both kinds of force are measured in the same units.

make the same fact apparent, since there it is shown that above the conductor the circular field is in accord with and therefore strengthens the magnet's field, while below the conductor the reverse obtains.] The full lines of (c) also indicate the general shape of the

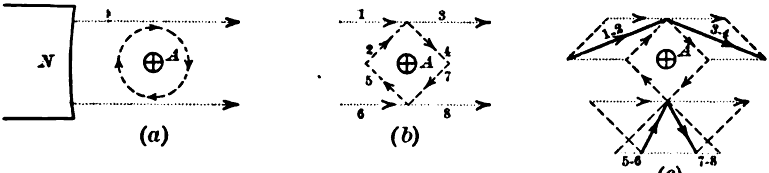


FIG. 120.

field, both above and below *A*. If the method of Fig. 120 had been applied to more lines of force than used in that figure, the resultant field would have shown much as in Fig. 121.

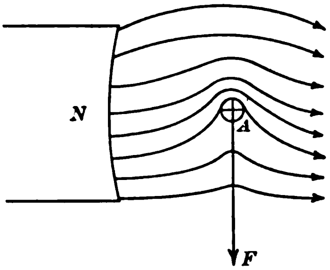


FIG. 121.

Stresses, whether magnetic or otherwise, tend to shorten to straight lines their paths in the medium traversed, exerting a continuous pressure on that which distorts them from a linear direction. The distorting factor in this case is the electrified conductor, which may be regarded as mechanically attached to its own field and, hence, to the resultant field. Or the lines of Figs. 120 (c) and 121 may be considered as elastic rubber bands in contact with and placed under tension by the conductor. In consequence, it is evident that the field exerts a continuous pressure, proportional to its intensity, on the conductor in a direction perpendicular to its own general trend. Such pressure is indicated in Fig. 121 by *F*. It is obvious that the direction of the distortion of the field and, consequently, the direction of *F* would be reversed were the current or the polarity of the magnet—but not both—to be reversed.

Measurement of Current.—The intensity of the field created by the current varies directly as the strength of the current. In consequence, with a constant magnet field the intensity of the combined field and, therefore, the pressure on any given conductor would be proportional to the current. An alteration in the length of the conductor or in the intensity of the magnet's field would affect the total pressure on the conductor in like ratio. Hence, by the reaction between the fields of a magnet and a conductor carrying current a means of measuring current is afforded, and, accordingly, the **absolute unit of current** may be defined as **that current which when flowing in a conductor placed at right angles to a magnetic field of unit intensity causes each centimeter of the conductor's length to be acted on with a force of 1 dyne.**

The practical unit of current, the ampere, is $\frac{1}{10}$ of the absolute unit.

Torque and Power.—When a force acts tangentially to the periphery of a circle and so produces a turning moment about the center of the circle, the product of that force and the radius of the circle is called "torque," and is expressed in pounds-feet, dynes-centimeters, etc. The symbol for torque herein used is T.

Torque is not energy or power, nor is it force, although it is sometime called "angular force." It may be defined as **that which produces or tends to produce torsion.** Power, however, may be expressed in terms of torque and angular velocity.

Let the conductor of Fig. 121 be considered as one of the inductors of the armature winding of a bipolar dynamo rotating at n revolutions per second in a circle whose radius is r centimeters. The linear distance (s) moved through by the conductor in one second is $2\pi rn$ centimeters. If f be the average force in dynes applied to the conductor tangentially to its circular path, then:

$$\text{Power } (P) = \frac{\text{Work}}{\text{Time}} = \frac{fs}{1} = 2\pi nfr = \omega T, \qquad (15)$$

for

$$fr = T \text{ and } 2\pi n = \omega.$$

If the length of the conductor be l centimeters, if the intensity of the field be H, and if a current of I absolute units flows in the conductor; then, from the definition of the absolute unit of current it is evident that

$$F = HlI \text{ dynes.} \qquad (16)$$

where F acts perpendicular to the field.

Since the conductor revolves, the tangential pull of the field is the component of F at right angles to the conductor's radius of rotation. This component, throughout a revolution, varies as sin ϕ or in accordance with the curve of sines, and consequently its values are proportional to those of the instantaneous electromotive force. Therefore, f, the **average** tangential component, which may be styled the rotational force, is related to F, the **maximum** rotational force, as are E_a and E. Hence:

$$f = F \times \frac{2}{\pi} = \frac{2}{\pi} HlI.$$

If there are Z inductors in the armature winding the total average rotational force exerted on the armature is:

$$f = \frac{2}{\pi} HlZI. \qquad (17)$$

Substituting (17) in (15):

$$P = 2\pi nr \times \frac{2}{\pi} HlZI = n \times 2rlH \times Z \times 2I. \qquad (18)$$

Let I_a be the total current flowing into the armature. Then, since the dynamo is bipolar,* having two paths through the armature winding, $2I = I_a$. Again since the dynamo is bipolar, $E_a = n\Phi Z$. Also, in any dynamo $\Phi = 2rlH$ (Chapter X). Hence, substituting in (18):

$$P = E_a I_a, \qquad (19)$$

or **the power developed by any dynamo is equal to the product of its armature electromotive force and its armature current.**

In substituting in equation (19), as in all other expressions herein given, it is immaterial whether absolute or practical units be used, provided either the one or the other be adhered to consistently. Using practical units in (19) we have: 1 watt = 1 volt × 1 ampere. Substituting for these their equivalents in absolute units: 10^7 ergs per second = 10^8 abvolts × 10^{-1} abamperes, which checks. If P is expressed in horse-power and the voltage and current in volts and amperes, P must be converted to watts. 746 watts = 1 horse-power.

* The same result would have been reached had a multipolar dynamo been selected for illustration.

Equating the value of P obtained in (19) to that obtained in (15):

$$E_a I_a = 2\pi n f r = 2\pi n T,$$

or

$$T = \frac{E_a I_a}{2\pi n} = \frac{n\Phi Z I_a}{2\pi n} = \frac{\Phi Z I_a}{2\pi}, \qquad (20)$$

where if I_a is expressed in absolute units T is in dyne-centimeters.

Expression (20) shows that in a dynamo **the torque is independent of the angular speed and that it varies as the armature current and the field.**

Generator Action.—Hitherto in this and the chapter immediately preceding all that has been said applies without distinction to both the motor and the generator, the term "dynamo" covering the two. Both machines are generators in that they generate electromotive

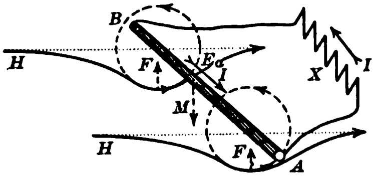


FIG. 122.—Generator Action.

force. However, in the machine commonly designated as the "generator," the electromotive force induced causes the flow of a current through its windings and the receiving circuit; whereas, in the motor the armature electromotive force resists the passage through the armature of a current driven by a stronger external and opposed electromotive force. The generator's armature is rotated by mechanical power, which the machine converts into electrical power. The motor's armature is rotated by electrical power, which the machine converts into mechanical power.

The action of the dynamo as a generator will now be analyzed. In Fig. 122 let the conductor AB, shown in perspective, be moved by a mechanical source of power in the direction M perpendicular to AB and to the magnet field indicated by the dotted lines. The direction, relative to the field, of the motion of the conductor is then such as to establish in the conductor an electromotive force, E_a, setting from B towards A. If now the terminals of AB be joined electrically through an external resistance X a complete circuit will be formed, in which E_a will produce a current I, in accordance with Ohm's law, or $I = \frac{E_a}{r_a + r_x}$, where r_a is the resistance of AB and r_x the external resistance. The conductor AB, by virtue of its motion, has become a source of electromotive force—as much so as a voltaic cell. A battery of E_a volts and r_a ohms internal resistance could be substituted for AB without altering I. The direction of I is, of course, the direction of E_a and such as to tend to establish about the conductor the circular magnetic field indicated by the broken-line circles. Referring to the discussion relative to Figs. 120 and 121, it is evident that the combination of this field and the field of the magnet produces the resultant field represented by the full lines, and that the force, F, exerted on the conductor by such resultant field is opposite in direction to the direction, M, of the motion of the conductor. This is an exemplification of Lenz's law that "in all cases of electromagnetic induction the induced currents have such a direction that by their reaction they tend to stop the motion which produces them."

In order that there shall be motion in the direction M, F must be balanced by an equal * and opposite force mechanically applied. Such application of a force, resulting in motion, requires the expenditure of mechanical energy or power. The mechanical power so expended produces electrical power in the conductor's circuit, which, by the law of the conservation of energy, must equal—subject to the losses incident to transformation—the mechanical power from which it was converted.

If the conductor is an armature inductor and f is the average rotational force of the field, f and the armature radius constitute a torque, fr, about the axis of rotation, to which the power driving the generator—say a steam engine—must oppose an equal † counter-torque. Such torque may be expressed in electrical factors, as in

* Neglecting losses.

† Considering losses negligible. In reality the driving torque exceeds the armature torque because of the reactive force of friction and other losses. See under "Dynamo losses," p. 244, and "Stray loss torque," p. 249.

equation (20). If the torque and angular velocity of the engine's driving shaft be known, the power developed by the engine may be computed as in equation (15), and this, less losses, may be equated to the electrical power of the armature, determined as in equation (19).

As has been seen, the pressure or drag, and, consequently, the torque, exerted by the field on the rotating armature arises from the presence of current in the inductors. Should the latter not form part of a closed circuit—in other words, should the terminals of the armature not be connected to a receiving circuit—no current can flow in the winding or its component parts; and hence the inductors can create no individual fields to furnish, by their reaction with the fields of the magnets, the armature drag and torque. This principle is demonstrated mathematically by equation (20), in which, with $I_a=0$, $T=0$. With the generator on open circuit, therefore, the armature offers no resistance to rotation other than that caused by friction and the reactive effect of hysteresis and eddy currents, to be discussed later. In consequence, no power, except that necessitated by the losses mentioned, is required to revolve it. This fact is also evident mathematically from equation (19), where, with $I_a=0$, P becomes 0. The generation of electromotive force, for which the expenditure of energy is not requisite, is, of course, not interfered with by placing the generator on open circuit.

Constant Voltage and Constant Current.—Electrical energy is generally supplied under one of two conditions: either at constant voltage or with constant current. A variable power service is usually demanded of a generator—as when a receiving circuit operates lights or motors in varying numbers—and but one of the two component factors of the power can be kept constant. If in a receiving circuit lights are connected in parallel it is necessary for their proper operation that the supplied voltage should not vary; whereas, if the lights are in series the current should be invariable.

From the fundamental equation of the dynamo, $E_a=\frac{pn\Phi Z}{p'}$, it is seen that in any given generator, for which p, p' and Z are constants, **the armature electromotive force is determined by the angular speed and the field.** Hence, when a generator supplies power at constant voltage the rotational speed of the armature and the field flux * are kept uniform. The value of the current then is determined by and varies inversely with the combined resistance of the receiving and generator circuits. If, however, the machine is to furnish a constant current, its voltage must be controlled so as to maintain an invariable ratio to the varying resistance of the circuit supplied. This can be effected by **manipulating either the speed or the field, or both.**

Motor Action.—The elementary principle of motor action is depicted in Fig. 123, which is similar to Fig. 122, except that a battery is substituted for the external resistance X of that figure. The conductor AB is not acted on by a force mechanically applied, but is

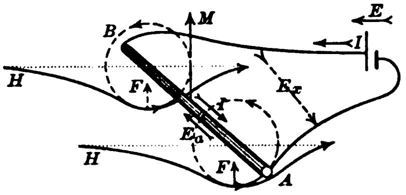


FIG. 123.—Motor Action.

instead free to move. The electromotive force of the battery is E, and its direction is such as to send a current, I, through AB from B to A. Since this current flows in a direction similar to that of the current of Fig. 122, the magnetic fields of both figures are alike, and in consequence the conductor of Fig. 123, is, like the conductor of Fig. 122, urged upwards by the reactive force of the field. In this case no mechanical power prevents the conductor from moving upwards, and it does so move. But as it progresses across the field it cuts the lines of the field and thereby generates in itself an electromotive force, E_a, whose direction is from A to B, or in opposition to E. [It may be noted that the direction of the induced electromotive force in Fig. 123 is opposite to the direction of the induced electromotive force in Fig. 122, which is to be expected, since the direction of the motion of the conductor is reversed.] E and E_a may be likened to

* Not strictly true. The field is regulated to compensate for the ohmic drop through the armature, keeping the terminal voltage constant.

the electromotive forces of two voltaic cells connected in series and in opposition. The total electromotive force acting in the circuit is therefore $E - E_a$, and $I = \frac{E - E_a}{r_a + r_x}$, where r_a is the resistance of AB and r_x the resistance of the battery and leads. Or I may more conveniently be expressed by:

$$I = \frac{E_x - E_a}{r_a}, \qquad (21)$$

where E_x is the voltage impressed by the battery on the terminals of AB. E_x is designated as the "**applied**" or "**terminal**" electromotive force, and E_a, since it is counter to E_x, is the **back** or **counter** electromotive force.

The conductor moves with a force F, which may, through the conductor, be applied to a machine, producing motion therein, and thereby doing mechanical work. The electrical energy of the conductor will thus be converted into mechanical energy, and, as in the case of the generator, the electrical power supplied, less losses, must equal the mechanical power produced.

A rotary motion may be imparted to the machine if the conductor AB is one of the inductors of an armature winding to which current is supplied by an external source of electrical power. An armature so supplied will rotate continuously in one direction, as is demonstrated by Fig. 124. Here the inductors of a bipolar ring-wound armature * are drawn in cross-section and their front connections in broken lines. For clearness the inductors themselves are represented as being commutator bars. The current enters at the upper brush and flows through the winding as indicated. A few lines of the field formed by the combined action of current and pole-pieces are shown. It is obvious that in the right-hand hemisphere the conductors are urged up and in the left-hand hemisphere, down; or, that a counter-clockwise rotation is produced.

The inductors at or near the brushes have no rotational force acting on them, since in that position the reaction of the field is directly away from the center of rotation, and if the armature winding were a single rectangular coil it would not revolve when placed

* Form of winding is immaterial.

under the brushes. However, if another coil at right angles to the first were added to the winding, the combination would revolve with a force and, consequently, a speed that would fluctuate in the same manner that the electromotive force in the winding would fluctuate, for the electromotive force and the rotational force are in phase. Further insertion of armature coils in the winding would reduce the fluctuations of the rotational force and speed in proportion to the number of coils added, until, finally, **by the use of a large number**

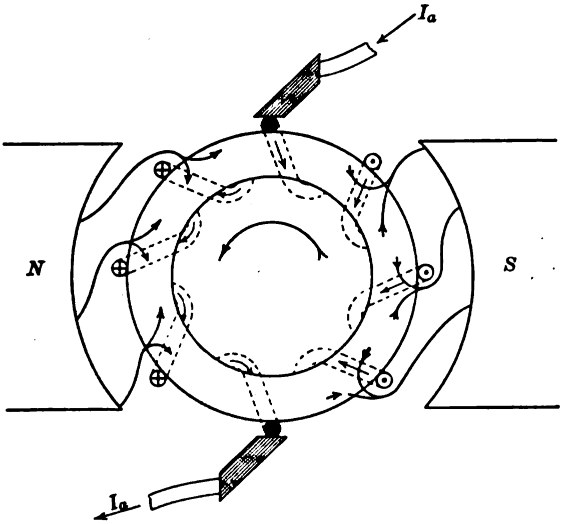


FIG. 124.—Motor Action, Ring-Wound Armature.

of coils equally spaced around the armature core, a uniform speed of rotation would be obtained. The analogy between this process and that for obtaining a steady electromotive force is plain.

It is evident from equation (21) that in a motor the armature current is proportional to the difference between the motor's terminal and counter electromotive force, or:

$$I_a = \frac{E_x - E_a}{r_a}, \qquad (22)$$

where r_a is the armature resistance, E_x the voltage at the motor terminals, and E_a the electromotive force generated in the motor armature. [The generating action of a motor should be kept clearly in mind. The means, whether electrical or mechanical, by which a conductor is moved across a magnetic field are immaterial as far as the induction of electromotive force is concerned. That in the motor the rotating power is electrical in no way alters the process of induction.] Since in producing E_a the motor acts as a generator, the fundamental equation of the dynamo (14) applies, and we may write:

$$E_a = \frac{p}{p'} n\Phi Z. \tag{23}$$

If the motor has a ring or a lap-wound armature, $p = p'$, and (22) becomes:

$$E_a = n\Phi Z. \tag{24}$$

For simplicity it will be assumed hereafter that all motors have **lap-wound** armatures. Accordingly (21) may be written

$$I_a = \frac{E_x - n\Phi Z}{r_a}. \tag{25}$$

Equation (25) is the **fundamental equation of the motor.**

In the motor as in the generator the torque developed is proportional to the armature current and is determined by equation (20). Again as in the generator, the torque developed electrically is equalled * by the counter-torque developed mechanically. Should the counter-torque, through reduction of the motor's mechanical load, become momentarily less than the armature torque, the excess of the latter will cause the motor to increase its speed of rotation and thereby the counter electromotive force E_a, which in turn decreases the armature current. By equation (25), in which r_a and E_x may be regarded as constants, this principle is demonstrated mathematically. With a decrease in the armature current the electrical torque falls in proportion. Should the current decrease so much as to reduce the electrical torque below the counter-torque of the driven machine, the latter will slow down the motor and in consequence decrease the counter electromotive force, and so increase the current and the armature torque. These processes will continue until a balance is established.

* Neglecting losses. See under "Dynamo losses" and "Stray loss torque."

It follows, therefore, that, as in the generator, in the motor:

$$T=\frac{\Phi Z I_a}{2\pi}=f'r',^*$$

where f' is the tangential pull on the armature shaft and r' is the radius of the shaft. But $f'r'$ is a measure of the mechanical work done by the motor. Hence it is evident that **in a motor the armature current is determined by the mechanical load.**†

In the motor, as in the generator, the external, mechanical power may be determined as in equation (15) and the internal, electrical power as in equation (19), and the difference between the two powers is the loss due to the transformation.

Motor Speed Control.—The fundamental equation of the motor may be written:

$$n=\frac{E_x-I_a r_a}{\Phi Z}, \tag{26}$$

in which the term $I_a r_a$ is small in comparison with E_x because of the low resistance of the armature winding, and Z, for any given motor, is a constant. Hence, if Φ be assumed constant, it is clear that n is approximately proportional to E_x. Therefore, it may be stated that **the speed of a motor whose field excitation is unvaried is nearly proportional to the electromotive force impressed on the motor's terminals.**

It is evident also from equation (26) that should the field be varied the motor's speed will be affected in inverse ratio, or that **a motor will speed up when its field is weakened and slow down when the field is strengthened.** The same deduction may be arrived at from a physical standpoint, thus: an increase in the field intensity increases the counter electromotive force temporarily, resulting in a temporary decrease in the armature current and armature torque, whereupon the excess counter-torque of the mechanical load slows down the armature. As the armature slows down the counter electromotive force decreases and consequently the armature current increases until finally both reach their former values, when the

* Neglecting losses. See under "Dynamo losses" and "Stray loss torque."

† See under "Stray loss torque."

balance between the load torque and the armature torque is re-established, stopping further change in speed, but leaving the motor running at a lower speed than before. The converse of this reasoning of course holds good also.

It is to be noted, then, that **the speed of a motor may in general be controlled by manipulating either the field or the applied voltage or both.**

Dynamo Losses.—When power is converted in dynamo-electric machines, there are certain power losses incident to the transformation which are common to both generators and motors, and whose sum is the difference between the power delivered to the machine and the power delivered by the machine. These losses are classified under two general heads as follows:

(a) **Stray** loss, (b) **copper** loss. The stray loss may be subdivided into **mechanical** losses and **core** or **iron** losses. The latter may be further subdivided into the loss due to **hysteresis** and the loss due to **eddy currents.**

The copper loss may be subdivided into the **armature** loss and the **field** loss.

Mechanical Losses.—Mechanical losses are those due to the friction exerted on the moving parts of the dynamo: friction in the bearings, at the brushes, and the air friction of the armature. The retarding frictional force creates a torque counter to the driving torque, to overcome which the expenditure of power is necessary. The frictional loss does not vary to any great extent under load and may be considered constant.

Hysteresis.—Iron when magnetized displays a tendency to maintain its magnetic state, and does not immediately reverse its polarity upon being subjected to a magnetizing force of opposite sign. To this phenomenon—the lagging of a magnetic state behind its producing cause—is given the name of hysteresis.

The iron core of an armature is situated in a magnetic field and is magnetized with a polarity dependent upon the polarity of the field. Fig. 125 shows a ring armature core rotating counter-clockwise in the magnetic field NS. When the core is at rest its polarity is as indicated by S_1N_1. Let it be supposed that when the core begins to rotate the region N_1 is carried into the position N_2. The tendency of the magnetizing force NS is to make N_2 a position of no free magnetism, or neutral. But due to hysteresis the region N_1, when it arrives at N_2, retains a part of its positive magnetism. Similarly, S_2 is a region of negative magnetism. In consequence, a magnetic drag, counter to the direction of rotation, is exerted on the armature core by the two pairs of poles, NS_2 and SN_2. Such drag, like friction, creates a counter-torque which the rotating power must overcome.

The extent of the action of hysteresis is dependent upon the flux density and the rapidity with which the magnetizing force is reversed,* which, in the case of an armature core, is determined by the

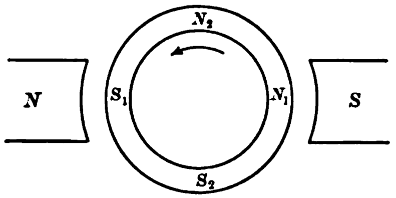


FIG. 125.

armature speed. Hence, with constant field and speed the hysteresis loss is constant and independent † of the load on the dynamo.

Eddy Currents.—The armature core may be regarded as being composed of a bundle of uninsulated conductors lying parallel to the armature inductors. As the core revolves such conductors will have electromotive forces induced in them, having the same directions as the electromotive forces of the inductors. In consequence, since the conductors, being uninsulated, form part of a closed circuit, currents will flow in them—which is to say, in the core. Such currents will have irregular paths (hence the name of "eddy" currents), following the course of least resistance; but in general they will parallel their electromotive forces. In a generator, therefore, their direction will be that of the armature current; in a motor it will

* Hysteresis loss varies as $fVB^{1.6}$, where f is the magnetic frequency, V the volume of the core, and B the flux density.

† Distortion of the flux under load causes the hysteresis loss to increase slightly.

be opposite to the direction of the armature current. Hence, in both machines the magnetic reaction of the eddy currents will oppose the rotation of the armature and, like friction and hysteresis, necessitate the expenditure of driving power to overcome the counter-torque so formed.

By local variations in the flux intensity eddy currents may be created in pole pieces and in armature inductors, if the latter are massive and mounted on smooth cores. Eddy currents in pole pieces are produced when armatures have slotted cores, as in Fig. 126a.

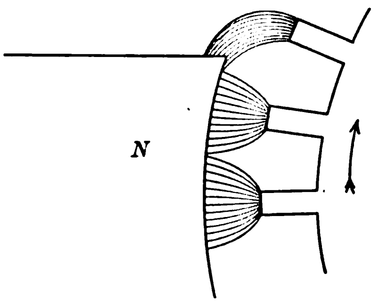


FIG. 126a.—Formation of Eddy Currents in Pole Pieces.

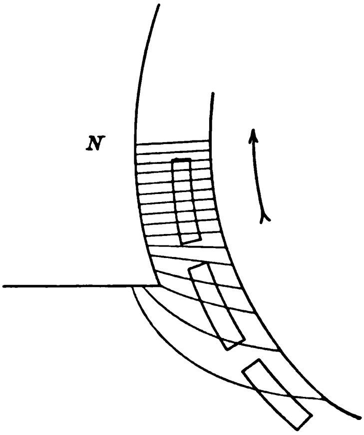


FIG. 126b.—Formation of Eddy Currents in Inductors.

The teeth forming the slots concentrate the field flux in tufts as shown, and as the core revolves these tufts sweep along the face of the pole, thereby forming eddy currents. The concentration of the flux is greatest at the "forward horn" of the pole piece—the horn which points in the direction of the rotation of the armature—and here the eddy current loss is the greatest. If the armature core is smooth and its inductors are massive bars, as in Fig. 126b, each inductor, as it enters or leaves the field, has its sides momentarily in regions of different magnetic intensity, as indicated, and in consequence the electromotive forces induced in the two sides are not equal. A difference of potential is thereby created tending to send current down one side of the bar and up the other, and although this difference of potential may be small, it acts in a circuit which may be regarded as being formed by the two longitudinal halves of the bar joined at their ends. Such circuit has a negligible resistance, and the resultant eddy current loss may therefore be large. Placing the inductors in slots does away with such loss.

Since eddy currents arise from inductive action their strength and, consequently, the loss caused by them are dependent on the flux intensity and the speed of armature rotation.* Therefore, as with hysteresis, the eddy current loss is constant and independent of the load when the field and speed are constant.

Armature Loss.—The armature loss is the power consumed in forcing current through the armature winding. Such power is not available for work in the receiving circuit, if the dynamo is a generator, or for rotating the armature, if a motor. The armature loss may be divided into three parts: first, the loss occasioned by the armature current flowing through the armature resistance, equivalent to $I_a^2r_a$ and forming the chief constituent of the armature loss; second, the power consumed by the passage of current between the brushes and the commutator; third, the power waste of local currents in the armature windings caused by the short-circuiting at the brushes of armature elements, or by unbalanced electromotive forces in the windings, due to improper design.

Since the armature loss depends upon the armature current, it varies greatly with the load.

Field Loss.—The magnetic field of dynamos is created by electromagnets whose windings are excited by current taken from the dynamo terminals.† The exciting circuit may be either in series with the armature winding, in which case the machine is **series** wound, or in parallel with the armature winding, when the dynamo is **shunt** wound, or the electromagnets may be excited by both series and shunt windings, when the machine is said to be **compound** wound.

The field loss is the power consumed in forcing current through the field windings, equivalent to the product of the square of the

* Eddy current loss varies as f^2VB^2.

† Except when a dynamo is separately excited. See under "Dynamo Windings," p. 259, and in Chapter XIII under "Excitation."

current and the resistance of the winding. Such power, like the armature loss, is not available for external work.

The current in the series field is the armature current,* and therefore the series field loss varies greatly with the load. The shunt field current, however, is approximately constant, for the terminal voltage of shunt and compound dynamos varies little. Hence the shunt field loss may be regarded as constant and independent of the load.

Determination of Losses.—The power waste of the various losses appears as heat in the bearings, core, pole pieces and windings. Such heat cannot be accurately measured.

The stray loss cannot be satisfactorily calculated. It is determined by experiment. The simplest method for determining the stray loss of a dynamo is as follows: The machine is run as a motor without load at its rated speed and with its prescribed degree of field excitation, and the power it takes from the supply mains is measured. Such power, less the copper loss, is the stray loss. This is evident when it is considered that the motor when running without load exerts no power externally; hence all the power that it consumes is that occasioned by the sum of its losses. If the copper loss be subtracted from this sum the remainder is the stray loss of the motor under the conditions of field and speed of the experiment. It is also the stray loss of the dynamo, whether run as a motor or a generator, under normal conditions, since the stray loss is dependent on field and speed, and these are normal.

The first part of the armature loss is $I_a^2 r_a$. The second part may be included in the first by considering the brush resistance a part of the armature resistance.† It will be so treated. The third part of the armature loss cannot be calculated. In properly designed machines it is small and may—and herein will—be neglected.

The field losses are computed by multiplying the resistance of each field circuit by the square of the current flowing through it. Should a field regulating rheostat be included in the circuit its power waste is a part of the field loss.

* In a compound short-shunt dynamo series current = armature current ± shunt current.

† Sufficiently accurate except when the dynamo has low voltage and heavy current.

Stray Loss Torque.—It has been seen that each of the three component parts of the stray loss is occasioned by a torque counter to the application of the driving power. The cumulative effects of these three torques may be called the stray loss torque.

It is evident that if a dynamo be a generator the driving engine must apply a force sufficient to overcome not only the drag of the armature inductors but in addition the drag created by the factors of the stray loss. Or, if the machine be a motor, it is equally evident that the electromagnetic pull of the armature inductors must overcome the stray loss drag as well as the reactive force of the mechanical load. Hence, calling the stray loss torque T_s, the torque of the armature winding T_a, and the torque of the driving engine or the mechanical load T_m, it is seen that in a generator:

$$T_m = T_s + T_a, \tag{27}$$

and in a motor:

$$T_a = T_s + T_m. \tag{28}$$

The reference contained in the footnotes under "Generator Action," p. 237, and "Motor Action," pp. 242, 243, is now made plain.

Referring to the equation: $T = \frac{\Phi Z I_a}{2\pi} = f'r'$, under "Motor Action," it is evident that when the effect of the stray loss is considered this equation becomes: $T_a = \frac{\Phi Z I_a}{2\pi} = T_s + f'r'$, from which it is seen that although the armature current of a motor is determined by the mechanical load, as previously stated, it is not directly proportional thereto. However, if the stray loss torque of the motor is small in comparison with the load torque, the armature current varies approximately as the load, similar to the manner in which the speed of the motor varies approximately as its terminal electromotive force.

Efficiencies of Dynamos.—Equations (27) and (28) may be converted into equations of power by multiplying each term by the angular velocity of the armature shaft [see equation (15)], thus:

$$\text{Generator,}\quad 2\pi n T_m = 2\pi n T_s + 2\pi n T_a. \tag{29}$$

$$\text{Motor,}\quad 2\pi n T_a = 2\pi n T_s + 2\pi n T_m. \tag{30}$$

Here $2\pi n T_m$ is the mechanical power **input** of a generator and the mechanical power **output** of a motor, $2\pi n T_s$, is the stray power loss;

and $2\pi nT_a$ is the **power developed** by the armature. The stray power loss may be designated S, the mechanical power, P_m, and for $2\pi nT_a$ may be substituted E_aI_a [equation (19)]. Equations (29) and (30) then become:

$$\text{Generator,} \quad P_m = S + E_aI_a. \tag{31}$$

$$\text{Motor,} \quad E_aI_a = S + P_m. \tag{32}$$

From equations (29)-(32) it is evident that **in a generator the stray loss is the difference between the power input and the armature power developed,** and that **in a motor the stray loss is the difference between the armature power developed and the power output.**

The ratio of the armature power developed by a generator to the power input is known as the **efficiency of conversion** of the generator. Or:

$$\text{Generator: Efficiency of conversion} = \frac{E_aI_a}{P_m}. \tag{33}$$

(33) may be written:

$$\text{Generator: Efficiency of conversion} = \frac{E_aI_a}{E_aI_a + S}. \tag{34}$$

The ratio of the power output of a motor to the armature power developed is known as the **mechanical efficiency** of the motor. Or:

$$\text{Motor: Mechanical efficiency} = \frac{P_m}{E_aI_a}. \tag{35}$$

(35) may be written:

$$\text{Motor: Mechanical efficiency} = \frac{E_aI_a - S}{E_aI_a}. \tag{36}$$

Let E_x represent the voltage at the terminals of a dynamo, whether motor or generator, and I_x the external current. Then E_xI_x is the electrical power **output**, if a generator; and the electrical power **input**, if a motor. Suppose, for the sake of illustration, that the machine be a compound-wound "long shunt"* dynamo. Its circuits are then represented by Fig. 127. Here t_1 and t_2 are the dynamo terminals, c the series field, s the shunt field, a the armature winding. Let the resistance of the shunt field be r_s, of the series field, r_c. Let the shunt current be I_s. Assume the directions of

* See under "Dynamo windings."

E_a, E_x, and I_s to be as indicated, whether the machine is a generator or a motor. Then, if a generator, I_a flows through c to the right, and:

$$E_x = E_a - I_a(r_a + r_c), \tag{37}$$

and

$$I_x = I_a - I_s. \tag{38}$$

$$\therefore E_x I_x = E_a I_a - I_a^2(r_a + r_c) - E_x I_s,$$

or

$$E_x I_x = E_a I_a - (I_a^2 r_a + I_a^2 r_c + I_s^2 r_s). \tag{39}$$

Here $I_a^2 r_a$ is the armature power loss, $I_a^2 r_c$, the series field loss, and $I_s^2 r_s$, the shunt field loss; the sum of the three constituting the

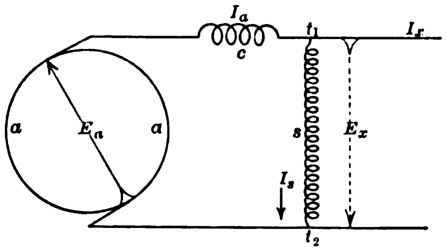


FIG. 127.

copper loss. Hence **in a generator the copper loss is the difference between the armature power and the power output.**

The ratio of the power output of a generator to the armature power developed is called the **electrical efficiency** of the generator. Or:

$$\text{Generator: Electrical efficiency} = \frac{E_x I_x}{E_a I_a}. \tag{40}$$

If the dynamo of Fig. 127 be a motor, then I_a flows to the left through c, and:

$$E_x = E_a + I_a(r_a + r_c), \tag{41}$$

and

$$I_x = I_a + I_s. \tag{42}$$

$$\therefore E_x I_x = E_a I_a + I_a^2(r_a + r_c) + E_x I_s,$$

or

$$E_x I_x = E_a I_a +, (I_a^2 r_a + I_a^2 r_c + I_s^2 r_s). \tag{43}$$

Hence **in a motor the copper loss is the difference between the power input and the armature power.**

The ratio of the armature power of a motor to the power input is called the **efficiency of conversion** of the motor: Or:

$$\text{Motor: Efficiency of conversion} = \frac{E_a I_a}{E_x I_x}. \quad (44)$$

The efficiency of conversion, whether with reference to a generator or a motor, is sometimes called the "gross" efficiency.

The copper loss, as found in equations (39) and (43), was dependent on the form of the dynamo winding, and those equations are not suitable for use with other than compound-wound long shunt dynamos. The method used in deriving them is, of course, applicable to any form of winding.

If in general terms A represents the armature loss, F_c the series field loss, and F_s the shunt field loss, then in any generator the copper loss may be determined by:

$$E_x I_x = E_a I_a - (A + F_c + F_s), \quad (45)$$

and in any motor by:

$$E_x I_x = E_a I_a + (A + F_c + F_s). \quad (46)$$

Combining equation (31) with equation (45), we have, for a generator:

$$P_m = S + A + F_c + F_s + E_x I_x; \quad (47)$$

and combining equation (32) with equation (46), we have, for a motor:

$$E_x I_x = S + A + F_c + F_s + P_m. \quad (48)$$

Hence **in any dynamo the sum of all the losses is the difference between the power input and the power output.**

The ratio of the power output of any dynamo to its power input is called the **commercial efficiency** of the dynamo. It is also sometimes called the "true" or "net" efficiency. In a generator:

$$\text{Commercial efficiency} = \frac{E_x I_x}{P_m}; \quad (49)$$

and in a motor:

$$\text{Commercial efficiency} = \frac{P_m}{E_x I_x}. \quad (50)$$

It may be noted that the commercial efficiency is the product of the other two efficiencies.

Sparking.—Fig. 128(a) represents an element of the armature winding of a generator attached to its two commutator segments

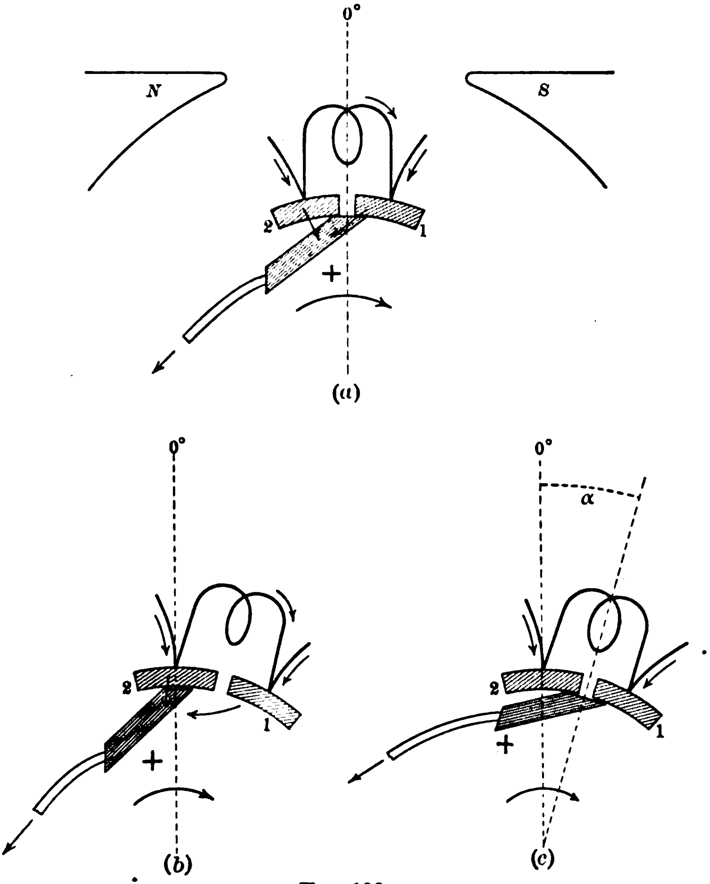


FIG. 128.

1 and 2, and at the instant under consideration at the position of minimum electromotive force, which we will still consider, as heretofore, to be halfway between two adjacent poles. The armature is supposed to have a clockwise rotation. The brush, for clearness, is

depicted as being inside the commutator, and also at the zero position.

With the coil located as shown it is the seat of no electromotive force, and since it is short-circuited by the brush, no current should flow in it. But, if the angular speed of the armature be sufficiently great, it may be that the brief interval during which the coil is short-circuited is not long enough to permit the complete cessation of the current which was flowing in the coil prior to its arrival at the brush, and that the self-inductance of the coil continues a part of this current during the period of short-circuiting. However, this is not material with the coil in the position shown, for the inductance current could flow directly into the brush, as flow the currents from the left- and right-hand hemispheres of the windings. Let it next be supposed that the coil has moved into the position of (b), the commutator segment 1 having left the brush. It now forms part of the right hemisphere circuit of the armature winding and the current in that portion of the winding tends to flow through it. But even if the coil be now perfectly idle, owing to its self-inductance the current of the right hemisphere cannot immediately attain its full value in the coil; and, if in addition, there still lingers in the coil some of its former current, the choking effect on the new current is aggravated. Hence, the latter, finding its path through the coil barred, sparks from the commutator segment across to the brush, as indicated by the arrow. Sparking constitutes a loss of power and is injurious to the brushes and commutator.

As the coil passes the zero position its electromotive force reverses and tends to assist the passage through it of the current of the right hemisphere. The coil does not, however, become a part of the right hemisphere circuit until after it passes the brush. If, then, the brush be advanced in the **direction of rotation** of the armature, as in (c), until it reaches a position such that the coil, when short-circuited by it, is the seat of sufficient reversed electromotive force to overcome the effects of self-inductance, then when the coil leaves the brush the current of the right armature circuit can instantly attain its full value in the coil, and no sparking will occur.

The angle, (a), measured from the position of zero electromotive force, through which the brushes are so advanced is called the **lead** of the brushes. The line joining the positions of minimum electromotive force is called the **neutral axis** of the armature; the line joining the brushes is called the **axis of commutation.** In a motor the lead is negative or lag; that is, the brushes are shifted opposite to the direction of rotation. If in Fig. 128 the current is considered as flowing in directions reverse to those indicated, as would be the case were the machine a motor, it will be evident that to prevent sparking the brushes must be shifted counter-clockwise.

Giving lead to the brushes decreases the electromotive force delivered by the generator, since it introduces a counter electromotive force in each armature circuit.* The fundamental equation of the dynamo and the discussion relative to dynamo windings in Chapter X are based on the assumption that the brushes have zero lead.

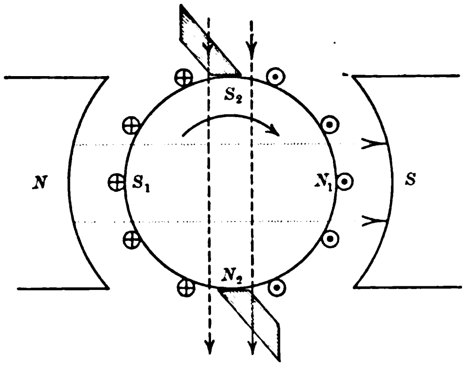


FIG. 129.

When a generator is on open circuit obviously no lead is necessary. The amount of the lead given the brushes depends upon the armature current.

Armature Reaction.—Hitherto it has been assumed that the position of minimum electromotive force is located midway between two adjacent poles, and it is so located if no current flows in the armature winding. But with the advent of current the field becomes distorted, and the neutral axis is advanced—in a generator—in the direction of rotation of the armature.

Fig. 129 shows the drum-wound armature of a generator rotating clockwise in the field represented by the two dotted lines *NS*. With

* Discussed in Chapter X.

such direction of field and rotation the armature current will flow towards the observer in the right-hand inductors and away from him in the other inductors, as indicated, if the brushes are placed on the vertical diameter of the armature core.* When the current flows thus its magnetizing effect is such as to make a negative magnetic pole of the region of the core shown as underneath the upper brush, and a positive pole of the opposite locality. The general direction in the core of the flux so created is represented by the two broken lines S_2N_2. The magnetizing action of the field NS creates in the core the poles S_1N_1, and the flux joining them in the core has the general direction of the dotted lines. In consequence, as a result of the simultaneous magnetic action of pole pieces and current, two magnetic forces lying perpendicular to each other are superimposed, the one on the other, and their resultant may be found in the usual manner.

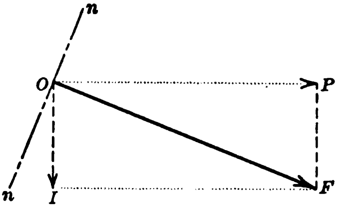


FIG. 130.

In Fig. 130 let OP, by its direction and length, represent the direction and intensity of the flux S_1N_1, and similarly let OI represent the flux S_2N_2. The resultant flux is then shown by OF, and its general direction relative to core and pole pieces is indicated by the two full lines FF in Fig. 131 and more in detail by Fig. 132. From the latter it will be perceived that the flux is concentrated in the upper half of the positive pole piece and the lower half of the negative pole piece. Such concentration increases the saturation of the iron and the length of the path of the flux, both in iron and in air, thereby in turn increasing the reluctance of the magnetic circuit. Both of these factors decrease the flux.

It is clear that the field is now distorted in **the direction of the rotation of the armature**, and that the neutral axis, which lies perpendicular to the field, is shifted in the same direction from the

* For clearness the commutator is omitted and the connections of the inductors are supposed to be radial; that is, each brush has the same angular displacement from the vertical diameter as the element which it short-circuits.

vertical position which it occupies when no current flows in the armature winding. The broken-dotted line *nn*, perpendicular to *OF*, in Figs. 130, 131 and 132, is the neutral axis. If the brushes are to be so placed as to be in contact with the commutator segments of in-

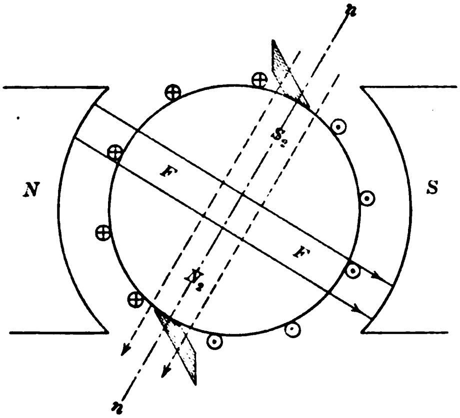


FIG. 131.

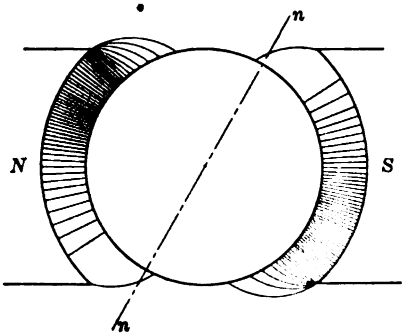


FIG. 132.

ductors moving parallel to the field they must be advanced until they lie on *nn*, as in Fig. 131. But when thus advanced the direction of current flow in the armature inductors and of the magnetic flux due to the current becomes as indicated in Fig. 131; the oblique direction of the current flux further distorts the field, shifting clockwise the line *OI* and, consequently, *OF* and *nn* in Fig. 130, which necessitates giving the brushes greater advance, and thereby again the field is distorted. This process continues until finally the axis of commutation coincides with the neutral axis. If, in Fig. 130, an arc of a circle be described about *P* as a center with a radius equal to *OI* it will contain all the positions of *F* resultant from the rotation of *OI* about *O;* and when *OF* is tangent to the arc further clockwise rotation of *OI* will cause *OF* to move towards *OP;* or, in other words, reduce the distortion of the field. This construction is used in Fig. 133. Here *OF'* is the final direction of the field; the angle $OF'P = F'OI = 90°$,

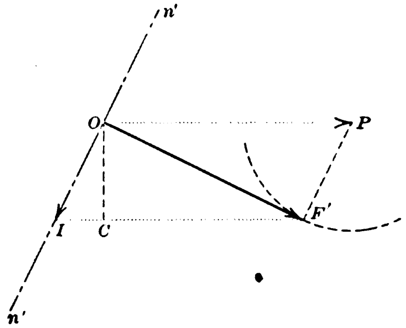


FIG. 133.

and *n'n'*, the neutral axis perpendicular to *OF'*, coincides with *OI,* the axis of commutation.

OI may be resolved into a component *OC* perpendicular to the field of the pole pieces, and a component *CI,* parallel but opposed to the field of the pole pieces. The former is the **cross-magnetizing** component, tending to distort the field; the latter the **demagnetizing** component, tending to weaken the field. The effects of both may be neutralized by increasing the magnetomotive force of the poles.

In a motor the armature reaction shifts the neutral axis in a direction **opposed to the direction of rotation.** This will be made evident if the directions of the current in the armature shown by Fig. 129 are considered reversed, as would be the case were the machine a motor.

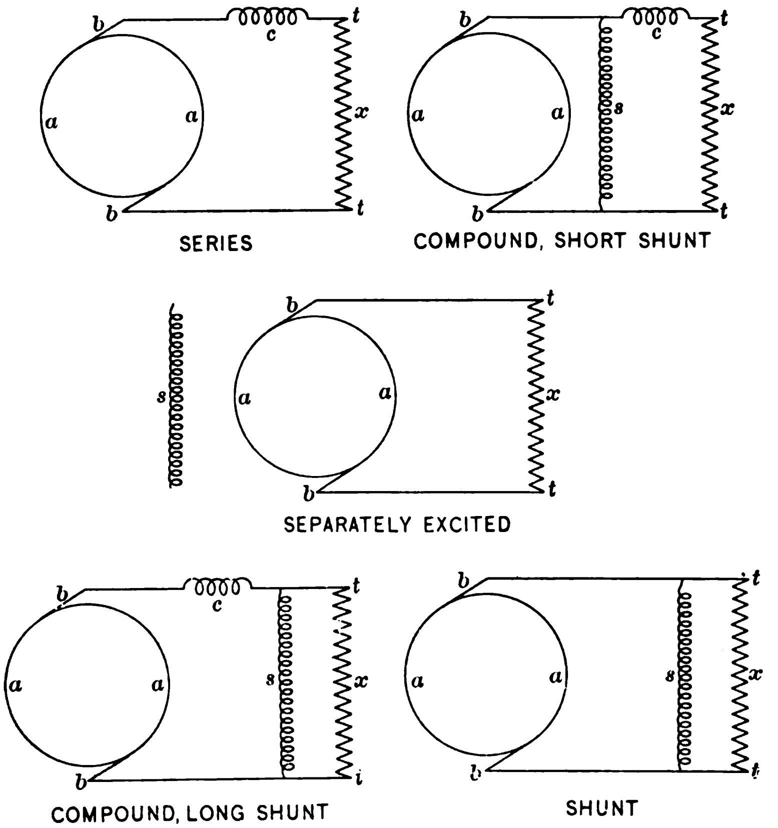


FIG. 134.—Dynamo Windings.

Dynamo Windings.—Fig. 134 consists of elementary diagrams of the connections of dynamo windings. In these diagrams the various parts are:

a, armature winding,
b, brushes,
c, series field circuit,
s, shunt field circuit,
t, terminals,
x, external circuit.

Problems.

In solving problems dealing with the physics of the dynamo, reliance should be placed on a thorough comprehension of the principles explained in Chapters X and XI, and the use of formulæ should be avoided. If the diagrams of Fig. 134 are kept in mind, current values and copper losses can be easily calculated by the application of Ohm's law. Dynamo circuits may frequently be treated as divided circuits and dealt with according to Kirchoff's laws.

1. A straight conductor, 2 meters long, lying perpendicular to a magnetic field of intensity 8000, is moved across the field in a direction perpendicular to itself and the field at a velocity of 30 meters per second. The conductor forms part of a circuit whose resistance is 6 ohms. Find (a) the drag on the conductor, and (b) the power expended in moving it. [Neglect losses.]

Solution.

(a) $E_a = 200 \times 8000 \times 3000 = 48 \times 10^8$ abvolts $= 48$ volts.

$$I = \frac{48}{6} = 8 \text{ amperes} = \frac{8}{10} \text{ abamperes.}$$

$$F = \frac{8}{10} \times 200 \times 8000 = 1{,}280{,}000 \text{ dynes.}$$

(b) $P = 48 \times 8 = 384$ watts.

2. A straight conductor, 50 centimeters long, lies parallel to the left-hand edge of the paper. The positive direction of the lines of force of a uniform magnetic field of intensity 4000 is perpendicular to the paper from up-down. The conductor is moved to the right in the plane of the paper at a uniform velocity of 20 meters per second. It forms part of a closed circuit of 2 ohms resistance. (a) What current flows in the conductor? (b) In what direction does it flow? (c) What is the drag on the conductor? (d) What is the power expended in moving the conductor? (e) What is the electrical power developed?

Ans. (a) 2 amperes, (b) up, (c) 40,000 dynes, (d), (e) 8 watts.

3. A compound-wound long shunt generator delivers 198 amperes to the receiving circuit at a terminal E. M. F. of 100 volts. Resistance of armature winding, 0.15 ohm; series field, 0.05 ohm; shunt field, 50 ohms. The driving engine develops 50 horse-power (shaft). Find the (a) lost amperes, (b) lost volts, (c) armature current, (d) armature E. M. F., (e) copper loss, (f) stray loss, (g) efficiency of conversion, (h) electrical efficiency, (i) commercial efficiency.

Solution.

NOTE.—The lost amperes are the shunt current; the lost volts, the armature and series field drop. They are so-called because they are unavailable for work in the external circuit.

(a) $I_s = \frac{E_x}{r_s} = \frac{100}{50} = 2$ amperes.

(c) $I_a = I_x + I_s = 198 + 2 = 200$ amperes.

(b) $I_a(r_a + r_c) = 200(.15 + .05) = 40$ volts.

(d) $E_a = E_x + I_a(r_a + r_c) = 100 + 40 = 140$ volts.

(e) $F_s = I_s^2 r_s = 4 \times 50 = 200$ watts,

or $F_s = I_s \times E_x = 2 \times 100 = 200$ watts.

$F_c + A = I_a^2 r_c + I_a^2 r_a = \overline{200}^2 \times .2 = 8000$ watts,

or $F_c + A = I_a \times$ lost volts $= 200 \times 40 = 8000$ watts.

$F_s + F_c + A = 200 + 8000 = 8200$ watts,

or $F_s + F_c + A = E_a I_a - E_x I_x = 140 \times 200 - 100 \times 198 = 8200$ watts.

(f) $S = P_m - E_a I_a = 50 \times 746 - 140 \times 200 = 37{,}300 - 28{,}000 = 9300$ watts.

(g) Efficiency of conversion $= \frac{E_a I_a}{P_m} = \frac{28{,}000}{37{,}300} = 75$ per cent.

(h) Electrical efficiency $= \frac{E_x I_x}{E_a I_a} = \frac{19{,}800}{28{,}000} = 70.7$ per cent.

(i) Commercial efficiency $= \frac{E_x I_x}{P_m} = \frac{19{,}800}{37{,}300} = 53$ per cent.

4. A series generator delivers 50 amperes to the external circuit at a terminal E. M. F. of 55 volts. Resistance of series field 0.04 ohm, of armature 0.06 ohm. Shaft horse-power 5. Find (a) copper loss, (b) stray loss, (c) the three efficiencies.

Ans. (a) 250 watts, (b) 730 watts, (c) 80.46 per cent, 91.7 per cent, 73.7 per cent.

5. A shunt generator supplies a lighting circuit with 100 amperes at 120 volts. Resistance of armature 0.05 ohm, of shunt field, 40 ohms. Stray power loss, 200 watts. Find (a) armature current, (b) lost volts, (c) field power loss, (d) armature power loss, (e) armature power, (f) power input.

Ans. (a) 103 amperes, (b) 5.15 volts, (c) 360 watts, (d) 530.45 watts, (e) 12,890.45 watts, (f) 13,090.45 watts.

6. A compound-wound short shunt generator generates an armature E. M. F. of 150 volts and an armature current of 60 amperes. Resistance of armature 0.1 ohm, of shunt field, 48 ohms, of series field, 0.05 ohm. Find (a) E. M. F. at brushes, (b) shunt current, (c) external current, (d) E. M. F. at terminals, (e) copper loss.

Ans. (a) 144 volts, (b) 3 amperes, (c) 57 amperes, (d) 141.15 volts, (e) 954.45 watts.

7. A shunt generator, armature resistance 0.05 ohm; field resistance 18 ohms, terminal electromotive force, 108 volts, supplies current to a lighting circuit, resistance of mains 0.2 ohm. (a) How many lamps in parallel, each taking 0.75 ampere and having a resistance of 130 ohms,

can be operated? (b) What is the power developed in the armature? (c) What is the external power? (d) If the commercial efficiency is 82 per cent what horse-power is applied to the armature shaft?

Solution.

(a) $x =$ number of lamps. $r_x = .2 + \frac{130}{x}$. $I_x = \frac{E_x}{r_x} = \frac{108}{.2 + \frac{130}{x}} = .75x$.
$x = 70$.

(b) $I_x = 70 \times .75 = 52.5$. $I_s = \frac{E_x}{r_s} = \frac{108}{18} = 6$. $I_a = I_x + I_s = 58.5$.
$E_a = E_x + I_a r_a = 108 + 58.5 \times .05 = 110.93$.
$E_a I_a = 110.93 \times 58.5 = 6489.5$ watts.

(c) $E_x I_x = 108 \times 52.5 = 5670$ watts.

(d) $.82 = \frac{E_x I_x}{P_m} = \frac{5670}{\text{H. P.} \times 746}$; H. P. $= 9.26$.

8. A shunt generator, armature resistance 0.02 ohm; field resistance 20 ohms, terminal voltage 80 volts; supplies current to a circuit whose resistance is 0.4 ohm. Find (a) the armature current, (b) lost volts, (c) the copper loss.

Ans. (a) 204 amperes, (b) 4.08 volts, (c) 1152.32 watts.

9. A shunt generator, armature electromotive force 100 volts, resistance of armature 0.12 ohm, of field 16 ohms, supplies current to 75 lamps in parallel, each lamp having a resistance of 100 ohms. Resistance of mains 0.2 ohm. Find (a) the external current, (b) the copper loss.

Solution.

(a) $r_x = .2 + \frac{100}{75} = 1.53$. Let R be total resistance of the complete electrical circuit.

$$R = r_a + \frac{1}{\frac{1}{r_s} + \frac{1}{r_x}} = .12 + \frac{1}{\frac{1}{16} + \frac{1}{1.53}} = 1.52.$$

$$I_a = \frac{E_a}{R} = \frac{100}{1.52} = 65.8. \quad I_a r_a = 65.8 \times .12 = 7.9.$$

$$E_x = E_a - I_a r_a = 100 - 7.9 = 92.1.$$

$$I_s = \frac{E_x}{r_s} = \frac{92.1}{16} = 5.8. \quad I_x = I_a - I_s = 65.8 - 5.8 = 60 \text{ amperes.}$$

(b) $E_x I_s = 92.1 \times 5.8 = 534.2$.
$I_a^2 r_a = \overline{65.8}^2 \times .12 = 519.6$.
$F_s + A =$ 1053.8 watts.

10. A compound-wound long shunt generator generates an armature E. M. F. of 130 volts and supplies current to a lighting circuit consisting of 40 incandescent lamps in parallel, each of 240 ohms resistance (hot).

Resistance of mains negligible. The resistance of the armature is 0.15 ohm, of the series field, 0.05 ohm, of the shunt field, 30 ohms. The driving engine develops 5 horse-power. Calculate (a) the current supplied the lighting circuit, (b) the terminal voltage, (c) the heat loss in each field and in the armature winding, (d) the stray loss, (e) the efficiency of conversion, electrical and commercial efficiencies.

Ans. (a) 20.83 amperes; (b) 125 volts; (c) F_s, 521.5 watts, F_c, 31.25 watts, A, 93.75 watts; (d) 480 watts; (e) 87.1 per cent, 80.1 per cent, 69.8 per cent.

11. In a given generator, the loss in the armature is 1000 watts, in the field magnets 600 watts, hysteresis and other losses 280 watts, loss in engine 5920 watts. If 57,800 watts are supplied to the engine, how many 16 c. p. lamps at 4 watts per c. p. can be lighted? What is the commercial efficiency of the plant?

Ans. No. of lamps 781.
Commercial efficiency 86.5 per cent.

12. A long shunt compound-wound generator, working with 3.6 ohms in the regulator, is furnishing a current in the external circuit of 117 amperes with a difference of potential at the terminals of 108 volts. The resistance of the shunt is 32.4 ohms, of the series field .015 ohm, and of the armature .045 ohm. Calculate (a) the lost volts, (b) current in armature, (c) current in the field coils and (d) the efficiencies, the power applied at the shaft being 20 H. P.

Ans. (a) 7.2 volts, (b) 120 amperes, (c) 3 amperes, (d) 92.65 per cent, 91.4 per cent, 84.69 per cent.

13. A compound-wound long shunt generator, resistance of armature .023 ohm, of series field .012 ohm and of shunt 20 ohms, maintains 300 110-volt 20 c. p. lamps, each lamp requiring 4 watts per c. p. Find (a) the total E. M. F. of the machine. Allowing 15 per cent for friction and other losses, find (b) the H. P. of the engine required to run the generator. *Ans.* (a) 117.8 volts, (b) 41.55 H. P.

14. A compound-wound generator, long shunt, maintains a difference of potential between the mains of the external circuit of 80 volts. 260 incandescent lamps of 16 c. p. each are placed in multiple arc between the mains, each lamp requiring 4 watts per c. p. The resistance of the armature is .02 ohm, series coils .005 ohm, and shunt current is 7 amperes. Find the efficiency of conversion, net, and electrical efficiencies when 26 H. P. is applied to the shaft of the generator.

Ans. 94.61 per cent, 90.65 per cent, 85.77 per cent.

15. A long shunt compound-wound generator maintains a difference of potential of 80 volts between the mains of the external circuit. 250 incandescent 16 c. p. lamps are placed in parallel on the mains and each

lamp consumes 4 watts per c. p. Resistance of armature = .0177 ohm, of series coil = .005 ohm. Shunt current = 7 amperes. Find the efficiency of conversion, net, and electrical efficiencies when 25 H. P. is applied to dynamo shaft. *Ans.* 94 per cent, 91 per cent, 86 per cent.

16. The machine in the preceding example develops a total E. M. F. of 83 volts; find the number of 16 c. p. lamps, resistance 100 ohms, placed in parallel that it will maintain, allowing 4 watts per c. p. Resistance of shunt = 5.8 ohms. *Ans.* 148 lamps.

17. A short shunt compound-wound generator delivers 50 amperes of current at 110 volts at the terminals. Calculate the commercial efficiency. Resistance of shunt field 55 ohms, of series field .02 ohm, of armature .14 ohm. All losses except copper losses equal 700 watts.

Ans. 80.3 per cent.

18. Compound-wound long shunt generator; terminal voltage 120 volts; shunt resistance 24 ohms; armature resistance, 0.08 ohm; series field resistance, 0.02 ohm; shaft horse-power, 10; external current 45 amperes. Find (a) armature current, (b) lost volts, (c) heat losses in various windings, (d) stray loss.

Ans. (a) 50 amperes; (b) 5 volts; (c) F_s, 600 watts, F_c, 50 watts, A, 200 watts; (d) 1210 watts.

19. A compound-wound long shunt generator has the following characteristics: $r_a = 0.07$ ohm; $r_c = 0.03$ ohm; $r_s = 40$ ohms; $I_x = 97$ amperes; $E_x = 120$ volts. The generator is driven by an engine which develops 20 H. P. on its shaft. Calculate (a) field losses, (b) armature loss, (c) stray loss, (d) the three efficiencies.

Ans. (a) F_s, 360 watts, F_c, 300 watts; (b) 700 watts; (c) 1920 watts; (d) 87 per cent, 89.5 per cent, 78 per cent.

20. A shunt generator, armature resistance 0.2 ohm, field resistance 50 ohms, delivers 25 amperes to a receiving circuit at a terminal voltage of 100 volts when the field is normally excited and the armature's speed is 1500 r. p. m. (a) What will be the armature E. M. F., the terminal E. M. F., the external current, and the added resistance in the field circuit if the generator's speed is increased to 2000 r. p. m., the field current being kept constant by means of a field rheostat? [Neglect demagnetizing effect of armature current.] (b) What will be the armature E. M. F., the terminal E. M. F., and the external current, when the speed is 2000 r. p. m., if then the field excitation is increased 30 per cent, the field resistance remaining 50 ohms?

Solution.

(a) $r_x = \frac{E_x}{I_x} = \frac{100}{25} = 4,\ I_s = \frac{E_x}{r_s} = \frac{100}{50} = 2.$

$I_a = 25 + 2 = 27,\ E_{a_1} = 100 + 27 \times .2 = 105.4.$

$\frac{E_{a_1}}{E_{a_2}} = \frac{n_1 Z_1 \Phi_1}{n_2 Z_2 \Phi_2}$, $Z_1 = Z_2$, and, since I_s is constant and the demagnetizing effect of the armature current is neglected,

$\Phi_1 = \Phi_2,\ \therefore E_{a_2} = \frac{E_{a_1} \times n_2}{n_1} = \frac{105.4 \times 20}{15} = 140.5$ volts.

$140.5 = .2[I_x + 2] + 4I_x$ (Kirchoff).

$4.2I_x = 140.1.\quad I_x = 33.36$ amperes.

$E_x = I_x r_x = 33.36 \times 4 = 133.44$ volts,

or $E_x = E_a - I_a r_a = 140.5 - 35.36 \times .2 = 133.43$ volts.

$r_s = \frac{E_x}{I_s} = \frac{133.44}{2} = 66.72,\quad 66.72 - 50 = 16.72$ ohms, added by rheostat.

(b) $\frac{E_{a_1}}{E_{a_3}} = \frac{n_1 Z_1 \Phi_1}{n_3 Z_3 \Phi_3}$, $Z_1 = Z_3,\quad \Phi_3 = 1.3\,\Phi_1,$

$\therefore E_{a_3} = \frac{E_{a_1} n_3 \Phi_3}{n_1 \Phi_1} = \frac{105.4 \times 20 \times 1.3}{15} = 182.7$ volts,

or $E_{a_3} = E_{a_2} \times 1.3 = 140.5 \times 1.3 = 182.7$ volts.

$$I_a = \frac{E_a}{R} = \frac{182.7}{.2 + \frac{1}{\frac{1}{50} + \frac{1}{4}}} = \frac{182.7}{3.9} = 46.85.$$

$E_x = 182.7 - 46.85 \times .2 = 173.3$ volts.

$I_x = \frac{E_x}{r_x} = \frac{173.3}{4} = 43.33$ amperes.

The value of I_x may also be obtained by Kirchoff's laws, solving the following equations for I_x:

$$182.7 = .2I_a + 4I_x.$$
$$182.7 = .2I_a + 50I_s.$$
$$I_a = I_s + I_x.$$

21. A shunt generator develops an armature E. M. F. of 150 volts when running at 1200 r. p. m., field normal. What E. M. F. will it generate if (a) the speed is increased to 1500 r. p. m., field unchanged? (b) the field is increased 40 per cent, speed remaining 1200 r. p. m.? (c) the speed is increased to 2000 r. p. m., the normal field decreased 20 per cent, and the armature rewound with twice the number of turns?

Ans. (a) 750 volts, (b) 210 volts, (c) 400 volts.

22. A series generator, internal resistance 0.2 ohm, delivers a current of 50 amperes to an arc light circuit at a terminal voltage of 90 volts

and at a speed of 1000 r. p. m. If the resistance of the external circuit is doubled what must be the speed of the generator to deliver the same current?

Solution.

$$E_{a_1} = E_{x_1} + I_a(r_a + r_c) = 90 + 50 \times .2 = 100.$$
$$E_{x_2} = 2E_{x_1} = 180. \quad E_{a_2} = 180 + 50 \times .2 = 190.$$

Since I_a is constant, Φ is constant, and

$$\therefore \frac{E_{a_1}}{E_{a_2}} = \frac{n_1}{n_2}. \quad \frac{100}{190} = \frac{1000}{n_2}. \quad n_2 = 1900 \text{ r. p. m.}$$

23. A series generator, internal resistance 0.2 ohm, delivers a current of 50 amperes to a certain circuit at a terminal voltage of 90 volts when the speed is 1000 r. p. m. At what speed must it be driven to deliver a current of 80 amperes to the same circuit, assuming that the increased current increases the field excitation of the generator 25 per cent?
Ans. 1280 r. p. m.

24. A series generator, internal resistance 0.2 ohm, delivers a current of 50 amperes to a certain circuit at a terminal E. M. F. of 90 volts, when speed is 1000 r. p. m. At what speed must it be driven to deliver a current of 80 amperes to the same circuit, assuming that such increased current increases the field excitation 25 per cent, and that the armature is rewound with twice as many turns as originally, resistance of armature remaining unaltered? *Ans.* 424 r. p. m.

25. A shunt generator, armature resistance 0.2 ohm, field resistance 24 ohms including rheostatic resistance, delivers, when running at 1200 r. p. m., 60 amperes to a lighting circuit consisting of 130 lamps in parallel, each of 260 ohms resistance; resistance of mains and branches negligible. If one-half of the lamps are extinguished at what speed must the generator be run to maintain a constant terminal E. M. F., (a) if the field flux remains unchanged, (b) if the field flux is increased 40 per cent by means of the field rheostat? Assume field current proportional to field flux. *Ans.* (a) 1146 r. p. m.; (b) 821 r. p. m.

26. A shunt generator runs at constant speed and its voltage is controlled by a rheostat in the field circuit. Resistance of armature 0.2 ohm. It delivers current at a constant terminal voltage of 120 volts to a lighting circuit consisting of incandescent lamps in parallel, each taking one-half ampere. When the resistance of the field circuit including rheostat is 60 ohms, 96 lamps are supplied with full current. Assuming that the field current varies as the square of the field flux, what must be the resistance of the shunt field circuit, including rheostat, when 600 lamps are supplied with full current? *Ans.* 30.6 ohms.

27. A current of 10 amperes is sent through a series of 10 arc lamps, each of 3.8 ohms resistance, by a generator whose armature is making

1000 revolutions a minute. The arc lamps are then replaced by 8 incandescent lamps, each of 120 ohms resistance and arranged in 4 series of 2 each; the armature is then made to turn at 1044 revolutions per minute. The resistance of the generator is 3 ohms. Assuming that the E. M. F. developed is proportional to the speed; find the strength of current in each lamp. *Ans.* 1.7 amperes.

28. A given shunt generator gives a total E. M. F. of 100 volts when run at a speed of 1000 revolutions per minute. The shunt resistance is 50 ohms. What total E. M. F. will this generator induce if run at a speed of 1500 revolutions per minute, if the shunt field is kept constant? What will have to be the resistance of the shunt to keep the field constant? Neglect the resistance of the armature. *Ans.* E. M. F. 150 volts.
Resist. 75 ohms.

29. The total E. M. F. of a shunt generator decreases from 125 volts to 100 volts when the speed is reduced from 1200 to 1000 revolutions per minute. The armature flux at the higher speed is 10,000,000 lines. (1) What is the armature flux at the lower speed? (2) What would be the E. M. F. of the generator at the lower speed if the armature flux were kept constant at 10,000,000 lines? *Ans.* 9,600,000 lines.
E. M. F. = 104.2 volts.

30. A series generator has a combined armature and field resistance of .1 ohm. It gives a terminal voltage of 98 volts with a current of 20 amperes when driven at a speed of 1200 revolutions per minute. Find the terminal voltage if when driven at a speed of 1500 revolutions per minute, it delivers a current of 30 amperes, assuming this current increases the field flux by 50 per cent. *Ans.* 184.5 volts.

31. A series generator, internal resistance 0.2 ohm, delivers 10 amperes at 100 volts when the speed is 1020 r. p. m. When run at 5000 r. p. m. its current is 25 amperes and the field flux is doubled. Find its terminal voltage at the higher speed. *Ans.* 295 volts.

32. A straight wire, 1 meter long, resistance 0.2 ohm, lies perpendicular to the lines of a magnetic field of intensity 5000, and is free to move. When its terminals are connected to a battery having an electromotive force of 10 volts and a resistance of 4.8 ohms the wire moves across the field. At the instant when the current flowing through the wire is 1 ampere with what (a) velocity and (b) force is the wire moving? (c) What E. M. F. is induced in it? (d) At what rate is it doing work?

Solution.

(a) $E_a = E - I(r_a + r_x) = 10 - 1 \times (.2 + 4.8) = 5.$
$5 \times 10^8 = 100 \times 5000 \times v. \quad v = 1000$ cm. per second.

(b) $F = 100 \times 5000 \times \frac{1}{10} = 50{,}000$ dynes.

(c) $E_a = 5$ volts.

(d) $E_a I_a = 5 \times 1 = 5$ watts,
or $W = Fv = 50{,}000 \times 1000 = 5 \times 10^7$ ergs per second.

33. A straight conductor 2 meters long, of resistance 2 ohms, lying perpendicular to the lines of a magnetic field of intensity 8000, is connected to the terminals of a battery of 80 volts E. M. F. and 4 ohms internal resistance. When a current of 8 amperes flows in the conductor with what (a) velocity and (b) power is the conductor moving? *Ans.* (a) 2000 centimeters per second, (b) 256 watts.

34. A straight conductor 1 meter long, free to move, lies perpendicular to a magnetic field of intensity 5000. The terminals of the conductor are connected to a battery whose E. M. F. is 10 volts. The total resistance of the circuit so formed is 2 ohms. At the instant when the battery is sending a current of 1 ampere through the wire with what (a) force and (b) velocity is the wire moving? (c) What is the maximum velocity which the conductor could attain?

Ans. (a) 50,000 dynes, (b) 1600 centimeters per second, (c) 2000 centimeters per second.

35. A shunt motor whose armature resistance is 0.5 ohm and whose terminal voltage is 100 volts, takes an armature current of 20 amperes and runs at 1800 r. p. m. when the field is fully excited. If the field is decreased and the armature current increases, both by 50 per cent, at what speed does the motor run?

Solution.

$$E_a = E_x - I_a r_a. \quad E_{a_1} = 100 - 20 \times .5 = 90.$$
$$E_{a_2} = 100 - 30 \times .5 = 85.$$
$$\frac{E_{a_1}}{E_{a_2}} = \frac{n_1 \Phi_1 Z_1}{n_2 \Phi_2 Z_2}. \quad \Phi_1 = 2\Phi_2. \quad Z_1 = Z_2.$$
$$\therefore \frac{90}{85} = \frac{1800 \times 2}{n_2}. \quad n_2 = \frac{85 \times 1800 \times 2}{90} = 3400 \text{ r. p. m.}$$

36. A shunt motor has an armature resistance of 0.5 ohm and takes current from constant potential 90-volt mains. When the armature current is 6 amperes and the field is normally excited the motor's speed is 1200 r. p. m. (a) If the motor is loaded until the armature current is 64 amperes, what is the speed? (b) If, with the armature current 64 amperes, the field excitation is decreased 50 per cent, what is the speed? *Ans.* (a) 800 r. p. m., (b) 1600 r. p. m.

37. A shunt motor, armature resistance 0.5 ohm, runs at 1800 r. p. m. when the terminal voltage is 120 volts and the armature current is 40 amperes. The motor delivers a constant electrical torque (*i. e.*, mechanical load and stray loss constant). If the terminal voltage falls to 105 volts, thereby decreasing the field excitation 20 per cent, what (a) armature current will the motor take, and (b) what will be its speed?

Solution.

(a) $T_a = \frac{\Phi Z I_a}{2\pi}$. $T_{a_1} = T_{a_2}$. $Z_1 = Z_2$.

$\therefore \frac{I_{a_1}}{I_{a_2}} = \frac{\Phi_2}{\Phi_1}$. $\frac{40}{I_{a_2}} = \frac{80}{100}$. $I_{a_2} = \frac{40 \times 100}{80} = 50$ amperes.

(b) $E_{a_1} = 120 - 40 \times .5 = 100$. $E_{a_2} = 105 - 50 \times .5 = 80$.

$\frac{E_{a_1}}{E_{a_2}} = \frac{n_1\Phi_1}{n_2\Phi_2}$. $\frac{100}{80} = \frac{1800 \times 100}{n_2 \times 80}$.

$n_2 = \frac{1800 \times 100 \times 80}{100 \times 80} = 1800$ r. p. m.

38. A shunt motor, armature resistance 0.5 ohm, stray loss and mechanical load constant, takes an armature current of 20 amperes and runs at 1800 r. p. m. when the terminal voltage is 120 volts. Assuming field flux proportional to ampere turns of field, what would be the speed and armature current (a) if the terminal voltage should drop to 80 volts, resistance of field circuit unaltered; (b) if, with the terminal voltage 120 volts, the armature should be rewound with twice the original number of turns, using wire of double cross-sectional area?

Solution.

(a) $\frac{I_{a_1}}{I_{a_2}} = \frac{\Phi_2}{\Phi_1}$. Φ is proportional to I_s, which is proportional to E_x.

$\therefore \frac{I_{a_1}}{I_{a_2}} = \frac{80}{120}$,

or $I_{a_2} = \frac{120 \times 20}{80} = 30$ amperes.

$E_{a_1} = 120 - 20 \times .5 = 110$. $E_{a_2} = 80 - 30 \times .5 = 65$.

$\frac{E_{a_1}}{E_{a_2}} = \frac{n_1\Phi_1}{n_2\Phi_2}$. $\frac{110}{65} = \frac{1800 \times 120}{n \times 80}$. $n = 1595.5$ r. p. m.

(b) $\frac{I_{a_1}}{I_{a_2}} = \frac{\Phi_2 Z_2}{\Phi_1 Z_1}$. $\Phi_1 = \Phi_2$. $2Z_1 = Z_2$.

$\frac{20}{I_{a_2}} = \frac{2}{1}$. $I_{a_2} = 10$ amperes. $r_{a_1} = r_{a_2}$.

$E_{a_1} = 120 - 20 \times .5 = 110$. $E_{a_2} = 120 - 10 \times .5 = 115$.

$\frac{E_{a_1}}{E_{a_2}} = \frac{n_1 Z_1}{n_2 Z_2}$. $\frac{110}{115} = \frac{1800 \times 1}{n_2 \times 2}$. $n_2 = 941$ r. p. m.

39. A shunt motor, armature resistance 0.5 ohm, supply voltage 100 volts, runs at 1400 r. p. m. when the field is fully excited and the armature current is 2 amperes. If the field excitation is decreased to 60 per cent of its former strength and the load is increased until the armature current is 10 amperes, what is the motor's speed?

Ans. 2239 r. p. m.

40. A shunt motor, armature resistance 0.2 ohm, terminal voltage 70 volts, runs at 600 revolutions per minute and takes an armature current of 30 amperes. What resistance must be added in series with the armature to decrease the speed to 400 r. p. m., armature current unchanged?

Solution.

$$E_{a_1} = 70 - 30 \times .2 = 64. \quad E_{a_2} = 70 - 30(.2 + x).$$

$$\frac{n_1}{n_2} = \frac{E_{a_1}}{E_{a_2}}. \quad \frac{600}{400} = \frac{64}{64 - 30x}.$$

$$192 - 90x = 128. \quad x = .71 \text{ ohm.}$$

41. A shunt motor delivers a constant armature torque. Its field flux is to be considered proportional to the field ampere turns. A rheostat (variable resistance) is in series with the armature and another rheostat is in series in the field circuit. Resistance of field circuit 40 ohms, exclusive of rheostatic resistance. Resistance of armature, 0.4 ohm. Terminal voltage 120 volts. With resistance of both rheostats zero motor takes an armature current of 10 amperes and makes 2320 r. p. m. Find speed and armature current (a) when field rheostat has a resistance of 20 ohms, and armature rheostat has a resistance of 5 ohms, simultaneously; (b) when, with both rheostats having zero resistance, armature is rewound with twice as many turns as originally, using wire of the same cross-sectional area (*i. e.*, r_a is doubled).

Ans. (a) 15 amperes, 1170 r. p. m.
(b) 5 amperes, 1160 r. p. m.

42. A series motor, internal resistance 0.5 ohm, takes an armature current of 20 amperes at a terminal voltage of 110 volts and runs at 1200 r. p. m. When run as a generator at 1800 r. p. m. it delivers the same armature current. What is its terminal voltage as a generator?

Solution.

Motor: $E_a = 110 - 20 \times .5 = 100.$

Generator: $E_a = 100 \times \frac{1800}{1200} = 150.$ [Φ is constant.]

$E_x = 150 - 20 \times .5 = 140.$

43. A shunt motor, stray loss constant, terminal voltage 100 volts, field resistance 50 ohms, armature resistance 0.3 ohm, takes an armature current of 20 amperes when there is a pull of 7 pounds on the

end of the arm of a friction brake on the motor's shaft. Length of arm, 1¼ feet. Motor's speed is 1200 r. p. m. Calculate (a) the motor's output and (b) the stray loss. If the pull on the arm is increased to 14 pounds, what is (c) the armature torque, (d) the armature current, and (e) the speed?

Solution.

(a) $P_m = 2\pi nT = 2 \times \frac{22}{7} \times 20 \times 7 \times 1.25 \times \frac{746}{550} = 1492$ watts.

(b) $I_s = \frac{100}{50} = 2.$ $I_x = I_a + I_s = 20 + 2 = 22.$

$E_x I_x = 100 \times 22 = 2200.$ $F_c = E_x I_s = 100 \times 2 = 200.$

$A = I_a^2 r_a = \overline{20}^2 \times .3 = 120.$ $E_x I_x - F_c - A = 1880 = E_a I_a.$

[Or: Armature input $= 100 \times 20 = 2000;$ $2000 - \overline{20}^2 \times .3 = 1880.$]

$S = E_a I_a - P_m = 1880 - 1492 = 388$ watts.

(c) $\frac{T_a}{T_m} = \frac{E_a I_a}{P_m}.$ $\frac{T_{a_1}}{7 \times 1.25} = \frac{1880}{1492}.$ $T_{a_1} = 11.03.$

$T_s = T_{a_1} - T_{m_1} = 11.03 - 7 \times 1.25 = 2.28.$

$T_{m_2} = 14 \times 1.25 = 17.5.$ $T_{a_2} = T_{m_2} + T_s = 17.5 + 2.28 = 19.78$ pounds-feet.

(d) $\frac{I_{a_1}}{I_{a_2}} = \frac{T_{a_1}}{T_{a_2}}.$ $\frac{20}{I_{a_2}} = \frac{11.03}{19.78}.$ $I_{a_2} = \frac{20 \times 19.78}{11.03} = 35.86$ amperes.

(e) $E_{a_1} = 100 - 20 \times .3 = 94.$ $E_{a_2} = 100 - 35.86 \times .3 = 89.24.$

$\frac{94}{89.24} = \frac{1200}{n_2}.$ $n_2 = \frac{1200 \times 89.24}{94} = 1139$ r. p. m.

44. A shunt motor, armature resistance 0.2 ohm, terminal voltage 220, delivers a constant electrical torque and runs at 1500 r. p. m. when the field is normally excited and the armature current is 50 amperes. (a) At what speed will it run if, by means of a regulator, the resistance of the field circuit is doubled? Consider field excitation proportional to ampere turns of field winding. (b) What then will be the armature current? *Ans.* (a) 2857 r. p. m., (b) 100 amperes.

45. When the field of the machine in Problem 44 is normally excited, what resistance must be added in series with the armature to make the speed 1200 r. p. m.? *Ans.* .84 ohm.

46. A shunt motor connected to 110-volt mains when unloaded takes 3 amperes in the armature and runs at a speed of 997 revolutions per minute. The armature resistance is .11 ohm. Calculate the resistance that must be connected in series with the armature to reduce its speed to 800 revolutions per minute when the armature current is 50 amperes. *Ans.* .33 ohm.

47. In the preceding example the shunt current was 2.6 amperes and at full load, 50 amperes, the actual speed was 980 revolutions per

minute. This machine is now driven as a generator at a speed of 980 revolutions per minute and the field rheostat is adjusted to give the same field current as before. Find (a) the terminal voltage of the generator when the armature current is 50 amperes, and the difference in the resistance of the field (field and rheostat) in the two cases when acting (b) as a generator, and (c) as a motor.

Ans. (a) 99 volts, (b) 38.1 ohms, (c) 42.3 ohms.

48. A shunt motor has an armature resistance of .04 ohm and a shunt resistance of 20 ohms. A current of 36 amperes is supplied at an E. M. F. of 80 volts; the armature makes 1500 revolutions a minute, giving a tangential pull of 44 pounds at the surface of a pulley whose circumference is 18 inches. Find (a) the loss by heat in the armature and field, (b) the counter E. M. F., (c) the current in the armature and shunt, and (d) the efficiency (net).

Solution.

(c) $I_s = \frac{80}{20} = 4. \quad I_a = I_x - I_s = 36 - 4 = 32.$

(a) $A = I_a^2 r_a = \overline{32}^2 \times .04 = 40.96$ watts.

$F_s = E_x I_s = 80 \times 4 = 320$ watts.

$A + F_s = 360.96$ watts.

(b) $E_a = E_x - I_a r_a = 80 - 32 \times .04 = 78.72$ volts.

(d) $P_m = 2\pi nT = 2 \times \frac{22}{7} \times \frac{1500}{60} \times 44 \times \frac{1.5}{2 \times \frac{22}{7}}$ foot-pounds per second.

$P_m = \frac{1650}{550} \times 746 = 2238$ watts.

$E_x I_x = 80 \times 36 = 2880$ watts.

Net efficiency $= \frac{P_m}{E_x I_x} = \frac{2238}{2880} = 77.7$ per cent.

49. A shunt motor has a field resistance of $33\frac{1}{3}$ ohms, and an armature resistance of .06 ohm. The difference of potential is 100 volts and the current 48 amperes. The radius of the pulley is 3 inches. The difference of the weights of a flexible band dynamometer is 63 pounds and the number of revolutions is 1800 per minute. Required: the efficiencies, and the loss in heating the coils.

Solution.

$I_s = \frac{E_x}{r_s} = \frac{100}{33\frac{1}{3}} = 3. \quad I_a = I_x - I_s = 48 - 3 = 45.$

$E_a = E_x - I_a r_a = 100 - 45 \times .06 = 97.3.$

$E_x I_x = 100 \times 48 = 4800.0.$

$E_a I_a = 97.3 \times 45 = 4378.5.$

$E_x I_x - E_a I_a = A + F_s =$ 421.5 watts.

$P_m = 2\pi nT = 2 \times \frac{22}{7} \times \frac{1800}{60} \times \frac{1}{4} \times 63 = 2970$ foot-pounds per second.

$P_m = \frac{2970}{550} \times 746 = 4028$ watts.

Efficiency of conversion $= \frac{E_a I_a}{E_x I_x} = \frac{4378.5}{4800} = 91.2$ per cent.

Mechanical efficiency $= \frac{P_m}{E_a I_a} = \frac{4028}{4378.5} = 92$ per cent.

Commercial efficiency $= \frac{P_m}{E_x I_x} = \frac{4028}{4800} = 83.9$ per cent.

50. In a shunt motor, resistance of field coils 50 ohms, of armature .2 ohm, total current entering 25 amperes, difference of potential 100 volts, H. P. as indicated by dynamometer 2.75; find the efficiencies.

Ans. 87.7 per cent, 93.5 per cent, 82 per cent.

51. An electric motor, shunt, has an armature resistance of .055 ohm and field resistance of 32 ohms. When making 1400 revolutions per minute the tangential pull on a pulley 7.6 centimeters radius is 25 kilos. The current supplied to the motor at a voltage of 105 is 35 amperes. Calculate (a) the counter E. M. F., (b) the heating effect, and (c) the gross and true efficiencies.

Ans. (a) 103.26 volts; (b) 400 watts; (c) 89 per cent, 74.4 per cent.

52. The motor of a motor generator is compound-wound long shunt, maintains a constant speed, and is connected to 120-volt supply mains. Resistance of shunt field, 30 ohms; of series field 0.02 ohm; of armature, 0.06 ohm. The generator is series wound; internal resistance, 0.1 ohm. (a) Find the terminal voltage of the generator when it delivers 40 amperes to an arc lamp circuit, assuming that then the power input of the motor is 6.48 kilowatts; that the motor delivers 5.4 kilowatts to the generator and that the stray losses of the two machines are equal. (b) Find the motor's output and its mechanical efficiency when the current delivered by the generator is 80 amperes, assuming that such increased load increases the field strength and stray loss of the generator 60 per cent and decreases the stray loss of the motor 20 per cent.

[NOTE.—A motor generator consists of a motor and a generator whose armatures are mounted on the same shaft, the motor driving the generator.]

Solution.

(a) Motor: $I_x = \frac{E_x I_x}{E_x} = \frac{6480}{120} = 54.$

$I_a = I_x - I_s = 54 - \frac{120}{30} = 50.$

$E_a = E_x - I_a(r_a + r_c) = 120 - 50 \times .08 = 116.$

$S = E_a I_a - P_m = 116 \times 50 - 5400 = 400.$

Generator: $E_a I_a = P_m - S = 5400 - 400 = 5000.$

$E_a = \frac{E_a I_a}{I_a} = \frac{5000}{40} = 125.$

$E_x = E_a - I_a(r_a + r_c) = 125 - 40 \times .1 = 121$ volts.

(b) Generator: $\frac{E_a}{125} = \frac{1.6\Phi}{\Phi}$. $E_a = 125 \times 1.6 = 200.$

$E_a I_a = 200 \times 80 = 16{,}000.$

$P_m = E_a I_a + S = 16{,}000 + 400 \times 1.6 = 16{,}640$ watts.

Motor: $E_a I_a = P_m + S = 16{,}640 + 400 \times .8 = 16{,}960.$

Mechanical efficiency $= \frac{P_m}{E_a I_a} = \frac{16{,}640}{16{,}960} = 98$ per cent.

53. The field current of a shunt motor is 5 amperes and its armature resistance is 0.5 ohm. It drives as a generator a machine whose construction is identical with that of the motor and whose field is regulated to have the same field current. Assuming that the stray loss of each machine is 200 watts, find the motor input when the generator delivers 31 amperes to the external circuit at a terminal voltage of 82 volts.

Ans. 5400 watts.

54. The motor and the generator of a motor generator are shunt-wound machines having lap-wound drum armatures carrying 100 inductors, armature resistance 0.5 ohm. The terminal voltage of the motor is 120 volts; the field resistance 20 ohms; the field flux 5×10^6 lines. The field resistance of the generator is 30 ohms. When the motor generator runs at 1200 r. p. m. the field flux of the generator is 4×10^6 lines, and the total stray loss of the motor generator is 800 watts. Find (a) the current supplied to, and (b) the current delivered by the motor generator. *Ans.* (a) 46 amperes, (b) 38 amperes.

55. The motor and the generator of a motor generator are shunt-wound machines having lap-wound drum armatures carrying 180 inductors; armature resistance 0.5 ohm. The motor takes an armature current of 32 amperes; its field resistance is 20 ohms; its field flux 4×10^6 lines. The field resistance of the generator is 30 ohms; the field flux 3×10^6 lines. The speed of the motor generator is 1200 r. p. m. The generator produces an armature current of 36 amperes. Find (a) the commercial efficiency of the motor generator, (b) its total stray loss. *Ans.* (a) 46.4 per cent, (b) 720 watts.

56. A motor generator is built up of a motor and generator mounted on a common shaft. Characteristics of motor: drum-wound armature with 65 complete coils, armature flux 8,000,000 lines; difference of potential at terminals 110 volts; resistance of armature .1 ohm, of shunt winding 44 ohms, external current 62.5 amperes. Characteristics of generator: long shunt, compound wound; ring armature with 120 coils; armature flux 9,200,000 lines; resistance of armature .09 ohm, of series winding .11 ohm, of shunt winding 50 ohms; total external resistance 2 ohms. Calculate the current the generator will deliver.

Ans. 50 amperes.

CHAPTER XII.

THE CONSTRUCTION OF THE DYNAMO.

NOTE.—Many of the illustrations used in this chapter were taken from the catalogues of the Westinghouse Electric and Manufacturing Company and while representing general principles of dynamo construction refer particularly to dynamo machinery manufactured by this company.

Essential Parts and Their Functions.—The earliest dynamos were bipolar, and although this type has become nearly obsolete, for reasons shortly to be given, yet by it the construction of the dynamo

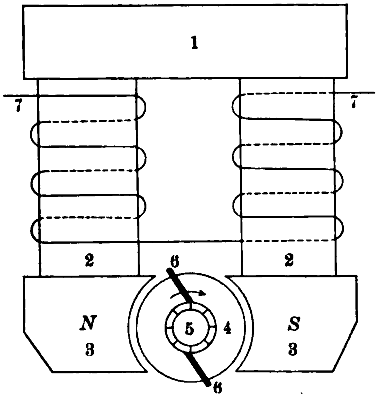


FIG. 135.—Bipolar Dynamo.

can most readily be made plain. Fig. 135 shows a bipolar machine and all the parts essential to any dynamo.* These are as follows: (1) the **yoke,** (2) the **field cores,** (3) the **pole pieces,** (4) the **armature core,** (5) the **commutator,** (6) the **brushes,** (7) the **field winding,** and the **armature winding** (not shown). The **yoke, field cores** and **pole pieces** constitute the **field-magnet frame.**

The field-magnet frame is of iron or steel, and together with the armature core and the air gaps between the core and the pole pieces

*** Except the armature winding, omitted for clearness.**

forms the **magnetic circuit** of the dynamo, or the path of the magnetic flux. The function of the yoke is merely to supply an iron path for the flux, thereby decreasing the reluctance of the magnetic circuit. The function of the field cores is to produce the magnetic flux, either by virtue of the permanent magnetism residual in them or through the exciting effect of the current in the field winding, or both. The function of the pole pieces is to render as nearly uniform as possible the magnetic field in which the armature revolves and to decrease the reluctance of the magnetic circuit by shortening the length of the air gaps.

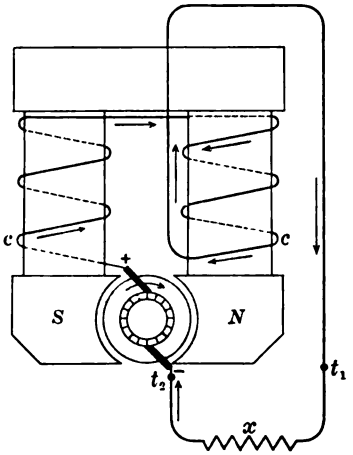


FIG. 136.—Series Dynamo.

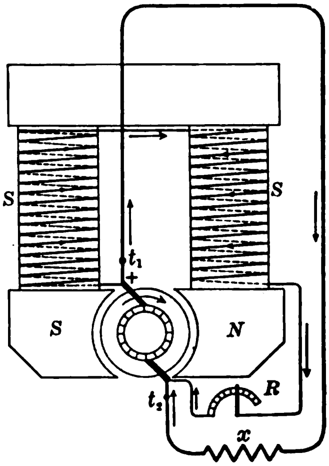


FIG. 137.—Shunt Dynamo.

The armature core is of iron, and serves a three-fold purpose: it carries the armature winding; it reduces the reluctance of the magnetic circuit; it concentrates the flux in the path of the rotating armature inductors, leaving little magnetism free to be ineffective for the production of electromotive force.

The commutator rectifies the alternating electromotive force generated in the armature winding.

The brushes are simply sliding contacts whereby the rectified armature electromotive force is impressed on the external circuit.

The field winding carries the current which excites the field cores.

The armature winding generates the electromotive force of the dynamo and carries the load of the machine.

Methods of Winding.—As stated in Chapter XI and explained by elementary diagrams, dynamos are classed with reference to the connections of their field windings as separately excited, series, shunt,

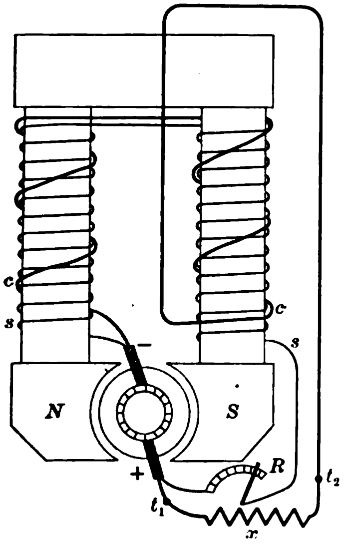


FIG. 138.—Short-Shunt Compound Dynamo.

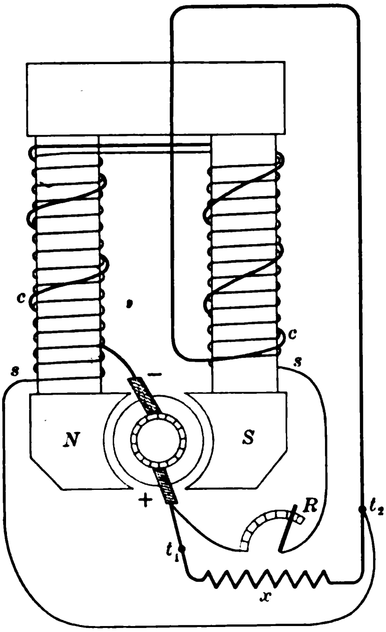


FIG. 139.—Long-Shunt Compound Dynamo.

short-shunt compound, and long-shunt compound machines. Fig. 135 may be regarded as depicting a separately excited dynamo; the other types are illustrated by Figs. 136, 137, 138 and 139. An inspection of these figures and a comparison of them with the elementary diagrams of Chapter XI will make evident the different methods of winding. It is to be noted that in the short-shunt, compound dynamo the terminals of the shunt field are the brushes; whereas in the long-shunt machine one terminal of the shunt field is advanced from the brush to beyond the series field, hence the name of " long shunt."

Since the shunt field of a dynamo cross-connects the terminals of the machine its resistance must be high to prevent short circuiting the armature; its wiring in consequence is fine; and it can carry little current. Accordingly, in order to obtain the number of ampere-turns in the shunt field requisite for the proper degree of field excitation, the winding must have many turns. The resistance of the series field, on the other hand, should be low to minimize the loss by ohmic heating, and it may carry a heavy current. Therefore few turns are required in the series field, and these are of large wire.

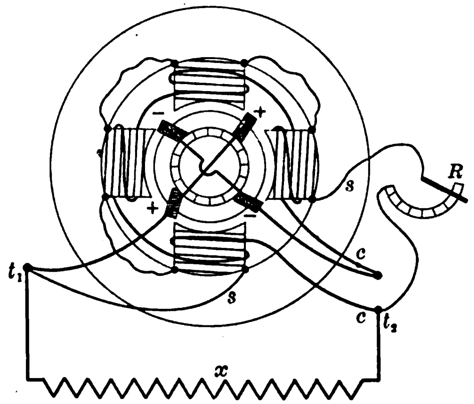


FIG. 140.—Multipolar Compound-Wound, Long-Shunt Dynamo.

In Figs. 136, 137, 138 and 139, as in the elementary diagrams, *s* denotes the shunt-field winding, *c* the series-field winding, *x* the external circuit, and t_1 and t_2 the dynamo terminals. In compound- and shunt-wound dynamos a variable resistance, *R*, is inserted in series in the shunt-field winding to permit regulation of the exciting current and, consequently, of the field excitation.

There is no essential difference between the windings of bipolar dynamos and multipolar dynamos. Fig. 140 shows a four-pole compound, long-shunt machine. The leads of its windings are practically identical with those of the machine of Fig. 139. Fig. 141 is a photograph showing the field leads of a compound-wound dynamo.

The Series Shunt.—The purpose of compound-wound dynamos is to deliver a constant terminal voltage under varying load. To effect

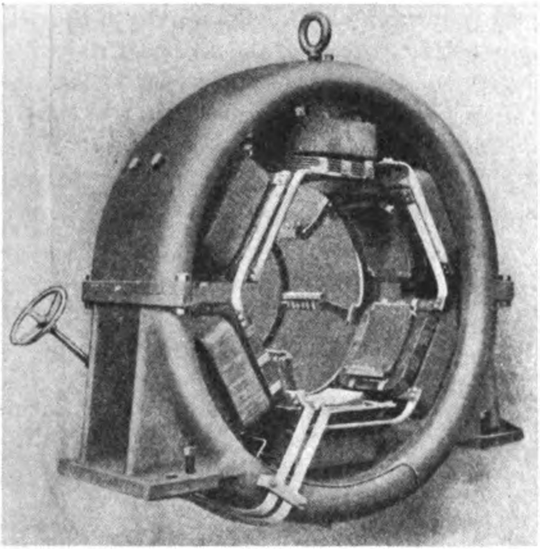


FIG. 141.—Showing Field Coil Connections, 6-Pole Dynamo.

this, as will be explained in a later chapter, the ampere-turns of the series and shunt fields must bear a certain definite relation to each

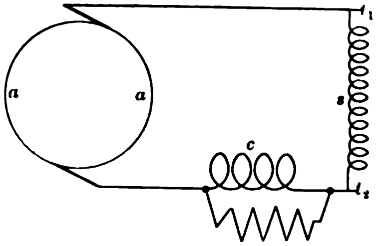


FIG. 142.—Series Shunt.

other. In adjusting the series field coil to obtain such relation it is often the practice to short circuit the terminals of the coil by a

German silver or an iron resistance which acts as a by-pass, permitting only a part of the armature current to flow through the coil and excite the series field. (See Fig. 142.) Such a short-circuiting lead is known as a **series shunt.** If of iron its resistance will increase relative to the resistance of the field coils, which are of copper, with the heating consequent upon a rise in load, and the increased proportion of the armature current thereby forced through the coils will alter to some extent the compounding of the dynamo. The adjustment of the series shunt is a part of the construction of the dynamo; it is not altered in the operation of the machine.

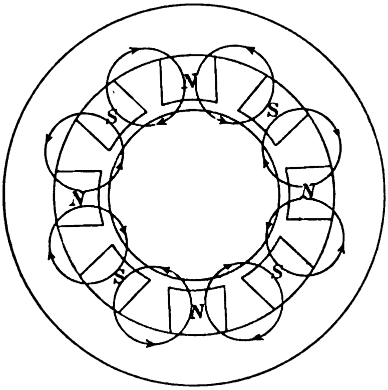


FIG. 143.—Magnetic Circuits, Multipolar Dynamo.*

Advantages of Multipolar Dynamos.—As has been stated the bipolar dynamo is now practically obsolete, having been supplanted by the multipolar machine. The advantages of the latter over the former may be briefly stated as follows:

(a) Economy of Iron.—The paths of the magnetic flux in an eight-pole multipolar dynamo are indicated by Fig. 143. It is evident that each complete magnetic circuit through any two adjacent poles, air gaps, armature and yoke is shorter than would be the magnetic circuit of a bipolar dynamo having the same armature and pole surface; that is, having the same total effective flux. Fig. 144 represents the magnetic circuit of such a bipolar dynamo. From these two figures it is clear that for the production of equal electro-

* The cross-section of the yoke should be half that of a field core if the same material is used.

motive force by both machines, assuming identical armature windings and speeds of revolutions, more iron is required for the bipolar machine.

(b) Economy of Field Copper.—Since in the multipolar dynamo the paths of the magnetic flux are shorter, their reluctance is less, and in consequence less magnetomotive force is required to obtain the requisite flux. In other words, fewer ampere-turns of the field coils are needed.*

(c) Reduction of Sparking.—It has been seen (Chapter XI) that the shifting of the neutral axis due to the cross-magnetizing effect of the armature current causes sparking. The cross-magnetizing effect of the armature current is proportional to the number of armature inductors under a pole-face, since all the inductors under any pole-face tend to magnetize the armature with the same polarity. An increase, therefore, in the number of poles will decrease the cross-magnetization of the armature and, in consequence, the tendency to spark.

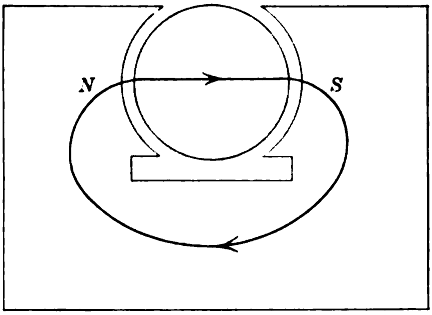


FIG. 144.—Magnetic Circuit, Bipolar Dynamo.

Disadvantages of Multipolar Dynamos.—When the number of poles of a dynamo is excessive, poles of opposite polarity are so close together that a considerable portion of the flux leaks direct from pole tip to pole tip without cutting the armature inductors. The effective flux and therefore the armature electromotive is reduced in proportion to the magnetic leakage so caused.

An increase in the number of poles of a dynamo requires a corresponding increase in the number of brushes and field coils, and, in consequence, of the cost of the machine.

The bipolar type is still used for low-power high-speed units.

* Assuming the same total effective flux and the same flux density, the yoke and armature cross-section will be inversely proportional to the number of poles, thus reducing the total weight of iron. In such a case, the total number of ampere-turns would be the same, but the average winding length would be inversely proportional to the square of the number of poles, thus requiring less weight of field copper.

Interpoles.—Interpoles are magnetic poles that are placed between the main field poles of a dynamo. The armature current is led around these poles in such a direction that the flux produced by it tends to reduce the distortion of the field. As this increases with increase of armature current, the current of the interpoles increases in a like degree and the distortion is, to a great extent, corrected. This eliminates the necessity of shifting the brushes on changes of load, and is especially efficient on motors whose speed is varied by field regulation. The speed of ordinary shunt motors becomes greater as the normal field flux is weakened. Without interpoles the weakening of the field to accomplish this necessitates shifting of the brushes to prevent injurious sparking, which in turn increases the demagnetizing effect and a condition might be reached when the armature flux would reverse the field flux over a portion of a main field pole and excessive sparking would occur and the motor would race to an unsafe speed. The interpole current reduces these armature reactions, and permits of greater range of speed without shifting of brushes and permits the commutation of the current to be effected without sparking.

The primary object of interpoles is to assist in the commutation so that all sparking with its injurious heating effects may be avoided. If the brushes could be placed in a position where the voltage between adjacent commutator bars was a minimum and very small, there should be little sparking, but with high speed generators with small commutators this condition is difficult to obtain. In the case of high speed in motors caused by weakening the field, the voltage between commutator bars is comparatively high and commutation troubles are apt to occur. Perfect commutation requires the generation within the armature coil under commutation of an electromotive force of the proper value and sign to reverse the current while it is still under the brush.

In Fig. 145 is shown the distribution of magnetic flux under the pole faces of a two-pole machine without interpoles both for light and full-load current. The curve for light load, shown by broken line, shows a fairly uniform distribution of the flux over the whole pole face, and that for full load, shown by full line, shows the distortion due to the armature reactions above considered, the flux being dragged in the direction of rotation and being strong under one pole tip and weak under the other.

Considering the full-load curve, it is seen that the coil under brush *B* has electromotive force induced in it which tends to keep the current flowing in the same direction as it does up to that point and with the brush in this position commutation would be very imperfect and bad sparking would occur. The electromotive force generated in this coil under the brush opposes what is intended to be

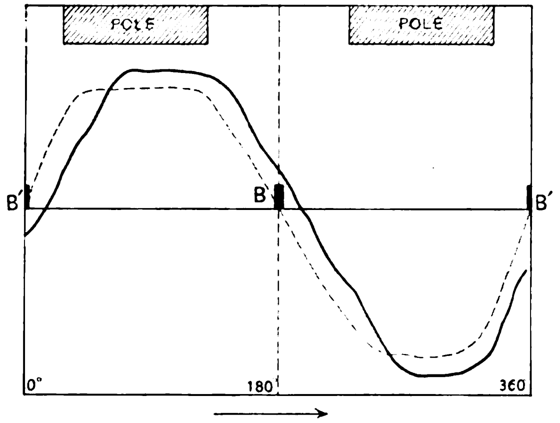


FIG. 145.—Distribution of Magnetic Flux without Interpoles.

done, *i. e.,* the reversal of the current before it leaves the brush. The field is such that the electromotive force actually tends to generate more current in the same direction rather than to reverse it. In the above condition there is another effect acting against sparkless commutation. This is due to the lines of force around the coil under the brush which, as the currents tend to reverse, acts to prevent it, due to the self-induction of the coil. The local electromotive force due to this self-induction causes the current to keep in its original direction and so opposes reversal.*

* See under "Sparking," Chapter XI.

Fig. 146 is drawn similar to Fig. 145 and shows the distribution of flux due to the full-load current without interpoles in full and broken lines, and the flux due to the interpoles in dotted lines; with the resultant flux due to full-load current and interpoles in full line.

It will here be seen that the coil under brush *B* is passing through a flux that will generate an electromotive force of opposite sign to that of the current to be reversed. This is of material help in causing reversal of the current, and the self-induction effect mentioned

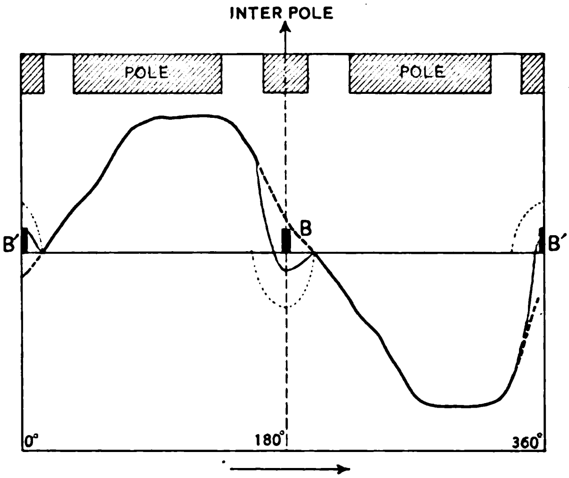


Fig. 146.—Distribution of Magnetic Flux with Interpoles.

above is also reversed, both causes tending to good commutation. It will be noticed that as the flux due to the interpoles is caused by the armature current, this increases with the load, and if good commutation is effected for one load it should be expected at all loads without any change of brushes.* In motors, as the speed is varied with constant load, the armature current changes, and consequently the interpole flux varies with the main field flux to such an extent that the whole arrangement is almost perfectly automatic.

As the interpole current is in series with the armature current, the reversal of one reverses the other, and in all cases of interpoles, the current flowing around them must be considered as armature current.

* Assuming that the interpoles do not become saturated.

Interpoles are nearly always used on generators that are driven by turbines at a high rate of speed in order to suppress the sparking caused by the high frequency of commutation.

It is possible to get very close speed regulation on an interpole machine that is especially designed for this feature. In general, the speed regulation on an interpole motor can be made very small by giving the brushes a motor lead.* A very slight movement causes a big change in speed and improves speed regulation. Care must be exercised, however, as a backward lead tends to make the motor unstable and when the load is put on it will "race." A backward motor lead in the case of a generator increases the compounding as does also too strong an interpole winding.

The interpole machine in general has the following characteristics:

1. Good commutation under all conditions of load.

FIG. 147.—Interpole and Main Pole.

2. Low commutator temperatures and long-lived commutators on account of this good commutation.
3. Excellent speed regulation as motors and voltage regulation as generators.
4. Ability to start quickly and to commutate under sudden and large change of load.
5. Less weight and floor space for a given output than in the case of a machine without interpoles.
6. Large variations in speed can be obtained, ratios from 5 to 1 are frequent.

Interpoles are more fully discussed under "Notes and Care of Motors," in Chap. II, Vol. II.

* This action could be taken only when the direction of rotation is not to be reversed. The word "regulation" must not be confused with "control." It would be a very dangerous practice to attempt to control the speed of an interpole motor by shifting the brushes. As machines are now constructed, very little brush shift is allowable, for a very small change would bring the brush in contact with a coil entirely outside of the commutating field.

The usual construction of interpole motors is to have an interpole between each pair of main field poles. However, the interpoles of the four-pole motor shown in Fig. 148 are so designed that the necessary commutating effect is produced by two interpoles.

The Field Magnet Frame.—The field magnet frame may be cast in one piece of iron or steel, but usually the cores are made separately from the yoke. Cast iron * is cheaper than cast steel, but magnetically inferior, requiring more material to permit the production of a given flux and more ampere-turns in the field coils. The yoke is generally circular in shape and is divided into two parts so that the upper part can be lifted off to permit the removal of the armature.

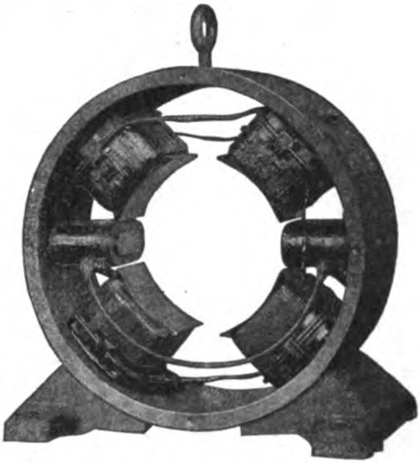


FIG. 148.—Field Frame and Field Coils of Motor Fitted with Interpoles.

Field magnet cores, when constructed separately, are bolted to the yoke, and are made of cast steel, laminated steel, or laminated wrought iron. Wrought iron is the best magnetic substance available. Fig. 149 shows a laminated field core.

Pole pieces encircle the armature and are somewhat larger than the cores, thereby producing a more uniform distribution of the magnetic flux. They too may be constructed separately and bolted to the cores. Pole pieces are of cast iron, cast steel, or laminated soft steel or wrought iron.

* Cast iron is generally used for the yoke to give the necessary stiffness. Cast iron has the advantage of being more easily moulded into complex forms.

The laminations of cores and pole pieces are made as thin as is practicable and insulated from each other by coatings of hard varnish. They lie perpendicular to the direction in which eddy currents tend to flow and so prevent, practically, the formation of such currents and the consequent power waste. Furthermore, the laminated construction insures a uniform quality of metal throughout the entire pole which tends to produce a better distribution of the magnetic flux and tends to insure equal magnetization of all poles. With a cast pole internal flaws and blow holes may increase the magnetic reluctance of one pole over another and cause electric unbalance in the completed machines.

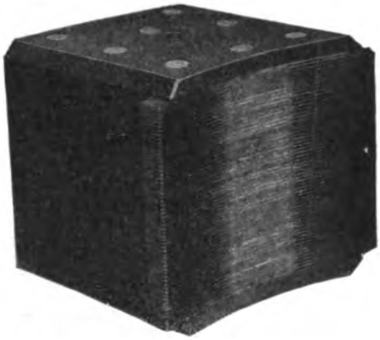


FIG. 149.—Laminated Field Core.

Fig. 150 shows a photograph of a 100 kilowatt turbo-generator similar in design to the 300 kilowatt generating units installed on board the later battleships.*

The field magnet frame consists essentially of a circular yoke of cast iron divided horizontally into two parts and mounted upon a bed plate of cast iron, to which are bolted the pedestals which carry the armature bearings. The poles are built up of punchings of soft steel riveted together between end plates and firmly bolted to the frame. The pole tips are spread to properly form the magnetic field and to support the field coils. Any pole and its coils may be readily removed. The inner surface of the yoke is carefully machined to form seats for the poles which are shaped to fit. The holding bolts which pass through the yoke are threaded and screwed into the poles. They do not penetrate the pole faces, which are left smooth and unbroken.

Field coils are of copper wire, ribbon, strap, or bars, depending on the strength of the current they are required to carry. They are

* Except that the 300-kilowatt generating units are provided with double commutators.

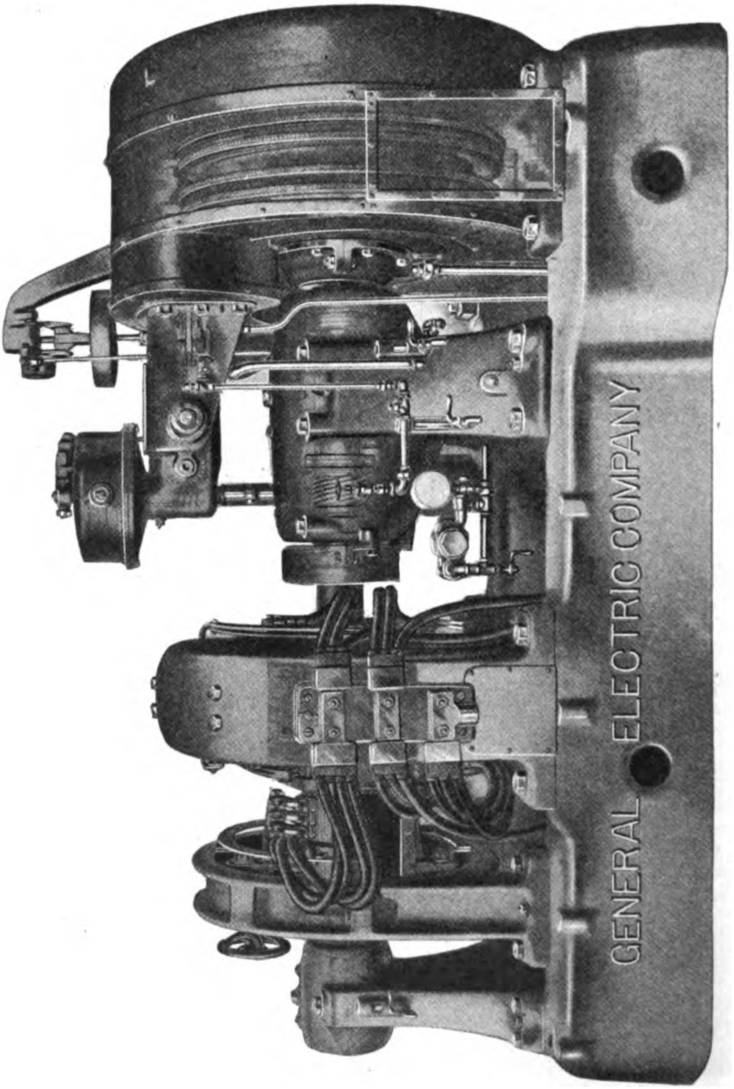


FIG. 150.—Phantom View of Curtis Steam Turbine Direct Connected to 100 K. W. Direct-Current Generator.

usually held in place by the spreading tips of the pole pieces. Field coils are sometimes wound on metallic bobbins, but experience has shown that such procedure prevents the rapid radiation of the heat developed in the winding. In the earlier dynamos, shunt and series windings were wound over each other on the same spool, but now they are generally separated for the sake of better ventilation and

FIG. 151.—Shunt Field Coils.

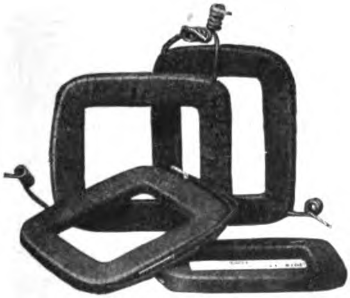


FIG. 152.—Series Field Coils.

greater accessibility. Except in differentially wound machines the connections of both windings for any pole must be such as to produce similar magnetism. Adequate insulation, ventilation, and protection of the coils, are insured by the method of construction.

Figs. 151 and 152 show generator field coils. The shunt coils are wound on insulated shells of uniform size for a given generator. The coils consist of insulated copper wire, after being wound they are first taped and then impregnated with insulating compound by the vacuum process. Each coil is thereby made a solid, perfectly insulated, water-proof mass which radiates heat very readily. The series coils are more frequently made of copper strap, as shown in Fig. 153.

Another type of field coils is shown in Fig. 153. This is constructed in accordance with new designs which permit of thorough ventilation and compact construction. An air space is provided between the inside of the shunt coil spools and the sides of the poles.

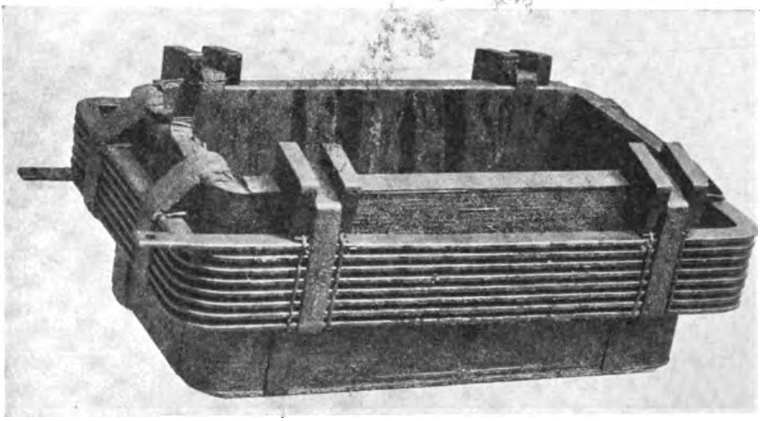


FIG. 153.—Field Coils.

Air is blown into these spaces by the armature and all parts of the coil are thereby maintained at a uniform temperature. The series coils have bare, edge-wound, strap copper windings. There is an air space between adjacent turns and between each shunt and series coil permitting a free circulation of air about each conductor.

Figs. 154 and 155 show the field coils of an interpole motor. The main field coils are wound with flat copper strap with the turns separated by asbestos ribbon. The coil is impregnated in a vacuum tank with an insulating, heat-conducting and water-proof compound and finished by repeated tapings, followed by dippings in the best grades of insulating compounds and varnishes, the result being a sealed coil that remains practically moisture and heat proof. The coils are protected from injury by metal coil shields and are so firmly held in place against the pole tips by heavy flat steel springs that vibration or chafing is prevented and grounding practically eliminated. The

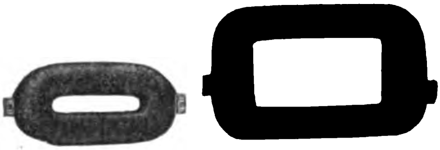


FIG. 154.—Interpole and Main Field Coils.

FIG. 155.—Parts of the Interpole.

interpoles are wound with copper strap and constructed, insulated and finished in substantially the same manner as the main field coils. Each is supported and protected against injury by a bronze casting securely pressed into a groove around the tip of the interpole. The coils are so firmly held in position by steel springs that all vibration is prevented.

FIG. 156.—Pole and Field Coils.

Fig. 156 shows a pole with its field coils. The bolts for securing the pole to the circular yoke are also shown.

Armature cores should be of magnetic material in order to concentrate the field flux and to decrease the reluctance of the magnetic circuit. The retentivity of the material should be small, that the loss by hysteresis may be minimized.* Accordingly armature cores are

* That is, the hysteresis loop for the material employed should have a small area. (See page 170.)

constructed of soft wrought iron or mild steel. To reduce the effects of eddy currents, the cores of armatures, like those of field magnets, are laminated in thin discs insulated from each other by coatings of varnish and sometimes by shellac or paper. The laminations are perpendicular to the axis of rotation of the armature; that is, perpendicular to the general directions in which eddy currents tend to flow. Such process does not entirely prevent loss by eddy currents, as small currents will still form in each disc, but the thinner the discs the less will be the loss. If, however, the discs are made too thin the power saved through eddy current reduction will

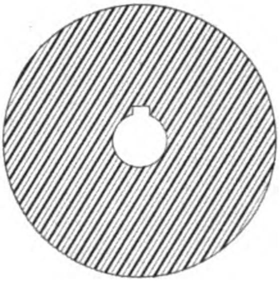


FIG. 157.—Armature Core Disc [Smooth Core].

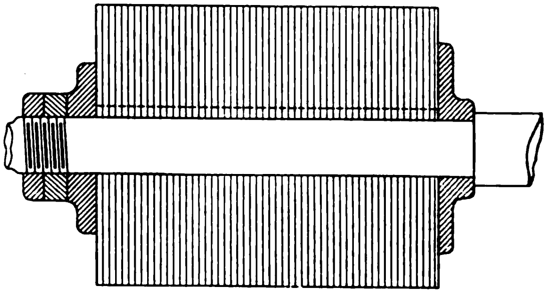


FIG. 158.—Armature Core.

be over balanced by the loss introduced through the decrease of the magnetic area of the core by the space utilized for the insulation.

For small armatures the discs are punched in one piece and are mounted directly on the armature shaft and keyed to it. Flanges and locking nuts on the shaft press and hold the discs together. Figs. 157 and 158 illustrate the construction. Air passages through the core for ventilation are usually provided.

For large armatures the discs are built up of segments assembled on an iron spider (Figs. 159 and 160), the spider being pressed on and keyed to the armature shaft. Successive joints in the laminations are staggered.

The laminations are separated at intervals, thus forming radial air ducts which permit the radiation of the heat developed by eddy currents, hysteresis, and the armature current. Spacing pieces, con-

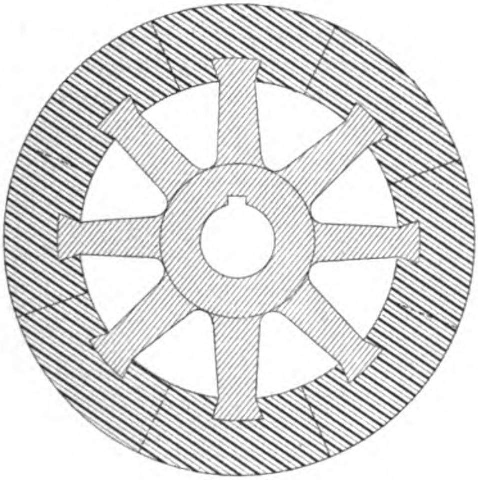


FIG. 159.—Spider Carrying-Core Segments.

FIG. 160.—Showing Open Construction of Armature.

sisting of blocks of non-magnetic material, such as brass, are interposed between the separated laminations, insuring the rigidity of the core. Fig. 161, showing one radial air duct, illustrates how the armature is ventilated. The rotation of the armature causes air to pass in through the spider openings, and out through the air ducts

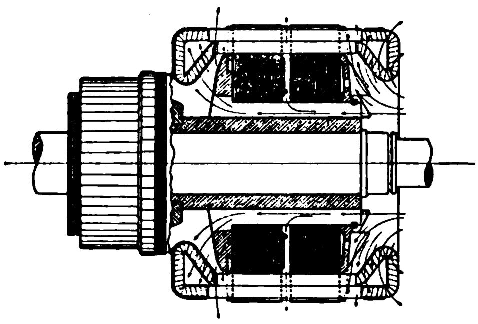


FIG. 161.—Cross-Section of Armature, Showing Method of Ventilation.

and through the overhanging ends of the armature coils, as indicated by the arrows in the accompanying figure. From the armature the air is blown outward against the pole faces and around the field coils, thus keeping all the active parts of the electric and magnetic circuits cool.

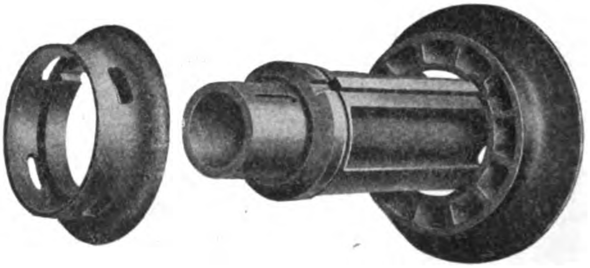


FIG. 162.—Armature Spider and End Ring.

The laminations are usually soft steel punchings. They are assembled under heavy pressure and held securely in place by flanges, heads, or end rings on the spider. Fig. 162 shows a spider with head and end ring.

The commutator is generally mounted on an extension of the spider, although sometimes it is carried on the armature shaft.

The advantages of the spider armature construction are as follows:

(a) It permits the easy removal of a bent or damaged shaft without disturbing the armature winding.

(b) The spider so reinforces the shaft that there is little danger of springing or breaking the shaft in service.

(c) Building the core on the large diameter of the spider reduces the strain on the keys. The shaft is forced into the spider with a pressure that causes expansion, takes up all looseness and minimizes the possibility of the core getting loose on the shaft.

(d) It insures keeping the armature core and commutator in the same relative position and eliminates all breakage of leads due to

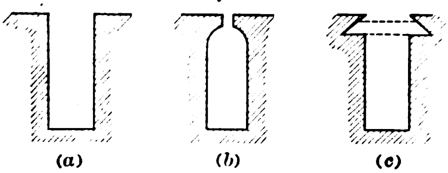


FIG. 163.—Armature Slots.

shifting of the commutator on the core, besides making it practically impossible for the commutator to loosen on the shaft.

Armature core discs are now made with deep slots for receiving the armature inductors. Smooth cores, as exemplified by Fig. 157, were formerly used, the inductors being carried on the surface of the core and there bound. This arrangement interposed a thick layer of copper and air, both non-magnetic, between the core and the pole faces, thereby adding to the reluctance of the magnetic circuit of the dynamo. Furthermore, the exposed inductors were liable to mechanical injury, and the armature drag was likely to displace them when the armature current was heavy. With a slotted core the inductors are securely held in place and protected, and the air gap may be reduced.

Two types of armature slots are generally employed: the open and the partly closed. Fig. 163 shows examples of each. The open slot (a) is the usual construction for direct-current machines. It facilitates the winding of the armature. The partly closed slot (b) simplifies securing the windings. Often slots are fitted with recesses at their tops to permit the insertion of wooden wedges whereby to hold the inductors in place (c).

Fig. 164 is a photograph of a slotted armature core. Fig. 165 is a photograph showing the armature core with its commutator. The space between the core and flange at the back and between the core and commutator at the front is for receiving the overlapping ends of the armature coils. The radial ventilation ducts and their spacing pieces are shown.

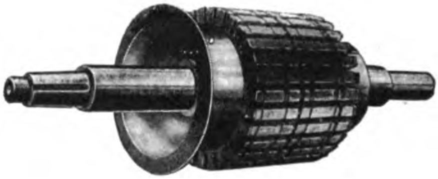


FIG. 164.—Slotted Armature Core.

FIG. 165.—Armature Core and Commutator.

The commutator is formed of hard-drawn copper bars insulated from each other by mica * segments. These bars are assembled on and securely clamped to a steel bushing, from which they are insulated, also by mica. The bushing is pressed on a machined seat extending from the armature spider (in some cases on the armature shaft, as has been stated) and keyed, making the armature and commutator a unit. Each commutator bar carries a radial lug (see Figs.

* Besides being a good insulator mica has the added advantage of wearing at the same rate as copper.

165, 166 and 167) on the back end to which the leads from the armature winding are attached. Fig. 167 shows the shape of a bar longitudinally. *l* is the radial lug connecting with the armature winding. The bushing on which the bar is mounted clamps in the

FIG. 166.—Commutator.

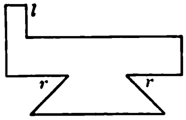


FIG. 167.—Commutator Bar.

recesses, *r*, *r*. In cross-section the bar tapers to an extent sufficient to make the complete commutator a compact cylindrical structure.

Another type of commutator having bars of slightly different construction is shown in Fig. 168.

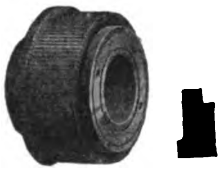


FIG. 168.—Commutator and Commutator Bar.

The tendency of a dynamo to spark at the brushes has been shown (Chapter XI) to depend in part upon the reactance voltage of the armature coils at commutation, and, in consequence, upon the number of turns in each coil. It is therefore desirable to employ commutators of large diameter, as these may carry many bars, permitting the reduction of the number of turns in the sections of the armature winding.

It is essential that the commutator should be smooth. A rough commutator causes vibration of the brushes, which in turn produces sparking with its loss of power and injury to the mechanism. Loose commutator bars have the same effect.

Armature windings are of copper, either as wire or in bars. Armatures are wire wound, generally, when their current output is small, and bar wound when their current output is large. The coils or sections of an armature winding are formed individually and are interchangeable. In the event of damage to a coil it may be removed and replaced without disturbing the rest of the winding. The several conductors or turns that constitute a coil are insulated separately, using mica, cotton or linen tape, insulating compound, or varnished cloth or paper. They are then fastened together and wrapped with a few layers of insulating tape, occasionally providing first a mica covering, and the whole is filled and sealed by dippings in moisture-proof varnish. This protects the coil and gives it a finished appearance. Before the coils are placed in the slots the latter are generally lined with insulating materials, using mica, fiber, or paper pulp. The core ends are insulated wherever the windings can touch them.

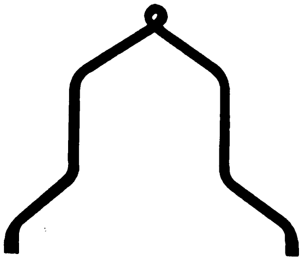


FIG. 169.

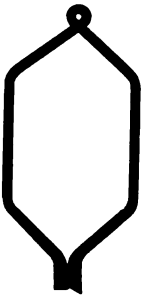


FIG. 170.

Armature Coils.

Fig. 169 shows a section or coil of a wave-wound armature, and Fig. 170 the section of a lap-wound armature. When the armature inductors are so large that they cannot be bent, each half of each turn is individually insulated and placed in its slot. A copper bridge is then soldered to the bare ends of the inductors at the rear, thus completing the electrical circuit.

In large armatures the inductors are usually held in place by wooden or fiber wedges driven in the tops of the slots, as illustrated by Fig. 163. With small armatures bands of binding wires of phosphor bronze, brass, or steel, wrapped around the periphery of the core and insulated therefrom, secure the inductors. Some of the laminations are made of smaller diameter than the others to afford grooves for the binding wires, allowing the latter to sink below the surface of the core.

The ends of the armature coils which constitute the leads are brought out and soldered into slots in the lugs of the commutator bars. Each coil is carefully tested for grounds and short circuits before connecting it to the commutator; the complete armature is also similarly tested. Both back and front connections of the coils

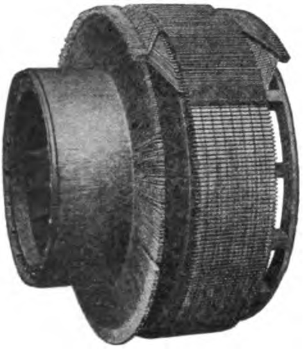


FIG. 171.—Partially Wound Armature.

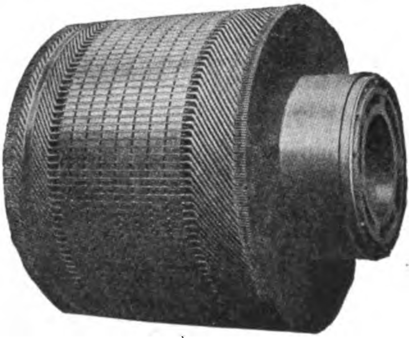


FIG. 172.—Complete Armature (Shaft Removed).

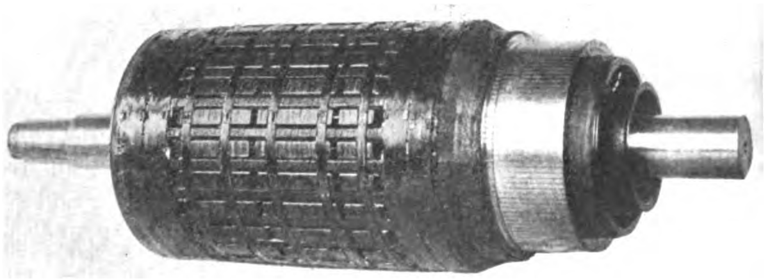


FIG. 173.—Banded Armature.

are firmly bound to withstand the centrifugal force of the revolving armature.

Fig. 171 illustrates the method of winding an armature. Fig. 172 shows a completed armature whose inductors are secured by fiber wedges driven in grooves in the core teeth. Fig. 173 shows a completed armature whose inductors are bound by bands of wire.

To keep within limits, the reactance voltage developed in the short-circuited armature coils at commutation the number of turns in each coil is usually not more than three for machines of moderate size. For the same purpose it is desirable to shorten the axial length of the armature core, that the length and consequently the inductance of the inductors may be lessened. Shortening the core necessitates increasing its diameter to obtain equal power,* but with large cores large commutators may be employed, with the advantage previously explained.

Brushes are now generally made of graphitic carbon in hard blocks. Formerly metal brushes, in the shape of a bundle of metal leaves or wires, were used, but these roughened the commutator, and, in consequence, they have been discarded except for low-voltage

FIG. 174.—Brush-Holder and Brush.

dynamos, where the resistance of carbon brushes would be too great, and in some high-speed turbo-generators. Carbon wears well mechanically, furnishing its own lubrication in the form of graphite, and, in addition, because of its higher resistance it decreases the tendency of the armature to spark at the brushes.

In Chapter XI, it is shown that the tendency to spark is dependent in part upon the time of commutation. The latter, in turn, depends upon the width of the brush as well as the rotational speed of the armature. Therefore, sparking might be lessened by increasing the width of the brush. If, however, the brush be made too wide, short circuiting too many armature coils, the reactance voltage at com-

* Increasing the diameter of the core permits the utilization of a greater effective flux.

mutation and thereby the tendency to spark will be so much increased as to neutralize the counter-effect of widening the brush.

Brush-holders support the brushes, pressing them firmly against the commutator. Springs form part of the brush-holder mechanism, insuring that the contact of the brushes with the commutator is constant throughout the life of the brush and that it is not disturbed by an irregular commutator. The spring does not form part of the electrical circuit, current being led from the brush to the stationary

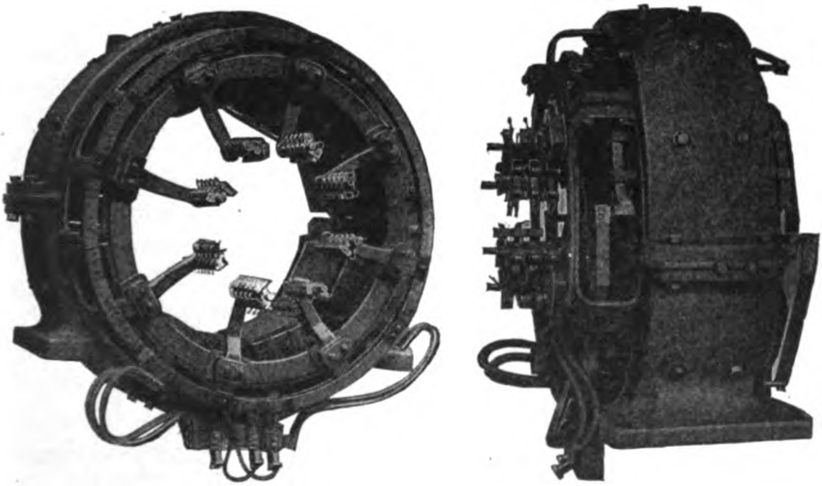


FIG. 175.—Field Frames Showing Rocker Rings and Brush-Holders.

part of the holder by flexible connections. The holder is insulated from the dynamo frame. Devices for adjusting the tension of the springs are provided. Brushes are usually set at an angle with the surface of the commutator except for dynamos which reverse their direction of rotation, when they are set radially. Fig. 174 shows a brush-holder.

The **rocker ring** carries the brush-holders. This is a ring mounted concentric with the commutator and capable of being rotated. By it the brushes may be moved to the position of minimum sparking. Suitable mechanism for rotating the ring and clamping it firmly in any position is provided. In Fig. 141 is shown a handwheel and shaft fitted to permit of the rocker ring being rotated as desired.

With the improved construction of dynamos, it is rarely if ever necessary to shift the position of the brushes for variation in load. In most types of interpole motors the brushes are rigidly secured and no means of shifting them are provided. Fig. 175 shows the brush-holders and the rocker ring of a dynamo. The two smaller rings shown in front of the rocker ring are of insulated copper and are known as "bus rings." To one of them all the positive brush-holders are electrically connected; to the other, all the negative brush-holders. From the bus rings the leads to the dynamo terminals are taken.

The brush-holder gear for high-powered high-speed turbo-generators as illustrated in Fig. 150 is specially designed to give rigidity and provide ample brush area for the large currents delivered. It comprises a split ring provided with broad feet for securing to the base and a large rocker ring which can be rotated within the fixed ring and which carries six insulated brush-holder brackets. Bus rings for connecting brushes of same polarity are also provided. A stiff anchor bolt extends from the top of the fixed ring to the top of the magnet frame to prevent vibration due to the high armature speed.

CHAPTER XIII.

THE GENERATOR.

Excitation.—The field of a separately excited generator becomes energized upon connecting the terminals of the field windings to a source of current supply. With the shunt, series, and compound generators, however, which are self-excited, the process of energizing the field is a gradual one and involves the rotation of the armature.

In the pole pieces of a generator there usually exists a certain amount of residual magnetism. When the armature of a self-excited generator is revolved there is a small electromotive force induced in the armature coils due to the magnetic field produced by the residual magnetism. This small electromotive force produces a current which, flowing through the field circuit, *strengthens* the field, which in turn induces higher electromotive force; this produces greater current, which still more strengthens the field, and so on until the machine is built up to full voltage. This operation is called **building up**, and there can be no building up unless there is some residual magnetism. If the field magnets show no residual magnetism whatever, the field circuit should be connected with some outside source of current, either a few cells of a storage battery or the leads from a running machine.

If the connections of the field are such that the current, due to the rotation of the armature, tends to *weaken* the residual magnetism, then the machine cannot build up at all. With a given direction of rotation of the armature and a certain polarity, the current tends to flow in a certain direction. If now the connections are such that the magnetic effects due to this current are opposed to residual magnetism, the field will be weakened and less current will flow. If the current was strong enough to reverse the polarity of the field magnets, then the armature current would flow in the opposite direction and would be again acting to weaken the field.

If with a given direction of armature rotation and given field connection, a generator does build up, it cannot build up if its direction of rotation be reversed or if its field connection is reversed; but it will build up, however, if both the direction of rotation and field connections are reversed at the same time.

If a generator does not build up because of reversed connections, it may be made to do so either by changing the direction of rotation of the armature or by changing the field connections.

The polarity developed by a generator in building up is dependent upon the direction of the residual magnetism if the direction of rotation of the armature be fixed. Ordinarily the generator will always develop the same polarity, but on occasions the residual magnetism may be reversed by some external disturbance, such as a lightning discharge or the field of another machine. In this event the generator when next started will build up with opposite polarity, and the former positive brush will become the negative brush. In connecting up generators in parallel, care must be taken that their polarities are not reversed.

The voltage to which a generator can build up is determined by the speed and the field strength of the machine.* Mechanical limitations fix the former and the saturation point of the field poles fix the latter. When the poles have reached the state of magnetic saturation, further increase in the exciting current will not increase the field strength of the generator and, consequently, the voltage.

In a series generator the connections to the external circuit must be closed before the machine will build up. If open, no current can flow through the field coils. Furthermore, the external resistance must not be too great; otherwise the initial electromotive force of the generator may not be sufficient to force current through the external circuit and the field coils.

A shunt generator, on the other hand, will not build up unless the connections to the external circuit are open. With them closed practically all of the current generated would flow through the low external resistance, avoiding the high resistance of the shunt field

* Fundamental equation of the generator, Chapter X.

circuit, and the field would not become fully energized. If, while the machine is in operation, the resistance of the external circuit should be sufficiently decreased, so much of the field current would be diverted to the external circuit that the field excitation and, in consequence, the voltage, would fall materially, resulting in further decrease of the shunt current and voltage, until finally the machine unbuilds, both electromotive force and current dropping to zero.

Voltage Control.—Although the speed as well as the field strength is a factor in determining the voltage of a generator, still, as generators are usually driven at a practically constant speed, variations

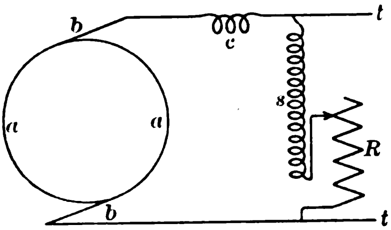


FIG. 176.—Voltage Control, Compound Generator.

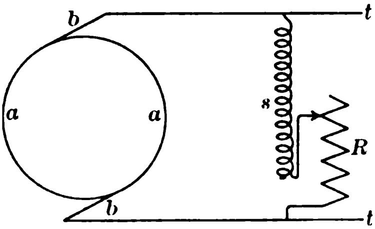


FIG. 177.—Voltage Control, Shunt Generator.

in the voltage are generally effected by regulating the current in the field coils. Such regulation is obtained by means of rheostats (variable resistances) connected in the field circuits. In Chapter XII the connections of the rheostats for compound and shunt-wound dynamos are shown. Figs. 176 and 177 are the elementary diagrams of the same connections. *R* is the regulating rheostat in series in the shunt field winding by which the resistance of the circuit and consequently the exciting current, the field strength, and the voltage can be altered at will. With shipboard electric plants the field rheostat is operated by hand.

If in the series generator a regulating resistance were connected in series with the field coil, as in the shunt and compound machines, the current in the external circuit would be weakened. The current in the coil, however, may be controlled without materially affecting

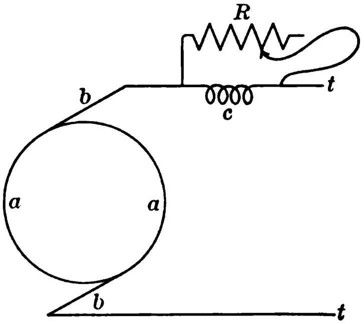


FIG. 178.—Voltage Control, Series Generator.

the external current by shunting the coil with a variable resistance, as shown in Fig. 178.

Other methods of controlling the voltage of a generator are cutting in or out or short-circuiting turns of the exciting coils, or shifting the brushes. It has been seen (Chapter X) that when the brushes are moved from the neutral axis, the electromotive force they deliver is decreased; consequently a means of voltage control is thereby afforded.

Characteristic Curves of Series Generator.—The characteristic curve of a generator is a name given to a curve that may be plotted to show the relation between the number of volts generated in a generator and the resulting number of amperes, using volts as ordinates and amperes as abscissæ. The volts used may be the total volts and the amperes the total amperes, in which case the curve is called the *total* or internal characteristic curve. In the case of the series generator, if the curve is plotted with the electromotive force at the terminals and the external current, also in this case, the internal current, the curve is called the *external* characteristic curve.

The curve used in compounding generators is the external characteristic curve, but as all curves show the interior workings of the generator under varying conditions an example of each is given with a mention of some of the facts that can be learned from it.

In Fig. 179 the line *OE* represents the total characteristic curve of a series generator for a given speed, the ordinates being volts and the abscissæ amperes, being plotted from the total electromotive force generated and the resulting current. This curve starts a little distance above the zero line, showing a certain amount of residual magnetism. The curve ascends first at a steep angle, then curves around and again assumes nearly a straight course. In this generator the magnetization increases with the current, and so the electromotive force increases rapidly at first, giving the straight portion of the curve. As the current increases, the magnets approach saturation, so any increase in current does not produce a corresponding increase in electromotive force and this is shown by the curving or flattening for a short space in the curve. If the current still further increases, armature reactions, demagnetizing, and cross magnetizing effects take place.* A shifting of the brushes to prevent sparking with an increased current causes a marked demagnetizing

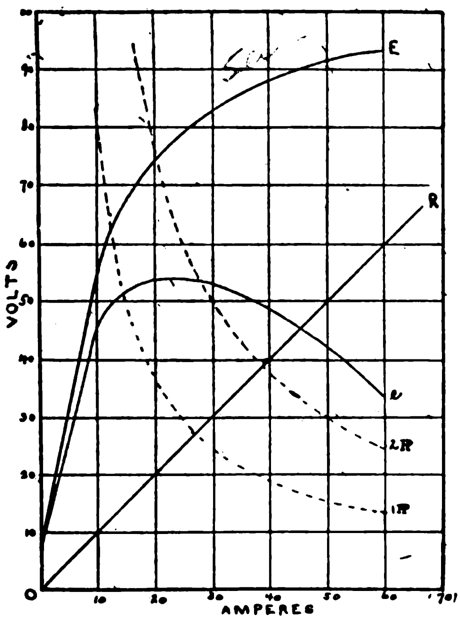


FIG. 179.—Characteristic Curves of Series Generator.

effect and in some generators causes a decided drop in the curve. This curve shows at what point saturation commences to be manifested, when the saturation point has been reached, and the current necessary to produce the maximum electromotive force, or rather the current produced by the maximum electromotive force and at what time the most serious of the armature reactions take place. It

* That is, after the magnets approach saturation, a further increase of current may cause a drop in the curve as the slight increase of flux will be more than counterbalanced by the effects of the increased armature reactions.

also shows at what current, or through what limits of current, the total electromotive force is most nearly constant.

The curve *Oe* is plotted for the total current and the difference of potential at the brushes or terminals. The difference in the ordinates of the total and external characteristics shows the volts that are lost in overcoming the internal resistance, that of the armature and series windings, and from being useless as far as external electrical energy is concerned are called "lost volts." This curve shows between what limits of the external current the difference of potential at the terminals is most nearly constant, consequently at what load the machine could be used with the least variation in electromotive force.

The full straight line *OR* is the curve showing the voltage drop through the armature and series field and its ordinate at any point represents the "lost volts" for the corresponding current, and is equal to that current multiplied by the sum of the armature and series winding resistances. This curve then represents the difference between the other two, and therefore having any two of the curves, the remaining one may be plotted. As the internal resistance is known, the curve *OR* may be easily drawn as it makes an angle with the horizontal whose tangent is equal to the resistance of the armature and series field, and the data for the external characteristic may be obtained by properly connecting an ammeter in circuit and attaching a voltmeter to the terminals. Then by adding to the ordinates of the external characteristic curve the corresponding ordinates of the curve *OR*, the total curve can be plotted.

Horse-Power Lines.

Another interesting fact in connection with these curves is that they can be made to show the horse-power which is being developed at any particular part of the curve. These horse-power lines constitute a system of rectangular hyperbolæ, the axes of volts and amperes being the respective asymptotes. That is $xy = \text{a constant}$, x being volts and y amperes. The one horse-power line should be the locus of all the points such that the product of the ordinate and the abscissa of any point is equal to 746 watts. Thus one point would be 74.6 volts and 10 amperes, another 37.3 volts and 20 amperes, and so on. The two horse-power line should be a curve such that the product of the ordinate and the abscissa at any point should be 2 × 746 watts.

An examination of the resistance curve or line shows that, if the resistance is above a certain value, the angle it makes with the ampere line being greater than the angle made by the slope of the total characteristic curve, the machine cannot build up; and it also shows that while running, if from any cause the resistance is

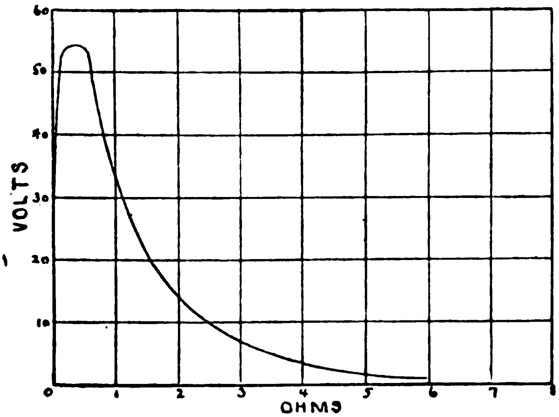


FIG. 180.—Curve Showing External Resistance and Terminal Voltage, Series Generator.

suddenly increased, the machine will rapidly unbuild or lose its magnetism, that is, the ordinate of the resistance becomes negative as applied to the external curves. These curves explain a great many things in connection with the running of generators that were known before simply as facts.

Another interesting curve useful in compounding generators is a curve showing the relation between the external resistance and the difference of potential at the terminals. A typical curve is shown in Fig. 180, but its application will be deferred until compound generators are considered.

Characteristic Curves of Shunt Generator.—There are five curves that show relations existing between the volts and amperes in a shunt generator, one internal characteristic and four external curves. The internal curve, plotted with the total volts and the total current when the external circuit is open is very similar to the total characteristic curve of the series generator. When the external circuit is closed, there are four variable quantities, namely, the total electromotive force, the electromotive force at the brushes or terminals, the armature or total current, and the external current. Calling the total electromotive force E_a, the electromotive force at the terminals E_x, the total current I_a, and the external circuit I_x, four curves can

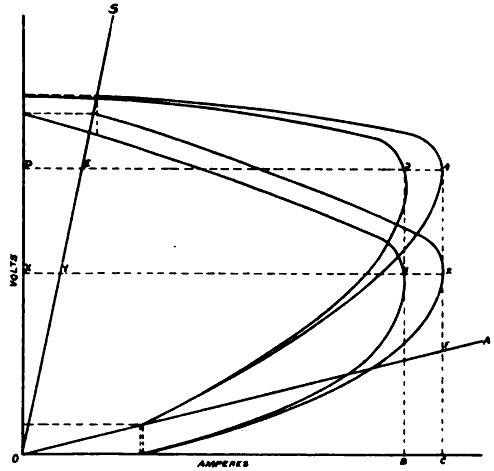


FIG. 181.—Characteristic Curves of a Shunt Generator.

be plotted, E_x and I_x, E_x and I_a, E_a and I_x, E_a and I_a. Of these the first is the one principally concerned in the compounding of generators, though all are of interest and are shown in Fig. 181.

Curve No. 1 is plotted from E_x and I_x, No. 2 from E_x and I_a, No. 3 from E_a and I_x, and No. 4 from E_a and I_a. OA is drawn at such a slope that the tangent of the angle it makes with the ampere axis represents the resistance of the armature, and OS at such a slope that the tangent of its angle represents the resistance of the shunt winding.

If curve 4, obtained with the total electromotive force and the total current, is plotted, the others may all be obtained from it.

Curve 2 is obtained from 4, by subtracting from the ordinates lengths which are included between *OA* and *OC*. Thus the point 2 is obtained by subtracting the distance *CF* from *C*4. The distance *CF* represents the " lost volts " for the current *OC* corresponding to the electromotive force *C*4, and similarly the ordinates represent the lost volts for any corresponding armature current.

Curve 3 is obtained from 4 by subtracting the abscissæ lengths which are included between *OS* and *OD*. Thus the point 3 is obtained by subtracting the distance *XY* from *D*4. The distance *XY* represents the amperes in the shunt circuits, or the " lost amperes " for the difference of potential *C*2, and similarly the abscissæ between *OS* and *OD* represent the lost amperes for any corresponding difference of potential.

Curve 1 is obtained by taking the ordinates (lost volts) from curve 3 and the abscissæ (lost amperes) from curve 2 corresponding to any point on curve 4.

In practice, it is customary to plot curve 1, by observing the difference of potential at the terminals with a voltmeter and measuring the external current with an ammeter. Curves 2 and 3 can then be drawn, and from these two, curve 4 can be plotted.

Curves 1 and 4 are generally the only ones required. Curves 2 and 3, when drawn, are for the purpose of facilitating the construction of curve 4 from curve 1 and the curves giving " lost volts " and " lost amperes."

These curves are curiously different from those of the series generator. The volts are a maximum when the external circuit is open, and as the external current gradually increases, the difference of potential gradually falls, due to the fact that a smaller proportion of the total current is now flowing around the field magnets. At first this fall is gradual, but at a certain current the curve rapidly turns and then descends rapidly towards the origin in a nearly straight line. This shows why a shunt generator will not build up if the external circuit is closed, and how it rapidly unbuilds if the external resistance is lowered to a certain amount. The straight portion shows the critical state, and shows that if the external resistance is altered the slightest degree, both the volts and amperes alter to a very great degree.

These curves show that the shunt generator will only work if the resistance of the external circuit is greater than a certain value, while the series generator will only work if the resistance is less than a certain value.

A curve (Fig. 182) showing the relation between the volts and resistance is instructive, as by its combination with the corresponding curve of the series generator the curve for the compound generator is made.

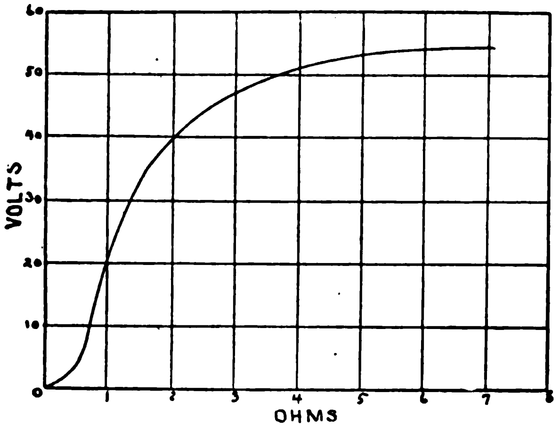


FIG. 182.—**Curve Showing External Resistance and Terminal Voltage, Shunt Generator.**

Compound Generators.—Having now seen the principles upon which the series and shunt generators are built, we are in a position to take up the compound generator, which is simply a combination designed to produce a constant difference of potential at the terminals irrespective of the external current or resistance: A compound generator can then best be considered as a shunt generator, upon which there is also wound a few turns of series windings. Under the curve for the shunt generator it was seen that as the external current was increased, or what amounts to the same thing the external resistance decreased, the difference of potential gradually fell and in the series curve, the difference of potential gradually increased under the same circumstances. So by combining these two curves, a curve of constant potential or a straight line might be produced, and that is the sole object of the compound generator. This could be well represented by combining the two external curves of the series and shunt generators, but is still better shown by combining the two curves plotted with volts and ohms, for each generator as shown under the respective heads of series and shunt generators. These curves are shown in the figure.

The shunt curve in Fig. 183 shows what was seen before, that the greatest electromotive force occurs when the external resistance is

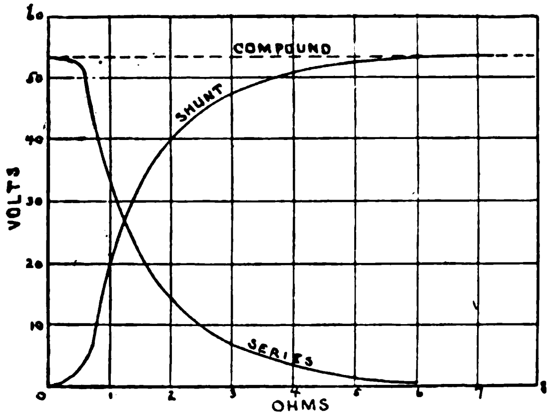


FIG. 183.—Curve of Compound Generator.

greatest, or when the external circuit is open, and as the resistance is gradually decreased, or the external current gradually increased the electromotive force gradually fell. The opposite takes place in the series generator, for when the resistance is high scarcely any current flows around the field spools, and there is practically no electromotive force, but as the resistance decreases or current increases, the electromotive force gradually rises. If there is a proper relation between the resistances of the two windings, one will raise the electromotive force just as much as the other lowers it so the sum of their ordinates at any point will be constant, and the compound characteristic is represented by the dotted straight line, marked "compound."

The type of compound generator used in the navy is fitted with the series shunt described in Chapter XII. When the machine is being compounded the shunt is adjusted to produce a constant terminal voltage within the limits of load for which the generator is designed. When once adjusted it should not thereafter be tampered with. Variations in the voltage may be then controlled by the shunt field rheostat.

Summary of the effects of increased load on the terminal voltage of generators running at constant speed, voltage uncontrolled. In all generators an increase in the armature current produces an increased ohmic drop in the armature windings and the series field coils, if fitted, and a greater armature demagnetization. Both of these effects tend to lower the terminal voltage of the machine.

In the **series** generator, however, this tendency at first is overbalanced by the greater field strength created by the increased current, and in consequence the voltage rises with the current, although not in direct proportion, until the saturation point of the pole pieces is neared. From then on the internal drop and the armature reaction prevail, and the voltage falls as the current continues to rise.

The field current of the **separately excited** generator does not alter with change of load. Therefore its terminal voltage falls with increased load in proportion to the internal drop and the armature reaction.

In the **shunt** generator the terminal voltage falls on increase of load not only because of the internal drop and the armature reaction, but in addition because of the decreased field strength. Since the terminals of the field circuit are the terminals of the generator, the decreased terminal voltage due to the internal drop and the armature reaction weakens the field current and excitation, which produces a further drop in the voltage. Consequently, the decrease of terminal voltage on increased load is greater proportionately in the shunt generator than in the separately excited.

In the **compound** generator the terminal voltage remains approximately constant on increase of load if the increased excitation of the series field is sufficient to counteract the internal drop and the armature reaction. The machine is then said to be "**flat compounded.**" If, however, the excitation of the series field predominates the internal drop and the armature reaction, the terminal voltage rises on increase of load, and the generator is then said to be **over compounded.**

Over Compounding.—By proper adjustment of speed and resistances, machines can be made to give a constant difference of potential for a certain range of external current which may not be constant over the entire limit of external current. A machine is said to be over compounded when the difference of potential at the terminals is higher than the electromotive force at some point in the circuit over which the electromotive force is to be constant for the range of current used. It is usually due to a preponderance of the series winding over the shunt. There is no necessity of over compounding generators on board ship for the leads are short and their resistances low. It is, however, absolutely essential to know over just what range of external current the electromotive force is constant. Thus, of two machines built entirely alike of 100-ampere capacity, one might have an absolutely constant electromotive force from 0 to 50 amperes, and not so constant for the rest of the load, while the other might be not quite so constant in the first half of its range, but entirely constant in its second half. In running these machines in parallel, they would only automatically work, so to speak, over the range of current common to both in which the electromotive force was constant, though of course they could be regulated so as to divide their loads equally by adjusting the shunt rheostats.

Generators are over compounded in order to maintain a constant difference of potential at a point on the external circuit distant from the terminals. With increased load the terminal voltage rises sufficiently to compensate for the increased ohmic drop in the feeders running to the point. For lighting service generators are about 4 per cent over compounded; for railway service, about 10 per cent.

Voltage Regulation.—By the term "voltage regulation" is meant the change of voltage of a generator from full load to no load when running at constant speed, expressed as a percentage of the voltage at full load. It should not be confused with "voltage control."

As an example of voltage regulation, suppose a generator develops 100 volts at full load and 110 volts at no load. Its voltage regulation is then:

$$\frac{110-100}{100}=10 \text{ per cent.}$$

Power Supply at Constant Voltage.—Electrical power is usually distributed at constant voltage; that is, the lamps and motors connected up in the receiving circuit of a generator are in parallel with each other and are fed by mains whose difference of potential is kept constant regardless of the current supplied. Fig. 184 * illustrates the general scheme of the distribution of power at constant voltage. From the terminals, *t, t,* of the generator, *G,* feeders are led to distribution centers, where mains carrying lamps, *L,* and motors, *M,* in parallel, are tapped off. The voltage at the terminals of the generator is maintained at a fixed strength, partly by the design of the generator and partly by manipulating the field rheostat, *R.* With

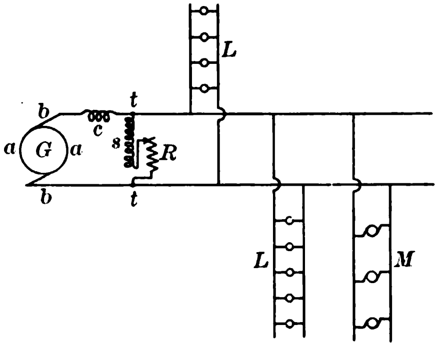


FIG. 184.—Power Supply at Constant Voltage.

constant terminal voltage the electromotive force between the feeders and mains will also be constant, neglecting variations in the ohmic drop in the line due to the changing current. Each lamp or motor, therefore, will always operate on a fixed voltage, which will be the voltage for which it was designed. Switching on or off a lamp or motor will not affect the operation of the other lamps or motors in the circuit. It will, however, increase or decrease the current supplied by the generator by the amount required for the appliance manipulated.† Accordingly the generator must deliver a varying current.

* Switches, circuit-breakers, and fuses omitted.

† With constant terminal voltage the external current is inversely proportional to the resistance of the external circuit. Connecting or disconnecting lamps or motors alters the resistance of the circuit and consequently the current.

The characteristic curve of the shunt generator shows that within limits the machine maintains a nearly fixed voltage under varying load, while the voltage of the compound generator is more constant still. Either of these machines may be used for supplying power at constant voltage. Variations in the terminal electromotive force on change of load are corrected by the field rheostat, which is manipulated by the attendant. The compound generator is used on shipboard.

The characteristic curve of the series generator makes it evident that that machine is not suited to the delivery of a varying current at constant voltage.

Power Supply at Constant Current.—When lamps are distributed over a wide area the constant voltage system of supply, necessitating large conductors to carry the heavy current of the line, would require a considerable expenditure for conducting material. If the lamps are in series the feeders need only be large enough to carry current ficient for the operation of one lamp. Since a lamp operates perly only when receiving current of the strength for which it is gned it is necessary that the generator supplying lamps connected in series should deliver a constant current. Alterations in the number of lamps in the circuit will affect the resistance of the circuit in proportion, and the voltage of the generator must vary accordingly to maintain the current constant. If the number of lamps is approximately fixed the variations of the generator voltage can be kept within the range of practicability, and the series connection is feasible. The foregoing considerations limit the constant current system of power supply to the lighting of city streets.

The characteristic curves of the shunt and compound generators make it evident that these machines are not adapted to the supply of a constant current at varying voltage. It would be possible to fit a shunt generator to deliver a constant current if there could be had a device for automatically controlling the voltage so as to keep the current unchanged on alterations in the external resistance; but an attempt at such an appliance would result in a voltage control too slow in its action for good results, and one likely to endanger the line by permitting a sudden heavy current in the event of a short circuit. Furthermore, as the resistance of lamps in series is great, the voltage of the generator must be high, and high voltage shunt generators are expensive because of the great quantity of fine wiring required for their field coils. To this objection the series generator, with its heavy field coils of few turns, is not open.

The characteristic curve of the series machine shows that this generator is better adapted to the delivery of a constant current than either the shunt or compound generators. In addition, it is practicable to design the series generator so that it will automatically and efficiently regulate its voltage to meet changes in the resistance of the external circuit. Automatic voltage control is an essential to machines supplying constant current, for which hand control would be tardy and inexact.

Accordingly, the series generator is always used for constant current supply. Fig. 185 illustrates the system. The lamps are shown connected in series in the supply line. When it is desired to throw a lamp out of service its terminals are short circuited by a shunt or by-pass of low resistance.

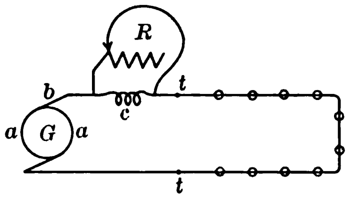


FIG. 185.—Power Supply at Constant Current.

It is principally by its armature reaction that the generator is made self-regulating. The armature is so designed that the demagnetizing effect of the armature current is great and varies with the slightest change in the current, whereas the magnetism of the pole pieces is made insensible to small changes of the current by working the field cores at a high magnetic density, near to saturation. As a result, whenever a decrease in the resistance of the external circuit permits a momentary increased current to flow in the armature and field windings, the demagnetization of the armature is increased without a corresponding increase in the pole flux, and the voltage and consequently the current of the generator are cut down. The machine thereby becomes self-regulating for small and sudden fluctuations of the current. Larger and more gradual changes are taken care of by mechanical devices which automatically control the voltage, either by shifting the brushes or by varying the ampere turns of the field coils.

The constant current system of power distribution has no application on shipboard.

Limit of Output.—In the case of a generator designed to give a constant difference of potential at the terminals, the amount of current flowing through the armature depends on the external resistance. As this resistance is reduced by adding incandescent lamps in parallel, it becomes a matter of importance to know how far it may be lowered; or, in other words, how much current can be safely taken from the generator. In a given generator the calculations are based on a given maximum current, and the conductors of the armature are calculated to withstand safely this current; but the question is to determine what limits the current and what should be the basis of the calculation.

One limitation on the output of a generator is the **heating effect** of the armature current and eddy currents. The heat formed by the currents tends to dissipate itself into the surrounding air, but if the heat is produced by the current faster than it is radiated, it is very evident that the temperature of the parts themselves will be increased. If the generator is at rest and has been for some time, all of its parts will attain the temperature of the air; if now the generator is made to supply an external current, heat is formed in the conductors, and if it is radiated as fast as produced there will be no rise in temperature. This is seldom the case, however, and the temperature of the parts will go on slowly rising. The greater the current taken from the generator, the greater will be the increase in temperature for the same time. Now it is very evident that one limit of the amount of current is the temperature limit due to that current. At a certain temperature the materials used in the insulation of the conductors and the different windings of the generator, such as paper, cotton, silk, etc., will char and disintegrate to such an extent as to be worthless for what they were designed. For a short time they may stand a temperature somewhat higher than the charring temperature, but if submitted for any length of time to a temperature of 180° F., they will quickly break down. Consequently, no current should ever be taken from a generator such that the heat formed should raise its temperature to 180° F.

If the temperature of the air is as high as 180° F., it is very evident that the machine should not be run at all, for all parts will be at that temperature, and there could be no allowable rise in temperature, due to the generator currents, so in stating the allowable rise, it is very necessary that it should be a rise in temperature above that of the surrounding air. If the machine could be kept in a room at the freezing point, and the heat imparted to the air so carried away that it would remain at the freezing point, the allowable rise due to the current would be 180° – 32°, and from this generator under those conditions, a greater current could be safely carried than at any initial higher temperature.

The specifications for generators used in the service state that after a four-hour full-load trial, no part of the machine shall be at a temperature 40° C., greater than the temperature of the room; or, in other words, the temperature attained, due to the heating effects of the current and other operating conditions, shall not be greater than 40° C., above the temperature of the room. The average room temperature is taken as 25° C.

A second limitation on the output is **sparking**, the causes of which have been explained. With excessive current the armature reaction may become powerful enough to overcome the flux of the pole pieces, in which event the neutral axis vanishes, and no position in which sparking will not occur can be found for the brushes.

Sparking is very injurious, and when heavy, rapidly burns away the brushes and the commutator segments, rapidly pitting and scarring them, and the heat due to the sparking may be great enough to fuse two or more adjacent segments, thereby short circuiting their coils, and soon burning them out. Sparking can be reduced by good preliminary design; by making the field magnets relatively very powerful in relation to the armature field, but still in any generator, a current in excess of the designed amount may produce injurious sparking, so that this also limits the amount of current that may safely be taken from the machine.

A third limitation on the output of a generator to be used for constant voltage supply is the excessive drop in the terminal voltage. By referring to the characteristic curves given in this chapter, it will be seen that a large current output may cause an excessive voltage drop.

The maximum current which can be taken from a generator without causing excessive heating or sparking or excessive drop in terminal voltage determines the rated output of the machine.

Summary of the Uses of Different Classes of Generators.

Separately excited generators are used mostly for testing where a constant E. M. F. is desired or where changes of speed affect but slightly the terminal voltage. Generators used for charging storage batteries are usually separately excited, as they are working against an opposing E. M. F. which would act back through the generator if it were not immediately disconnected on stopping. Separately excited generators are much less likely to have the field magnetism reversed. They are also used largely for electroplating.

Series generators cannot be used where constant voltage is desired, but can be used for supplying constant current at varying voltages, the voltage being regulated by devices to keep the current constant on changes of the external resistance.

Shunt or compound generators are used for delivering varying current at constant voltage, as in electric lighting and in most forms of power. They are driven at or near constant speed by the motive power available.

Measurements.—When operating a generator it is essential that the attendant should be at all times informed of the terminal voltage and external current developed by the machine. Accordingly each generator is fitted with a voltmeter connected across its terminals and an ammeter in series in one of the terminal leads. Sometimes a wattmeter is also supplied for measuring the power delivered to the external circuit, although with direct-current machines the power may be obtained by taking the product of the readings of the voltmeter and ammeter.

Fig. 186 shows the connections of voltmeter, *V*, and ammeter, *A*, for a long-shunt, compound-wound generator. *t, t* are the terminal switches for connecting the generator to the external circuit,* *B, B* are circuit-breakers; automatic switches designed to open if the generator develops excessive current, thereby protecting the machine from overload.

* At the switchboard.

On board ship generators are directly connected to the shaft of the prime mover, either by a solid shaft or a flange coupling. The power applied to the shaft may be obtained by taking indicator cards of the engine or readings of the torsion meter when generator is turbine driven. The power delivered simultaneously by the generator is determined from the voltmeter and ammeter readings. From this data the commercial efficiency of the generator may be obtained. If in addition the resistances of the various generator windings are known, the efficiency of conversion and the electrical efficiency may be calculated as explained in Chapter XI. It is to be noted that the efficiency of a generator is different at different loads; therefore, in stating its efficiency the condition of load should be specified. The efficiency is usually measured when the generator is

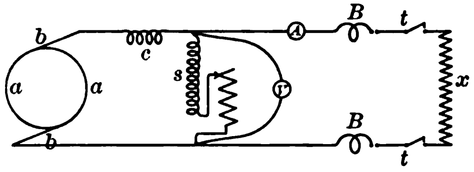


FIG. 186.—Connections of Instruments.

delivering its rated output; in other words, at full load, and the machine is designed so that its efficiency will then be a maximum.

It can be shown mathematically that the maximum efficiency of a shunt or compound generator occurs when the sum of the variable dynamo losses (series field and armature loss) equals the sum of the constant losses (shunt field and stray power loss).

To start and connect up a shunt- or compound-wound generator the machine should first be brought up to its rated speed with the terminal switches open. As the voltage rises the field rheostat is manipulated until finally the voltage is steady at a value slightly above the standard. The circuit-breakers may then be closed, and finally the terminal switches. If the circuit-breakers are closed last, thereby completing the circuit and throwing the load on the machine, the hand, in the act of closing them, prevents their functioning in the event of an overload occurring at that instant, and so endangers the generator. The object in raising the voltage slightly above the standard before taking the load is to allow for the armature drop of the loaded machine, leaving the terminal voltage about standard when the terminal switches are closed. As soon as the load is taken the standard voltage should be maintained by the field rheostat.

To stop and disconnect the load should first be reduced as much as possible by reducing the load and throwing into the field circuit all the resistance of the rheostat. The circuit-breakers may then be tripped by hand, the terminal switches opened, and the engine shut down. It is advisable to trip the circuit-breakers before opening the terminal switches in order that the arc consequent upon breaking the circuit may be formed on the carbon contact pieces of the circuit-breakers instead of on the easily fusible brass terminal switches.

If there is a switch in the shunt field circuit **it should never be opened until all the regulating resistance is in.** Owing to its many turns the inductance of the shunt winding is great, generating a high self-induced electromotive when the circuit is broken. With the resistance of the rheostat out of the winding this induced electromotive force might produce sufficient current to injure the coil.

In both starting and stopping the precautions usual in handling steam engines or turbines should be observed.

Generators in Parallel.—It is sometimes necessary to couple two or more generators together so that they may supply to a circuit a larger quantity of electric energy than either could do singly. To increase the current it is usual to connect generators in parallel exactly in the same manner that electric cells are connected in parallel; that is, by connecting the positive terminals together or to a common conductor and by connecting the negative terminals together or to a common conductor.

Suppose a ship's plant was composed of three units of 800 amperes each. As long as the current to be carried is below the capacity of one machine, it is very evident that only one machine would need be in operation. It would be better to allow the load on one machine to increase to its full capacity before starting another machine than to divide the full capacity of one machine between two machines, whether connected in parallel or not. A machine that is running at its rated capacity has a greater efficiency than when running at a reduced load. If one machine can deliver all the current necessary, besides the gain in efficiency, it is clear that there can be no good reason for running two, which would simply mean extra wear on the moving parts, extra lubrication, and the extra attention necessary from the dynamo tender.

When the current necessary increases above the capacity of one machine, then it is obvious another machine must be connected in circuit. Suppose 1200 amperes were called for; this could be delivered by one machine at its full capacity of 800 amperes, and by a second machine running independently at 400 amperes. The case now becomes different, for two generators are necessary and whether running singly or in parallel, the wear and tear, oil consumption, and attention are practically the same. One would be running at its highest efficiency and the other at a considerably reduced efficiency. If any extra load were called for, it could be thrown on the light-loaded machine only and this would involve extra care on the part of the tender that is not necessary, that of picking out the right bus bars to throw the switches on. This is a very slight matter, but it involves at least a question of time. If the two generators are connected in parallel, the total load of 1200 amperes could be equally divided between them, so each would take 600 amperes and the combined efficiency would be greater than when one is running at its highest and the other at a reduced efficiency. If extra load was now called for, it is immaterial on which bus bars the switches are closed, for all being in parallel any increase will be equally divided between the two machines. When the load is equally divided, there is a general balancing all around of the electric energy; no one part is being strained while another part is subjected to little or no strain; the engines of the generating sets are doing an equal amount of work; there is the same amount of loss in the field regulators, and the same heating effect in all the parts of the generator. Any sudden call for current falls on both machines alike and the evils, if there are any, of sparking and consequent shifting of the brushes are on each machine reduced by half.

The two machines should be kept in parallel until their combined capacity is equal to the current called for, and if the current still increases, a third machine should be connected in parallel with the other two. If 1800 amperes were required it could be furnished with two machines in parallel, each producing 800 amperes, and the third machine would then only have to supply 200 amperes, but if all three were connected, there would be 600 amperes on each, and there would be no danger of overloading any one machine as any additional current would be divided equally among the three.

Connecting Shunt Machines in Parallel.—There is no difficulty in running shunt generators in parallel, all that is necessary is to be sure to have the correct terminals connected together. The chief precaution to be observed is that when an additional generator is to be switched into circuit its field should be fully excited and the armature running at full speed before it is connected to the mains; otherwise the current from the mains might prevent the building up of the field and the induction of electromotive force.

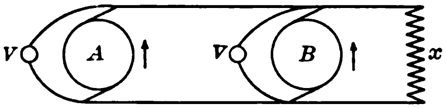


FIG. 187.—Generators in Parallel.

Let it be supposed that a shunt machine, *B*, carrying no load, is to be coupled in parallel with a shunt machine *A*, carrying load, the field of *B* being fully energized. On open circuit the terminal electromotive force of *B* may be considered its armature electromotive force, for the armature drop due to the small shunt current is negligible. If, then, the voltage of *B*, before connection, is adjusted until it equals the voltage of *A*, both as determined by terminal voltmeter readings, upon connecting *B* its armature electromotive force will be opposed by the equal and opposite terminal electromotive force of *A*, and *B* will therefore take none of the load. Although *A* and *B* are in parallel with reference to the external circuit, they are in series and in opposition in the circuit formed by themselves alone (Fig. 187), and if *A's* terminal voltage equals *B's* armature electromotive force, the total electromotive force acting through *B* is zero, and no current can flow in *B*. In this case *A's* armature electromotive force exceeds *B's* armature electromotive force by the lost volts, or armature drop, in *A*.

If before connecting *B's* voltage be raised above *A's,* then upon connection *B's* armature electromotive force will no longer be balanced by *A's* terminal voltage, and current will be supplied by *B*. Since *B* now takes part of the current, *A's* armature drop will decrease and *A's* terminal voltage will rise; whereas *B's* armature drop will increase and *B's* terminal voltage will fall, *A* and *B* arriving at the same terminal voltage. The amount of current which *B* takes depends upon its voltage before connection. If its voltage is less than the armature electromotive force of *A, B* will take less than half the load. If its voltage equals the armature electromotive force of *A, B* will take half the load. If its voltage is greater than the armature electromotive force of *A, B* will take more than half the load. If the voltage of *B* is less than the terminal voltage of *A, A* will force current through *B,* and the latter will be run as a motor.

Problem 5 at the end of this chapter illustrates the principle under discussion. In this problem separately excited generators instead of shunt generators are used to avoid complicating the issue by the feature of the armature drop of the shunt current.

The above discussion presupposes equal speeds, though if one were heavily loaded it would probably slow down and if the resulting difference of terminal voltages were not too great, the engine governors might act to adjust the speed to bring the voltages within limits so that the machines would take their equal share of the load.

It is evident from the foregoing that before throwing a machine in parallel with another, in addition to seeing that the polarity is the same in each, the terminal voltage of the one to be coupled should be the same as or slightly higher than the one carrying the load.

Connecting Series Machines in Parallel.—Two series machines cannot be directly connected in parallel without some additional connections. If they were connected simply in parallel they might function if the electromotive force at the terminals could be kept the same, and the internal resistances of each were exactly equal, but this could hardly occur. If the electromotive force of one fell the slightest, current from the other would flow through the series coils in the opposite direction tending to weaken the current still more and reverse the polarity and in the end finally running it as a motor. To obviate this, not only the terminals of the machines are connected in parallel, but the *brushes* are also connected by a conductor called the *equalizer*. If now either generator tends to reduce its voltage, current from the other will flow through the equalizer and through the series coils in the same direction as that of the current of the generator itself, thereby building up the field and increasing the electromotive force. This equalizer also prevents any reversal of polarity, a very necessary precaution in parallel running.

Connecting Compound Generators in Parallel.—The only trouble in connecting compound generators in parallel arises from the series coils, the shunt being connected directly in parallel without any other connections, exactly as in the case of shunt generators. The series coils are connected with an equalizer exactly as in series generators, so for compound generators, it simply amounts to connecting the brushes of same polarity together as well as connecting the terminals.

Necessity of an Equalizer.—The equalizer helps to divide the load more exactly among the different machines. If there were no equalizer, as seen in series machines, the current from each armature would flow through its own series coil. When the load is increased, it might happen that one machine, being a little more sensitive than another, would take more than its share of the load, and this extra current going through its series coils would strengthen its field and cause it to generate more and more current, until it might blow its fuse and open the circuit. Another reason is given under the connection for series machines, that is, the difference of electromotive force whereby one would tend to run another as a motor.

Equalizing the Load.—By coupling all the machines to the equalizer so that there is a common connection between the armature and the series coils, the currents from all the armatures unite and then divide among the different series coils. If one armature tends to deliver more than its proportion of the whole current, it strengthens the current in the series coils of all the machines and not its own alone. If one tends not to take its full share, some of the current from the other machines goes through its series coils and helps build up its field so that it delivers more current.

Operation of Generators.

Fig. 188 is an elementary diagram of a generator panel showing the connections of generator to bus bars and the location of instruments required for the operation and control of two generators. This figure is an elementary diagram of a paralleling board built at

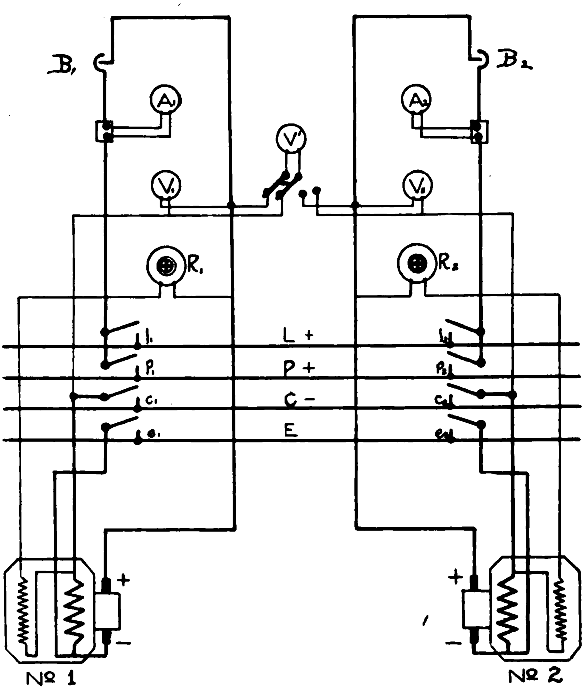


Fig. 188.—Elementary Wiring Diagram of Generator Board for Operating Two Generators Singly or in Parallel.

the Naval Academy and used by midshipmen in the practical operation of generators in parallel. This board was patterned after the generator panel installed on board the U. S. S. *New York.** One of

*** The generator panel U. S. S. *New York* contains a wattmeter and the calibrating voltmeter is fitted also as a ground detector. These are not shown in the diagram.**

these is installed in each dynamo room for the control of two 300-kilowatt turbo-generators. A_1A_2 are ammeters for measuring the output of the machines. V_1V_2 are the voltmeters, one being connected across the terminals of each generator. B_1B_2 are single-pole automatic circuit-breakers connected in the positive lead of generator. R_1R_2 are the field rheostats, one being connected in series with the shunt field of each generator for controlling the voltage. V' is the calibrating voltmeter so fitted that it can be readily thrown in parallel with either one of the generator voltmeters. This permits of the voltage of both machines being taken with the same instrument preparatory to being operated in parallel and avoids any difficulty that might otherwise arise due to the generator voltmeters not being properly calibrated. E is the equalizer bus. Suitable switches are provided for connecting this bus to the negative brush of each machine. C is the common negative. Suitable switches are provided for connecting this bus to the negative terminals of each machine. P is the positive power bus for supplying power circuits and has switches for connecting it with the positive generator leads. L is the positive lighting bus and is provided with switches for connecting it with the positive generator leads.

The methods of operating the generators under the various conditions are given below.

Operating Singly:

To start a dynamo for light or power or both, everything being stopped:

1. See that bus bar and equalizer switches are open.
2. Turn field rheostat handwheel to "low voltage."
3. Bring engine to speed as previously described.
4. Move rheostat handwheel until voltmeter reads about 130, then reduce to 125 volts.
5. Close the circuit-breaker, positive lighting, power or both, and common negative bus-bar switches of the generator to be run.

To Stop Dynamo:

1. Stop engine.
2. Open circuit-breaker and switches mentioned above.

To Stop Dynamo in an Emergency:

1. Trip the circuit-breaker.

2. Stop the engine.
3. Open the rest of the switches.

Operating in Parallel:

To place dynamo No. 2 in parallel with dynamo No. 1 already running under load:

1. See that the circuit-breaker and switches connected with dynamo No. 2 are open. These switches are: Equalizer switch, common negative bus switch, positive lighting switch, and positive power bus switch.
2. Turn field rheostat handwheel to "low voltage."
3. Bring the engine to speed.
4. Move rheostat until the voltage of No. 2 is the same as that of generator already in operation.
5. Close circuit-breaker.
6. Close equalizer switch of both machines.
7. Close common negative switch. This allows half the current from No. 1 machine to flow through the series field of No. 2 machine.
8. Check voltages of the two machines using calibrating voltmeter. The voltage of No. 2 machine should now be about one volt higher than that of No. 1 due to the series field excitation.
9. Close positive power switch, positive lighting switch or both.
10. Adjust load by moving the rheostat.

To Stop Dynamo No. 2 Running in Multiple with Dynamo No. 1:

1. Move rheostat until ammeter reading shows that No. 1 machine has nearly all the load.
2. Trip the circuit-breaker.
3. Open bus switches on No. 2.
4. Open equalizer switch.
5. Stop the engine.

Problems.

1. Plot the external, internal and total characteristic of a series generator from the following data:

Resistance of armature, 0.2 ohm.

Resistance of field coil, 0.1 ohm.

SIMULTANEOUS READINGS OF AMMETER AND VOLTMETER.

Current.	Terminal voltage.	Current.	Terminal voltage.
0 amperes	10 volts.	25 amperes	54 volts.
10 "	45 "	30 "	53 "
15 "	51 "	40 "	48 "
20 "	54 "	50 "	42 "

Solution.

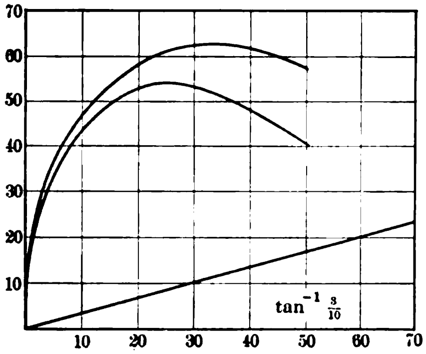


FIG. 189.

2. Plot the external, internal and total characteristic curve of a series dynamo from the following simultaneous readings of ammeter and voltmeter, the ammeter being connected in the line and the voltmeter across the terminals of the generator. Armature resistance, 0.3 ohm; field resistance, 0.5 ohm.

1. 10 volts	0 amperes.	6. 54 volts	20 amperes.
2. 20 "	4 "	7. 53 "	30 "
3. 30 "	6 "	8. 50 "	36 "
4. 40 "	8 "	9. 42 "	50 "
5. 50 "	14 "	10. 40 "	52 "

For Solution, see Fig. 190 on the next page.

3. A shunt generator, armature resistance 0.08 ohm, 3000 turns in the shunt field winding, gives a terminal voltage of 150 volts when the shunt current is 5 amperes and the external circuit is open. How many turns must a series field coil have to make this a short-shunt, flat, compound generator when supplying a current of 400 amperes to the external circuit? Neglect the resistance of the series field and the demagnetizing effect of the armature current. Assume the field flux proportional to the ampere turns of the field coils.

For Solution, see next page.

Solution to Problem 2.

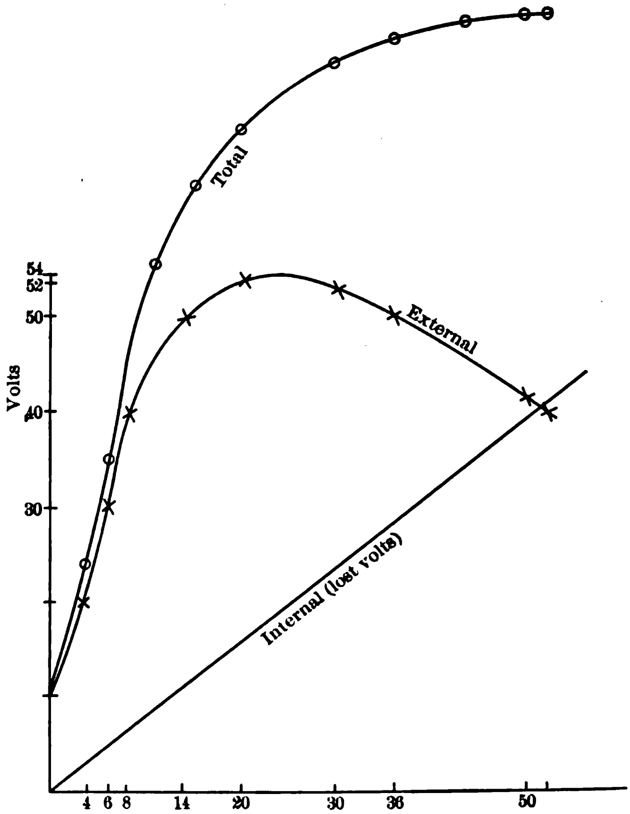


FIG. 190.

Solution to Problem 3.

$E_{a_1} = 150 + 5 \times .08 = 150.4, \; E_{a_2} = 150 + 405 \times .08 = 182.4.$

$$\frac{E_{a_1}}{E_{a_2}} = \frac{\Phi_1}{\Phi_2}, \quad \Phi_2 = \frac{E_{a_2}\Phi_1}{E_{a_1}} = \frac{182.4 \times 5 \times 3000}{150.4} = 18{,}240.$$

$$18{,}240 - 5 \times 3000 = 3240, \; \frac{3240}{400} = 8 \text{ turns}.$$

4. A shunt generator gives a full-load current of 100 amperes at a terminal voltage of 125 volts, and an excitation of 20,000 ampere turns is required. To give the same voltage at zero load, 15,000 ampere turns are required. Find the number of turns required in a series field to give constant voltage. *Ans.* 50 turns.

5. A separately excited generator, armature resistance $\frac{1}{2}$ ohm, supplies current to an external circuit of 2 ohms resistance at a terminal voltage of 80 volts. A second separately excited generator, of the same armature resistance, is started up preparatory to being connected in parallel with the first. Using Kirchoff's laws find what must be the terminal voltage of the second generator before being connected and its terminal voltage after being connected in order that it may (1) take $\frac{1}{2}$ the load, (2) take $\frac{1}{4}$ of the load, (3) take no load, (4) be run as a motor. (5) What would be the current through each generator and the external circuit if the induced E. M. F.'s of both were equal and the polarity of the second were reversed?

Solution.

Call first generator A, second B. Terminal E. M. F. of B on open circuit equals induced E. M. F.

$$I_x = \frac{80}{2} = 40,\ E_a = 80 + 40 \times .5 = 100.$$

(1) $I_a = I_b,\ I_a + I_b = 2I_a = 2I_b = I_x.$
$100 = .5I_a + 2I_x = .5I_a + 4I_a = 4.5I_a.$
$I_a = I_b = \frac{100}{4.5},\ E_b = .5I_b + 2I_x = 4.5I_b.$
$E_b = 4.5 \times \frac{100}{4.5} = 100,\ E_x = 100 - \frac{100}{4.5} \times .5 = 88.9.$

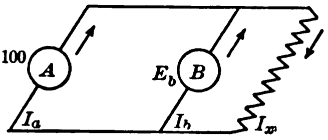


FIG. 191.

(2) $I_a = 3I_b,\ I_a + I_b = I_x = 4I_b = \frac{4}{3} I_a.$
$100 = .5I_a + \frac{8}{3} I_a = \frac{9.5}{3} I_a,\ I_a = \frac{300}{9.5},\ E_b = .5I_b + 8I_b.$
$E_b = \frac{.5}{3} I_a + \frac{8}{3} I_a = \frac{8.5}{3} I_a = \frac{8.5}{3} \times \frac{300}{9.5} = 89.5.$
$E_x = 100 - \frac{300}{9.5} \times .5 = 84.2.$

(3) $I_b = 0,\ I_a = I_x,\ 100 = .5I_a + 2I_x = 2.5I_a,\ I_a = 40.$
$E_b = .5I_b + 2I_x = 0 + 2 \times 40 = 80,\ E_x = 80$ (by inspection).

(4) Any voltage below 80 will cause B to run as a motor. Take 78 and prove.
$100 = .5I_a + 2(I_a + I_b) = 2.5I_a + 2I_b \qquad E_x = 78 + 2.2 \times .5$
$78 = .5I_b + 2(I_a + I_b) = 2I_a + 2.5I_b \qquad E_x = 79.1.$
$400 = 10I_a + 2I_b \qquad -4.5I_b = 10I_b = -\frac{10}{4.5} = -2.2$
$390 = 10I_a + 12.5I_b.$ Neg. value of I_b proves B motor.

(5) By inspection $E_x = 0 \therefore I_x = 0.$
$I_a = I_b = \frac{100 + 100}{.5 + .5} = 200$ amp.

CHAPTER XIV.

THE MOTOR.

Excitation.—All motors may be regarded as separately excited dynamos, since their field current is supplied by an external source of power.

Windings of Motors.—Motors, like generators, are classified according to their field connections, as shunt, series, and compound wound. There is no essential difference between the windings of generators and motors except in the compound-wound machines. Compound generators are **cumulative** wound; that is, the series coil is so connected that it strengthens the magnetism of the shunt field. Whereas compound motors may be either **cumulative** wound or **differential** wound. In the differential compound motor the series coil opposes the magnetism of the shunt field.*

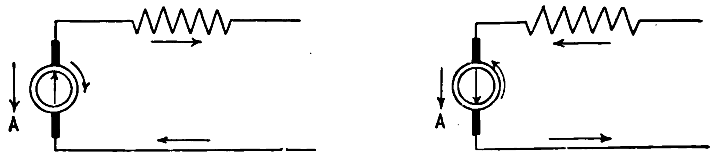


FIG. 192.—Series Generator and Motor.

Generators as Motors.—Generators designed for continuous currents may be used, in all cases, as motors with some slight changes.

A **series generator** used as a motor will run in the *opposite* direction to that in which it must be driven in order to build up as a generator.

Fig. 192 shows a diagrammatical sketch of a series generator and series motor. The left-hand figure represents a series generator, the curved arrow indicating the direction of rotation of the armature, with the resulting current in the external circuit and through the armature, represented by the arrows in those parts. The arrow *A* in the motor represents the resultant mechanical force exerted by

* The cumulative compound motor is generally referred to as a "compound motor" and the differential compound motor as a "differential motor."

the field upon the armature conductors, and in the generator the counter force that the power driving the armature overcomes.

With given connections of field to the armature, the *relative* direction of current through field and armature is the same whether used as a generator or motor, and consequently there is *no* change in the direction of mechanical force with which the field acts on the armature conductors. In the generator the power overcomes this force, but in the motor, it produces the motion; so, consequently, the force that has been overcome in the generator acts to produce *opposite* rotation when the dynamo is used as a motor.

It is immaterial which way the current flows when used as a motor, for the reversal of the supply current simply reverses both the direction in the armature and in the field and does not change the relative directions, so there is no change in the direction of the force exerted by the field on the conductors.

FIG. 193.—Shunt Generator and Motor.

To reverse the direction of rotation in the series motor, the armature current must be reversed without shifting the direction of the field current, by shifting the connections to the brushes.

A **shunt generator** with given connections of field to armature will run as a motor in the same direction that it must be run to build up as a generator.

Fig. 193 shows a diagrammatical sketch of a shunt generator and shunt motor. The left-hand figure represents a shunt generator, the curved arrow indicating the direction of rotation of the armature, with the resulting current in the various parts represented by straight arrows. The arrow *A* in the motor represents the resultant mechanical force exerted by the field upon the armature conductors and in the generator, the counter force that the power driving the armature overcomes.

In the generator, it is noticed that the current in the armature and in the field are in opposite directions, while in the motor, they are in the same direction. Consequently, in the motor, there is a *relative* change in the direction of the armature and field currents and this causes the mechanical force that represents the resultant action of the field on the armature conductors to act in the opposite direction. In the generator this force is overcome by the power driving the armature, and in the motor the force being reversed, drives the armature in the *same* direction.

In this case, also, it is immaterial which way the current flows in the motor circuit for a given connection to the brushes; for the reversal of the supply current simply reverses the current in both armature and field without producing any relative change, so there is no change in the direction of the mechanical force, and the motor armature revolves in the same direction as before.

To reverse the direction of rotation of the shunt motor, either the current through the armature or through the field should be reversed, *but not both.*

Compound Generator.—A *compound-wound* generator when run as a motor may run in either direction, depending on the relative strength of the two fields.

Speed Control.—From the fundamental equation of the motor (Chapter XI) it is seen that the **speed of a motor is dependent upon its applied voltage and its field strength**; consequently alterations in either will alter the speed of the motor.

Motors are usually driven by power supplied from mains whose difference of potential is constant. To control the motor's speed by varying the applied voltage it is necessary to insert **a variable resistance in series with the motor armature,** as in Fig. 194. Varying this resistance alters the ohmic drop through it and in consequence the voltage applied at the brushes. This method produces a power loss in the rheostat.

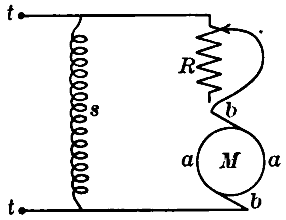


FIG. 194.—Armature Rheostat Control.

In some cases as in the Ward-Leonard system of motor control, the difference of potential of the supplying mains is not constant. **The motor's speed is then varied by manipulating the voltage of the driving generator.**

Speed control by manipulation of the field flux of the motor may be attained either by **varying the ampere-turns of the field coils or changing the reluctance of the magnetic circuit of the motor.**

With a shunt motor, variation of the ampere-turns of the field coil is economically obtained by inserting a regulating rheostat in series in the field circuit, as in shunt generators. As the shunt current is small the power waste by ohmic heating in the rheostat is not large. With the series motor, however, a rheostat in series with the field coil would also affect the terminal E. M. F. The field current of a series motor may be controlled by shunting the coil by a variable resistance, as explained for the series generator.*

With a given magnetomotive force or, which amounts to the same thing, a fixed number of ampere-turns energizing the field magnets, the magnetic flux produced will be inversely proportional to the reluctance of the magnetic circuit. As the reluctance of air is very much greater than that of iron or steel, the reluctance of the magnetic circuit of a dynamo depends mainly upon the length of the air gaps. Any change in their length will therefore materially alter the reluctance of the circuit and, in consequence, the flux.

This principle is taken advantage of in the Reliance Adjustable Speed Motor. Both the armature and inner faces of the pole pieces are given a slight taper, and represent surfaces of truncated cones, one within the other. Any movement of either, parallel with the shaft, increases or decreases the distance between the surfaces corresponding with the air gap. The normal position of the armature is directly beneath the pole pieces and in this position the air gap is a minimum, the reluctance least, and the flux the greatest. By withdrawing the armature laterally, the air gap not only increases in length, but also decreases in area; that is, the area of the air gap no longer corresponds with the area of the inner face of each pole, as there is a smaller surface of the armature core now directly under the pole pieces. Both these effects increase the reluctance and produce a gradual decrease in the magnetic field, and consequently a gradual increase of speed.

As the armature is withdrawn into regions of weaker fields, ordinarily there would be a tendency to brush sparking, particularly if the operation was accompanied by a change of load. This sparking is due to excessive currents in the coils when they are short

* This method of speed control for series motors is not used in the naval service. Varying the field of a series motor in this manner generally causes heavy sparking unless the motor is fitted with special interpoles.

circuited by the brushes and to the reversal of the current in the coil while its terminals are passing under the brush. In the Reliance Motor, at the instant of commutation, the coil enters a field opposed to the main field. This is produced by special commutating poles, interpoles, whose energizing turns are in series with the armature conductors. These interpoles are displaced in a direction towards which the armature is withdrawn. The result of this is, that at all positions of the armature, the commutating effect varies with the load, and as the armature is withdrawn to a region of weaker field, it comes more and more under the influence of the interpoles, giving increased commutating effect as the main magnetic flux decreases.

In another type of motor designed on the same principle, the length of air gap is increased by radially moving the pole pieces away from the armature, the pole pieces consisting of plungers within a magnetic shell which are actuated by handwheels.

Effect of Temperature on Speed.—Since the resistance of a metal conductor increases with rise of temperature, the increased drop through the series field and armature windings of a motor occasioned by heating decreases the motor's speed. However, the resistance of the series field and armature windings is so small that the variation in speed is negligible.

When the resistance of the shunt field winding increases with rise of temperature the field current and excitation are weakened and the motor speeds up. As the resistance of the shunt field is large and its variation on being heated may amount to about 20 per cent, the change of speed thereby occasioned is considerable. If it is desirable that the motor should have the same speed when cold—that is, at starting—as when hot, such change of speed is objectionable. It may be overcome by employing a saturated field, when moderate variations in the field current will produce only a small alteration in the flux.

Relation Between Brush Lead and Speed.—A dynamo generates its maximum electromotive force when the brushes are at zero lead, or have no lead. In the case of a shunt motor, the speed is a minimum when the brushes have zero lead, and any movement of the brushes either forwards or backwards, will ordinarily increase the speed and this is particularly noticeable in a motor running light.

When the brushes are moved from the zero position, the counter electromotive force is reduced by the demagnetizing effect of the armature current. As a result a greater current flows, producing an increased torque which causes the motor to speed up until the counter electromotive force attains such a value as to reduce the current to the value necessary to supply the required torque.

In some shunt motors under full load the distribution of the flux due to armature reactions is such that a forward shift of brushes strengthens the field and causes the motor speed to decrease. This is particularly noticeable in motors fitted with interpoles.*

Comparison of Methods of Speed Control.—The **armature rheostat** method is wasteful of power, and with large variations of load the speed fluctuates greatly, the control being dependent upon the ohmic drop created in the rheostat by the armature current and in consequence upon the load. On the other hand the method is simple, cheap, permits of fine gradations of speed, and gives a control ranging from zero to full speed.

The **field rheostat** method is limited in its range, for the field flux cannot be increased above the saturation point, nor can it be decreased below a certain value because of the consequent decrease in torque and the danger that the armature reaction may overpower the weakened field. Its advantages are that it is economical of power, simple, cheap, does not produce great fluctuations of speed with change of load, and may be used to give fine gradations of speed.

The **change of reluctance** method gives fine gradations of speed over a wider range than the field rheostat method, and it does not produce great fluctuations of speed with change of load. On the other hand, although it saves the cost of a rheostat, it requires a specially designed and rather expensive motor.

Self-Regulation of Motor.—To a certain extent the motor is entirely automatic as regards relation of current to external load. A certain amount of current is necessary at all speeds to furnish the torque necessary to overcome the motor losses, and if there is not sufficient current to overcome these losses, there will be no motion. Suppose the motor is running at a certain speed with a certain load, or doing a certain amount of external work, then if the load is increased, the current flowing at that time cannot furnish sufficient

* In the practical operation of motors, the shifting of the brushes is never used to control the speed.

torque to perform this extra work, and the motor slows down. This slowing down reduces the counter electromotive force and consequently the current increases until the torque is sufficient to perform the extra work the motor is called on to do. If the load is decreased, the armature has too much torque, and speeds up, thereby increasing the counter electromotive force and decreasing the current until the torque is reduced to the proper amount.

The Starting Resistance.—If the armature of a motor at rest were suddenly connected to a source of current supply, an abnormally large current would flow through the armature owing to its low resistance. This arises from the fact that as the armature is at rest, it can develop no counter electromotive force to reduce the incoming current. It does, however, generate electromotive force the moment it commences to revolve, and as its speed increases sufficient counter electromotive force is produced to reduce the current to its normal flow.

To prevent this first sudden inrush of current, it is usual in all forms of dynamos that are to be used as motors alone to introduce a resistance in series with the armature, so that when the circuit is first established only enough current flows through the armature to produce sufficient torque to cause revolution of the armature. As soon as the armature starts to revolve and counter electromotive force is generated, the current is reduced so some of the resistance may be cut out which will allow more current to flow and greater torque to be produced. As the armature speeds up, the resistance is gradually cut out until the armature terminals are directly connected to the full voltage of the supplying mains and the armature is running at its full speed.

The Shunt Motor.—Fig. 195 shows the elementary connections of a shunt motor. If a shunt motor is operated by power supplied from constant potential mains its field current and, in consequence, its field excitation are constant, and therefore its speed will vary little under changing mechanical load. The fundamental equation of the motor makes this fact evident. Writing that equation:

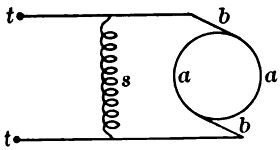


FIG. 195.—Shunt Motor.

$$n = \frac{E_x - I_a r_a}{\phi Z},$$

it is seen that with E_x, ϕ and Z constant, the value of n can be altered only by the factor $I_a r_a$, which because of the low resistance of the armature is always small.

When the load on a shunt motor is increased the motor slows slightly, thereby decreasing the counter electromotive force and in consequence permitting the armature current to increase sufficiently to supply the requisite additional torque. The increased armature current adds to the demagnetizing effect of the armature, and, weakening the field, causes an increase of speed. Therefore the change of speed is less than it would be if the field were absolutely constant. In the case of a decrease of load the converse of this reasoning, arriving at the same result, holds good.

If the magnetic circuit of a shunt motor be considerably below saturation the motor will run at a speed approximately constant even though the applied voltage varies widely. This is because field flux is nearly proportional to the field current and hence to the applied voltage when the poles are not saturated. The effect of the terminal voltage on the speed is counteracted by the opposing effect of the flux. The ratio between the speed variation of a shunt motor and the change of voltage at its terminals indicates the degree of saturation of the magnetic circuit. When the percentage of saturation is zero the motor's speed is independent of the applied voltage; when the percentage of saturation is 100 the speed is directly proportional to the voltage. (See Definitions, Chapter XVII.)

There is no danger of a shunt-wound motor attaining such a speed as to become dangerous; for, as it tends to speed up, the field remaining constant, the current and consequently the torque is decreased, due to the increased counter electromotive force, and the motor will soon attain a speed such that the torque just balances the friction or whatever the resistances to motion may be.

On account of the small variations in speed, shunt motors are used for operating machinery where an approximately constant speed is required or where moving parts would be damaged if the speed became excessive, such as ventilating sets, or pumps, and machinery where there is not much starting and stopping, or where excessive torque is not required at starting. One disadvantage of the shunt motor is that, the field being constant, there is a constant loss of energy.

The Series Motor.—Fig. 196 shows the elementary connections of the series motor.

With this form of motor the field varies with the strength of current. If the load on a series motor is reduced, the increase of torque, or rather the excess, causes the speed to increase, thereby diminishing the current and weakening the field, again causing the speed to increase and to a greater extent than in the case of the shunt motor. If the load is increased there is a deficit of torque, the speed falls, the current increases, thereby increasing the field so that the speed must decrease considerably in order to reduce the counter electromotive force to the proper amount. The speed, therefore, of the series motor varies considerably with the changes in load.

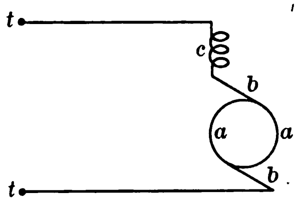


FIG. 196.—Series Motor.

The field of the series motor may be varied in exactly the same way as the electromotive force in a series generator is varied by cutting out some of the series turns, or introducing a resistance in parallel with the series windings.*

One disadvantage of the series motor is that if by any chance all the load is thrown off, the required current is very small, and so weakens the field that it requires a very high speed to generate the proper counter electromotive force and the speed may become so great as to rack the armature to pieces. An advantage of this motor is that it allows a strong current and consequently strong torque at starting, a very important element in getting heavy weights such as anchors, or boats started. On this account, the motor is used on street cars, ash hoists, boat cranes, turret rammers or in general where there are wanted both variations in the load and speed.

In certain cases, a good method of regulating these motors is to regulate the electromotive force of the supplying generator, starting with a high electromotive force where great torque is required, and cutting it down as the speed rises. This is not as wasteful as introducing a resistance in the main circuit, and keeping the supplying electromotive force constant, as is sometimes done.

* See footnote page 337.

Series-Parallel Control of Series Motor.—The principal application of the series motor is for electric traction. In the United States nearly all electric cars are operated by series motors. For heavy cars two or more motors are needed, and to obtain the requisite speed variation the series-parallel method of connection is adopted. By this the motors may be thrown either in series or in parallel with each other. Thus, if two motors are used they may first be thrown in series with each other and with the starting resistance. When the latter is cut out each motor will receive one-half the line voltage and run at half speed. The motors may now be thrown in parallel with each other and in series with the starting resistance. As the starting resistance is gradually cut out the motors will speed up, reaching full speed when the resistance is all out and each motor is receiving the full line voltage.

Compound Motors.—As the object of compound generators is to produce a constant potential at all external loads, so the object of **differential** wound compound motors is to produce constant speed under all external loads. This problem is solved by building motors with a compound field consisting of the ordinary windings of the shunt motor with a few turns of series windings, so arranged that they are opposed to each other, one tending to magnetize and the other to demagnetize. The effect of this method of winding can be illustrated by taking the case of a shunt motor supplied from constant potential mains. If the load is suddenly reduced, the excess of torque causes the motor to increase in speed which will increase the counter electromotive force and cut down the armature current. This tends to reduce the torque, but due to the internal resistance of the armature, the speed will not fall to exactly what it was before. Now in the case of the differential motor, there is at all times a constant demagnetizing effect due to the series windings. Therefore, when the load is reduced and the armature tends to speed up reducing the current, the field is strengthened and the required counter electromotive force is produced to counterbalance the effect of the armature resistance and keep the speed constant. It is evident then that there should only be enough series turns to make up for the energy lost in overcoming the motor resistances; friction and core losses.

The speed at which the differential motor runs should be the same speed as, when as a generator, would yield an electromotive force equal to that of the supplying source. At this speed it should run so fast as to reduce the armature current to a minimum. By making the shunt field strong enough the required speed can be made as low as desired.

In starting some types of differentially wound motors it is advisable to have an arrangement for keeping the series turns out of the circuit until the motor has speeded up, for if the series and shunt windings are properly proportioned to govern exactly, there might not be any resulting magnetism, or if the effect of the series winding overbalanced that of the shunt winding, the motor might start to run the wrong way.* In the type used in the navy, the preponderance due to the shunt field renders this precaution unnecessary.

On board ship the differential compound winding is sometimes used for the motors of the motor generators of radio sets, where a constant speed under a varying load is an essential. Aside from this, however, the motor has little use, as the speed of the shunt motor is constant enough for most purposes.

The differential motor is objectionable because it cannot supply a large starting torque, owing to the demagnetizing action of its series field. Furthermore, on overload the field may be so much weakened that the torque is not sufficient to maintain rotation, the counter electromotive force falls to zero, and a burnt-out armature or blown fuses result.

In the **cumulative** compound motor both series and shunt fields have the same polarity and in consequence the speed of this motor is not constant under varying load. On the contrary, because of its series field, the speed alters considerably on change of load. This disadvantage may be overcome by short circuiting the series field after the motor is started, permitting it to run as a shunt motor.

The cumulative compound motor, by virtue of its series field, has the advantage, like the series motor, of furnishing a large starting torque. It is superior to the series motor in that, because of its shunt field, it will not race when the load is suddenly thrown off. The greater the relative strength of the shunt field the more constant is the speed.

* When the motor is started under heavy load the effect of the series field may be apparent before that of the shunt field, due to its relatively low inductance.

The cumulative compound motor finds an extensive application in operating elevators, hoists, and other machinery requiring a large starting torque and to which constancy of speed is not an essential. Electric winches on board naval vessels are operated by it.

When used for elevator service the series field must be cut out or short circuited when the motor reaches full speed. Otherwise, if the speed were increased by an over-balanced elevator and the motor in consequence run as a generator, the reversal of the direction of the current in the series winding might overpower the shunt magnetism and cause a burn-out.

Summary of the Effects of Increase of Load on the Speed of the Different Types of Motors, Operated at Constant Voltage, Field Excitation Uncontrolled.—With a given increase of load: The series motor slows down greatly. The cumulative compound motor slows down considerably, but less than the series motor. The shunt motor slows down slightly. The differential compound motor maintains its speed.

Speed Regulation.—By the "speed regulation" of a motor is meant its change of speed from full load to zero load expressed as a percentage of the full-load speed. For example, if at full load the speed of a motor is 1000 revolutions per minute and at zero load its speed is 1080 revolutions per minute, then the speed regulation is:

$$\frac{1080-1000}{1000}=8 \text{ per cent.}$$

The term should not be confused with "speed control." The analogy to the term "voltage regulation" is plain.

Measurements.—The electrical input of a motor, like the output of a generator, may be determined by a voltmeter and ammeter properly connected at the motor terminals. The mechanical output of the motor can be found by measuring the speed of revolution and the torque of the armature shaft. Given the input and the output the commercial efficiency of the motor is readily calculated, and if the resistances of the various motor windings be known or measured, the efficiency of conversion and the mechanical efficiency can be found.

The torque of the armature shaft can be measured in several ways. One method is: by finding the difference in tension of the sides of a belt that runs on the armature pulley, or by means of the Prony brake, which is simply an arrangement for measuring the friction exerted between the pulley and an arm connected to a spring balance. Still another method is by means of the Brackett cradle, in which the motor is mounted in a cradle and accurately balanced. When running with any load, the tendency of the field frame to turn around the armature axis by which it is balanced is measured as so many pounds-feet, by finding how many pounds weight at a certain distance will balance this tendency, or the motor measures its own output. (See chapter on Measurements.)

The efficiency of a motor, like that of a generator, differs at different loads. A motor is generally designed to give its maximum efficiency at the load at which it is most likely to be worked, whether or not this is its full load.

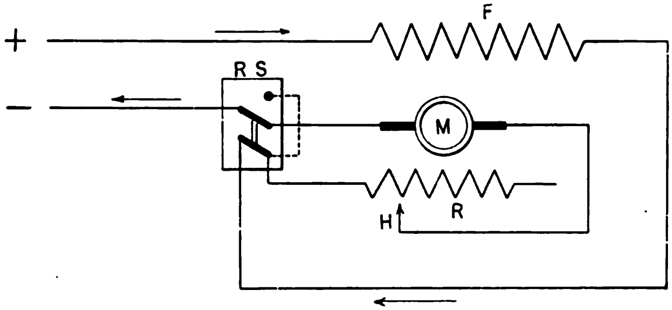


FIG. 197.—Series Motor.

It can be shown mathematically that the maximum efficiency of a shunt motor occurs when the armature loss equals the sum of the stray power and the field loss, or, in other words, when the variable loss equals the constant loss.

Limits of Output.—The same considerations, heat and sparking, which limit the output of a generator limit the output of a motor.

Operation of the Series Motor.—Fig. 197 shows the elementary connections.

To Start.—The field coil *F* is in series with the armature through the rheostat *R* and connected to the supply lines marked + and − through the reversing switch *RS*. When the switch *RS* is first closed, all the resistance *R* is in circuit, but as the armature *M* commences to turn and develop counter electromotive force the resistance is gradually cut out until the arm *H* rests on the last contact of the resistance when the armature receives the full line voltage. This constitutes the rheostatic control for starting. In actual starting devices for series motors, the armature and field are connected to the mains at the same time by means of the switch or controller, after which the resistance is gradually cut out.

To Stop.—To stop it is only necessary to reverse the operation of starting, moving the rheostat arm over the contact points until the last is reached when the field and armature current is broken at the same time by the switch. It is well to make the motions quickly to break the arcs that might occur when the circuits are broken.

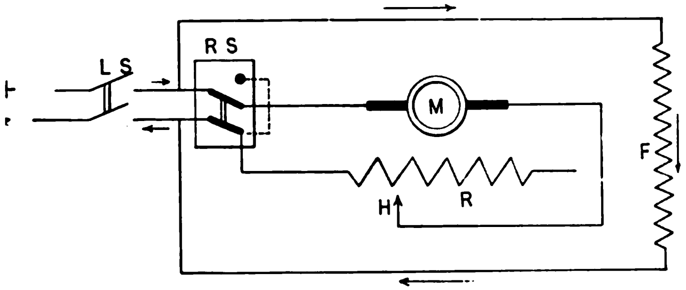


FIG. 198.—Shunt Motor.

To Reverse.—To reverse the direction of rotation of the armature it is only necessary to move the switch *RS* to the other contact points indicated, when an inspection will show that though the current through the field is in the same direction as before, the direction through the armature has been reversed. To do this, however, the armature must first be brought to rest with all the resistance in circuit.

Operation of the Shunt Motor.—Fig. 198 shows the elementary connections. In addition to the reversing switch, which in the case of the series motor also acts as a starting switch, a shunt motor should be provided with a double-pole switch in the main line and the usual starting resistance.

To Start.—Close the double-pole switch *LS* which sends current through the shunt coils *F* and excites them from the constant potential mains marked + and −. It is important to note that in all cases the motor field is energized before any voltage is applied to the armature. The switch *RS* should then be closed one way or the other, sending current through the resistance *R* in series with the motor armature *M*. The resistance *R* is then gradually cut out as in the case of the series motor and the armature brought to speed.

To Stop.—The line switch *LS* should be opened, cutting off the armature current, and allowing the armature to come to rest. Then the arm *H* should be run back throwing in all resistance ready for starting again.* By opening the switch *LS* the difference of potential at the terminals is gradually reduced while the motor is stopping.

If the rheostat arm is moved first there is likely to be bad sparking or flashing when the off position is reached and when the line switch is opened, as full line potential now exists between the terminals of the field winding, there is apt to be a long arc and an excessive induced E. M. F. endangering the field coil insulation.

Cause of Flashing.—This is caused by the induced E. M. F. in the field circuit as the field current commences to weaken. The induced E. M. F. tends to keep up the field current and on account of the number of turns in the field winding and the iron core, this circuit has a high inductance and a high electromotive force is induced which manifests itself by the spark when the circuit is broken.

To Reverse.—When the motor is at rest, it is only necessary to shift the reversing switch *RS* to its other contacts, and it will be then seen that, as the field connections are beyond this switch, the current through the field will be as before, while the current through the armature is reversed.

Compound motors are started and stopped in the same manner as shunt motors.

The Ward-Leonard Control.—In the rheostatic method of control it is seen that in starting motors only a small portion of the line voltage is applied to the armature terminals at first, the voltage being gradually increased as the motor gets up its speed. It has also been

* In all motor starters, the arm *H* is automatically returned to the starting position when the line switch is opened. In large motors, a circuit breaker is installed in the line which may be operated to break the heavy line current.

shown that this is effected by means of a resistance in series with the armature. It has been further shown that the rheostatic method of speed control for motors results in a loss due to the energy absorbed by the rheostat. This is a great loss in economy and the object of the Leonard control is to generate only enough voltage to produce the desired speed without the intervention of the wasteful resistance.

This system of control found its greatest application to ships' motors, in turret-turning and gun-elevating motors, and will be fully

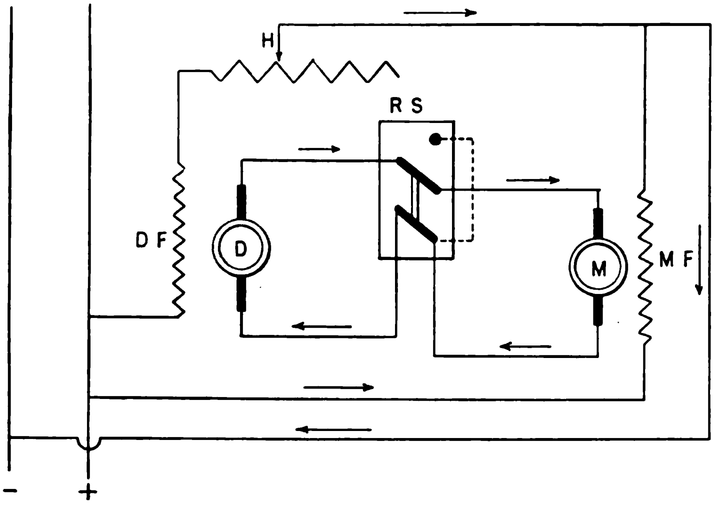


FIG. 199.—Ward-Leonard System of Control.

described later; at this time only the elementary principles being explained.

The elementary diagram illustrating this method of control is shown in Fig. 199.

In the figure *D* is a generator whose armature is driven at a constant speed by a prime mover not shown. The generator brushes are electrically connected to the brushes of the motor *M*. The fields of the motor and generator are separately excited from constant potential mains. By varying the resistance in the generator field the E. M. F. induced and supplied to the terminals of the motor can be varied and its speed controlled accordingly.

By referring to the motor speed equation, $n = \frac{E_x - I_a r_a}{\Phi Z'}$, it will be seen that fine gradations of speed can be produced by thus varying the value of E_x the terminal E. M. F. of the motor.

As long as the generator field is broken by the arm *H* being off the rheostat *R*, the field of the generator is not energized and there is no voltage generated in it, though the motor field is fully excited from the mains.

When *H* first makes contact with *R* a small current then flows through the generator field and the generator armature revolving in this field generates a small difference of potential which is impressed on the motor terminals. As soon as this voltage is sufficient to generate enough current to produce the necessary torque the motor armature commences to turn, and will attain a speed proportional to the volts impressed on its terminals and which in turn is the full amount generated by the generator.

By cutting out the resistance in *R*, the voltage of *D* gradually increases, the voltage at *M* increases the same, and the motor armature gradually speeds up.

By this method of control there is no wasteful energy in motor armature resistances and the changes of speed are gradual and can be absolutely controlled by the generator field rheostat from start up to the maximum speed.

The direction of rotation of the motor armature can be changed by shifting the reversing switch *RS*.

If it is desired to increase the speed beyond that due to the maximum value of the E. M. F. for which the generator is designed, it may be accomplished by inserting a variable resistance in the field of the motor *M*. By increasing this resistance and thus reducing the motor flux when the terminal E. M. F. has its maximum value the speed of the motor is further increased.

To reduce the speed it is only necessary to cut in resistance in *R* and if this is done quickly the voltage at the terminals of *D* may fall much below that of *M* for the instant, in which case *M* will now tend to act as a generator and will generate large currents, quickly slowing it down until the voltage reaches that of *D*.

A device not shown in the figure is provided so that when the terminal voltage is reduced to zero, the motor terminals are short circuited and if the load on M tends to rotate it, the motor will then act as a generator short circuited at its terminals and the large currents generated will act as a counter drag on the armature conductors and quickly bring the motor to rest.

The Day Control.—This system of control finds its greatest application in hoisting work, in which it is necessary to have the hoisting mechanism overhaul itself as quickly as possible as well as to have its speed absolutely controlled. When a weight is to be lowered, it may not exert sufficient force to overcome the friction of the moving parts, in which case it is necessary to have the motor to start it, or it may fall by its own weight, requiring the motor to exert a braking effect to keep the weight under control. The braking action of the motor armature in controlling the speed in lowering constitutes the chief feature of the Day control.

For hoisting it is usual to have the resistance in series with the armature both for starting and for speed control. An elementary diagram showing this arrangement is given in Fig. 194. For lowering an entirely different combination is made and a resistance is connected across the line.

The elementary connections for lowering are shown in Fig. 200. M is a shunt motor whose field (not shown in figure) is energized from constant potential mains.

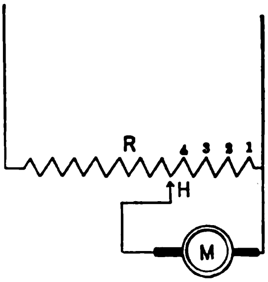


FIG. 200.—Day System of Control.

By moving the contact arm H the difference of potential at the brushes of the motor will vary and the motor speed controlled and the necessary torque provided to overcome the friction of the moving parts. By moving the contact arm to the left the E. M. F. applied to the terminals of the motor will be increased and the motor field being constant the torque will be increased. If the motor contact H is moved to the right the reverse action will take place.

If the weight speeds up due to its own inertia it may cause the motor to act as a generator and a current will flow through the circuit formed by the motor and that portion of the resistance included between the motor terminals. The direction of the current through the motor armature being reversed while the direction through the field remains as before it is evident that the direction of the mechanical force exerted on armature conductors is reversed and the motor tends to slow down. If the contact arm H is moved to the right the resistance in the circuit is decreased and the current and mechanical force increased, which causes the motor speed to still further decrease until when the motor brushes are short circuited such large currents will flow as to stop the rotation of the armature.

It is apparent, therefore, in lowering, that moving the contact arm to the left, the armature will be gradually brought to full speed, whether the motor is acting as a generator as has been shown, or whether it is taking current from the line.

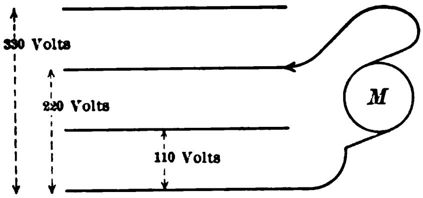


FIG. 201.—Multivolt Control.

In this way the speed can be controlled absolutely, no matter whether the motor is really lowering the load or whether the load is driving the motor.

This control at lowering cannot be accomplished with the ordinary rheostatic control since the resistance is in series with the armature, and more resistance turned into the circuit will cause the armature to run faster when it is driven by its load and there is no way of reducing its speed below the full-load speed.

Multivolt Control.—In this method current may be supplied to the motor over any pair of a set of mains between which constant electromotive forces are maintained. If the pair selected be two adjacent mains, the electromotive force impressed at the motor terminals will be low and the motor speed slow; if the pair be formed by alternate mains the electromotive force and the motor's speed will be doubled; and so on. (See Fig. 201.)

This method has no application in the naval service.

Problems.

1. The speed of a motor is controlled by the Ward-Leonard system. The generator which operates the motor has a lap-wound drum armature carrying 400 inductors. The resistance of the armature winding is 0.2 ohm, of the field winding, 30 ohms. The speed of revolution is 1500 r. p. m.; the normal flux per pole, 1.2×10^6 lines. The magnetization curve of the generator is a straight line. The motor has an armature resistance of 0.3 ohm, and a field resistance of 36 ohms. Its armature current is 10 amperes. The motor normally makes 1140 r. p. m. The resistance of the mains between the generator and the motor is 0.1 ohm. (a) What is the speed of the motor if the controller is turned so as to add 10 ohms to the resistance of the generator field? (b) What is the speed of the motor if 6 ohms be added to the resistance of the motor field, the 10 ohms added to the generator field being cut out and the armature current remaining 10 amperes? (c) If in (b) the armature current were 12 amperes, what would be the motor speed?

Solution.

Generator, $E_a = \dfrac{25 \times 400 \times 1.2 \times 10^6}{10^8} = 120.$

Motor, $E_a = 120 - 10(.1 + .2 + .3) = 114.$

(a) $E_a = \dfrac{30}{30 + 10} \times 120 = 90$ (generator).

$E_a = 90 - 10 \times .6 = 84$ (motor).

$n = \dfrac{1140 \times 84}{114} = 840$ r. p. m.

(b) $n = \dfrac{1140 \times (36 + 6)}{36} = 1330$ r. p. m.

(c) $E_a = 120 - 12 \times .6 = 112.8.$

$n = 1330 \times \dfrac{112.8}{114} = 1316$ r. p. m.

2. Shunt motor, constant field, is connected to constant potential 120 V. mains and runs a turret ammunition car. When hoisting with a resistance of 9.5 ohms in series with the armature the speed is 1000 r. p. m. and the armature current is 2 amperes. When lowering a resistance is thrown in parallel with the armature and across the mains as shown in the figure. If while lowering the weight of the car should speed the motor up to 1500 r. p. m., what, at that instant, would be the armature current and how would the motor's speed be affected thereby? Armature resistance, 0.5 ohm.

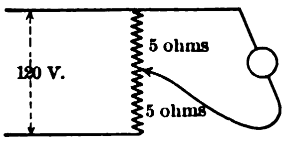


FIG. 202.

Solution.

$$E_{a_1} = 120 - 2(9.5 + .5) = 100, \frac{E_{a_1}}{E_{a_2}} = \frac{1000}{1500}, E_{a_2} = 150.$$

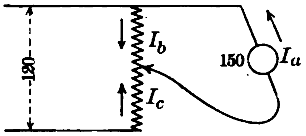


FIG. 203.

$$150 = .5a + 5b \qquad a = b + c$$
$$120 = 5b - 5c \qquad c = a - b$$
$$120 = 5b - 5a + 5b = 10b - 5a$$
$$150 = 5b + .5a$$
$$120 = 10b - 5a$$
$$300 = 10b + a$$
$$180 = 6a$$
$$a = 30 \text{ amp.}$$

Motor becomes generator; torque slows it.

CHAPTER XV.

THE PRINCIPLES OF ALTERNATING CURRENTS.

An armature core *A* mounted upon a shaft is fitted to revolve between two magnetic poles. A coil *aa'* is secured to armature as shown in Fig. 204 and the two ends of the coil toward the reader are connected to separate rings which are insulated from each other and from the shaft. If the armature is rotated at a constant speed, the

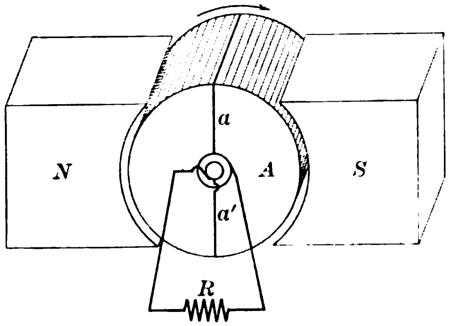


FIG. 204.—A Simple Alternator.

coil will have, in its various positions, different numbers of lines of flux threading through it and a varying E. M. F. or difference of potential will be produced at the rings and, if brushes are provided which are connected through an external resistance *R*, a varying current will flow through the external circuit. The magnitude of the induced E. M. F. is proportional to the rate of change of lines threading through the coil, *i. e.*, the rate of cutting of lines of magnetic flux. Let us assume that the coil is in a uniform magnetic field and that Φ represents the total flux through the coil in its present position, when the maximum number of lines are threading through. If the coil is rotated at a constant angular velocity through an angle θ to the right as shown in Fig. 205 it is evident that $\Phi \cos \theta$ will then represent the total flux through the coil. Hence, at any position of the coil the instantaneous value of flux will be $\Phi \cos \theta$. The rate of change of flux or the induced E. M. F. will then be $-d(\Phi \cos \theta) = \Phi \sin \theta \frac{d\theta}{dt}$ where $\frac{d\theta}{dt}$ is the angular velocity. If the coil makes f revolutions per second then $2\pi f$ will represent its angular velocity in radians, which we will call ω. If t represents the time interval in seconds, which has elapsed since the coil was in its zero position, then θ will equal ωt. By substituting these values the expression for the instantaneous E. M. F. becomes $e = \omega\Phi \sin \omega t$ abvolts. If the coil contains N turns the rate of cutting lines of magnetic flux will be N times as great, and the value of the instantaneous E. M. F. will then be given by the equation

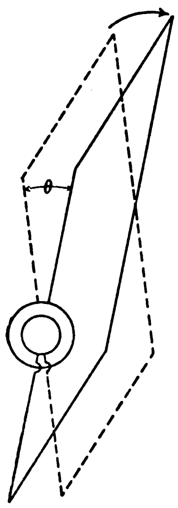


FIG. 205.—Illustrating the Principle of an Alternator.

$$e = N\omega\Phi \sin \omega t \text{ abvolts or } e = \frac{N\omega\Phi \sin \omega t}{(10)^8} \text{ volts.}$$

The maximum value E_0 of this E. M. F. will occur when ωt is equal to $\frac{\pi}{2}$ and the coil has been rotated to a position 90° from the position shown in figure. At that instant $\sin \omega t$ equal unity and the maximum value is given by the equation $E_0 = \frac{N\omega\Phi}{(10)^8}$ volts. The equation for the instantaneous values may therefore be written $e = E_0 \sin \omega t$ where E_0 is the maximum value.

The instantaneous values given by this equation can best be studied by reference to the sine or harmonic curve, where the abscissæ represent the angular distance from the zero position and the ordinates the corresponding values of the E. M. F. This curve will be as shown in Fig. 206.

The value of e increases until $\omega t = \frac{\pi}{2}$, then decreases until $\omega t = \pi$ when it becomes equal to zero again. It then becomes negative and increases until $\omega t = \frac{3\pi}{2}$ and then decreases until $\omega t = 2\pi$ when it becomes zero again and the cycle is complete.

Definitions.—The operation described above is called a cycle and the time required to complete a cycle is called the period and the number of cycles or periods per second is called the frequency. An E. M. F. or current which passes through a series of values as described above is called an alternating E. M. F. or alternating current

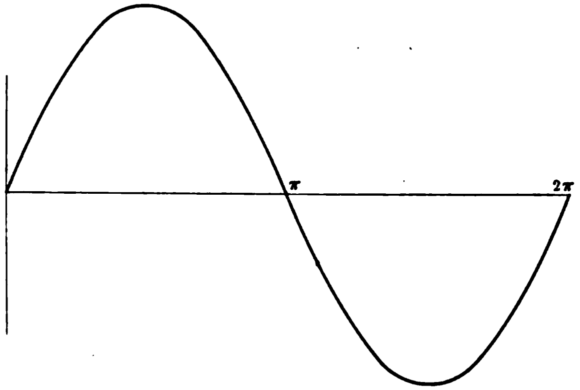


FIG. 206.—The Curve of Sines.

and a machine designed to produce such an E. M. F. is called an alternator. Referring to Fig. 204, it is evident that if we increase the number of poles to four that the E. M. F. would go through its series of values twice for every revolution of the armature or in general if p equal the number of poles, and n equal the number of revolutions per second, then the frequency $f = \frac{pn}{2}$. Thus, by increasing the number of poles, the number of conductors in the coil, the number of revolutions of armature, and the magnetic flux, the value of the E. M. F. may be increased. The half of a cycle, *i. e.,* from its zero value through its maximum value to its zero value again is called an alternation. The angle ωt representing the position of the coil at any instant is called the phase. If the frequency of an alternating E. M. F. is reckoned in thousands, it is called a high frequency alternating E. M. F. If it is reckoned in hundreds of thousands, it is called an electric oscillation.

Non-Inductive Circuits.—When the collector rings as shown in Fig. 204 are connected by brushes to an external circuit containing a non-inductive resistance only, an alternating current will flow which will be in phase with the E. M. F., and its instantaneous value may be obtained by Ohm's law $i = \frac{E_0 \sin \omega t}{R}$, where R is the value of the resistance. Since $\frac{E_0}{R}$ equals to I_0, the maximum value of the current, this equation becomes $i = I_0 \sin \omega t$.

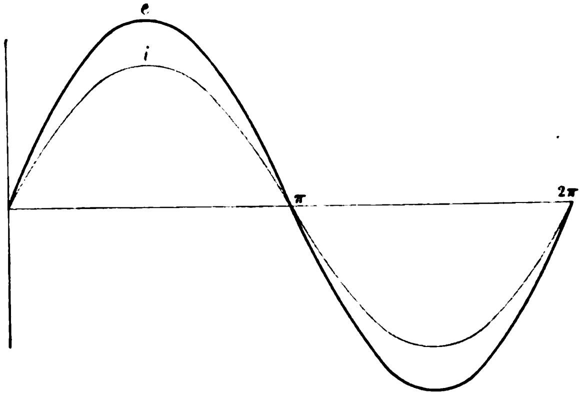


FIG. 207.—**Curves of E. M. F. and Current in a Non-Inductive Circuit.**

The curves will be as shown (Fig. 207), e being the curve of impressed E. M. F. and i the curve of current. The instantaneous value of e is equal to the product of R and the instantaneous value of i.

Inductive Circuits.—The action of the alternating E. M. F. up to this point presents nothing new, but now it becomes necessary to consider the effects of having an inductance in the circuit.* We know that if a circuit contains a coil of wire and the current is changing that an E. M. F. of self-induction is induced, which acts in a way to

* See Chapter IX.

oppose the change of current. This E. M. F. is proportional to the rate of change of current. The coefficient of self-induction L depends upon the nature of the circuit and represents the value of the opposing induced E. M. F. in volts when the current is changed at the rate of one ampere per second. The unit of inductance is the henry and it represents the self-induction of a circuit where the induced E. M. F. is one volt, when the current changes at the rate of one ampere per second. If i is the instantaneous value of the current flowing then $L\frac{di}{dt}$ will represent the magnitude of the opposing E. M. F. induced by the changing current. Therefore, if we have a circuit which contains a resistance R and also an inductance L it will be necessary to have an additional E. M. F. equal to $L\frac{di}{dt}$ to overcome this opposing E. M. F. in order that the current i will flow.

Let e represent the instantaneous value of the impressed E. M. F.

Let e_r represent the instantaneous value of the E. M. F. required to send a current through the resistance R.

Let e_b represent the instantaneous value of the E. M. F. required to overcome the E. M. F. due to inductance.

Then

$$e = e_r + e_b,$$
$$= Ri + \frac{Ldi}{dt} \text{ where } i = I_0 \sin \omega t.$$

Since

$$i = I_0 \sin \omega t, \quad \frac{di}{dt} = I_0 \omega \cos \omega t = I_0 \omega \sin(\omega t + 90°)$$

and

$$e_b = L\frac{di}{dt} = L\omega I_0 \sin(\omega t + 90°).$$

The maximum value of e_b is given by the equation $E_b = L\omega I_0$.

$L\omega$ is called the inductive reactance of the circuit and is designated by X_b. It is in the nature of a resistance and is given in ohms.

The expression for the instantaneous value of the impressed E. M. F. is therefore given by the following equation:

$$e = RI_0 \sin \omega t + L\omega I_0 \sin(\omega t + 90°).$$

In the above equation it is noted that both terms represent harmonic curves, but that the second term has its maximum value when the first term is zero. That is that the E. M. F. to counteract the effect of inductance is 90° ahead of the resistance E. M. F. in phase. The curves are shown in Fig. 208.

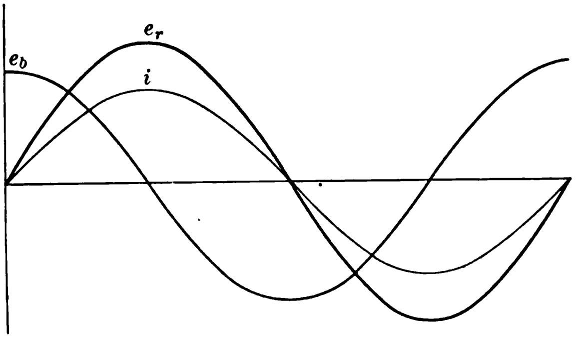


FIG. 208.—Curves of E. M. F. and Current in an Inductive Circuit.

To find the instantaneous value of the impressed E. M. F. at any time it will be necessary to take the algebraic sum of the corresponding ordinates of the two E. M. F. curves. This method involves some difficulties and the value can be obtained more readily by computation as will be shown.

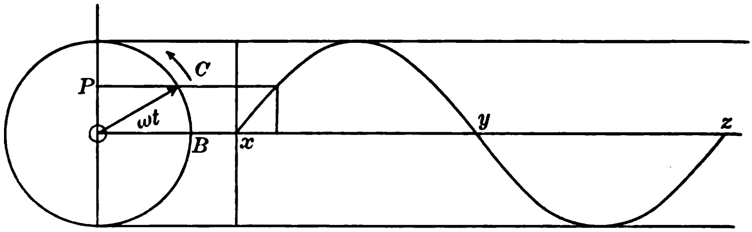


FIG. 209.—Illustrating the Construction of the Sine Curve.

The Curve of Sines.—The most convenient method of drawing a sine curve is by the aid of a circle as shown in Fig. 209. Let OC, the radius, represent the maximum value or amplitude of the curve. The distances xy and yz are each equal to π. By revolving OC

counter-clockwise, points on the curve may be determined as follows: The abscissa for any point of the revolving radius will be equal to ωt and the corresponding ordinate, $OC \sin \omega t$, will be the projection OP of the radius on the vertical diameter of the circle.

It will now be shown graphically that the resultant of two harmonic curves differing in phase, but having the same period, is a harmonic curve whose amplitude is the diagonal of a parallelogram, the sides of which are equal to the respective amplitudes of the two components, and the included angle the difference of phase.

Suppose that it is desired to draw two curves which differ in phase as in the case of the E. M. F. curves of an alternating circuit con-

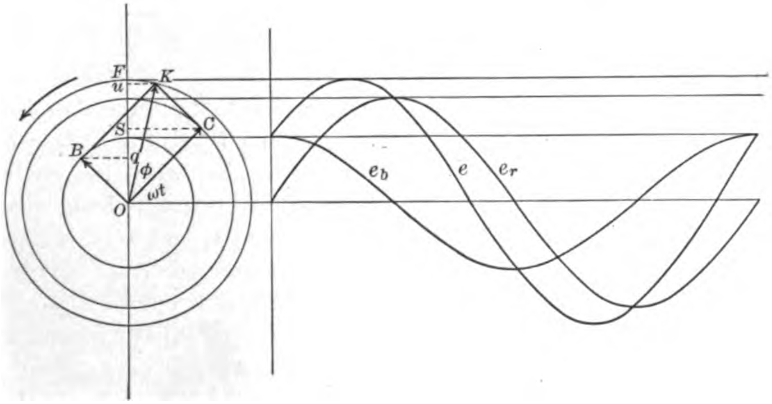


FIG. 210.—Finding the Result of Harmonic Curves Differing in Phase and Amplitude.

taining inductance as well as resistance. The method would be as shown in Fig. 210.*

In Fig. 210, OC represents the maximum value of the resistance E. M. F. which is in phase with the current, and OB represents the maximum value of the inductance E. M. F. which is 90° ahead of the current in phase. By following the method described above, two curves e_r and e_b are drawn as shown. Suppose now it is desired to

* It will be noted that the case given is a special case where the curves differ 90° in phase, but it is easily seen that the same method applies to any difference of phase.

find the instantaneous value of the impressed E. M. F. This could be done by adding the ordinates for any instant, but these ordinates are the corresponding projections of the radii OC and OB on the vertical axis. Take the phase as shown and the value of the total E. M. F. will be $Oq+OS$. At C erect CK equal and parallel to OB and complete the rectangle $OCKB$. Draw the diagonal OK, and since KC is equal and parallel to OB, the projection Su equals Oq. The total E. M. F. will therefore be equal to $OS+Su=Ou$. But Ou is the projection of the diagonal OK. Since the above figure represents any instant it is apparent that the instantaneous value of the impressed E. M. F. is equal to the projection of the diagonal of the rectangle of which one side is the resistance E. M. F. and the other side the inductance E. M. F. Hence, the impressed E. M. F. can be represented as a harmonic curve whose maximum ordinate equals the $\sqrt{E_r^2+E_b^2}$. This curve will reach its maximum value ahead of the resistance E. M. F.; the phase difference being KOC, which we call ϕ. This angle is called the angle of phase and when the curve of impressed E. M. F. is ahead of the current curve (which is in phase with the resistance E. M. F.) the current is said to lag and ϕ is called the angle of lag. If the reverse condition holds, the current is said to lead and ϕ is called the angle of lead. From the above it is apparent that the value of the impressed E. M. F. at any instant is given by the equation $e=\sqrt{E_r^2+E_b^2}\sin(\omega t+\phi)$.

Since $E_r=I_0R_0$, $E_r^2=I_0^2R^2$, and $E_b^2=I_0^2L^2\omega^2$, substituting in the above equation, we have $e=(\sqrt{R^2+\omega^2L^2})I_0\sin(\omega t+\phi)$.

The expression $\sqrt{R^2+\omega^2L^2}$ is called the impedance Z and is given in ohms. The equation now becomes $e=I_0Z\sin(\omega t+\phi)$.

Circuits Containing Condensive Reactance.

It now becomes necessary to investigate the effects of having a condenser and resistance in series in a circuit. Let us assume that an alternating current of instantaneous value i is flowing through the circuit and in and out of the condenser. The condenser at any instant will be charged with a quantity of electricity which we will call q. From the capacity equation we know that $q=Ce$ where C represents the capacity of the condenser in farads and e the E. M. F.

in volts at its terminals. Thus, we see that in order for the current i to flow we must not only have an E. M. F. e_r to force it through the resistance, but an E. M. F. e_c must be applied to the terminals of the condenser. The impressed E. M. F. then would be $e=e_r+e_c$: But $e_r=iR$, and $e_c=\frac{q}{C}$. Therefore, $e=iR+\frac{q}{C}$. Before these two E. M. F.'s can be combined to find the resultant it is necessary to know the difference of phase. Take the equation $q=Ce$. Differentiate this and we have $\frac{dq}{dt}=C\frac{de}{dt}$. But $\frac{dq}{dt}$ is the rate of change of quantity and must be the current flowing in the circuit, hence we know that $i=C\frac{de}{dt}$. This may be written

$$I_0 \sin \omega t=C\frac{de}{dt} \quad \text{or} \quad \frac{I_0}{C} \sin \omega t dt=de.$$

Integrate this and we have

$$e_c=-\frac{I_0}{C\omega} \cos \omega t=\frac{I_0}{C\omega} \sin(\omega t-90°).$$

Thus, we see that e_c may be represented by a harmonic curve which is 90° behind the current curve in phase, and, hence, capacity in a circuit causes the current to lead.

The expression $\frac{1}{C\omega}$ is called the condensive reactance of the circuit and is designated by the symbol X_c. It is in the nature of a resistance and is expressed in ohms. The instantaneous value of the impressed E. M. F. in a circuit containing resistance and condensive reactance is given by the equation $e=RI_0 \sin \omega t+\frac{I_0}{C} \sin(\omega t-90°)$.

The maximum value of the above expression $E_c=\frac{I_0}{C\omega}$.

The method used in Fig. 210 may now be employed to draw these curves or the resultant can be calculated from the principle developed by aid of that figure that the resultant of the two harmonic curves will be a harmonic curve whose amplitude is diagonal of a parallelogram whose sides are the amplitudes of the two component curves. By reference to Fig. 210, it will be understood that the resultant curve giving the instantaneous values of the impressed E. M. F. will differ in phase from the current curve by an angle ϕ where $\tan \phi = \frac{E_c}{E_r}$.

Circuits Containing Resistance, Inductance and Capacity in Series.

If a circuit contains resistance, inductance and capacity in series, it is evident from the foregoing that the impressed or total E. M. F. must be equal to the sum of these components discussed above, *i. e.*, $e = e_r + e_b + e_c$ or substituting their values we have

$$e = RI_0 \sin \omega t + I_0 L\omega \sin(\omega t + 90) + \frac{I_0}{C\omega} \sin(\omega t - 90°).$$

Thus, the inductance E. M. F. and the capacity E. M. F. differ 180° in phase, that is are exactly opposite, each being 90° different in phase from the resistance E. M. F. To find the resultant, following the method outlined in Fig. 210, one side of the rectangle will equal to the resistance E. M. F. as before, but the other side will be the algebraic sum of the inductance and capacity E. M. F. If the first of these is the greater the sum will be positive and the current will lag. If the second is the greater the resultant will be negative and the current will lead. The equation may now be written:

$$e = \sqrt{E_r^2 + (E_b - E_c)^2} \sin(\omega t + \phi),$$

$$e = I_0 \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \sin(\omega t + \phi).$$

The maximum value is

$$E_0 = I_0 \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}.$$

This term $\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$ is called the impedance and is designated by the symbol Z. It is in the nature of a resistance and given in ohms.

Thus, it is seen that where in a direct current circuit $E_0 = I_0 R$, that in an alternating circuit $E_0 = I_0 Z$, where Z equals the vector sum of R, the resistance and X_b, X_c or $(X_b - X_c)$ the reactance.

Effective Values of E. M. F. and Current.

It has been seen that in a direct current circuit power $= ei$ or i^2R. In an alternating current the instantaneous value of

$$P = i^2R = I_0^2R \sin^2\theta.$$

The average value of P for one-half a cycle

$$= \frac{I_0^2R}{\pi}\int_0^\pi \sin^2\theta d\theta = \frac{I_0^2R}{2\pi}\int_0^\pi (1-\cos 2\theta)\,d\theta$$

$$= \frac{I_0^2R}{2\pi}\left(\theta - \frac{\sin 2\theta}{2}\right)\Big]_0^\pi = \frac{I_0^2R}{2} = \left(\frac{I_0}{\sqrt{2}}\right)^2 R.$$

This value of the current $\frac{I_0}{\sqrt{2}}$ is called its effective value or root mean square value, it being the square root of the mean value of the squares of the instantaneous current. As it is this value of the current that is employed in all questions of alternating current where power is considered it is called the effective value and all ammeters for alternating current circuits are calibrated to give this value. In the same way, taking the equation $P = \frac{e^2}{R}$, we can deduce that $\frac{E_0}{\sqrt{2}}$ is the effective value of an alternating E. M. F. These values differ from the average values as will be shown. Take the equation $i = I_0 \sin\theta$. The average value will be

$$i_{\text{ave.}} = \frac{I_0}{\pi}\int_0^\pi \sin\theta d\theta = -\frac{I_0}{\pi}\cos\theta\Big]_0^\pi = \frac{2I_0}{\pi},$$

or the average value equals the maximum value multiplied by $\frac{2}{\pi}$. The same deductions will be true in the case of the average E. M. F.

Power in an Alternating Current Circuit.

To find the power in an alternating circuit take the equations

$$i = I_0 \sin\theta \text{ and } e = E_0 \sin(\theta + \phi).$$

Multiplying these we have

$$\begin{aligned} P(\text{instantaneous}) &= ei = E_0I_0 \sin\theta \sin(\theta+\phi) \\ &= E_0I_0 \sin\theta(\sin\theta\cos\phi + \cos\theta\sin\phi) \\ &= E_0I_0(\sin^2\theta\cos\phi + \cos\theta\sin\theta\sin\phi). \end{aligned}$$

The average value of P for one-half a cycle will equal

$$\frac{E_0 I_0}{\pi}\int_0^\pi \sin^2\theta\cos\phi d\theta + \frac{E_0 I_0}{\pi}\int_0^\pi \sin\theta\cos\theta\sin\phi d\theta$$

$$= \frac{E_0 I_0}{\pi}\left(\cos\phi\int_0^\pi \sin^2\theta d\theta + \sin\phi\int_0^\pi \sin\theta\cos\theta d\theta\right).$$

The value of the first term of this expression, as shown before, is $\cos\frac{\phi}{2}$, and the value of the second term between the limits chosen is zero. Hence,

$$\text{Average Power} = \frac{E_0 I_0 \cos\phi}{2}.$$

If E = the effective value of the E. M. F. and I = the effective value of the current, then

$$EI = \frac{I_0}{\sqrt{2}} \times \frac{E_0}{\sqrt{2}} = \frac{I_0 E_0}{2}.$$

Hence, $P = EI\cos\phi$ where E and I represent the effective values of E. M. F. and current respectively. The average power of a circuit is therefore equal to the product of the effective values of the E. M. F. and current, and the cosine of the angle of phase.

Harmonic Quantities as Vectors.

The construction of a sine curve by using a circle of reference has been explained. By referring to Fig. 211 the method of determining the instantaneous value of two E. M. F.'s differing in phase will be understood. By agreement among electrical engineers a counter-clockwise motion of the radius vector representing the amplitude is assumed in constructing a harmonic curve.

In Fig. 211, OC represents the maximum value of the resistance E. M. F., OB represents the maximum value of the inductance E. M. F., and BOC represents their difference of phase. By rotating OC and OB counter-clockwise at a constant angular velocity the curves e_r and e_x may be drawn as shown. As explained before the resultant curve giving the instantaneous values of the impressed E. M. F. can be obtained either by adding the ordinates of the two curves or constructing a curve in the same manner that these curves were constructed with OK as the value of the amplitude. The angle

KOC between the vector of the resistance E. M. F. or current vector and the vector of the impressed E. M. F. is the angle of phase. It is apparent, therefore, that, where the maximum values of two E. M. F.'s differing in phase are given, the resultant maximum

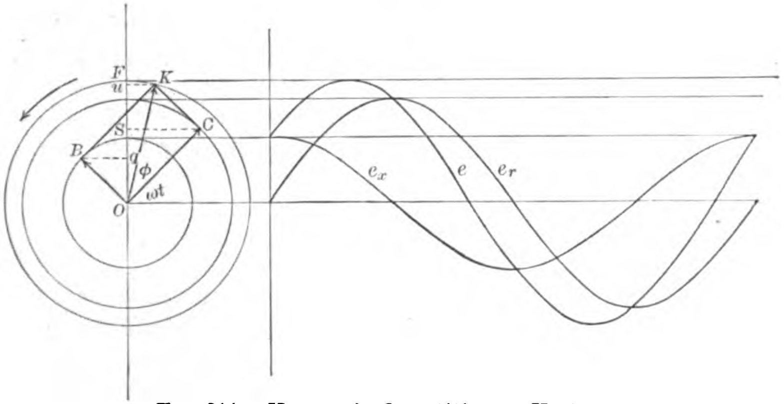


FIG. 211.—Harmonic Quantities as Vectors.

value cannot be obtained by simply adding these values together, but by adding these quantities vectorially a correct value may be obtained. This will be illustrated by a numerical example. The maximum value of the resistance E. M. F. of an A. C. circuit is 120 volts and the maximum value of the inductance E. M. F. is 50 volts. What is the maximum value of the impressed E. M. F. and what is the angle of phase?

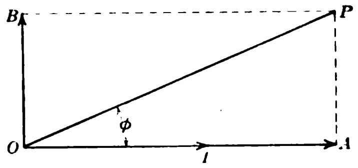


FIG. 212.—Vector Sum of Two Harmonic Quantities.

Lay off the horizontal line *OA* (Fig. 212) to represent the magnitude of the resistance E. M. F. which is in phase with the current and since it has been demonstrated that the inductance E. M. F. or the E. M. F. required to overcome the self-induction is 90° ahead of the other in phase, *OB* will represent the value and phase of that E. M. F. As shown graphically in Fig. 211, *OP* will be the amplitude of the curve formed by combining the two curves of E. M. F. or, that is, the maximum value of the impressed E. M. F. Hence,

$$OP = \sqrt{(120)^2 + (50)^2} = 130.$$

The angle POA or ϕ will represent the phase angle. Since OP is the vector sum of OA and OB, it is seen that if the maximum values of the various component E. M. F.'s in a series circuit are known, the maximum value of the resultant is the vector sum of the maximum values of the components. Since the effective values of E. M. F. and current bear a fixed ratio to the maximum values, the effective values may be added vectorially also. This is very important as the effective values are nearly always given in problems bearing upon alternating current circuits. The values of E. M. F. and current given by the ammeter and voltmeter in an A. C. circuit are the effective values.

Power and Power Factor.

If the impressed E. M. F. and current are not in phase as shown in Fig. 213, the average value of the power supplied will not be given

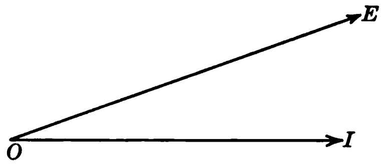


FIG. 213.—Clock Diagram of E. M. F. and Current in an Inductive Circuit.

by the product of the effective values of this E. M. F. and current since a portion of the impressed E. M. F. represents energy stored in the magnetic field which is returned during the cycle.* The power, therefore, is equal to the product of the current and the component of the impressed E. M. F., which is in phase with the current. $P = I \times E \cos \phi$ where E and I are the effective values and ϕ the angle between the current vector and the E. M. F. vector. The power factor is the fractional quantity which, if multiplied by the product of the effective values of the current and E. M. F., will give the value of the power consumed. Hence, power factor equals the cosine of the angle of phase.

Several typical numerical examples will be given to illustrate the application of vectors to alternating current circuits.

NOTE.—Values of E. M. F. and current are effective values unless otherwise stated.

* See Example 2 on next page.

Example 1.—An alternating E. M. F. of 110 volts is impressed upon a non-inductive circuit having a resistance of 5 ohms. What will be the resulting current?

The graphical and vectorial representation of the conditions of the problem are given in Fig. 214.

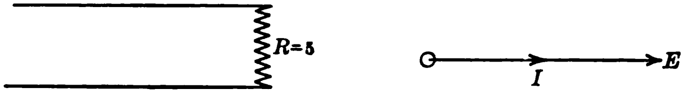


FIG. 214.

Since the impressed E. M. F. and current are in phase $E = IR$ and $I = \frac{110}{5} = 22$ amperes.

Example 2.—What will be the magnitude of the current flowing in a circuit of negligible resistance, but having an inductive reactance of 10 ohms when an E. M. F. of 120 volts is impressed on the circuit?

The graphical and vectorial representation of the condition of this problem are given in Fig. 215.

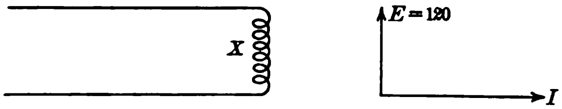


FIG. 215.

In this case $I = \frac{E}{X} = \frac{120}{10} = 12$ amperes. The power is equal to $IE \cos \phi = 0$.

Thus, in a circuit containing reactance only the average power equals zero. The energy stored up in the magnetic field during the first quarter of a cycle is returned to the source during the next quarter.

Example 3.—The impressed E. M. F. of an A. C. circuit is 130 volts, the resistance of the circuit 12 ohms, and the inductive reactance is 5 ohms. What is the magnitude of the current? What is the angle of phase? Does the current lag or lead? What is the average power of the circuit?

The graphical and vectorial representation of conditions of the problem are given in Fig. 216. The impressed E. M. F. is equal to

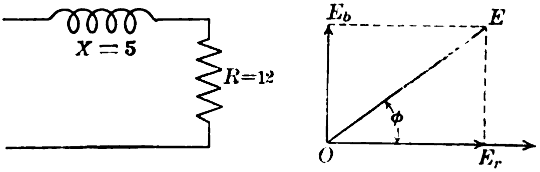


FIG. 216.

the vector sum of the resistance E. M. F. and the inductance E. M. F.

$$E=\sqrt{E_r^2+E_b^2}=\sqrt{IR^2+IX^2}=I\sqrt{R^2+X^2},$$
$$130=I\sqrt{(12)^2+(5)^2}=I\sqrt{169}=13I,$$
$$I=\frac{130}{13}=10 \text{ amperes},$$
$$\tan\phi=\frac{E_b}{E_r}=\frac{IX}{IR}=\frac{X}{R}=\frac{5}{12},$$
$$\cos\phi=\frac{E_r}{E}=\frac{IR}{E}=\frac{120}{130}=\frac{12}{13},$$
$$\text{Power}=IE\cos\phi=10\times130\times\frac{12}{13}=1200 \text{ watts}.$$

The impressed E. M. F. is ahead of the current in phase and hence the current lags.

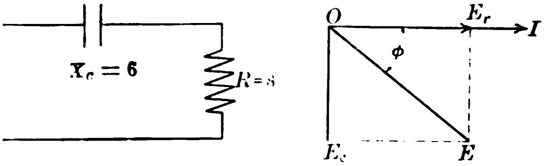


FIG. 217.

Example 4.—An impressed E. M. F. of 100 volts is applied to an A. C. circuit containing a resistance of 8 ohms and a condensive reactance of 6 ohms. What is the value of the current? The angle of phase? The average power and the reactance E. M. F.?

The graphical and vectorial representation of the conditions are shown in Fig. 217.

$$E=\sqrt{E_r^2+E_c^2}=I\sqrt{R^2+X_c^2},$$
$$100=I\sqrt{(8)^2+(6)^2}=I\sqrt{100}=10I,$$
$$I=\frac{100}{10}=10 \text{ amperes},$$
$$\tan\phi=\frac{E_c}{E_r}=\frac{IX_c}{IR}=\frac{X_c}{R}=\frac{6}{8}=\frac{3}{4},$$
$$\cos\phi=\frac{E_r}{E}=\frac{IR}{E}=\frac{80}{100}=\frac{4}{5},$$
$$P=IE\cos\phi=10\times100\times\tfrac{4}{5}=800 \text{ watts, or}$$
$$P=IE_r=I^2R=100\times8=800,$$
$$E_c=IX_c=10\times6=60 \text{ volts.}$$

Example 5.—An alternating E. M. F. of 260 volts is impressed on a circuit containing a resistance of 12 ohms, an inductive reactance of 8 ohms, and a condensive reactance of 3 ohms. What is the value of the current? What is the angle of phase? What is the average power and the value of the capacity E. M. F.?

The graphical and vectorial representation of conditions are shown in Fig. 218.

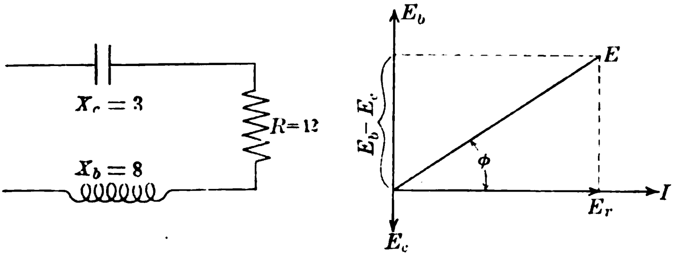


FIG. 218.

$$E=\sqrt{E_r^2+(E_b-E_c)^2}=I\sqrt{R^2+(X_b-X_c)^2},$$
$$260=I\sqrt{144+25}=13I,$$
$$I=\frac{260}{13}=20 \text{ amperes},$$
$$\tan\phi=\frac{E_b-E_c}{E_r}=\frac{I(X_b-X_c)}{IR}=\frac{8-3}{12}=\frac{5}{12},$$
$$P=IE_r=I^2R=400\times12=4800 \text{ watts},$$
$$E_c=IX_c=20\times3=60 \text{ volts.}$$

Parallel Circuits.

In the typical problems given above the different arrangements of series circuits have been explained. It now becomes necessary to consider the effect of parallel circuits. In a D. C. circuit containing two resistances in parallel as shown in Fig. 219, we know that I, the

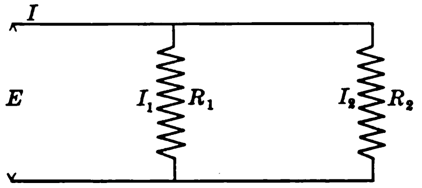


FIG. 219.

total current, is equal to the sum of I_1 and I_2, where $I_1 = \frac{E}{R_1}$ and $I_2 = \frac{E}{R_2}$. If an alternating E. M. F. be impressed upon this circuit the effective value of the current in the branches will be the same as in a D. C. circuit, that is, $I_1 = \frac{E}{R_1}$ and $I_2 = \frac{E}{R_2}$. Since both branches are non-inductive, the current in each branch will be in phase with the impressed E. M. F. and the effective value of the total current I will be equal to the sum of I_1 and I_2, the current in the two branches.

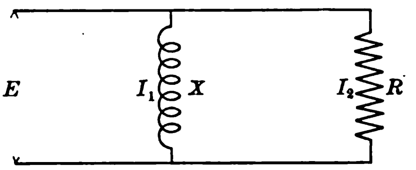


FIG. 220.—Parallel Circuits.

Let us now consider the condition shown in Fig. 220 where an alternating E. M. F. is applied to a circuit containing a resistance and an inductive reactance in parallel. It is apparent from the figure that the difference of potential between the terminals of the reactance and the resistance are each equal to the impressed E. M. F. or $E = I_1X = I_2R$. The effective value of the total current in this case cannot be obtained by simply adding the values of the current flowing through the branches as the currents are not in the same phase. Hence, to find the value of I the vectorial sum of I_1 and I_2 must be obtained. It has been shown that when an alternating E. M. F. is applied to the terminals of a non-inductive resistance a current will flow which is in phase with the impressed E. M. F., and when an alternating E. M. F. is impressed upon the terminals of inductive reactance of negligible resistance a current will flow which lags behind the E. M. F. 90° in phase. It has been demonstrated also that when an alternating E. M. F. is applied to the terminals of a condensive reactance of negligible resistance a current will flow which leads the E. M. F. 90° in phase. By applying these results it becomes easy to construct a vector diagram showing the conditions

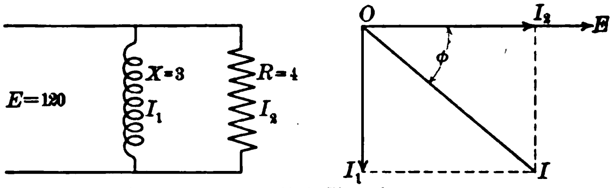


FIG. 221.—Parallel Circuits.

of the problem. Separate harmonic curves could be constructed to show the instantaneous value of the current in each branch and the resultant of these curves would be the total current curve, the ordinate of which would be equal to the instantaneous values of the total current. To obtain the effective or maximum values of the total current the vectorial sum of the respective effective or maximum values must be obtained. The principles involved will be illustrated by a few typical numerical problems.

Example 1.—An alternating E. M. F. of 120 volts is applied to a circuit containing a resistance of 4 ohms and an inductive reactance of 3 ohms in parallel. What is the magnitude of the current in each branch and the total current? What is the angle of phase? What is the power absorbed?

The graphical and vectorial representations of the conditions are shown in Fig. 221. In the vector diagram I_2 represents the value of the current flowing through the resistance and this current is in phase with the impressed E. M. F. The current I_1 flowing through the reactance is 90° behind the E. M. F. in phase. I is the vector sum of I_1 and I_2 and differs in phase from the E. M. F. by the angle ϕ.

$$I_1 = \frac{E}{X} = \frac{120}{3} = 40, \quad I_2 = \frac{E}{R} = \frac{120}{4} = 30,$$

$$I = \sqrt{I_1^2 + I_2^2} = \sqrt{(40)^2 + (30)^2} = 50,$$

$$\tan \phi = \frac{I_1}{I_2} = \frac{40}{30} = \frac{4}{3},$$

$$P = I_2 \times E = 30 \times 120 = 3600 \text{ watts.}$$

Example 2.—An alternating E. M. F. of 120 volts is applied to a circuit containing a resistance of 24 ohms and a condensive reactance of 10 ohms in parallel. What is the value of the current flowing in each branch of the circuit and the total current? What is the angle of phase?

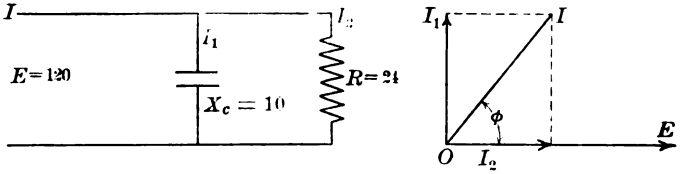


FIG. 222.—Parallel Circuits.

The graphical and vectorial representations are shown in Fig. 222.

$$I_1 = \frac{E}{X_c} = \frac{120}{10} = 12, \quad I_2 = \frac{E}{R} = \frac{120}{24} = 5,$$

$$I = \sqrt{I_1^2 + I_2^2} = \sqrt{(12)^2 + (5)^2} = 13,$$

$$\tan \phi = \frac{I_1}{I_2} = \frac{12}{5}.$$

Example 3.—An alternating E. M. F. of 120 volts is impressed upon a circuit containing a resistance of 24 ohms, an inductive reactance of 6 ohms, and a condensive reactance of 15 ohms in parallel. What is the value of the current in each branch of the circuit and the total current? What is the angle of phase?

The graphical and vectorial representation of conditions are shown in Fig. 223.

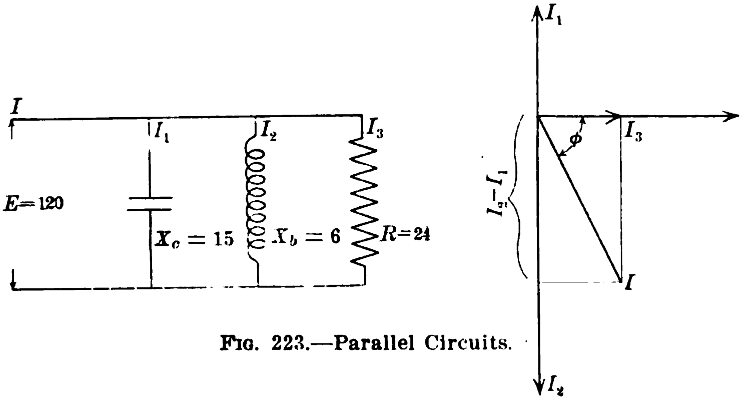


FIG. 223.—Parallel Circuits.

$$I_1=\frac{120}{15}=8,\quad I_2=\frac{120}{6}=20,\quad I_3=\frac{120}{24}=5,$$

$$I_2-I_1=12,$$

$$I=\sqrt{(I_2-I_1)^2+I_3{}^2}=\sqrt{144+25}=13 \text{ amperes},$$

$$\tan\phi=\frac{I_2-I_1}{I_3}=\frac{12}{5}.$$

Example 4.—An alternating E. M. F. of 130 volts is impressed upon a circuit consisting of two branches in parallel. In one branch is a resistance of 4 ohms and an inductive reactance of 3 ohms, and in the other branch a resistance of 12 ohms and a condensive reactance of 5 ohms. What is the value of the current in each branch and the total current? What is the angle of phase and the power?

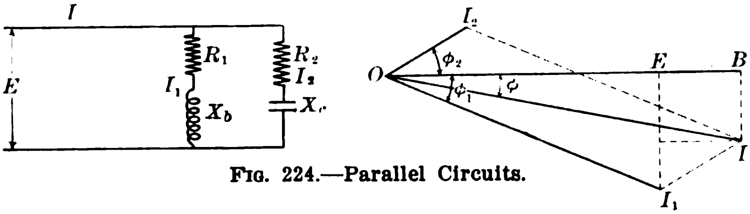


FIG. 224.—Parallel Circuits.

The graphical and vectorial representations of the conditions are given in Fig. 224.

In constructing the vector diagram lay off the horizontal line OE representing the direction of the impressed E. M. F. The current vector OI_1 is drawn making an angle ϕ_1 with the vector of impressed E. M. F., and the current vector OI_2 is drawn making an angle ϕ_2

with the E. M. F. vector. The values of ϕ_1 and ϕ_2 are obtained from the expressions previously deduced, $\tan\phi_1 = \frac{X_b}{R_1}$ and $\tan\phi_2 = \frac{X_c}{R_2}$. Since the first branch circuit contains inductance the current will lag behind the impressed E. M. F. in this circuit and since the second branch circuit contains capacity the current will lead in that circuit. The magnitudes of I_1 and I_2 are obtained as follows:

$$I_1 = \frac{E}{\sqrt{R_1^2 + X_b^2}} = \frac{130}{5} = 26 \text{ amperes},$$

$$I_2 = \frac{E}{\sqrt{R_2^2 + X_c^2}} = \frac{130}{13} = 10 \text{ amperes}.$$

I is the vector sum of I_1 and I_2. This value may be obtained graphically by constructing a diagram to scale or obtained by computation as follows:

$$I = \sqrt{I_1^2 + I_2^2 + 2I_1I_2 \cos(\phi_1 + \phi_2)}.$$

By referring to vector diagram it will be seen that

$$\tan\phi = \frac{BI}{OB} = \frac{I_1 \sin\phi_1 - I_2 \sin\phi_2}{I_1 \cos\phi_1 + I_2 \cos\phi_2}.$$

In the foregoing typical examples illustrating alternating current circuits the terms inductive reactance and condensive reactance have been employed. In many problems the value of the inductance or capacity is given. This involves no difficulty as it has been shown that the inductive reactance X_b equals ωL and condensive reactance equals $\frac{1}{\omega C}$ where ω equals $2\pi f$ the angular velocity, f being the frequency. This will be illustrated by a simple problem.

Example 5.—An alternating current circuit contains a capacity of $\frac{1}{220}$ farad and an inductance 10 millihenries. What is the value of the inductive reactance and of the condensive reactance, the frequency being 70?

$$X_b = \omega L = 2\pi f L = \frac{44}{7} \times \overset{10}{70} \times \frac{10}{(10)^3} = 4.4 \text{ ohms},$$

$$X_c = \frac{1}{\omega C} = \frac{1}{2\pi f C} = \frac{7 \times 220}{44 \times \underset{10}{70}} = .5 \text{ ohms}.$$

The Use of Circuit Constants for the Solution of Parallel Series Circuits.—It has been shown that in an alternating current circuit $I = \frac{E}{Z}$ where Z is called the impedance and is equal to $\sqrt{R^2+X^2}$, where R is the resistance and X the reactance.

Admittance is the reciprocal of impedance and is designated by the symbol Y; hence, $I = \frac{E}{Z} = EY$. The current I may be divided into components, one in phase with the impressed E. M. F. called the power component, and the other in quadrature with it, called the wattless component. The power component is as follows:

$$I_1 = I \cos\phi = \frac{E}{Z}\cos\phi = E \cdot \frac{R}{Z^2}, \text{ since } \cos\phi = \frac{R}{Z}.$$

$\frac{R}{Z^2}$ is called the conductance of the circuit and when multiplied by the impressed E. M. F. will give the component of the current in phase with the impressed E. M. F. In the same manner the wattless component of the current is obtained as follows:

$$I_2 = I \sin\phi = \frac{E}{Z}\sin\phi = \frac{E}{Z} \times \frac{X}{Z} = E \cdot \frac{X}{Z^2}.$$

$\frac{X}{Z^2}$ is called the susceptance and it is that quantity which, multiplied by the impressed E. M. F. will give the component of the current in quadrature with the impressed E. M. F. It is designated by the symbol B. The employment of these circuit constants simplifies the solutions of problems involving series parallel circuits. Given the circuit shown in Fig. 225 to find the value of the total current proceed as follows:

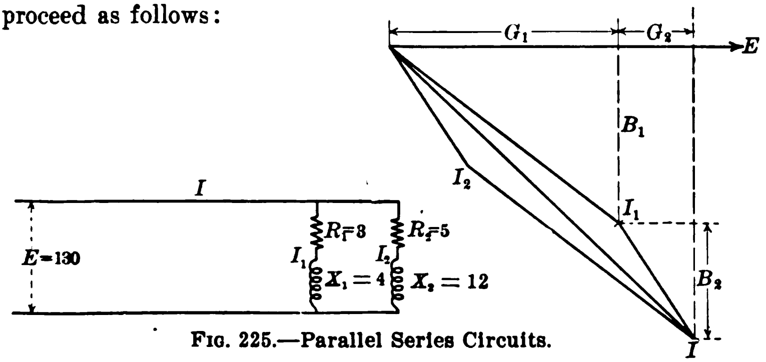
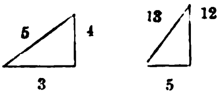


FIG. 225.—Parallel Series Circuits.



$Z_1=5,\ Z_2=13.$

$$G_1=\frac{R_1}{Z_1^2}=\frac{3}{25},$$

$$G_2=\frac{R_2}{Z_2^2}=\frac{5}{169},$$

$$B_1=\frac{X_1}{Z_2}=\frac{4}{25},\qquad I=130\sqrt{(G_1+G_2)^2+(B_1+B_2)^2},$$

$$B_2=\frac{X_2}{Z_2^2}=\frac{12}{169},\qquad \tan\phi=\frac{B_1+B_2}{G_1+G_2}.$$

This gives all the necessary data for the solution of the problem. By referring to the vector diagram of the preceding problem it will be seen that in a number of parallel series circuits the arithmetical sum of the conductances in the several branches is equal to the total conductance and the algebraic sum of the susceptances is equal to the total susceptance and vector sum of the total conductance and the total susceptance is equal to the total admittance.

If a circuit consists of three or more parallel series circuits, the solution of a problem by using circuit constants is much simpler than the method previously explained. The solution for circuits shown in figure would be as follows:

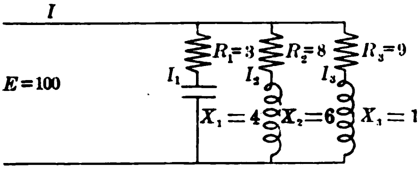


FIG. 226.

$$G_1=\frac{3}{25},\ G_2=\frac{8}{100},\ G_3=\frac{9}{225},\ G_1+G_2+G_3=\frac{108+72+36}{900}=\frac{36}{150},$$

$$B_1=-\frac{4}{25},\ B_2=\frac{6}{100},\ B_3=\frac{12}{225},\ B_1+B_2+B_3=\frac{-72+27+24}{450}=\frac{-7}{150},$$

$$I=\frac{100}{150}\sqrt{(36)^2+(7)^2},$$

$$I=\tfrac{2}{3}(36.69)=24.46 \text{ amperes},$$

$$\tan\phi=\frac{-21}{108} \text{ current leads.}$$

Kirchoff's Laws.

These laws previously explained in connection with direct current circuits are applicable to alternating current circuits if properly interpreted. These laws are directly applicable to alternating current circuits when instantaneous values are considered and when maximum or effective values are considered they are applicable if the word "sum" mentioned in these laws is interpreted to mean "vector sum."

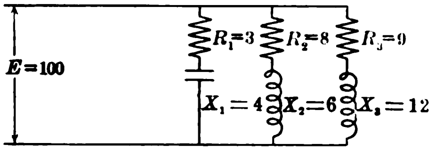


FIG. 227.

This method will now be used to solve the last problem given in order that the various methods may be compared.

The vector diagram of this circuit is shown in Fig. 228.

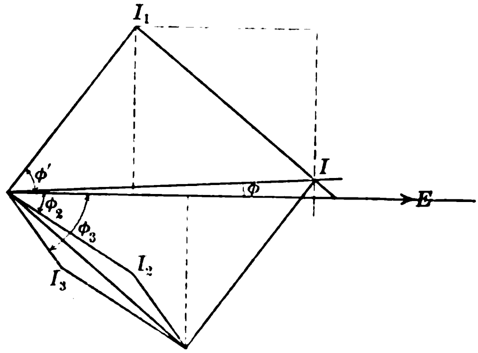


FIG. 228.—Vector Diagram Series Parallel Circuit.

$$E = I_1 Z_1 = I_2 Z_2 = I_3 Z_3,$$
$$Z_1 = 5,\ Z_2 = 10,\ Z_3 = 15,$$
$$\therefore I_1 = \frac{100}{5} = 20,$$
$$I_2 = \frac{100}{10} = 10,$$
$$I_3 = \frac{100}{15} = \frac{20}{3}.$$

$$I \cos \phi = I_1 \cos \phi_1 + I_2 \cos \phi_2 + I_3 \cos \phi_3,$$

$$\cos \phi_1 = \tfrac{3}{5},\ \cos \phi_2 = \tfrac{4}{5},\ \cos \phi_3 = \tfrac{3}{5},$$

$$I \cos \phi = 12 + 8 + 4 = 24,$$

$$\tan \phi = \frac{-I_1 \sin \phi_1 + I_2 \sin \phi_2 + I_3 \sin \phi_3}{I_1 \cos \phi_1 + I_2 \cos \phi_2 + I_3 \cos \phi_3}$$

$$= \frac{-(20 \times \tfrac{4}{5}) + (10 \times \tfrac{3}{5}) + (\tfrac{20}{3} \times \tfrac{4}{5})}{(20 \times \tfrac{3}{5}) + (10 \times \tfrac{4}{5}) + (\tfrac{20}{3} \times \tfrac{3}{5})}$$

$$= \frac{-\frac{14}{3}}{24} = -\frac{7}{36},$$

$$\cos \phi = \frac{3600}{3669}. \quad \text{Hence, } I = \frac{24 \times 3669}{3600} = 24.46 \text{ amperes.}$$

Resonance.

The effective value of the current in an A. C. circuit containing resistance inductance and capacity is given by the equation

$$I = \frac{E}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}.$$

It is evident that the value of the expression $\left(\omega L - \frac{1}{\omega C}\right)$ will depend upon the angular velocity. If the frequency is such as to make this expression equal to zero the value of the current I will be $\frac{E}{R}$. This is called the critical frequency and the maximum value of the current will occur at this time. This is called electric resonance, and if occurring in a circuit containing a very small resistance a very large current will result. This principle is made use of in radio telegraphy. The frequency at which resonance occurs may be found as follows:

$$\omega L - \frac{1}{\omega C} = 0,$$

$$\omega^2 = \frac{1}{LC}, \text{ or}$$

$$(2\pi f')^2 = \frac{1}{LC},$$

$$f' = \frac{1}{2\pi \sqrt{LC}}.$$

The Polyphase System.

The principles involved in the construction of an alternator were illustrated in Fig. 204. The alternator shown in this figure has only one coil and is called a single-phase alternator. If a like coil is added to the armature and its terminals taken to two separate insulated rings *c* and *d*, Fig. 229, the E. M. F. induced by this second coil will be similar to that induced by the first coil. If the rings *c* and *d* are provided with brushes connecting them to an external circuit containing a resistance R_2, an alternating current will flow

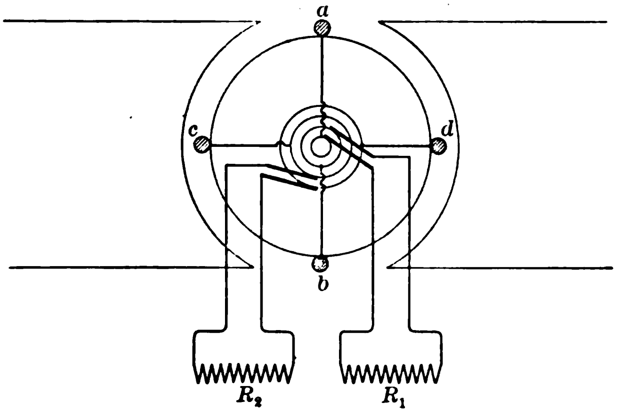


FIG. 229.—An Elementary Two-Phase Alternator.

through this circuit. The armature winding will then consist of two entirely independent coils each supplying E. M. F. to a separate circuit. An alternator constructed on this principle is called a two-phase or quarter-phase alternator. By referring to Fig. 229 it will be evident that the instantaneous values of the E. M. F. in the two circuits will differ in phase by 90°, that is when one coil is in the position of maximum cutting of magnetic lines the other coil will be in a position where the rate of cutting is zero. The two windings in alternators of this type are usually entirely separate, but in some cases only three rings are used, one terminal of each winding being taken to the same ring.

In this case three transmission lines are used as shown in Fig. 230. If the circuits are balanced so that the circuit having the impressed E. M. F., due to coil P, has the same resistance and the same inductance as the circuit having the impressed E. M. F., due to coil Q, this method will be satisfactory, but it is objectionable when the circuits are not completely balanced. The vector diagram showing the condition of a balanced two-phase alternator circuit is shown in Fig. 231.

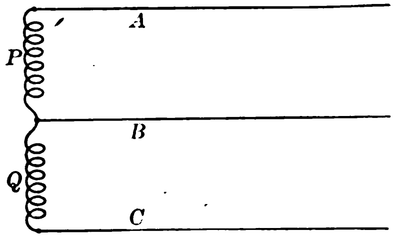


FIG. 230.—Transmission Lines, Two-Phase Alternator.

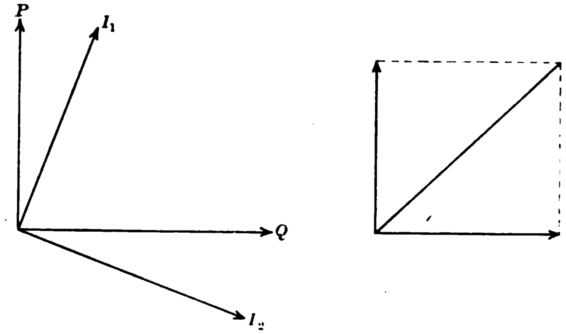


FIG. 231.—Vector Diagram Balanced Circuits.

The E. M. F. between A and C will be equal to the vector sum of P and Q, or since they are equal it will be represented by $P\sqrt{2}$ where P is the effective value of the E. M. F. induced in one of the coils. A four-phase or quarter-phase system may be formed from this system of winding by bringing the terminals of each winding to separate rings and connecting the centers of each coil to a fifth ring. (See Fig. 232.) The effective value of the E. M. F. from any of the terminals to G will then be equal to $\frac{E}{2}$ where E is the E. M. F. of any coil.

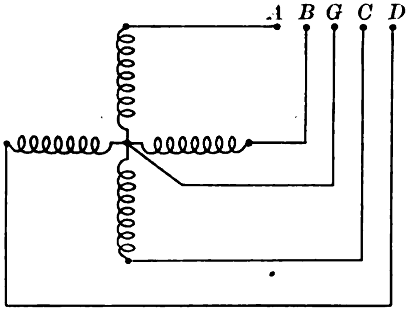


FIG. 232.—Quarter-Phase System.

Three-Phase Alternator.

If three conductors, A, B, C, are symmetrically arranged so as to be 120° apart on the surface of an armature revolving between two magnetic poles, and the terminals of the conductors are taken to separate collector rings at the front and rear ends of the shaft, and

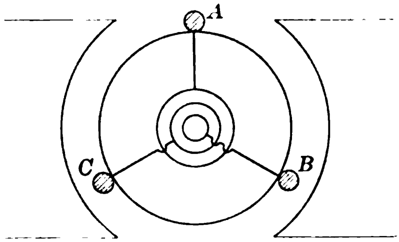


FIG. 233.—Elementary Three-Phase Alternator.

each pair of rings is connected to an external circuit by brushes, a similar E. M. F. will be impressed upon each circuit. The above arrangement constitutes the most elementary idea of a three-phase alternator. If the resistance and inductance in each of these circuits have the same values the circuits are said to be balanced and alternating currents of the same magnitude will flow in each circuit.

The E. M. F. of any circuit will differ in phase by 120° from either of the others. If the circuits are balanced the current in each circuit will lag behind its E. M. F. in phase by the same angle. Fig. 234 shows the phase relation of the E. M. F.'s and currents. If three similar coils are substituted for the three conductors and the terminals of the coil be taken to separate rings on one end of the shaft, the same electrical principles will be involved and the similar E. M. F.'s will have the same phase relation. This arrangement can be modified by taking one terminal of each coil to a common ring and thus reduce the number of collector rings to four. This method is illustrated in Fig. 235. Four transmission lines are required and three circuits are supplied. The currents have a common return as shown. The system just described is seldom if ever used in practice. The usual method is to interconnect the coils and use only three collector rings and three wires. There are two ways of connecting the armature windings for this purpose.

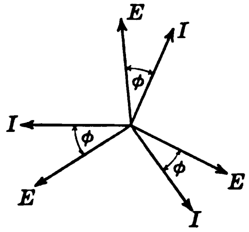


FIG. 234.

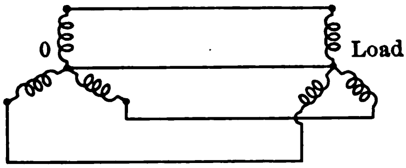


FIG. 235.—Four-Wire Three-Phase Circuit.

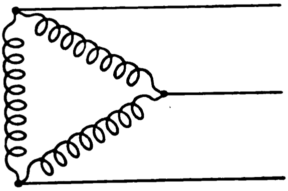


FIG. 236.—Δ-Connection Three-Phase Alternator.

The Δ-Connection.—When the three windings are connected together so as to form a closed circuit they are said to be Δ-connected. (See Fig. 236.)

The vector diagram showing the E. M. F. relations in the closed circuit formed by the three windings is shown in Fig. 237. From this diagram it is seen that if the coils are exactly alike and the E. M. F.'s differ exactly 120° in phase the vector sum of the

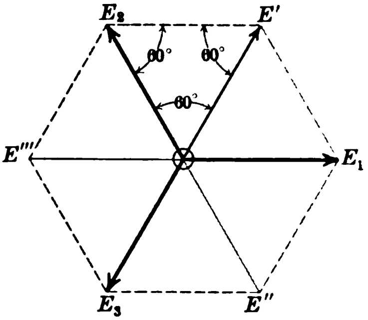


FIG. 237.—Vector Diagram Δ-Connected Windings.

E. M. F.'s is equal to zero. The vector sum of the E. M. F.'s of any two coils being equal and opposite in phase to the E. M. F. of the other. Referring to diagram the vector sum of OE_1 and OE_2 is OE', which is equal in magnitude and opposite in phase to OE_3. Since the value of the E. M. F. acting around the circuit is zero there will be no circulating current and the terminals can be therefore connected to three mains and supply current to three circuits.

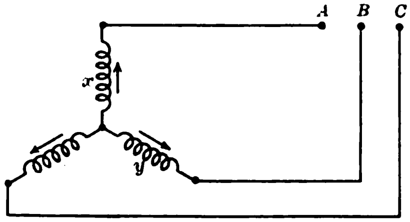


FIG. 238.—Y-Connection Three-Phase Alternator.

The Y-Connection.—When one terminal of each winding is carried to a common neutral junction and the other terminals to three collector rings, the windings are said to be Y-connected. This method is illustrated in Fig. 238.

In making this connection the starting ends of the windings are connected together to form a common neutral and the other ends form the respective terminals. The positive direction of the induced E. M. F. in each winding, if the same phase relation is retained, must be toward the common neutral or away from it. It is customary to assume the positive direction as away from the common neutral as shown in Fig. 238. It will then be seen that the E. M. F. between any two terminals as A and B is equal to the vector difference between the E. M. F.'s of windings x and y since the E. M. F.'s of these two windings are opposed in direction.

If E_0 equals the maximum value of the E. M. F. in winding, x and θ its instantaneous phase, the instantaneous value of the E. M. F. between A and B, will be given by the equation

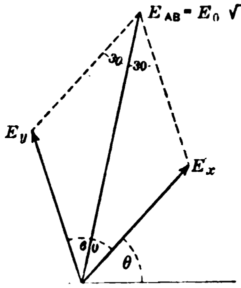


FIG. 239.—Vector Diagram.

$$e = E_0 \sin\theta - E_0 \sin(\theta - 120°).$$

Since the sine of an angle is equal in magnitude, but opposite in sign to an angle 180° greater than the angle, this equation may be written

$$e = E_0 \sin\theta + E_0 \sin(\theta + 60°).$$

This is the sum of two equal harmonic quantities differing in phase by 60° as shown in the vector diagram Fig. 239.

The instantaneous value is then given by the equation

$$e_1 = E_0\sqrt{3} \sin(\theta + 30).$$

Following the same method it can be shown that the E. M. F. between the other terminals would be given by the following equations:

$$e_2 = E_0\sqrt{3} \sin(\theta - 90°) \text{ and } e_3 = E_0\sqrt{3} \sin(\theta + 150°).$$

The maximum value of each of the above equations is $E_0\sqrt{3}$. Therefore, if E represents the effective value of the induced E. M. F. in any winding, the effective value of the E. M. F. between terminals will be $E\sqrt{3}$. It is thus shown that the E. M. F.'s between terminals are equal to one another and differ 120° in phase. If current is delivered to balanced circuits the effective values of the currents will be equal to another and will differ in phase by 120°. Referring to Fig. 235 we know that the vector sum of the currents meeting in the point 0 is equal to zero, but it has been shown in Fig. 237 that the vector sum of three equal harmonic quantities differing 120° in phase is equal to zero. Therefore, there will be no current flowing through the common return shown and hence the connection is not necessary and only three rings are required as in Figs. 238 and 240.

As noted before, if a three-phase alternator is used to supply current to unbalanced circuits the four-wire arrangement may be used, but as the energy is generally delivered to A. C. motors, which involve similar receiving circuits for each phase, the three-wire system is generally used. If supplying current to lamps it is generally feasible to distribute the load equally to the three circuits.

Electromotive Force and Current Relations for Y-Connections.

Electromotive force and current relations between mains and windings for the Y-connected system can be understood from Fig. 240.

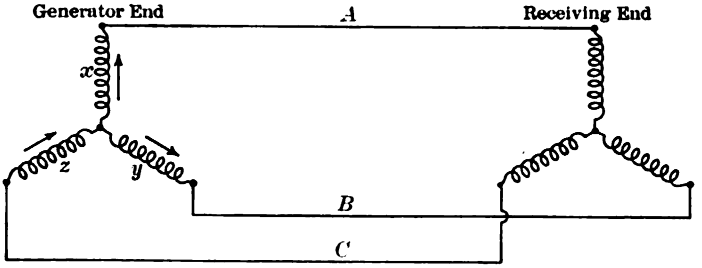


FIG. 240.—Electromotive Force and Current Relations for Y-Connections.

Generator End.—The E. M. F. between A and B will be the vector sum of the E. M. F. in windings x and y, and if the effective value of the E. M. F. of each winding is E the E. M. F. between mains is equal to $E\sqrt{3}$. From an inspection of Fig. 240 it is apparent that the same current flows through windings and mains.

Receiving End.—If E' represents the E. M. F. between mains $\frac{E'}{\sqrt{3}}$ will represent the E. M. F. delivered to each phase.

The Electromotive Force and Current Relations for △-Connections.

Generator End.—The E. M. F. between A and B (Fig. 241) is evidently the E. M. F. between the terminals of windings x. Hence, the E. M. F. between mains is equal to E. M. F. induced in any winding. The effective value of the current in A is equal to the vector difference of the currents in x and y; and, since these currents differ in phase by 120° this vector difference, as previously shown, will equal in magnitude the vector sum of two equal quantities

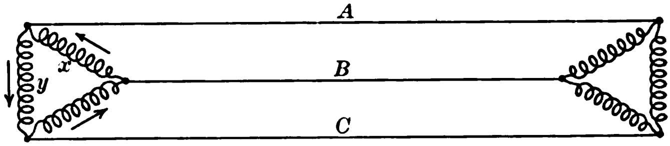


FIG. 241.—Electromotive Force and Current Relations for Δ-Connections.

differing 60° in phase. If I represents the current in either winding $I\sqrt{3}$ will equal value of the current flowing in the main.

Receiving End.—By the same reasoning the E. M. F. at the terminals of a winding will equal to E. M. F. between the mains and if I' represents the current flowing in any main $\frac{I'}{\sqrt{3}}$ will represent the current flowing in any winding.

Power.

To find the value of the power delivered by a three-phase alternator to balanced circuits it is convenient to calculate the power delivered by each phase, and then the total power will be three times the value thus obtained. Referring to the clock diagram shown in Fig. 242, E_1I_1, E_2I_2 and E_3I_3 represent effective values of the respective E. M. F.'s and currents in the three windings and ϕ_1, ϕ_2 and ϕ_3 the respective angles of phase. The power delivered by the different phases will be given by the equations

$$P_1=E_1I_1 \cos \phi_1, \quad P_2=E_2I_2 \cos \phi_2 \quad \text{and} \quad P_3=E_3I_3 \cos \phi_3.$$

If the circuits are balanced $E_1 = E_2 = E_3$, $I_1 = I_2 = I_3$ and $\phi_1 = \phi_2 = \phi_3$ and the total power $P = 3P_1 = 3E_1I_1 \cos \phi_1$.

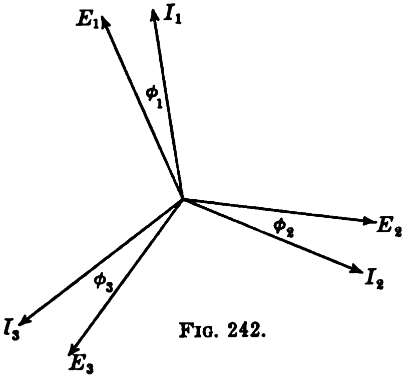


FIG. 242.

In measuring the output of an alternator it is convenient to connect the ammeter in the line and the voltmeter across the terminals, as shown in Fig. 243, for a Δ-connected alternator. The ammeter will then indicate the line current. It has been shown for this connection that when I_1 equals the current in a winding and I_1 equals the line current, $I_1 = \frac{I_1}{\sqrt{3}}$ and that E_1 the induced E. M. F. in a winding is equal to E, the terminal E. M. F.

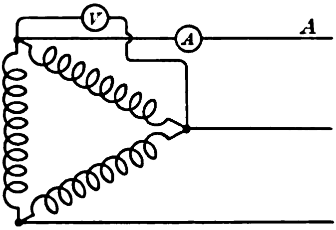


FIG. 243.—Connections for Measuring Output Three-Phase Circuits.

Hence, total power $P = 3E_1I_1 \cos \phi_1 = \sqrt{3}EI \cos \phi$ where E and I are the effective values of the terminal E. M. F. and line current, respectively, and ϕ is the angle of phase.*

In a Y-connected alternator the value of the total power delivered to balanced circuits is given by the same expression as deduced from the clock diagram. Hence, $P = 3P_1 = 3E_1I_1 \cos \phi$. By referring to

* If wattmeters are properly connected they will indicate directly the power absorbed. The readings of the wattmeters, voltmeters and ammeters supply the necessary data for computing the value of the power factor.

diagrams illustrating the Y-form of connections it will be seen that the line current is the same as the value of the current flowing through any winding, but that the E. M. F. between lines or the terminal E. M. F., E is equal to $E_1\sqrt{3}$ where E_1 represents the induced E. M. F. in any winding. Substituting these values in the equation above we have $P=\sqrt{3}EI \cos \phi$, which is the same expression for power as obtained before.

Alternating Current Measurements.

Alternating current ammeters give the average root mean square value of the current that is the square root of average value of the square of the instantaneous values during a cycle. In a continuous current circuit where the instantaneous values are equal to each other this root mean square value will be the same as the average value. Thus, while any instrument so designed that the force acting on the indicating device is proportional to the current will indicate correctly a continuous current when properly calibrated, it will be necessary to have an instrument whose force action is proportional to the square of the current to indicate correctly an alternating current.

All voltmeters excepting the electrostatic voltmeter depend for their action upon the current flowing through the instrument and, hence, are constructed on the same principle as ammeters. Ammeters are usually provided with low resistance shunts so that the resistance of the ammeter including the shunt is very small. This can be placed in the line and on account of the low resistance will not cause a great waste of energy when large currents are flowing through the circuit.

The voltmeter is provided with a high resistance in series with its coils and can be shunted across the terminals of a generator for, due to its high resistance, small current will flow through its coils and therefore small loss of energy results.

The usual method of calibrating an alternating current ammeter or voltmeter is by using direct currents or direct electromotive forces. The most reliable forms of A. C. ammeters and voltmeters are those which may be so calibrated and will then indicate effective A. C.

values. Most A. C. ammeters and voltmeters are constructed on the dynamometer principle which consists generally of two coils: one fixed and one movable; the force action depending upon the magnetic reaction caused by the current flowing through both coils. Since the magnetic action of any coil is proportional to the current flowing in that coil and the current flowing in each coil is proportional to the total current, it is evident that the force action is proportional to the product of these two currents and, hence, proportional to the square of the current. It should now be understood why an ammeter or voltmeter constructed on this principle may be calibrated by direct currents or direct E. M. F. and then indicate correctly effective A. C. values, provided that the inductive effect is negligible. In a like manner it can be seen that hot-wire ammeters can be so calibrated since the force action in this case is proportional to heat supplied to the instrument. The heat supplied in unit time by a current i flowing through a resistance R is equal to i^2R and, hence, the force action is proportional to the square of the current. The electrostatic voltmeter depends for its force action upon the pull between two plates oppositely charged. It has been shown that this pull is proportional to the square of electrostatic force and, hence, also, to the square of the difference of potential between the plates. The electrostatic voltmeter may be calibrated by direct electromotive force and will then indicate effective A. C. values. In the D'Arsonval type the force action depends upon the reaction of a constant magnetic field upon a coil carrying a current and is not proportional to the square of the current; and, furthermore, the direction of force action is reversed with a reversal of direction of current, hence, instruments constructed on this principle cannot be used for A. C. measurements.

The Wattmeter.—In a continuous current circuit the product of the readings of the ammeter (line current) and the voltmeter (terminal E. M. F.) gives the power delivered. In an A. C. circuit this product does not give the average power delivered on account of the difference in phase between the current and E. M. F. It is necessary, therefore, to use a wattmeter to measure the power delivered. The wattmeter when properly calibrated gives the average power. This instrument is constructed on the dynamometer principle with a fixed coil of comparatively heavy wire for a current coil and a movable coil of fine wire as a voltage coil. The force action causes the voltage coil to move. The motion of this coil being indicated by an arm moving over a scale. The force action in this case being proportional to the square of the current, it is practicable to calibrate a watt meter for alternating current measurements by using direct current and direct E. M. F., provided that the inductance of the voltage coil is small.

A full description of measuring instruments is given in another chapter.

Problems in A. C. Circuits.

1. A simple harmonic alternating E. M. F. of 100 volts, frequency 15, is impressed upon a circuit having a resistance of 10 ohms and an inductance of 0.04 henry. Compute the reactance, impedance, current and angle of lag. *Ans.* $X = 3.77$ ohms.
$Z = 10.69$ ohms.
$I = 9.36$ amperes.
$\phi = 20° 40'$.

2. Data same as problem (1) except that the frequency is 60.
Ans. $X = 15.08$.
$Z = 18.10$.
$I = 5.525$.
$\phi = 56° 27'$.

3. An alternating E. M. F. of 100 volts, frequency 60, is impressed upon a circuit containing a resistance of 1 ohm and a capacity of 100 microfarads. Compute the reactance, impedance, current and angle of lead. *Ans.* $X = 26.5$ ohms.
$Z = 26.5$ ohms.
$I = 3.77$ amperes.
$\phi = 87° 50'$.

4. Data same as problem (3) except that the frequency is 15.
Ans. $X = 106$ ohms.
$Z = 106$ ohms.
$I = 0.944$ ampere.
$\phi = 89° 27'$.

5. An alternating E. M. F. of 100 volts, frequency 30, is impressed upon two coils in series. The first coil has a resistance of 2 ohms and a negligible inductance. The second coil has a resistance of 1 ohm and an inductance of .021221 henry. Compute the value of the reactance in each coil and the total reactance; the impedance of each coil and the total impedance; the value of the current and the value of the E. M. F. across the terminals of each coil.

Solution.

$X_1 = 0$, $X_2 = 2\pi fL = 2 \times 3.1416 \times 30 \times .021221 = 4$ ohms.

$X = X_1 + X_2 = 4$, $Z_1 = 2$ ohms, $Z_2 = \sqrt{16+1} = 4.122$ ohms.

$Z = \sqrt{9+16} = 5$ ohms.

$I = \frac{100}{5} = 20$ amperes.

$E_1 = IZ_1 = 20 \times 2 = 40$ volts.

$E_2 = IZ_2 = 20 \times 4.122 = 82.44$ volts.

6. An alternating E. M. F. of 148.66 volts, frequency 60, is impressed upon a circuit containing a non-inductive resistance of 1 ohm and a coil in series. The difference of potential between the terminals of the resistance was found to be 100 volts and the difference of potential between the terminals of the coil was found to be 100.5 volts. Compute the value of the current and the resistance and inductance of the coil.

Ans. $I = 100$ amperes.	$r_2 = 0.1$ ohm.
$X_2 = 1$ ohm.	$L_2 = 0.00265$ henry

7. An alternating E. M. F. of 100 volts, frequency 60, is impressed upon a circuit containing a coil and a condenser in series. The resistance of the coil is 1 ohm and its inductance .02653 henry. The capacity of the condenser is 265.3 microfarads. Compute the reactance and impedance of each coil, the total reactance and total impedance, the E. M. F. across the terminals of the coil and the terminals of the condenser and the current.

Ans. $X_1 = 10$ ohms.	$Z_1 = 10.05$ ohms.	$I = 100$ amperes.
$X_2 = -10$ ohms.	$Z_2 = 10$ ohms.	$E_1 = 1005$ volts.
$X = 0$.	$Z = 1$ ohm.	$E_2 = 1000$ volts.

8. Data same as problem (7) except that the frequency is 55.

Ans. $X_1 = 9.167$ ohms.	$Z_1 = 9.222$ ohms.	$I = 49.75$ amperes.
$X_2 = -10.91$ ohms.	$Z_2 = 10.91$ ohms.	$E_1 = 458$ volts.
$X = -1.743$ ohms.	$Z = 2.01$ ohms.	$E_2 = 542$ volts.

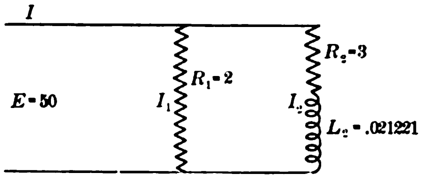


FIG. 244.

9. An alternating E. M. F. of 50 volts, frequency 30, is impressed upon circuit shown in diagram. (Fig. 244.) Compute X_1, X_2, X; Z_1, Z_2, Z, and I_1, I_2, I.

Ans. $X_1 = 0$.	$Z_1 = 2$ ohms.	$I_1 = 25$ amperes.
$X_2 = 4$ ohms.	$Z_2 = 5$ ohms.	$I_2 = 10$ amperes.
$X = 0.387$ ohm.	$Z = 1.563$ ohms.	$I = 32$ amperes.

10. An alternating E. M. F., frequency 60, is impressed upon the circuit shown in the diagram. (Fig. 245.) With the values given, compute E_1, R_2 and L_2.

Ans. $E_1 = 100$ volts.
$R_2 = 3.00$ ohms.
$L_2 = 0.01061$ henry.

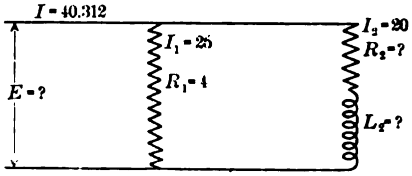


FIG. 245.

11. An alternating E. M. F. of 100 volts, frequency 30, is impressed upon circuit shown in diagram. (Fig. 246.) Compute I_1, I_2 and I.

Ans. $I_1 = 9.9$ amperes.
$I_2 = 9.95$ amperes.
$I = 1$ ampere.

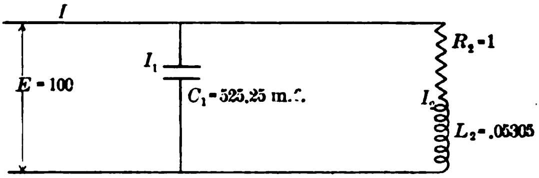


FIG. 246.

12. Same as (11) except frequency is 25.

Ans. $I_1 = 8.25$ amperes.
$I_2 = 11.90$ amperes.
$I = 3.845$ amperes.

13. An impedance coil of negligible resistance takes 3 amperes from 220-volt, 60-cycle mains. What current will it take from 220-volt, 25-cycle mains? From 110-volt, 60-cycle mains? *Ans.* 7.2, 1.5.

14. What current will an impedance coil which has a resistance of 2.7 ohms and an inductance of 0.05 henry take from 220-volt, 60-cycle mains? From 220-volt, 25 cycle mains? From 110-volt, 60-cycle mains? *Ans.* 11.55, 26.5, 5.78.

15. An impedance coil which has a resistance of 2.5 ohms takes 10 amperes from 220-volt, 60-cycle mains. What current will it take from 110-volt, 25-cycle mains? From 110-volt, 60-cycle mains?

Ans. 11.66, 5.0.

16. Across what direct E. M. F. must an impedance coil which has a resistance of 20 ohms and an inductance of 0.05 henry be connected in order that it may take the same current that it takes from 220-volt, 60-cycle mains? *Ans.* 160.2.

17. An impedance coil takes 25 amperes from 110-volt, 60-cycle mains. It also takes 25 amperes if connected across the terminals of a 10.5-volt storage battery. What are the resistance and the inductance of the coil? *Ans.* 0.42, 0.0116.

18. An impedance coil takes a current of 25 amperes when connected across 220-volt, 60-cycle mains. If this coil is connected in series with a resistance of 5 ohms across 110-volt D. C. mains the current is 17 amperes. What are the resistance and the inductance of the coil? *Ans.* 1.47, 0.023.

19. An impedance coil has a resistance of 5 ohms and an inductance of 0.1 henry. What current and what power will this coil take from 220-volt, 60-cycle mains? From 110-volt, 25-cycle mains? *Ans.* 5.8, 168; 6.68, 223.

20. An impedance coil which has a resistance of 2 ohms and an inductance of 0.05 henry is connected in series with a non-inductive resistance of 10 ohms across a 110-volt, 60-cycle circuit. What is the current? What is the voltage across the non-inductive resistance? What is the phase angle between the current and the impressed E. M. F.? Between the current and the voltage across the coil? The voltage across the non-inductive resistance? *Ans.* 4.92, 49.2, 57.5°, 83.9°, zero.

21. If the coil and non-inductive resistance in problem 70 are connected in series across a 220-volt, 25-cycle circuit, what is the current? What is the voltage across the non-inductive resistance? What is the phase angle between the current and the impressed voltage? The voltage across the coil? The voltage across the non-inductive resistance? *Ans.* 15.35, 153.5, 33.2°, 75.7°, zero.

22. Two impedance coils have resistances of 5 and 8 ohms and inductances of 0.01 and 0.2 henry, respectively. If these coils are connected in series across 220-volt, 60-cycle mains, what current will they take? What will be the phase relations of the current and the impressed voltage? The voltage across the first coil? The voltage across the second coil? *Ans.* 2.74, 80.7°, 37.0°, 83.9°.

23. An impedance coil which has a resistance of 3.4 ohms takes 7.7 amperes from 220-volt, 60-cycle mains. What should be the resistance and the inductance of another coil which takes the same current and absorbs the same power from 110-volt, 60-cycle mains? *Ans.* 3.4, 0.0369.

24. An impedance coil takes 250 watts at a power factor of 0.1 from 220-volt, 60-cycle mains. What non-inductive resistance must be connected in series with it across 220-volt, 25-cycle mains so that the coil will take 250 watts? *Ans.* 15.7.

25. When a non-inductive resistance and an impedance coil which has a resistance of 2 ohms are connected in parallel across a 60-cycle alternating E. M. F. they take 12 amperes and 9.5 amperes, respectively. When they are connected in series across the same potential the current is 6.7 amperes. What is the reactance of the coil at 60 cycles? *Ans.* 8.04.

26. When a non-inductive resistance and an impedance coil which has a negligible resistance are connected in parallel across a 60-cycle alternating E. M. F. they take 10 amperes. What current will they take when they are connected in series across a 25-cycle E. M. F. of the same effective value? *Ans.* 9.24.

27. A non-inductive resistance of 20 ohms in series with a condenser of 45 microfarads is connected across 220-volt, 60-cycle mains. What is the impedance of the circuit? What is the current? What is the power taken by the circuit? *Ans.* 62.2, 3.54, 251.

28. A non-inductive resistance of 10 ohms and a condenser of 60 microfarads connected in series take 4.9 amperes from 60-cycle mains. What should be the resistance and capacity of another circuit which will take the same current and absorb the same power from 110-volt, 60-cycle mains? *Ans.* 10, 132.

29. A non-inductive resistance of 10 ohms, an impedance coil which has a resistance of 1.7 ohms and an inductance of 0.1 henry, and a condenser of 60 microfarads capacity are connected in series across 110-volt, 60-cycle mains. What is the current? What is the voltage across each part of the circuit, and what are the phase relations of these voltages with respect to the current? *Ans.* 8.23, 82.3, 0°, 310, 87.4°, 363, 90°.

30. A 110-volt, 60-cycle E. M. F. is impressed on a series circuit which consists of a non-inductive resistance of 10 ohms, an impedance coil of 1 ohm resistance and 0.1 henry inductance, and a condenser of variable capacity. For what capacity will the current be a maximum? *Ans.* 70.3.

31. An impedance coil and a series circuit consisting of a non-inductive resistance and a capacity reactance of 60 ohms are connected in series across 220-volt, 60-cycle mains. The entire circuit is so adjusted that the voltages across each part and the power absorbed by each part are equal. If the entire circuit absorbs 500 watts what is the current? What is the voltage across each part of the circuit? What are the phase relations of the current and the voltage across each part? *Ans.* 2.27, 175.3, 51.1°.

32. Two impedance coils which have resistances of 5 and 20 ohms and inductances of 0.01 and 0.1 henry, respectively, are connected in parallel across 220-volt, 60-cycle mains. What is the total current taken from the mains? What is the phase relation of the impressed E. M. F. and the total current? The current in the first coil? The current in the second coil? *Ans.* 39.9, 40.2°, 37.0°, 62.0°.

33. A circuit consists of two parallel branches. The first branch has a resistance of 60 ohms and a condensive reactance of 30 ohms at 60 cycles. The second branch has a resistance of 5 ohms and a condensive reactance of 10 ohms at 60 cycles? What is the phase relation of the impressed voltage and the current in the first branch? The current in the second branch? The total current? *Ans.* 9.84, 26.6°, 63.5°, 58.4°.

34. Two circuits, each containing resistance and condensive reactance, are connected in parallel across 220-volt, 60-cycle mains. The first circuit takes a current of 5 amperes and absorbs 300 watts, and the second circuit takes a current of 3 amperes and absorbs 225 watts. What is the total current taken from the mains? *Ans.* 7.99.

35. An impedance coil which has a resistance of 5 ohms and an inductance of 0.08 henry is connected in parallel with a condenser of 60 microfarads capacity. What is the total impedance of this circuit at 60 cycles and what is the power factor? *Ans.* 9.06, 0.485.

36. An alternator delivers 180 amperes to incandescent lamps, and 92 amperes to start an induction motor. The power factor of the motor while starting is 0.35. What is the total current delivered by the alternator? *Ans.* 229.

37. A soldering iron built for 50 volts and 3 amperes is to be used on a 100-volt, 60-period circuit, with a choke coil. If the resistance of the choke is 1 ohm, required the E. M. F. around the choke coil; the inductive E. M. F. and the inductance. *Ans.* 84.85, 84.80, 0.0749.

38. Required the E. M. F. around a 3-ohm choke coil to be used in series with a 50-volt, 25-candle-power lamp, taking 1 watt per candle-power for use on a 110-volt circuit. Required also the efficiency. *Ans.* 94.09, 87.0 per cent.

39. An induction motor taking 5000 kilowatts at 10,000 volts and 85 per cent power factor is supplied through a line having a resistance of 1.2 ohm, and a reactance of 0.3 ohm. What must be the generator E. M. F.; also the drop in volts at the motor from no load to full load, and the regulation, that is, the per cent which the above drop is of the full-load voltage? *Ans.* 10,700, 6.55 per cent.

40. An induction motor taking 50 amperes and with a power factor of 0.7 has in parallel with it 200 $\frac{1}{2}$-ampere lamps in parallel. Find the total current. *Ans.* 139.6.

41. Fifteen 50-watt, 100-volt lamps are in parallel on a 100-volt system and in parallel with a circuit of 5 ohms and 0.005 henry; the frequency is 120. What is the current, the angle of lag and the power factor?

Ans. 22.45, 25° 22′, 90.3 per cent.

42. Required the inductive E. M. F. of a choke coil to be placed in series with a projection arc lamp taking 15 amperes at 35 volts when used on a 110-volt circuit, the resistance of the coil being ½ ohm. If 60 110-volt, ½-ampere lamps are in parallel with the above, and with each other, what will be the total current? *Ans.* 101.2, 25.06.

43. A common return wire is used for the two currents of a two-phase system. The system is balanced and each current is equal to 100 amperes. What is the current in the common return wire?

Ans. 141.4 amperes.

44. The electromotive force of each phase, problem 43, is 500 volts. What is the electromotive force between the outside wires?

Ans. 707 volts.

45. Three similar receiving circuits are Δ-connected to 3-phase mains, the electromotive force between each pair of mains being 110 volts. The power delivered to the three circuits is 150 kilowatts and the power factor of each circuit is 0.90. What is the current in each circuit and in each main? *Ans.* 505 amperes, 875 amperes.

46. Three similar receiving circuits are Y-connected to the 3-phase mains, problem 45; the total power delivered is 150 kilowatts and the power factor of each circuit is .90. What is the current in each circuit and in each main, and what is the electromotive force between the terminals of each circuit? *Ans.* 875 amperes, 875 amperes, 63.5 volts.

47. A given 3-phase alternator is provided with six collector rings so that it may be connected, Δ or Y, for experimental purposes. The electromotive force developed by each winding is 100 volts. Find (a) the current in each receiving circuit, (b) the current in each main, (c) the voltage between mains, and (d) the current in each armature winding, when the alternator is Δ-connected to the mains, and the mains are Y-connected to three similar receiving circuits, each one of which has a resistance of 4 ohms and a reactance of 3 ohms.

Ans. (a) 11.55 amperes, (b) same as (a), (c) 100 volts, (d) 6.67 amperes.

48. Find (a) the current in each receiving circuit, (b) the current in each main, (c) the voltage between mains, and (d) the current in each armature winding, when the generator specified in problem 47 is Y-connected to the mains and the mains are Δ-connected to the receiving circuits.

Ans. (a) 34.64 amperes, (b) 60 amperes, (c) 173.21 volts, (d) 60 amperes.

49. The electromotive force in each winding of a 2-phase alternator is 100 volts. What is the electromotive force given by the two windings connected in series? *Ans.* 141 volts.

50. The electromotive force developed in each winding of a 3-phase alternator is 100 volts. What is the electromotive force developed by the three windings in series? *Ans.* 200 volts, or zero.

NOTE.—Many of the problems given in this chapter were taken from Problems in Electrical Engineering by Prof. W. V. Lyon, published by McGraw Publishing Co. The reader is referred to this excellent book for numerous problems illustrating the principles of direct and alternating current.

CHAPTER XVI.

ALTERNATING-CURRENT MACHINERY.*

Alternating-current apparatus may be divided into three classes: (a) That used for transforming the power of the prime mover into alternating current; (b) that used for transforming the alternating current as generated by the alternator into electricity of another sort, *i. e.,* direct current or alternating current of another voltage or frequency, and (c) apparatus for the utilization of the electric power. In the first class are placed alternators; in the second, transformers, frequency changers, motor generator sets, converters, and rectifiers; and in the third, all types of motors, lamps, resistors, etc.

(A) ALTERNATORS.

Any machine which generates an E. M. F. which varies periodically from a maximum positive to a maximum negative and back again may be classed as an alternator. The development of this machine has passed through many stages.

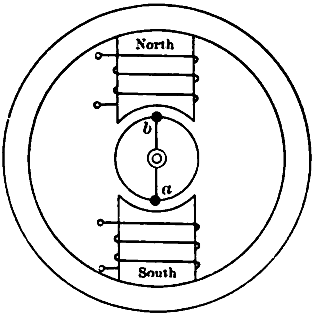


FIG. 247.

The simplest type is represented by Fig. 247.

Here *a* and *b* are opposite sides of a single coil revolving in a two-pole structure, the poles being of opposite polarity. An oscillograph record of the induced E. M. F. wave would approximate that shown in Fig. 248.

Increasing the number of coils not only makes more economical use of available armature space, but also results in a better shaped, induced E. M. F. wave as shown by the dotted resultant of Fig. 249.

* The subject of A. C. machinery ordinarily requires one or more volumes for a complete explanation. Therefore this chapter can do no more than make a bare statement of the salient facts.

The figure shows the effect of using four coils. Connecting these coils in series makes this a single-phase alternator. If the coils were connected in pairs, this would become a two-phase alternator. Various other arrangements of active conductors were tried.

The early types were: (a) The Mordey alternator with no revolving copper; (b) the Ferranti disc type, and (c) the inductor alternator, also with no revolving copper. These types are now

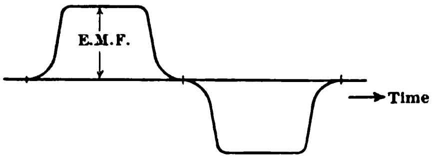


FIG. 248.

obsolete except that the inductor alternator is used commercially in some very high frequency machines. At present most alternators have the following construction. On the revolving member are mounted windings which produce a whole number of pairs of south and north poles, these windings being excited by direct current.

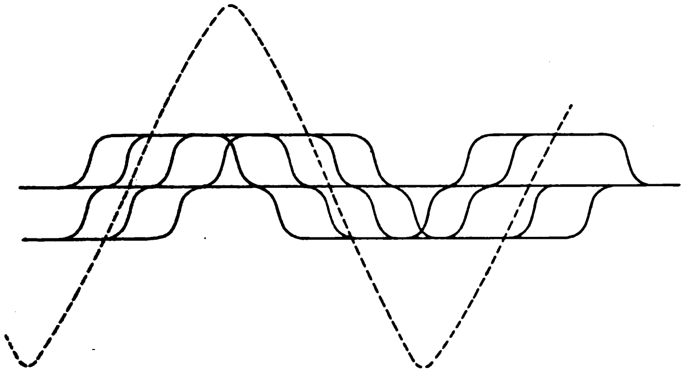


FIG. 249.

Ordinarily this direct current is obtained from a small motor generator set or exciter set which has a capacity of ½ to 1½ per cent of the main generator. The figures on page 402 represent rotors of alternators, Fig. 250 being for a slow-speed engine-driven alternator, and Fig. 251 being for a high-speed turbine-driven alternator.

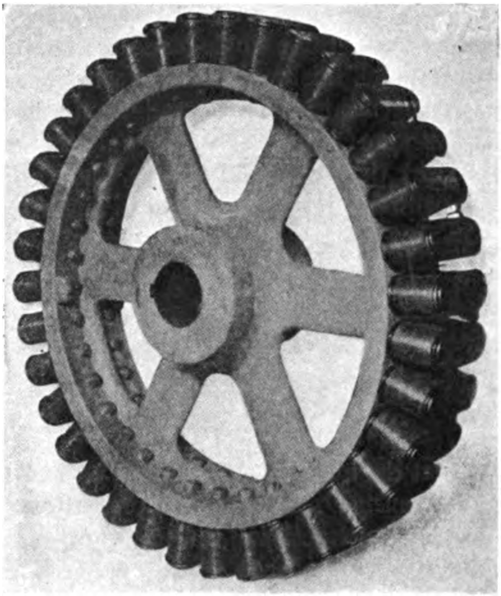


FIG. 250.—Revolving Field Structure. 36 Poles 200 R. P. M.

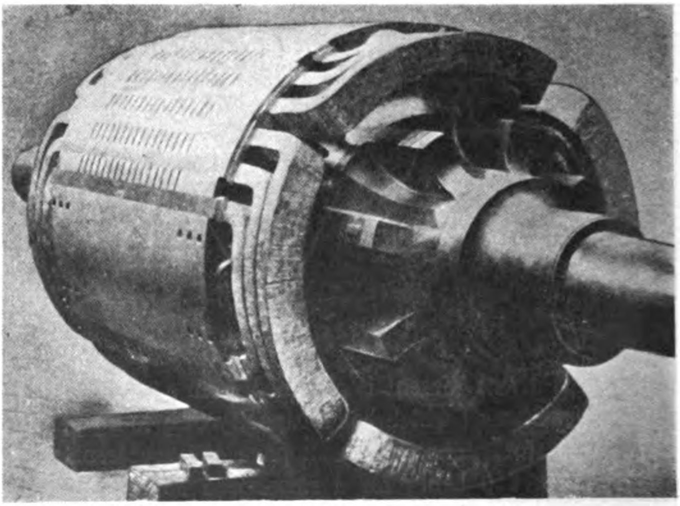


FIG. 251.—Four-Pole Field for a Turbo-Alternator.

The rotor revolves inside the stationary armature or stator with a clearance of from ¼-inch in small machines up to as much as 2 inches in the large high-speed machines. The stator consists of a frame in which are assembled laminations as indicated in Fig. 252, which shows the stator of a slow-speed alternator.

Stator windings are of various types. The early machines were built with few large slots and a *concentrated* winding. As such construction was not productive of a good sine wave of E. M. F. stators are now wound with *distributed* windings, *i. e.*, a large number of small slots per pole. The number of slots per pole per phase varies from one to six in alternators, one corresponding to a concentrated winding, while any greater number may be considered to give a distributed winding. For each phase of the stator winding there is a separate electrical circuit. If the winding were three-phase there would be six terminals to the armature winding and one-third of each pole pitch on the stator surface would be utilized by the slots of each phase.

Referring to Fig. 253, which shows the winding partly in place, the coils opposite *a* correspond to one phase; those opposite *b* to a second phase; and those opposite *c*, to the third phase. In this case there are three slots per pole per phase. There are many other types of alternating current windings besides the above very common type.

After the above brief description of the construction of alternators, consider the operation of alternators. In the first place the prime mover is expected to maintain synchronous speed for the set under all loads. To produce a frequency of 25 cycles per second, the following combinations of number of poles and synchronous speed in R. P. M. are available: 2, 1500; 4, 750; 6, 500; 8, 375; 12, 250, etc.; for 60 cycles per second use the following combinations: 2, 3600; 4, 1800; 6, 1200; 8, 900; 10, 720; 12, 600, etc. In general:

$$\text{Frequency} = \tfrac{1}{60}\,\text{R. P. M.} \times (\text{Number of pairs of poles}).$$

Generators can be designed to give any terminal voltage. Voltages of 2300, 6600 and 13,200 are fairly common in large machines, while a voltage of 440 is fairly common in small machines. The problem in the operation of alternators is that of maintaining the terminal voltage of the alternator constant under all conditions of

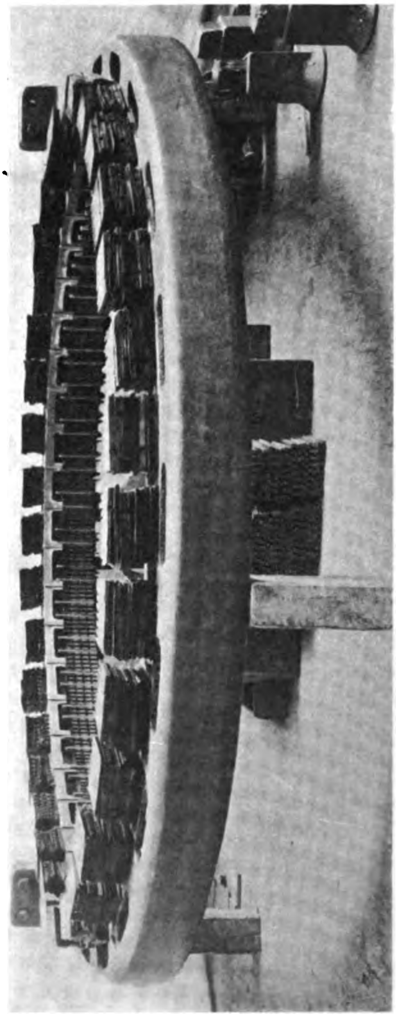


FIG. 252.—Current Generator, View Showing Laminations Partially Assembled.

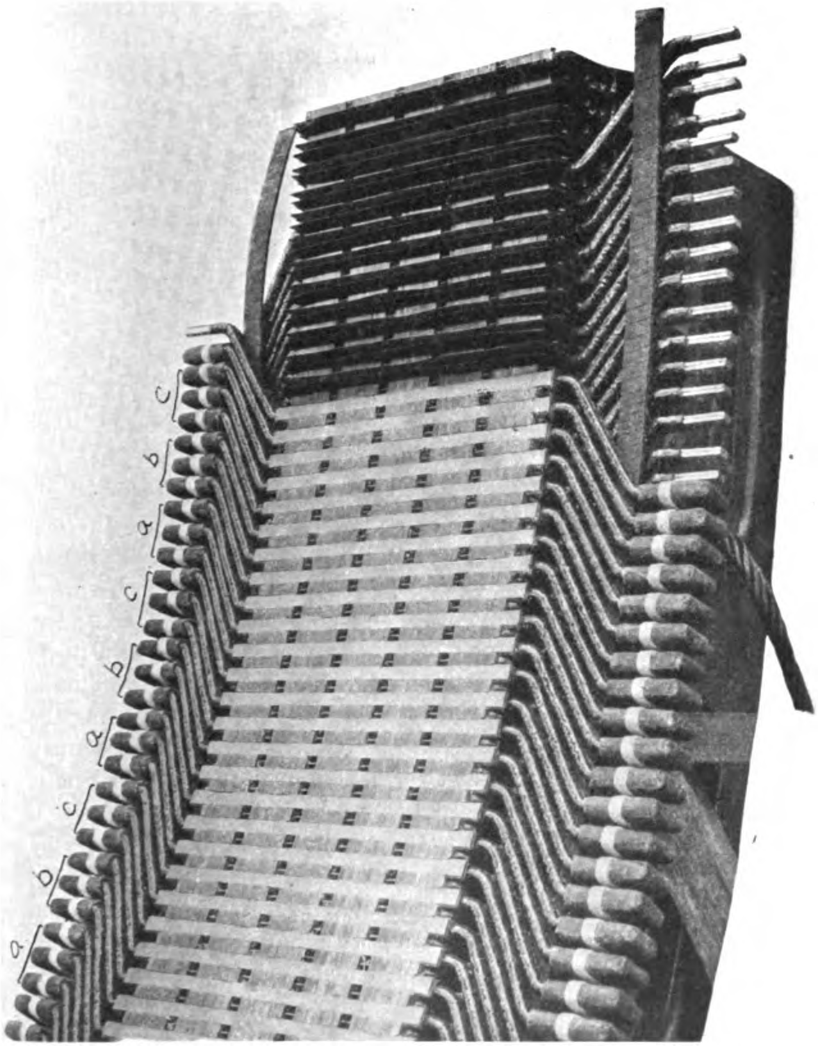


FIG. 253.—Bar Winding for Engine Type Alternator.

load. Fig. 254 shows the external characteristic of an alternator with constant speed and constant field excitation.

The fall in voltage from no load to full load is due to three causes: (a) IR drop in the stator winding; (b) IX drop in the stator winding, and (c) the weakening of the main field by the field set up by the armature. That the voltage does not always fall due to the increase of load is evident from the 90 per cent leading curve. This is due to the fact that the field due to the leading currents in the stator winding is in such a direction as to aid the main field.* This

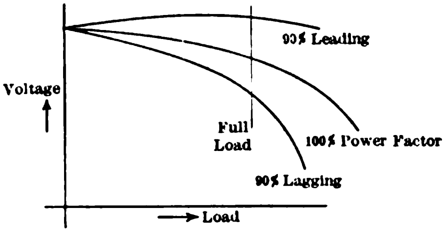


FIG. 254.

is shown by the three space-time-vector diagrams of Fig. 255. In all the diagrams of Fig. 255 $R=M+A$ vectorially.

To regulate the terminal voltage as load comes on, compounding was at one time resorted to but has now been abandoned, and in its place regulation is procured either by hand control or by a Tirrill regulator. As full voltage can be maintained only by increasing the field current as the load comes on, the output of an alternator may be limited by the space available for field ampere turns. Heating is the other limitation to the output. Since an alternator will give a very large current on short circuit and thus injure itself either by overheating or wrenching loose some of its coils by magnetic pulls, it becomes necessary to protect alternators against this. Protection is provided by connecting in series with the stator windings reactance coils. Thus, to limit the current in a 2300-volt winding of 2000 amperes normal current carrying capacity to 20,000 amperes,

* That is R, the resultant field is greater than M, the main field, with a leading current load, while with a non-inductive and inductive load R is less than M. Therefore E_a, the E. M. F. induced by the field R, is greatest in the case of leading loads, the other conditions remaining the same.

$\frac{2300}{20,000} = 0.115$ ohm of reactance should be in circuit, of which 0.015 might be due to the stator winding and the rest provided by an external reactance. This precaution is taken everywhere that large alternators are employed.

Commercial alternators are expected to produce a wave of E. M. F. which is a very close approximation to a sine wave. The deviation of wave form from the sinusoidal is determined by superposing

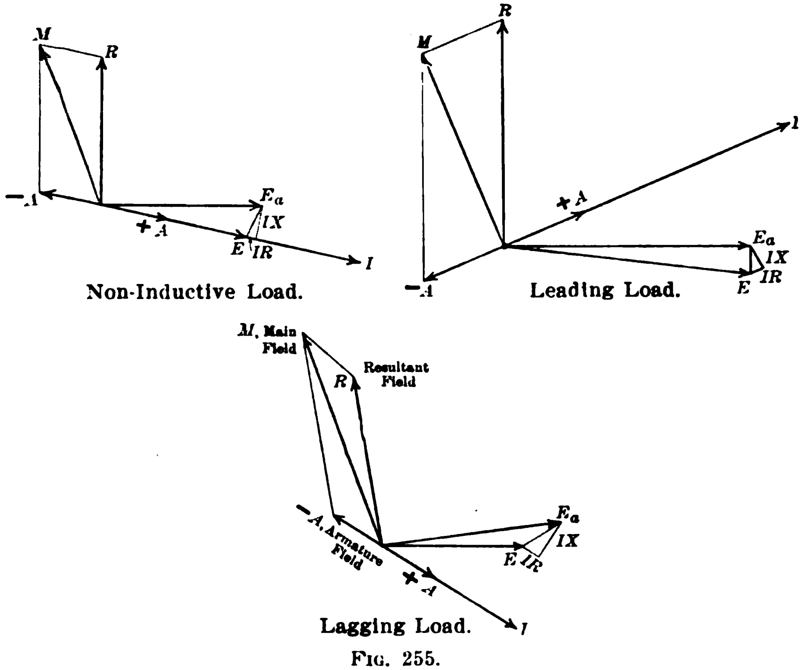


FIG. 255.

upon the actual wave (as determined by oscillograph), the equivalent sine wave of equal length, in such a manner as to give the least difference, and then dividing the maximum difference between corresponding ordinates by the maximum value of the equivalent sine wave. A maximum deviation of the wave from sinusoidal shape not exceeding 10 per cent is permissible, except when otherwise specified.

This ideal, or sine wave, is approached by the careful shaping of the pole faces, by the use of well-distributed windings, by the use of stator coils which have a spread somewhat less than the full-pole pitch, $\frac{5}{6}$th of the pole pitch being a common pitch for a stator coil.

In regard to testing the regulation of an alternator, the American Institute of Electrical Engineers makes the following suggestions:

Conditions for Tests of Regulation.*

Speed and Frequency.—The regulation of generators is to be determined at constant speed, and of alternating-current apparatus at constant frequency.

Power Factor.—In apparatus generating, transforming, or transmitting alternating currents, the power factor of the load to which the regulation refers should be specified. Unless otherwise specified, it shall be understood as referring to non-inductive load, that is to a load in which the current is in phase with the E. M. F. at the output side of the apparatus.

Wave Form.—In the regulation of alternating-current machinery receiving electric power, a sine wave of voltage is assumed, except where expressly specified otherwise.

Excitation.—In synchronous machines, the regulation is to be determined under the following conditions, so as to maintain the field adjustment constant at that which gives rated-load voltage at rated-load current. In the case of separately excited field magnets—constant excitation.

Tests and Computation of Regulation of A. C. Generators.—Any one of the three following methods may be used. They are given in the order of preference:

Method a.—The regulation can be measured directly by loading the generator at the specified load and power factor, then reducing the load to zero, and measuring the terminal voltage, with speed and excitation adjusted to the same values as before the change. This method is not generally applicable for shop tests, particularly on large generators, and it becomes necessary to determine the regulation from such other tests as can be readily made.

* For definition of "Regulation of Alternator," see page 483.

Method b.—This consists in computing the regulation from experimental data of the open-circuit saturation curve and the zero power factor saturation curve. The latter curve, or one approximating very closely to it, can be obtained by running the generator with over-excited field on a load of idle-running under-excited synchronous motors.* The power factor under these conditions is very low and the load saturation curve approximates very closely the zero power factor saturation curve. From this curve and the open-circuit curve, points for the load saturation curve for any power factor can be obtained by means of vector diagrams.

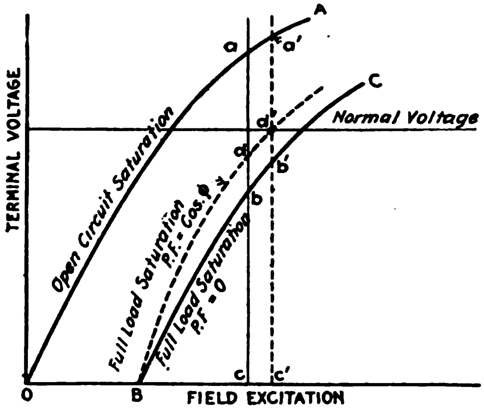


FIG. 256.

To apply method b, it is necessary to obtain from test, the open-circuit saturation curve *OA*, Fig. 256, and the saturation curve *BC* at zero power factor and rated-load current. At any given excitation *Oc*, the voltage that would be induced on open circuit is *ac*, the terminal voltage at zero power factor is *bc*, and the apparent internal drop is *ab*. The terminal voltage *dc* at any other power factor can then be found by drawing an E. M. F. diagram † as in Fig. 257, where ϕ is an angle such that $\cos \phi$ is the power factor of the load, *be*

* See last line of page 437.

† Method b, for deducing the load saturation curve, at any assigned power factor, from no-load and zero power factor saturation curves obtained by test, must be regarded as empirical. Its value depends upon the fact that experience has demonstrated the reasonable correctness of the results obtained by it.

the resistance drop (IR) in the stator winding, *ba* the total internal drop and *ac* the total induced voltage; *ba* and *ac* being laid off to correspond with the values obtained from Fig. 256. The terminal voltage at power factor $\cos\phi$ is then *cb* of Fig. 257 which, laid off in Fig. 256, gives point *d*. By finding a number of such points, the curve *Bdd'* for power factor $\cos\phi$ is obtained, and the regulation at this power factor (expressed in per cent) is $\frac{100 \times a'd'}{d'c'}$, since $a'd'$ is the rise in voltage when the load at power factor $\cos\phi$ is thrown off at normal voltage $c'd'$.

Generally, the ohmic drop can be neglected, as it has very little influence on the regulation; except in very low-speed machines, where

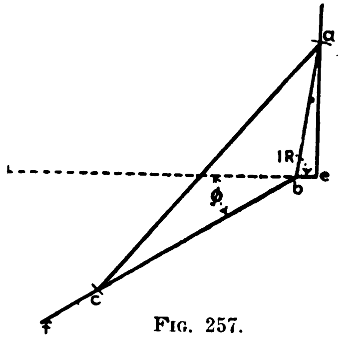


FIG. 257.

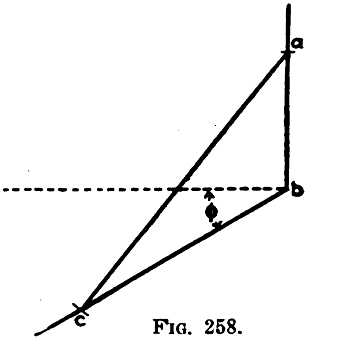


FIG. 258.

the armature resistance is relatively high, or in some cases where regulation at unity power factor is being estimated; for low-power factors, its effect is negligible in practically all cases. If resistance is neglected, the simpler E. M. F. diagram, Fig. 258, may be used to obtain points on the load saturation curve for the power factor under consideration.

Method c.—Where it is not possible to obtain by test a zero power factor saturation curve as in (b), this curve can be estimated closely from open-circuit and short-circuit curves by reference to tests at zero power factor on other machines of similar magnetic circuit. Having obtained the estimated zero power factor curve, the load saturation for any other power factor is obtained as in (b).

Thus method (c) is the same as (b); except that the zero power factor curve must be estimated. This may be done as follows: In

Fig. 259 *OA* is the open-circuit saturation curve and *OE* the short-circuit line as shown by test. The zero power factor curve corresponding to any given current *BF* will start from point *B* and for machines designed with low saturation and low reactance, will follow parallel to *OA*, as shown by the dotted curve *BD*, which is *OA* shifted parallel to itself by the distance *OB*. In high-speed machines, or in others having low reactance and a low degree of saturation in the magnetic circuit, the zero power factor curve will lie quite close to *BD*, particularly in those parts that are used for determining the

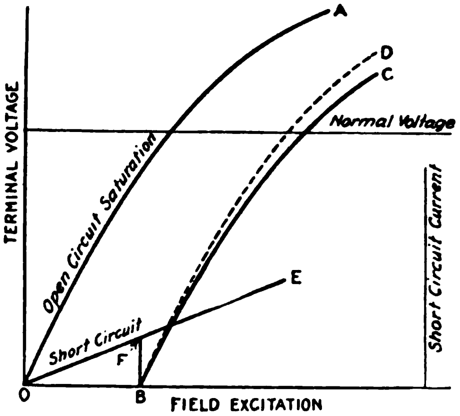


FIG. 259.

regulation. This is the case with many turbo-generators or high-speed water-wheel generators. In many cases, however, the zero power factor curve will deviate from *BD*, as shown by *BC*, and the deviation will be most pronounced in machines of high reactance, high saturation, and large magnetic leakage. The position of the actual curve *BC* with relation to *BD* can be approximated with sufficient exactness by investigating the corresponding relation as obtained by test at zero power factor on machines of similar characteristics and magnetic circuit. Or curve *BC* can be calculated by methods based on the results of tests at zero power factor. After *BC* has been obtained, the saturation curve and regulation for any other power factor can be derived as in method (b).

The operation of alternators in parallel will be treated under the heading of Synchronous Motors.

(B) CONVERSION OR TRANSFORMATION APPARATUS.

(1) Transformers.—Transformers are pieces of alternating-current apparatus designed for receiving power at one voltage and giving it out at another. Thus, with alternating current the transformation of voltage or current is easily done by transformers. A transformer consists of a magnetic circuit of laminated iron linked by two separate and distinct coils of wire in the ordinary transformer or by one coil of wire in the case of reactance coils, compensators, and auto-transformers. The winding which takes power from the source is called the primary whether it be low or high voltage. The winding that gives power to the receiver is called the secondary.

Figs. 260, 261, 262 show the ordinary arrangement of the windings.

The core type is used for very high-voltage transformers. The core and shell types are used for all ratings greater than 100 K. V. A. The cruciform type is used for distribution of power in small lots up to 100 K. V. A. In Fig. 262, one winding only is shown, but actually two windings are used, both being wound as the one shown (see Fig. 283).

Operation of the Transformer.—Application of E. M. F., E_1 to the primary of a transformer causes an exciting current to flow, which current is made up of two components, I_μ the current necessary to produce the flux ϕ called the magnetizing current, and a current I_{e+h} to supply the eddy current and hysteresis loss in the transformer. These facts may be represented by the vector diagram of Fig. 263. Neglecting the drop in the transformer due to this current I_0, which in practice is very small, experiment would show a voltage $E_2=E_1\frac{N_2}{N_1}$. This is the no-load condition.

Consider next the full-load condition. Then the voltage drop in the transformer is not entirely negligible, but is of the magnitude of 2 to 5 per cent. A large part of this drop is due to the leakage fluxes

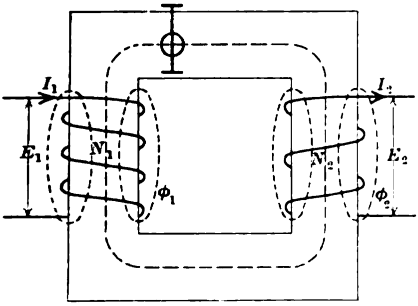


FIG. 260.—Core Type.

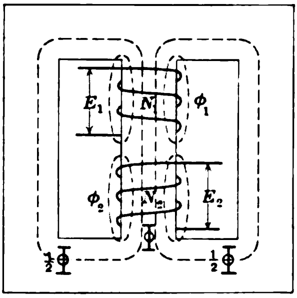


FIG. 261.—Shell Type.

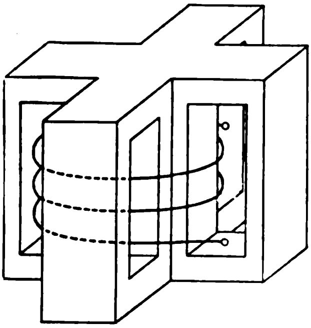


FIG. 262.—Cruciform Type.

ϕ_1 and ϕ_2, see Figs. 260 and 261. These produce a drop exactly like that produced by the insertion of a small reactance in series with

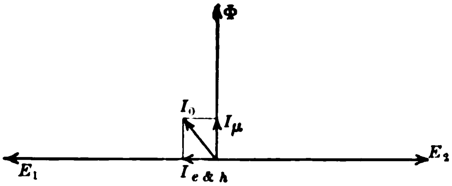


FIG. 263.

the transformer. Remembering this, the full-load vector diagram can be drawn. For explanatory purposes the construction should be carried out in this order:

(1) ϕ.

(2) E_1' and E_2', perpendicular to ϕ, E_2' being the E. M. F. induced in secondary by the flux, ϕ; and E_1' being that part of the impressed E. M. F. which goes to balance the E. M. F. induced in the primary.

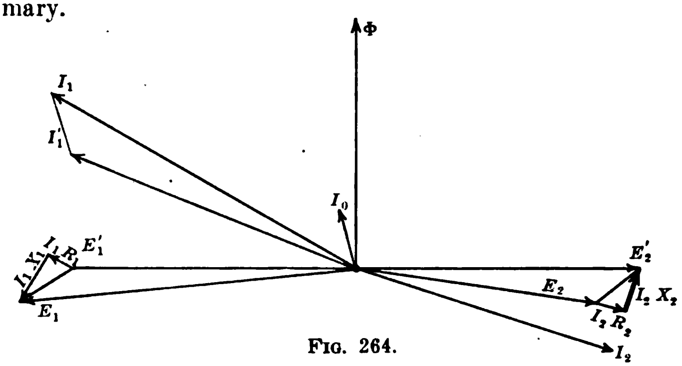


FIG. 264.

(3) Load current, I_2.

(4) Subtract I_2R_2 and I_2X_2, being respectively the ohmic drop and the drop due to leakage flux in the secondary, from E_2' and get E_2.

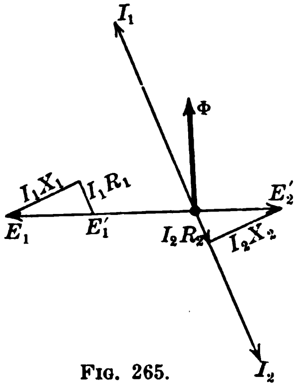


FIG. 265.

(5) Draw I_1' at an angle of 180° to I_2.

(6) Add I_0 to I_1', I_0 being the same current explained under the no-load condition. Call this total current I_1.

(7) Add I_1R_1 and I_1X_1 to E_1' and get E_1, the impressed E. M. F. of the transformer.

The (I_1X_1, I_1R_1) and the (I_2X_2, I_2R_2) lines are never as large as shown in Fig. 264, in practice being only 1 or 2 per cent of E_2' or E_1'.

On short circuit this diagram becomes as in Fig. 265, the resistances and the reactances being the only quantities to limit the current, the exciting current being negligibly small.

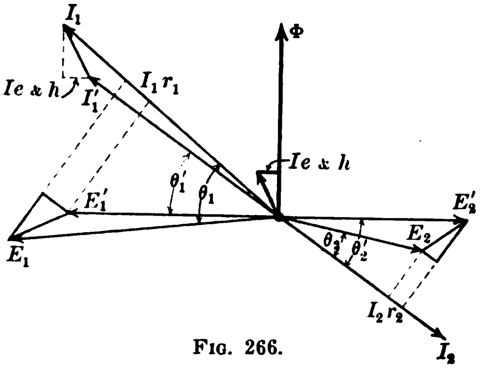


FIG. 266.

A study of the power flow may be made from Fig. 266 as follows:

$$\text{Watts Input} = P_1 = E_1I_1 \cos\theta_1 = I_1[I_1r_1 + E_1' \cos|E_1'I_1|]$$

$$P_1 = I_1^2r_1 + E_1'I_1 \cos|E_1'I_1|$$

$$= I_1^2r_1 + E_1'[I_1' \cos\theta_1' + I_{e\,\&\,h}]$$

$$= \underbrace{I_1^2r_1}_{\text{Copper Loss}} + \underbrace{E_1'I_{e\,\&\,h}}_{\text{Core Loss}} + \underbrace{E_1'I_1' \cos\theta_1'}_{\text{Power Transmitted to Secondary}}$$

$$P_1 = I_1^2r_1 + E_1'I_{e\,\&\,h} + E_1'I_1' \cos\theta_1'$$

$$I_1^2r_1 + E_1'I_{e\,\&\,h} + E_2'I_2 \cos\theta_2'$$

$$+ I_2(I_2r_2 + E_2 \cos\theta_2)$$

$$+ \underbrace{I_2^2r_2}_{+\text{ Copper Loss}} + \underbrace{E_2I_2 \cos\theta_2}_{+\text{ Output}}$$

This tracing through of the power enables us to calculate the efficiency, remembering that

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{Losses}}.$$

A further description of these losses is as follows: The Hysteresis Loss: $W_h = nVfB^{1.6} \times 10^7$, where W_h=watts lost, V=volume of iron core in cubic cm., f=frequency in cycles per second, B=maximum flux density in lines per sq. cm., n=variable constant=0.0021 approx. The Eddy Current Loss: $W_e = bVf^2t^2B^2$, t=thickness of laminations in cm., b=constant depending on the specific resistance of iron, usually about 1.6×10^{-11}. Although the losses in transformers are small, efficiencies of 95-99 per cent being common, yet the losses generate heat which in large transformers is too large in amount to dissipate naturally. Small transformers are air or oil cooled. Large transformers are cooled by air blasts or by water coils inserted in the oil at the top of the transformer case.

Self-cooled units are limited to 2000 to 3000 K. V. A. Water-cooled units are unlimited in size. They require about ¼ gallon of water per minute per kilowatt lost. Air-blast transformers require approximately 150 cubic feet of air per minute per kilowatt lost.

In constant-potential transformers the regulation is the difference between the no-load and rated-load values of the secondary terminal voltage, at the specified power factor (with constant primary impressed terminal voltage) expressed in per cent of the rated-load secondary voltage, the primary voltage being adjusted to such a value that the apparatus delivers rated output at rated secondary voltage.

Tests and Computation of Regulation for Constant-Potential Transformers.—The regulation can be determined by loading the transformer and measuring the change in voltage with change in load at the specified power factor. This method is not generally applicable for shop tests, particularly on large transformers.

The regulation for any specified load and power factor can be computed from the percentage resistance drop and percentage reactance drop in the windings as follows:

To compute the regulation of a constant-potential transformer, it is necessary to obtain the equivalent resistance R and impedance drop E_z. The equivalent resistance R of primary and secondary combined, is found by multiplying the secondary resistance by the square of the ratio of turns and adding it to the primary resistance. The impedance voltage E_z is found by short circuiting the secondary winding and measuring the volts necessary to send rated-load current through the primary. (See Fig. 265.)

The reactance drop is then

$$IX = \sqrt{\left(E_z^2 - \frac{P^2}{I^2}\right)},$$

where P = impedance watts as measured in the short-circuit test. Let

E = rated primary voltage,
IR = resistance drop in volts,
IX = reactance drop in volts,

$$q_r = 100 \frac{IR}{E} = \text{per cent resistance drop,}$$

$$q_x = 100 \frac{X}{E} = \text{per cent reactance drop.}$$

Then—

1. For unity power factor

$$\text{Per cent regulation} = q_r + \frac{q_x^2}{200}.$$

2. For inductive loads of power-factor m and reactive-factor n.*

$$\text{Per cent regulation} = mq_r + nq_x + \frac{(mq_x - nq_r)^2}{200}.$$

Transformer Connections.

Single-Phase Transformer.

Marking of Leads.—The leads of single-phase transformers should be distinguished from each other by marking the high-voltage leads with the letters A and B, and the low-voltage leads with the letters X and Y. They should be so marked that the potential difference between A and B shall have the same direction at any instant as the potential difference between X and Y.

In accordance with the above rule, the terminals of single-phase transformers shall be marked as follows:

(1) High- and low-voltage windings in phase:

A———B
X———Y

* See page 478.

(2) High- and low-voltage windings 180° apart in phase:

$$\begin{matrix} A \text{———} B \\ Y \text{———} X \end{matrix}$$

To operate transformers thus marked in parallel, it is only necessary to connect similarly marked terminals together (provided that the reactances and resistances of the transformers are such as to permit of parallel operation).

Single-Phase Transformers with More than Two Windings.—Transformers possessing three or more windings (each being provided with separate out-going leads), shall have the leads connected to two of their windings, lettered in accordance with the preceding paragraph. The remaining leads shall be distinguished from the others by a subscript. For example, transformers possessing four secondary leads connected to two distinct similar windings for multiple-series operation, shall be lettered as follows:

$$\begin{matrix} A \text{———} B \\ \left\{\begin{matrix} X \text{———} Y \\ X_1 \text{———} Y_1 \end{matrix}\right\} \end{matrix}$$

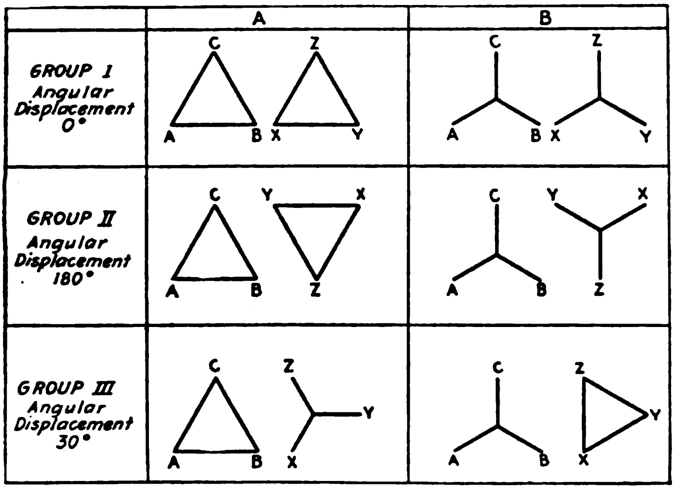
This indicates that the low-voltage winding consists of two disconnected parts, one part having terminals XY and the other part having terminals X_1Y_1. For multiple connection, X and X_1 are connected together and Y and Y_1 are connected together. For series connection, Y is connected to X_1.

Neutral Lead.—An out-going 50 per cent (neutral) tap lead should be lettered N.

Internal Connections.—The manufacturer should furnish a complete diagrammatic sketch of internal connections, and all taps and terminals of the transformer should be marked to correspond with numbers or letters in the sketch.

Three-Phase Transformers.—Three-phase transformers ordinarily have three or four leads for high-voltage, and three or four leads for low-voltage windings. To distinguish the various leads from each other, and also to distinguish between the various phase relations obtainable, the three high-voltage leads should be lettered A, B, C, and the three low-voltage leads X, Y, Z. In addition, it should be distinctly stated in which of the three groups given in the accompanying diagram the transformer belongs.

The rules given above for single-phase transformers in regard to the neutral tap, and also in regard to internal connections, are applicable to three-phase transformers.



Angular Displacement.—The angular displacement between high- and low-voltage windings is the angle in the accompanying diagram, between the lines passing from a neutral point through *A* and *X*, respectively. Thus, in group 1, the angular displacement is zero degrees. In group 2, the angular displacement is 180°, and in group 3 the angular displacement is 30°.

Parallel Operation of Three-Phase Transformers.—Three-phase transformers, lettered in accordance with the above rules, will operate correctly in parallel, if their percentage resistance drops are equal, and their percentage reactance drops, at their rated loads, are equal. It is furthermore necessary that the angular displacements between high-voltage and low-voltage windings shall be equal, *i. e.*, that the transformers shall belong to the same group in the accompanying diagram. It is then only necessary to connect together similarly marked leads.

Transformer Testing for Central Stations.*—The financial success or failure of a lighting or power plant is dependent on the efficiency of the system. In alternating current distribution the transformers are frequently scattered in large numbers throughout the system and their cumulative losses greatly affect the efficiency of the entire system. It is therefore essential to the self-protection of central stations that sufficient tests are made on the transformers to be sure that the guarantees are fulfilled. The following tests can be made without a great outlay for instruments:

Insulation Test. (Fig. 267.)—(1) Between primary and all other parts.

(2) Between secondary and all other parts.

(3) Between turns and sections of the windings.

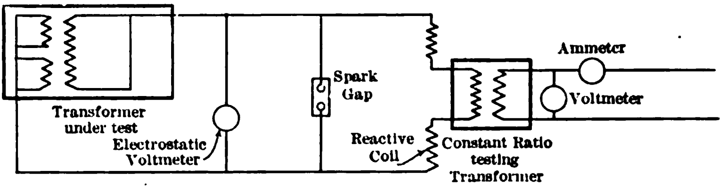


FIG. 267.

The method of connection is shown. In applying the high potential test to one winding the remaining winding should be carefully grounded to the core and frame to avoid statically induced strains. All primary leads should be connected together as well as secondary leads, in order to secure throughout the winding a uniform potential strain during the test.

(1) Set the spark gap for a voltage 10 per cent in excess of that which is to be applied.

(2) By means of the regulator on the low voltage side adjust the testing outfit to deliver minimum voltage.

(3) Connect the apparatus to be tested to the high-voltage side of the testing outfit.

(4) Close low-voltage switch and gradually increase the voltage until the desired potential is indicated on the electrostatic voltmeter.

(5) Reduce the voltage slowly.

* The information given on pages 420-425 was compiled from "Lefax" for Feb., 1913.

If the insulation under test be good there will be no difficulty in bringing the potential up to the desired value, provided the transformer be of sufficient capacity. If, however, the insulation be weak or defective it will be impossible to obtain a high voltage, and an excessive current will be indicated by the ammeter. A break down in insulation will result in a drop in voltage indicated by the electrostatic voltmeter and by an excessive current.

Standard Spark Gap.—

Kilovolts,	5	10	20	30	40	50	60	70	80
Gap Inches,	.2	.5	1.0	1.65	2.50	3.50	4.60	5.85	7.10

Kilovolts,	90	100	110	120	130	140	150
Gap Inches,	8.35	9.50	10.70	11.85	12.98	14.00	15.00

Core Loss. (Fig. 268.)*—(1) Estimate the capacity of the instruments required.

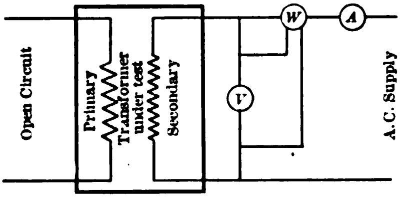


FIG. 268.

(2) Connect the selected instruments as shown to the low potential side of transformer on test, the high potential side being on open circuit. The generator speed should be observed by a tachometer or speed counter in case a frequency meter is not available.

(3) Connect leads from the transformer on test to the leads from the switch board or source of power through a double pole, single-throw switch.

(4) Close the switch and make a preliminary reading of the instruments at approximately the voltage and frequency required.

(5) Adjust the voltage and frequency of the circuit as desired and make simultaneous observations of the wattmeter, voltmeter, ammeter and frequency meter.

(6) Record the results and note the numbers of the instruments used with their corresponding constants.

NOTE.—The generator should carry no other load during the test.

* Fig. 263 is the vector diagram corresponding to the test shown by Fig. 268.

(7) Calculate the losses in the voltmeter and in the pressure coil of the wattmeter and subtract them from the observed reading of the watt meter. The result is the core loss of the transformer.

NOTE.—The losses in the voltmeter and in the pressure coil of the watt meter are equal in each case to $\frac{E^2}{R}$, R being the resistance of the coil in question.

Measurement of Resistance. (Fig. 269.)—This method of finding the resistance of a transformer is simply an application of Ohm's law, that is, $R=\frac{E}{I}$. Direct current is used.

Simultaneous readings should be taken on the voltmeter and ammeter at different values of current. Reduce the value of resistance to standard room temperature of 25° C. using the following equation:

$$\text{Resistance at } 25^\circ \text{ C.} = R\frac{238+25}{238+t} = R\frac{263}{238+t}.$$

R = resistance at t° C.

t = temperature of transformer on test.

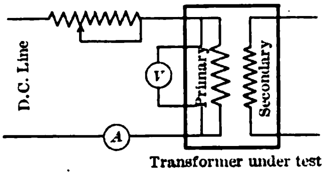


FIG. 269.

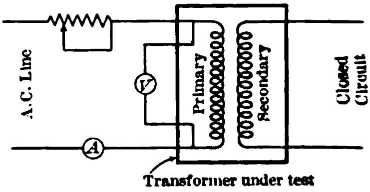


FIG. 270.

Impedance Loss. (Fig. 270.)*—Impedance may be considered as constant at all loads. It is generally measured at full-load current and the impressed voltage is then known as the impedance volts, and, when expressed in per cent of the normal rated voltage of the transformer, as the per cent impedance drop.

(1) Short circuit one of the windings of the transformer, preferably the secondary.

(2) Adjust the voltage to give full-load current in the winding of the transformer; then make simultaneous readings of the voltmeter, ammeter and frequency meter.

* Figure 265 is the vector diagram corresponding to the test shown by Fig. 270.

Record the results and calculate the impedance. In the equation,

$$I = \frac{E}{\sqrt{R^2 + (2\pi nL)^2}},$$

the expression $\sqrt{R^2 + (2\pi nL)^2}$ is the impedance in ohms.

Polarity. (Fig. 271.)—When transformers manufactured by different companies are to be run in parallel, it is necessary to test them in order to avoid the possibility of connecting them in such a way as to short circuit the one on the other.

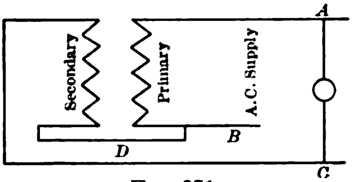


FIG. 271.

In the connections shown the leads are so brought out that the primary and secondary form a continuous winding, uniform in direction when B and D are connected together. Consequently, if with B and D connected a given voltage is impressed from A to B, the result of the voltage from A to C will be more than that impressed at AB, if the leads have been properly brought out, and less than the voltage impressed at AB, if they have not been properly brought out.

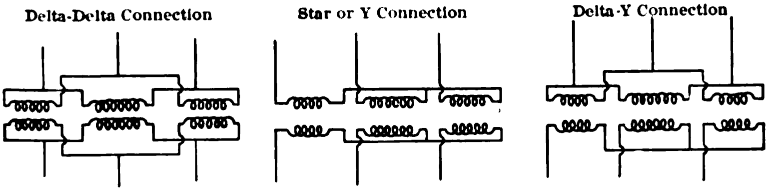


FIG. 272. FIG. 273. FIG. 274.

Transformer Connections.—In Fig. 272, the voltage per transformer is the same as that between the line wires, the current per transformer is equal to the current per line wire divided by $\sqrt{3}$.

In Fig. 273, the current per transformer is the same as that per line wire; the voltage per transformer is equal to the voltage between wires divided $\sqrt{3}$.

In Fig. 276, the voltage impressed across one transformer is only 86.6 per cent of that impressed across the other.

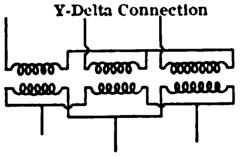


FIG. 275.

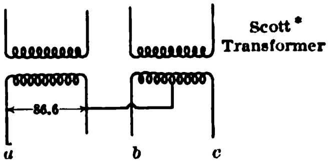


FIG. 276.

Limiting Temperature Rise.—The temperature rise should not exceed 50° C. in electric circuits by resistance and in other parts by thermometer.

Overload Capacity.—Constant potential transformers, 25 per cent for two hours, except in transformers connected to apparatus for which a different overload is guaranteed, in which case the same guarantee shall apply for the transformer as for the apparatus connected thereto.

Standard Ratios.—It is recommended that the standard transformer ratios should be applicable to the following voltages, which are standard: 6600, 11,000, 22,000, 33,000, 44,000, 66,000, 88,000, 110,000.

The ratio will usually be an exact multiple of 5 or 10.

Rules for Installing and Operating Transformers.—Must not be placed in any but metallic or other non-combustible cases. Must be constructed to comply with the following tests:

(1) Shall be run for eight consecutive hours at full load in watts under conditions of service, and at the end of that time the rise in temperature, as measured by the increase of resistance of the primary coil shall not exceed 135° F.

(2) The insulation of transformer when heated shall withstand continuously for five minutes a difference of potential of 10,000 volts (alternating) between primary and secondary coils and core, and between the primary coils and core; also must withstand a no-load run at double voltage for 30 minutes.

* For transforming from three-phase to two-phase, three-phase terminals being *a*, *b*, *c*, below and two-phase terminals being above.

In central or sub-stations the transformers must be so placed that the smoke from the burning out of the coils, or the boiling over of the oil, where oil-filled cases are used, can do no harm.

The neutral point of the transformer or the neutral wire of distributing systems may be grounded and when grounded the following rules must be complied with:

(1) Transformers feeding two-wire systems must be grounded at the center of the secondary coils.

(2) Transformers feeding systems with a neutral wire must have the neutral wire grounded at the transformer and at least every 250 feet beyond.

In general, in order to obtain minimum operating costs, transformers of the present standard performances should be used on a load which will bring them up to the maximum safe temperature rise.

Constant Current Transformers.—The constant current transformer in its simplest type consists of a core of the double magnetic type with three vertical legs and two coils placed around the central leg.* The primary is fixed and the secondary is suspended and balanced by counter weights so that it can move up and down. A flow of current in the coils causes a repulsion between them, causing them to separate to the position for which they are balanced. An increase of current due to cutting out of series lamps, for example, causes them to separate farther, increasing the leakage and thereby cutting down the induction. With any current less than normal the repelling force diminishes, and the primary and secondary coils approach each other, thereby restoring the current to its normal value.

Construction Details.—Some of the construction details mentioned in the preceding pages will now be illustrated by figures.

Consider first the shell type. Fig. 277 shows the coils alone and the coils assembled on the core for a small cylindrically wound shell-type transformer.

Figs. 279, 278 and 280 show the case, a single coil and coils completely assembled on the core for a shell-type transformer, employ-

* See Fig. 261.

ing flat or pancake coils. The corrugations on the case are to increase the radiating surface. The problem of heat dissipation is

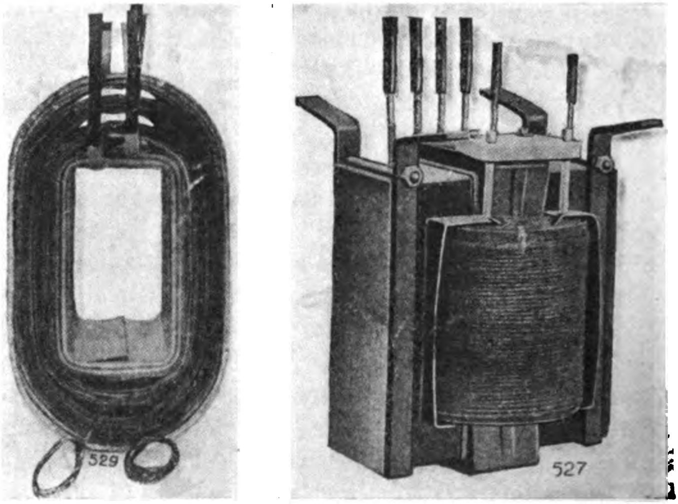


FIG. 277.—Shell-Type Transformer Cylindrical Coils.

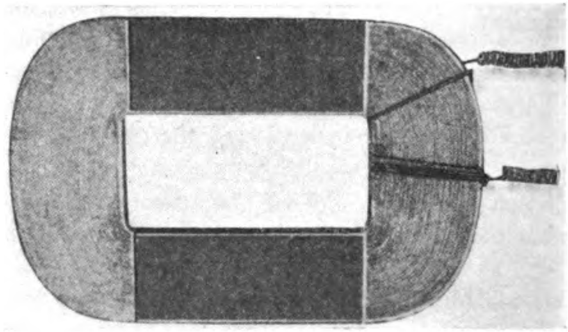


FIG. 278.

always a difficult one in large transformers, since the output and the losses of a transformer increase faster than the surface.

FIG. 279.—Case for 400 K. W. 20,000 Volt Transformer.

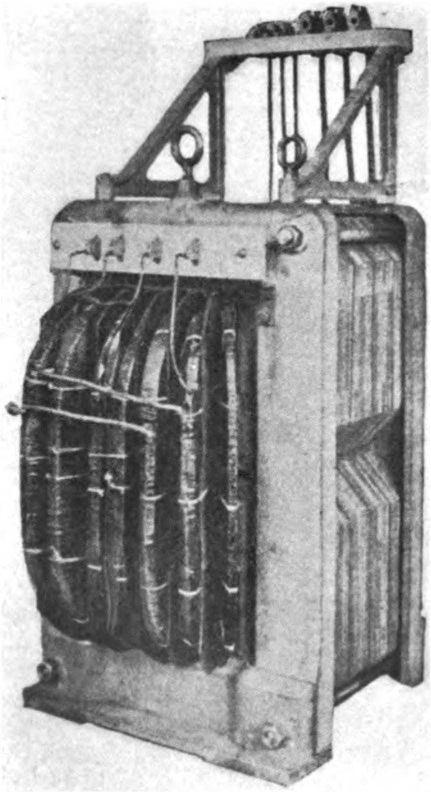


FIG. 280.—375 K. W. 15,000 Volt Transformer.

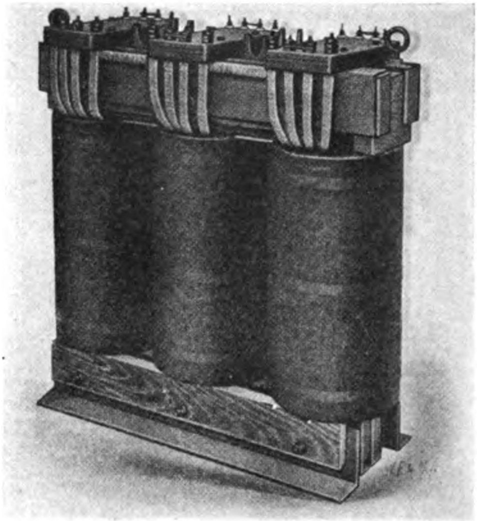


FIG. 281.—Westinghouse 100 K. W. Three-Phase Type C Transformer.

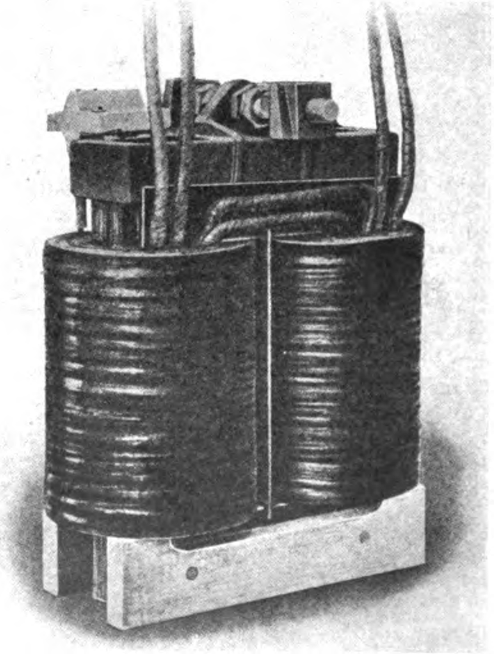


FIG. 282.—Core and Winding of Westinghouse Type C Transformer with Circular Coils Showing Low-Tension Leads.

The second type of transformer commonly in use is the core type. Figs. 282 and 281 show a single-phase and a three-phase transformer of this type.

Fig. 283 shows the cruciform type with case. This is a sort of compromise between a shell and core type and is at present the standard type for small distributing transformers.

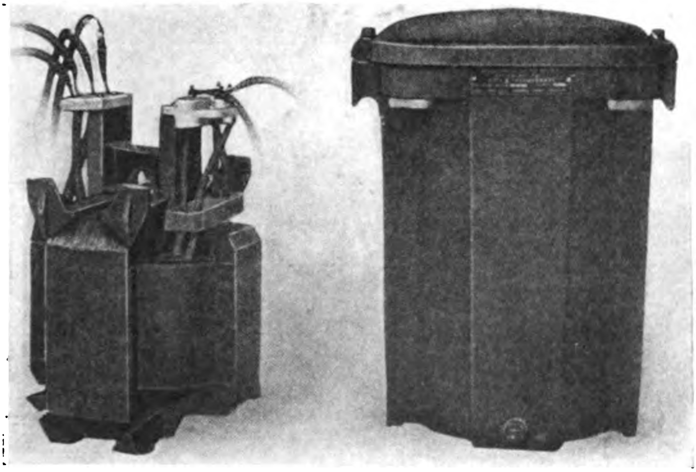


FIG. 283.—Westinghouse Type S Distributing Transformer.

(2) Frequency Changers.—Since various applications require different frequencies, as for example, 25 cycles for power, 60 cycles for lighting, and 500 cycles for radio telegraphy, apparatus for changing the frequency is often needed. The most common device for this purpose is the synchronous motor generator set, consisting of a synchronous motor driving an alternator. The synchronous motor will be explained later, suffice it to state at present that the synchronous motor runs at a speed to produce a back E. M. F. of the same frequency as the source of power. The alternator, driven by this motor, can be arranged with any number of poles to produce the desired frequency. See also pages 472 and 473.

Converters of A. C. into D. C.

(1) The Mercury Arc Rectifier.—The mercury arc rectifier depends for its action on the valve-like action of electrodes immersed in a mercury vapor. Referring to Fig. 284, *A*, *A′* and *B* are the electrodes; of these *A* and *A′* being made of iron or graphite, while *B* is of mercury. Electricity will not flow out of the tube at either *A* or *A′*, nor in at *B*. Thus, by a sort of selective action, *A* and *A′*

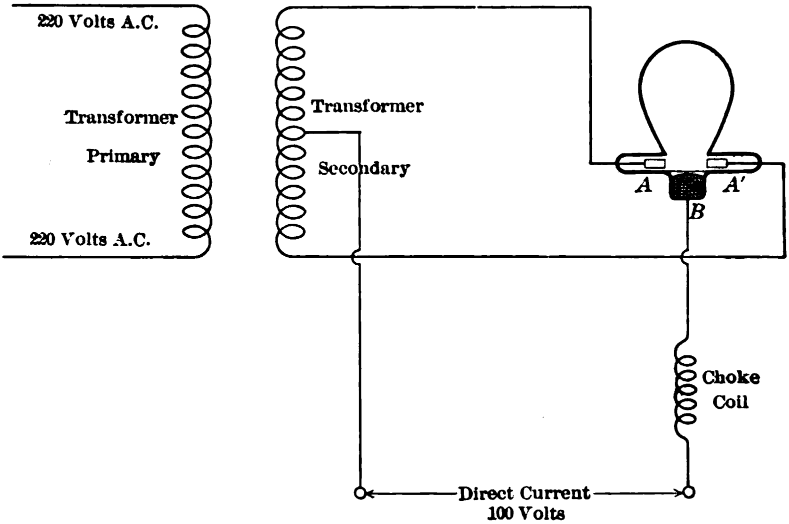


FIG. 284.

select only such current as is willing to flow into the tube. This action takes place only in a vacuum so the electrodes are moulded into a glass bulb, made large to condense the mercury vapor and prevent overheating.

The action of the rectifier is further illustrated by Fig. 285.

The starting of the rectifier is accomplished by tilting the bulb until mercury bridges the gap between *B* and *A* and then bringing the bulb back to the vertical position. This causes a flow of current, followed by an arc at the breaking of the circuit. This arc forms enough mercury vapor to make a conducting gas. In practice it is usual to supply a small starting electrode of mercury close to *B*. The process of starting is then as above explained that of tipping or sometimes by supplying a jump spark between *B* and the starting electrode from a small induction coil.

The arc rectifier finds useful application in charging storage batteries and running arc lights.

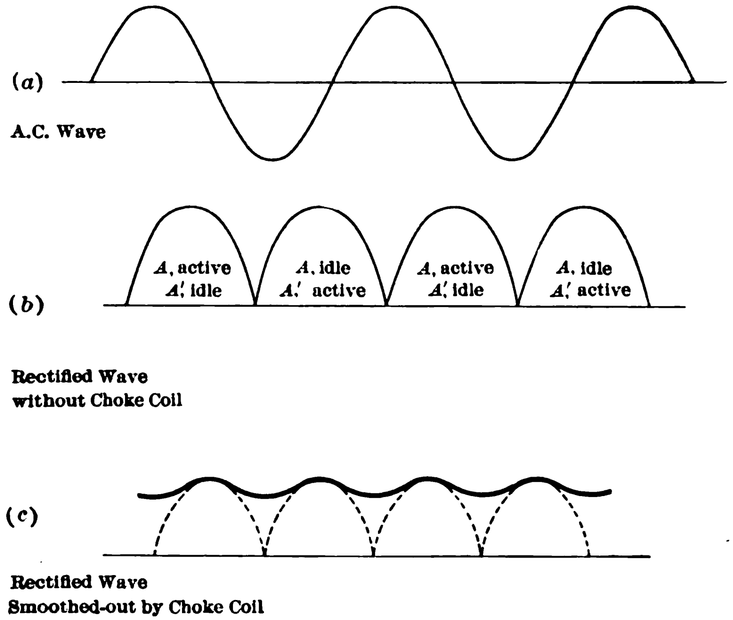


FIG. 285.

The efficiency is about 80 per cent when the D. C. voltage is 115. As there is a drop of 14 volts between *A* and *B* independent of the voltage applied, the efficiency is greater at higher voltage.

(2) The Mechanical Rectifier.—Electricity can be rectified by changing the connections in exact synchronism with the changes of sign of the alternating current. This has been done by driving commutators with synchronous motors or by tuning a vibrating contact to the line frequency. Such apparatus is limited to handling powers below 1 kilowatt and is therefore not of much importance.

(3) The Rotary Converter.—At present most of the conversion from A. C. to D. C. is by means of the rotary converter, a machine which is now in single units handling 7500 kilowatts.

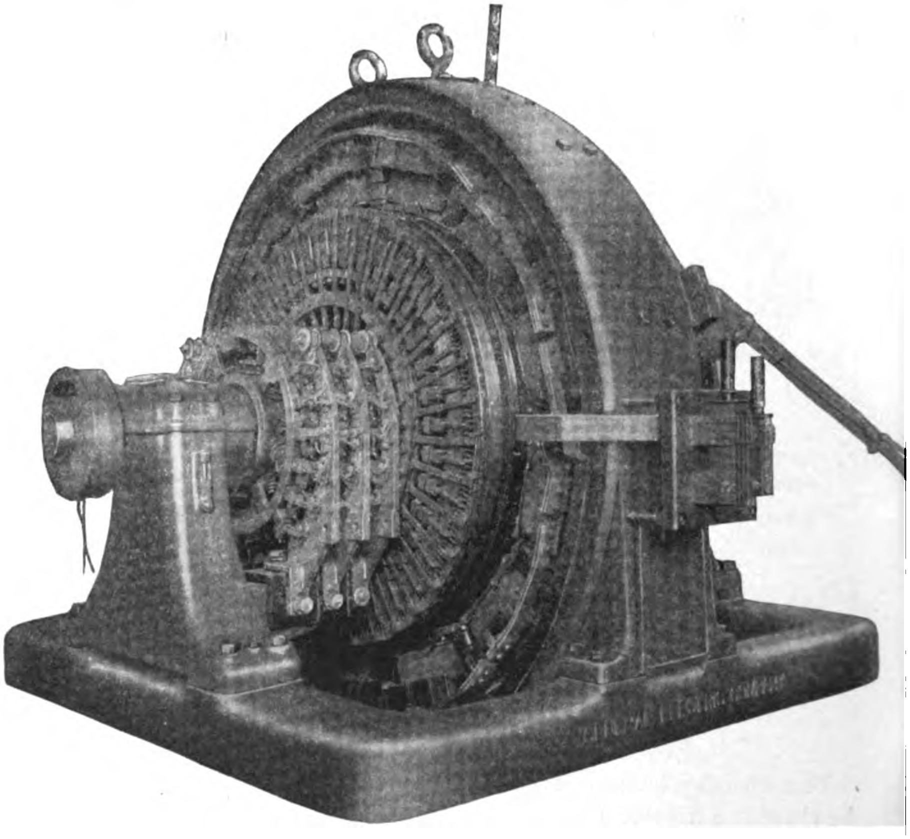


FIG. 286.—Standard 1500 K. W., 600 Volt, 60 Cycle Synchronous Converter.

Structurally, the rotary converter may be said to be a direct current generator with taps brought out from its armature winding to slip rings. Figs. 286 and 287 show such a machine with six slip rings.

Electrically, this machine is from the standpoint of the A. C. end a six-phase synchronous motor and from the standpoint of the D. C. end a direct-current generator, one armature and one field, each doing double duty. Since in the same armature winding both motor and generator currents are flowing simultaneously, there is a partial

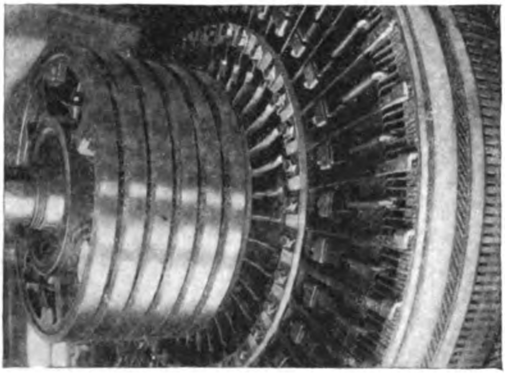


FIG. 287.—Detail of Armature—Collector Ring End.

neutralization of current and consequently less I^2R loss than there would be in either machine alone. This neutralization becomes more complete the larger the number of phases and so six-phase converters are widely used. Such facts as have to do with the synchronous motor side of this machine will be treated under the synchronous motor.

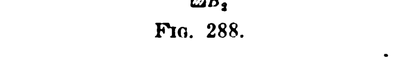


FIG. 288.

chronous motor side of this machine will be treated under the synchronous motor. A few special features, having to do with the voltage ratio, are taken up here. In Fig. 288 is shown a two-pole machine with a gramme-ring armature winding. R_1 and R_2 represent the slip rings to which is applied a single-phase alternating

E. M. F. B_1 and B_2 represent the two brushes on the commutator as in the ordinary two-pole D. C. generator. Once in every revolution of the armature the alternating E. M. F. will be applied directly to the brushes B_1 and B_2. This instant is the one shown in the above figure and is also the instant when the armature winding is inducing its maximum E. M. F. Therefore at this instant the brush E. M. F. or D. C. E. M. F. is equal to the maximum A. C. E. M. F., or the D. C. E. M. F. is equal to $\sqrt{2}$ times the R. M. S. single-phase E. M. F. By similar reasoning the following table is derived:

Direct-current voltage	100
Single-phase voltage (2 rings)........	70.71
Three-phase voltage (3 rings).........	61.24
Quarter-phase voltage (4 rings).......	50.00
Six-phase voltage (6 rings)...........	35.50

Since the D. C. voltage is to a large extent independent of the field excitation, affecting it only in so far as it can raise the impressed A. C. voltage by taking a leading current (see Synchronous Motors), field regulation can give but little voltage regulation. Voltage regulation is obtained by other methods, among which are variation of impressed A. C. E. M. F., use of split-pole converters, and use of booster converters.

Since converters do not operate efficiently single-phase, polyphase operation is universal. In Fig. 289 are shown means of obtaining the various polyphase connections between transformers and converters.

(4) The motor generator, which consists of either an induction motor or synchronous motor direct connected to an alternator needs no explanation. Its only advantage over the rotary converter is its wide range of voltage regulation. In all other respects, cost, efficiency, floor space, etc., the rotary converter has the advantage.

(5) Some of the above devices can be employed for converting D. C. to A. C. and in that instance are referred to as inverted converters.

(C) MOTORS.

For the utilization of A. C. power a large variety of A. C. motors have been developed, (1) series motors, (2) synchronous motors, (3) induction motors, and (4) miscellaneous motors.

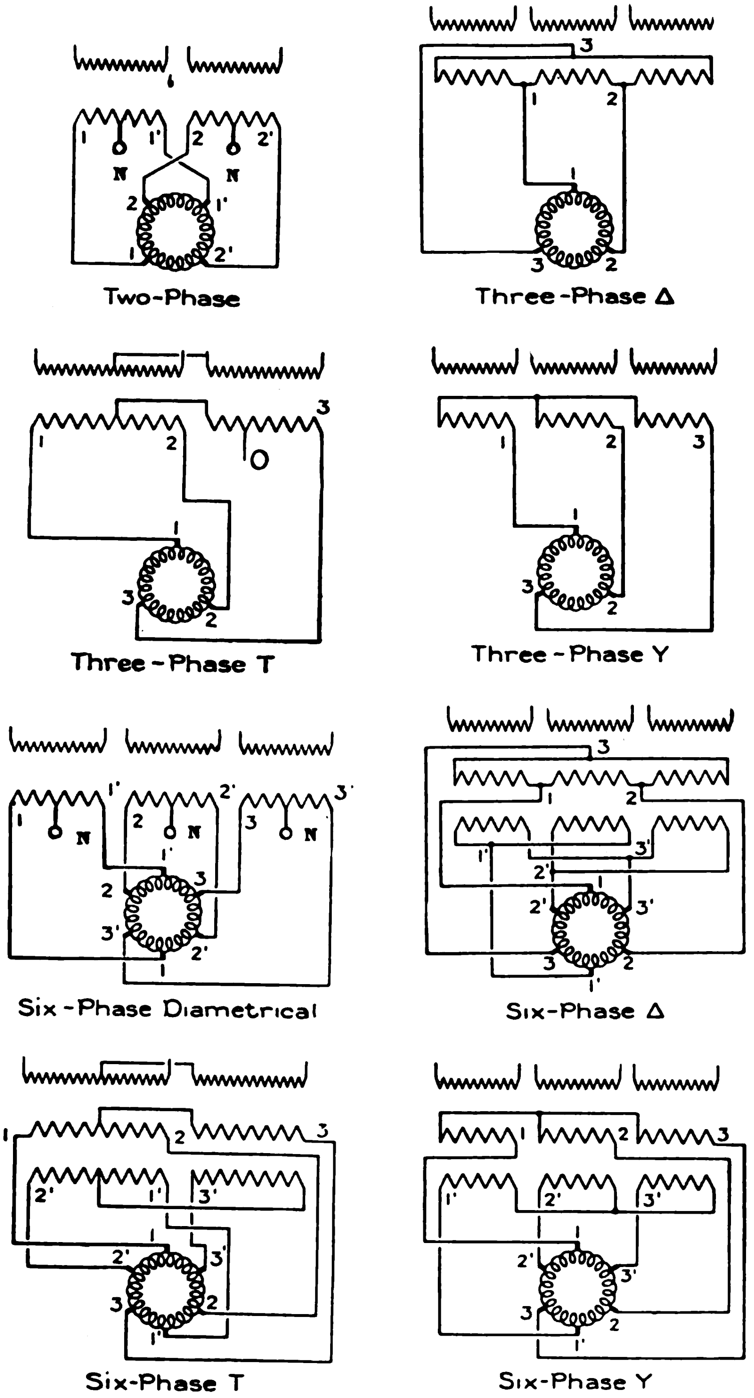


Fig. 289.—Methods of Connecting Transformers to Synchronous Converters.

(1) Series Motors.—This motor is like, in many ways, the direct-current series motor. The most important difference is that to get a reasonably high power factor the armature field strength must be from 2.0 to 1.0 times the field strength, while in the direct-current motor the field is always from 1 to 1.5 times the armature strength.

Another difference lies in the fact that the A. C. motor does not commutate as well as the D. C. motor. Of two motors of the same horse-power and speed ratings, one being D. C. and the other A. C., the A. C. motor would be found to be heavier. They could also be distinguished from one another in that the A. C. motor must have a laminated field structure. In operating characteristics the series A. C. motor is similar to the D. C. motor, both producing speed-torque curves, resembling rectangular hyperbolas. This motor is used in railway work and in small motors, serving well for the A. C.-D. C. fan motors.

(2) The Synchronous Motor.—The synchronous motor is of importance not so much of itself, but in so far as it enters into the theory of rotary converters, the theory of the operation of alternators in parallel, and in that its power factor may be varied over a wide range from lag to lead.

Synchronous motors have the same construction as alternators.

The operation is as follows: If the field of a synchronous motor be excited with a continuous current and the armature while stationary be supplied with an alternating current, this latter current will react upon the field in one direction during one-half of a cycle and in the opposite direction during the other half, these alternations of torque producing no motion but just a violent vibration. But if, by some external means the armature be rotated at synchronous speed, and if then the current in a given part of the armature is positive under a north pole, it will be negative under a south pole, so that there will be a unidirectional torque and a continuation of the rotation after the external power is removed. If the external driving power be retained it can be made to pump power through the running motor back into the alternating current system to which the armature is connected. In this case parallel operation of alternators is illustrated; in the other case synchronous motor operation is illustrated.

If two identical machines are considered, each one having two poles, then the vector diagram of Fig. 290 will have the following meaning:

E_S is the voltage of one machine, which will be called the source-machine. E_R is the voltage of the second machine which will be called the receiver-machine. The difference between E_S and E_R is made up by IZ drop in the whole circuit. The angle, ϕ, will represent the actual mechanical angle by which one machine lags behind the other. Suppose the receiver-machine were a motor, and more power were demanded of it, this demand would be met by an increase in the angle ϕ. If ϕ were increased so that E_R swung over into the quadrant $M'U$, the motor would fall out of step. If on the

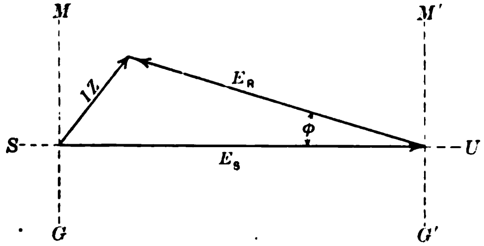


FIG. 290.

other hand instead of a demand for power being made on the receiver-machine, power were pumped into the receiver-machine from another mechanical source, ϕ would decrease to zero and soon E_R would swing down into the quadrant SG' and correspond to generator operation. Thus, below the line SU we have generator operation, above the line motor operation. To the right of $M'G'$ the operation is unstable. This figure brings out another point. Increasing the field excitation of the receiver-machine lengthens out E_R swinging IZ in a counter-clockwise direction. Expressed in another way, when IZ is in the quadrant MU the motor is taking a lagging current and when in the quadrant MS a leading current. Since by over-excitation of the field a synchronous motor can thus be made to take a leading current, such machines are often referred to as synchronous condensers.

If the angle ϕ has a tendency to increase and decrease and not take up a steady value, a condition exists which is called *hunting*. This hunting like any oscillation may, with certain circuit and machine constants, become so amplified as to throw E_R over into the $M'U$ quadrant or in other words throw the machine out of step.

Synchronous motors have to be started by means not inherent in the motor. For this purpose a small induction motor is sometimes built on the same shaft with the main motor. Instead of applying this induction principle to a small motor on the shaft end, it is common now to include the induction motor principle in the motor itself by placing a short-circuited squirrel-cage winding in the pole faces of the rotor of synchronous motors.* Often the iron poles themselves

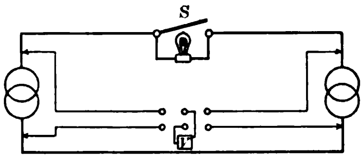


FIG. 291.

serve this purpose. This induction motor principle serves to bring the rotor up to within one per cent of synchronous speed, the residue of speed being obtained by a different motor action due to the salient poles. The field is left open while starting in this way and closed when the motor is up to speed.

Before finally closing synchronous motor apparatus on the A. C. supply circuit, exact synchronism must be made certain of. This is done by synchronizing lamps or by synchronism indicators. Fig. 291 illustrates the use of the synchronizing lamp.

The two machines are first brought to the same voltage as indicated by V. Then the speed of the incoming machine is varied until the lamp stops flickering and goes out, at which instant the switch, S, may be closed.

(3) **The Induction Motor.**—The induction motor involves a new conception. The following paper by Mr. B. G. Lamme is a simple and clear exposition of the polyphase induction motor:

* See pages 462 and 463.

The Polyphase Motor.*

General.—The polyphase motor is usually treated from the theoretical standpoint, and the results obtained are of interest mainly to designers and investigators. Such treatment has been principally of a mathematical nature, the object being to show how the various characteristics of the motor may be predetermined. This is what the designer requires, but it gives very little information to the practical man that uses the motor. In the following treatment of the subject, the general operation of the motor will be explained in a non-mathematical way by the use of diagrams which illustrate its characteristics under different conditions. Only the non-synchronous type of motors will be considered, and no distinction will be made between two- and three-phase motors; for, if properly designed, they are practically alike in operation.

It is necessary to understand the characteristics of the polyphase motor in order to consider properly its application to the different classes of work to be met with in practice. These characteristics can be presented in the most intelligible manner by means of curves, which represent the relations between the speed, torque or turning effort, horse-power expended and developed, amperes, etc. The speed-torque curve, which represents the speed in terms of the torque, is the most important one, as upon the characteristics denoted by this speed curve depend the adaptability of the motor to the various kinds of work. The starting conditions also depend upon the speed torque characteristics. Other curves of importance in practice are those showing the relations of current, efficiency, and power factor with torque. As these are dependent, to some extent, upon the speed-torque curve, this will be considered first, but before treating of its characteristics a short description of the motor itself will be given.

Construction and Winding.—The polyphase motor, like a direct-current motor, consists primarily of two parts, one stationary and

* An address presented by B. G. Lamme, Chief Engineer Westinghouse Electric & Manufacturing Company, at the twentieth convention of the National Electric Light Association, Niagara Falls, June 10, 1897, with supplement.

the other rotating, each of which carries windings. The inside bore, or face, of the **stationary** part is generally slotted, and carries windings that resemble those of the **rotating part**, or armature, of an ordinary direct-current motor without a commutator. The rotating part is also slotted on its outside face, and there are windings in the slots. Both cores, or bodies, are built up of thin iron or steel plates. The general arrangement is shown in Fig. 292. One of these windings, generally that on the stationary part, receives current from a two- or three-phase supply circuit. The coils of this winding, although distributed symmetrically over the entire face of the core,

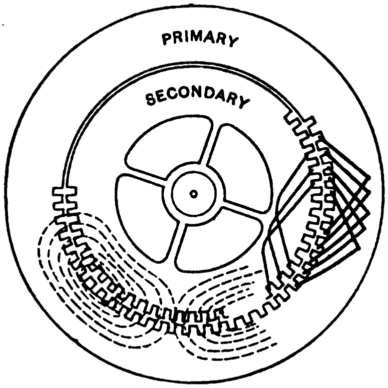


FIG. 292.—Arrangement of Windings of the Polyphase Motor and the Magnetic Fields Which are Produced.

are really connected to form distinct groups which overlap each other. These windings form the two or three circuits in the motor. When alternating electromotive forces are applied to these circuits, currents will flow which set up magnetic fields in the motor. These alternating fields in turn generate electromotive forces in the windings. The larger part of the current flowing in the windings represents energy expended usefully, some is expended in heating, and the remainder serves merely as magnetizing current. The magnetizing current, like that of a direct-current machine, is dependent upon the dimensions of the magnetic circuit and upon the magnetic density in the various parts. Even when the motor is running with no load, the magnetizing current is required.

The second part of the motor, generally the rotating part, receives no current from the supply circuit. The magnetic fields set up by the first set of windings pass through the second windings, and, under certain conditions, generate electromotive forces in them. If the second windings are arranged to form closed circuits, currents will flow in them. These currents are entirely separate from those of the supply circuits.

Speed and Slip.—When running at no load the motor has a maximum speed that is approximately equal to the alternations of the supply circuit divided by the number of motor poles in each circuit.

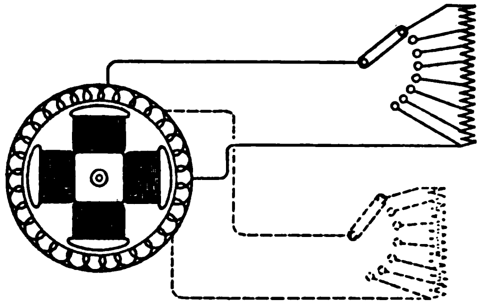


FIG. 293.—Diagram of Two-Phase Alternating-Current Generator Rotating Field Type.

As the load on the motor is increased the speed falls off almost in proportion to the load. The drop in speed is sometimes called the "slip," and is usually expressed in per cent of the maximum speed. If, for instance, a motor has a maximum speed of 1000 revolutions and drops 50 revolutions below this at full load, it has then a slip of 5 per cent.

Torque and Armature Current.—With this type of motor, a drop in speed is necessary for developing torque. A fairly simple illustration of this action may be obtained by considering the operation of an alternating-current generator under certain conditions. We will take a type of alternator having a stationary armature and a rotatable direct-current field magnet, which can be driven at various speeds, the arrangement being as shown in Fig. 293. Leads are carried out from the armature to adjustable resistances. To avoid complexity, the armature circuits and the resistances are considered as non-inductive.

When the field is rotated at a certain speed with the field coils charged, there is an alternating electromotive force set up in the armature winding. When the armature circuit is closed through a resistance, current flows and the armature develops power slightly less than the power expended on the field shaft, which is proportional to the product of the speed and the turning or driving effort, or torque, on the shaft. Consequently, at a given speed, a driving effort is required at the field shaft corresponding to the power developed by the armature; if the armature current is increased or decreased the power developed is increased or decreased also, and the driving effort varies in proportion.

If the field is rotated at half the speed, the armature electromotive force becomes one-half what it was before. Reducing the resistance in the armature circuit also to one-half, the current will remain unchanged. The power developed by the armature is now one-half and the speed of the field is one-half, consequently, the driving effort, or torque, is the same as before. Reducing the speed further, and decreasing the resistance in the armature circuit in proportion to keep the armature current constant, the driving effort on the field remains constant. Finally, if the speed is reduced so much that the external armature resistance is all cut out and the armature is short circuited on itself with the same current as before, the same driving effort is still required.

The field is now rotating very slowly, and the alternations in the armature are very low, being just sufficient to generate the electromotive force required to drive the armature current against the resistance of the windings. Any further reduction in speed diminishes the armature electromotive force, and hence the armature current and the driving effort also fall in proportion. An increase in speed increases the armature current and thus increases the driving effort required.

If only one armature circuit is closed, the driving effort and the power developed pulsate as the armature current varies from zero to a maximum value; but if the armature has two or more circuits having different phase relations, it develops power continuously and the driving effort is then continuous.

Illustration of "Slip."—The armature has been considered as stationary and developing power while a certain driving effort was applied to the field. According to the well-known law that any force is met by an opposing force, the armature must have a certain resisting effort. The armature really tends to rotate with the field, and the resisting effort is exerted to prevent this.

Assume the armature to be arranged for rotation, but held stationary by a brake adjusted for a torque equal to the resisting effort of the armature. Speed up the field, and the armature will speed up also, keeping a certain number of revolutions behind the field. This difference in speed is required for generating the electromotive force necessary for sending the current through the armature. The alternations in the armature must remain constant for a given armature current, independent of the speed at which the armature is running.

If the brake is tightened, the armature must drive more current through its windings to develop the required effort, the armature alternations must hence increase, and the armature will therefore lag behind its field more than before; in other words the slip is increased. If the brake is loosened, the armature runs nearer the speed of the field. If the field is driven at a constant speed and the brake released, the armature runs at practically the same speed as the field.

If the winding consists of but one closed circuit, the torque developed by the armature varies periodically, and that developed by the brake must vary also, but to a less extent, as it is steadied by the inertia of the rotating armature. But with two or more circuits having different phase relations, arranged for constant power developed in the armature windings, the torque developed is also constant at all times. Consequently, for constant torque at the brake, there should be two or more phases in the armature windings.

Difference Between Illustration and Actual Case.—This explanation of the development of the torque in the short-circuited armature is merely an attempt to illustrate certain of the actions in the polyphase motor armature by a comparison with the operations of other apparatus that is, in general, much better understood. We cannot infer from the above illustration, that an alternating-current generator would run as a motor under the assumed conditions, for, in the above operations, mechanical power is supplied to the field shaft, and mechanical power is delivered by the rotating armature to the brake. There is no true electromotor action; that is, there is no transformation of electrical power supplied to mechanical power developed.

The action of the short-circuited armature of the above generator and that of the polyphase motor is very similar in regard to drop in speed for developing torque. But in the polyphase motor, instead of the mechanically rotated field magnet, there is a stationary core provided with two or more windings which carry currents having different phase relation. These windings are placed progressively around the core, either overlapping or on separate poles. When the currents flow in the windings, resultant magnetic poles or fields are formed, which are progressively shifting around the axis of the motor. The closed or short-circuited armature, rotating in this field, develops torque by dropping in speed in the same way that it developed torque with mechanically rotated field magnets. But electrical power, instead of mechanical, is supplied to produce the rotating field, and the conversion from electrical power supplied to the field windings to mechanical power developed by the armature shaft is a transformer action which does not appear in the above illustration.

Rotating Magnetic Field Electrically Produced.—Fig. 294 shows diagrammatically a progressively shifting field, with two overlapping windings arranged for two-phase currents. Coils 1-1, etc., form one circuit, while coils 2-2, etc., form the other. Starting with the instant when the current in 1 is at its maximum value, the magnetizing force of this set of coils must be at its maximum. The current and magnetizing force of circuit 2 are at zero value. Four poles or magnetic fields, alternating *n-s-n-s* around the core, are formed directly over coils 1. As the current in circuit 1 begins to decrease, that in 2 rises, giving the combined magnetizing forces of the two overlapping windings. These two magnetizing forces act together at some points and are opposed at others, making the resultant magnetic field shift to one side of the former position. As the current in circuit 1 gradually falls to zero and that in circuits 2 rises to its maximum value the magnetic field shifts around until it is directly over coils 2. If the current in circuit 1 should next increase in the same direction as before, while that in circuit 2 dimin-

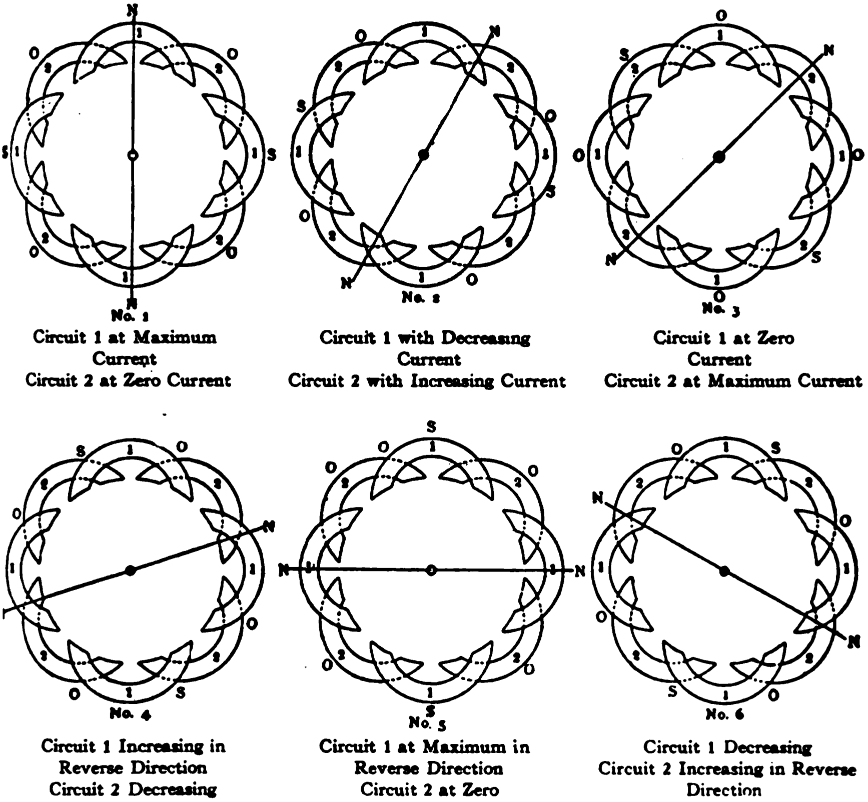


FIG. 294.—Diagram Showing Production of Rotating Magnetic Field by Two-Phase Currents.

ished, the magnetic poles would shift back again to their former position. But after reaching zero value, the current in circuit 1 rises in the opposite direction, while that in 2 falls. This shifts the resultant poles forward instead of backward, and they gradually shift ahead until they are again directly over coils 1. But the *n* poles now occupy the former position of the *s* poles. Thus, with the current in circuit 1 passing from a maximum in one direction to a maximum in the opposite, the poles have shifted forward the width of one polar space. Current in circuit 2 next arises in a reversed direction and the poles shift forward until, when the current in 2 is a maximum, they are over coils 2.

The diagrams, Nos. 1, 2, 3, etc., show the positions of the shifting field under certain conditions of current in the two circuits. In No. 2 the position shown is an arbitrary one, for it depends upon the relative values of the currents in the two circuits. With the two currents equal, the position of the line *N-N* would be half-way between coils 1 and 2.

These diagrams show that the magnetic field due to two-phase currents in properly arranged windings shifts progressively around the axis, just as if the field were rotated mechanically.

Speed-Torque Curve.—In polyphase motors, the part resembling the field in the above description and receiving the current from the line is usually called the primary, on account of its electrical resemblance to the primary of a transformer. The equivalent of the armature in the preceding description is called the secondary. If the alternations of the supply circuit are constant, the reversals of the current in the field, or primary, will occur at a uniform rate and the magnetic field will shift around its center at a definite speed, depending on the rate of alternation of the supply circuit and the number of poles in each circuit of the motor. If the armature, or secondary, rotates at the same speed as the field shifts, there will be no reversals or alternations in its magnetism, and there will be no currents and, consequently, no torque. If a load is thrown on, the speed will drop, and the resultant alternations in the secondary will generate electromotive forces which will drive currents through the windings, and thus develop torque. The speed will continue to fall and the secondary electromotive forces will continue to increase until a torque sufficient for the load is developed. As the load on the motor is increased the speed falls and the torque increases until zero speed is reached, giving an ideal speed-torque curve of the form shown in Fig. 295, curve *A*. But the shape of this curve is modified to a great extent in actual motors by certain effects which cannot be entirely eliminated.

Primary Resistance Reduces Magnetization at Heavy Loads.—In the case of the revolving field, the magnetization was supposed to remain constant under different conditions. But in the motor primary, the magnetism of the primary is not constant under all conditions and it does not all pass through the secondary circuits. The primary windings necessarily have some resistance, and a certain electromotive force is required to drive the primary current through this resistance. With a constant applied electromotive force, the primary counter-electromotive force will diminish as the drop in primary resistance increases, and the magnetic field will diminish also. Consequently, to develop the required secondary electromotive force for driving the secondary current through the windings, the speed must drop more than shown by curve *A*. Instead of being a straight line, the speed-torque curve s somewhat curved, as shown by curve *B*.

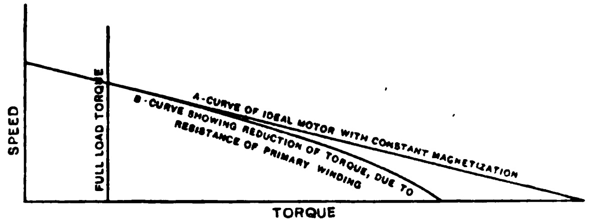


FIG. 295.—Speed-Torque Curve of Polyphase Motor.

Magnetic Leakage Limits Maximum Torque.—The effect of magnetic leakage on the speed-torque curve is even greater than that of the primary resistance. The primary and secondary currents, and their consequent magnetizing forces, are opposed to each other. The result is that part of the primary magnetism threads across between the primary and secondary windings without passing into the secondary. Thus the electromotive force of the secondary is reduced, or, for a required secondary electromotive force, the secondary alternations must be increased. This means a further drop in speed.

The secondary currents also tend to form local magnetic fields around their own coils. These local fields are alternating and set up electromotive forces in the secondary circuits. In consequence, the electromotive forces generated by the magnetism from the primary have to drive currents, not only against the resistance of the secondary windings, but also against these local electromotive forces. This necessitates a further drop in speed for the required torque. These local electromotive forces depend upon the secondary alternations and, therefore, vary with the drop in speed, and are greatest at zero speed. This introduces a very complicated condition in the secondary circuits. These magnetic fields which thread around only the primary or secondary windings are variously called the magnetic leakages, the stray fields, or the magnetic dispersion.

If the magnetic leakage is relatively large, that is, 20 to 25 per cent, of the total induction, and the secondary resistance is low, the

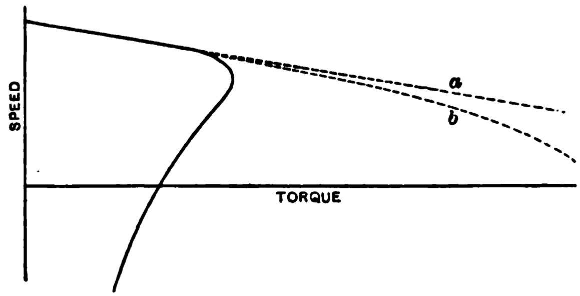


FIG. 296.—Speed-Torque Curve of Polyphase Motor, Showing Effect of Magnetic Leakage.

speed-torque curve will have the peculiar shape shown in Fig. 296. This curve shows the torque increasing as the speed falls, until a certain maximum is reached. Beyond this point the torque, instead of following the ideal curve *a* or the curve *b* which shows effect of primary resistance only, diminishes with further drop in speed. If the motor is loaded to the maximum torque, a slight increase in load causes a further drop in speed, the torque diminishes and the motor stops. As a consequence, the normal rating of the motor must be considerably below this "pulling-out point." The margin necessary depends upon the nature of the load to be carried.

The starting torque, speed regulation, etc., of the polyphase motor depends on the form of the speed-torque curves. The different methods of varying the form of these curves will be considered next.

Effect of Secondary Resistance on Speed Curve.—As the secondary electromotive force is that necessary to drive the secondary currents through the windings, it follows that the electromotive force required must depend on the resistance of these windings. A larger resistance means a larger electromotive force for the required current, and, therefore, a greater number of secondary alternations, or a greater slip. The torque being held constant, any variation of the secondary resistance requires a proportionate variation in the slip; if the slip with a given torque is 10 per cent, for instance, it will be 20 per cent with double the secondary resistance, or 50 per cent with five times the resistance. This is true only with the primary conditions of constant applied electromotive force and constant alternations. The secondary resistance may be in the windings themselves, or it may be external to the windings but part of the secondary body, or it may be entirely separate from the machine and connected to the windings by the proper leads.

Fig. 297 shows the speed-torque curves for a motor with different resistances in the secondary circuit. In curve *a* the secondary resistance is small. In curve *b* the secondary resistance is doubled. The maximum torque remains the same, but the slip for any given torque is doubled; the starting torque is much better than that in curve *a*. In curve *c* the resistance is again doubled and the slip is also doubled. The starting torque is increased, but the slip is rather large at the rated torque *T*. In curve *d* the slip is again doubled. In this case the torque is high at start and falls rapidly as the speed increases. In curve *e* the maximum torque is not yet reached at zero speed. Continuing these curves below the zero-speed line, that is, running the motor in the reverse direction, we get the general form of these different speed-torque curves. They are all of the same general shape, and all have the same maximum torque.

So far as torque is concerned, curve *d* is the best for starting. But for running, curve *a* gives the least drop in speed. Consequently, if a resistance is introduced at start that will give the speed-torque curve *d*, it should be cut out or short circuited for the running condition. This is one method of operation that has been much used.

Current Curve.—In determining the best starting condition, the current supplied to the primary must be considered in connection with the speed-torque curves. This current is plotted with the series of speed-torque curves shown in Fig. 297. Referring to this figure, curve A represents the primary amperes in terms of torque. Start-

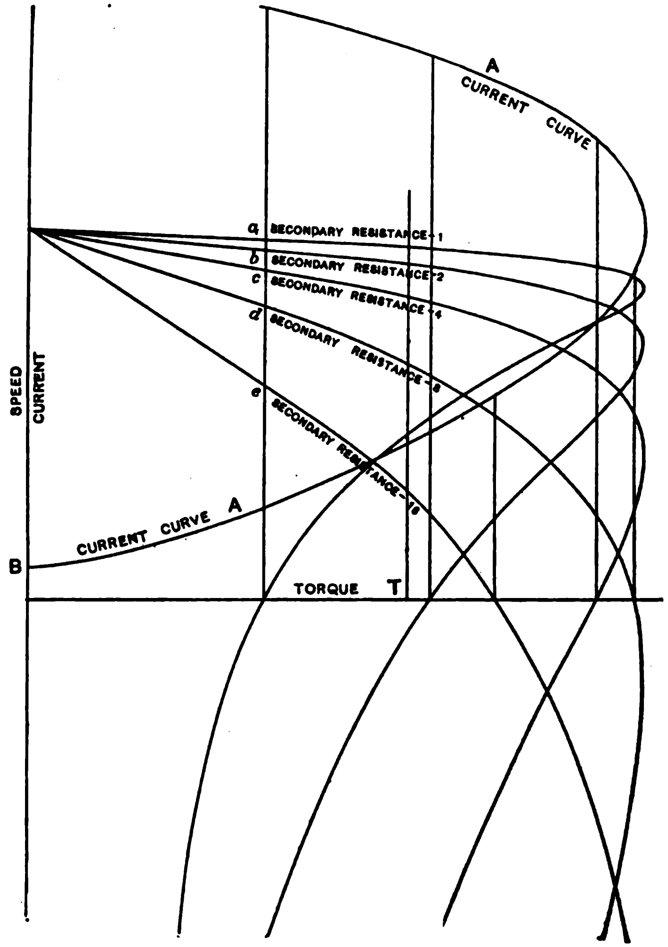


FIG. 297.—Speed-Torque and Current-Torque Curves of Polyphase Motor With Different Secondary Resistances.

ing at the point B of no load, or zero, torque, it rises at a nearly uniform rate until maximum torque is approached; that is, below the point of maximum torque the current is nearly proportional to the torque, but beyond this point the current continues to increase and reaches a maximum at the torque represented by zero speed. At reversed speed this current is further increased. This one current curve holds true for all the speed-torque curves *a, b, c, d,* etc.

Comparing the different curves, we see that *a* takes the most current at start, and gives low torque; *b* takes less current than *a,* and

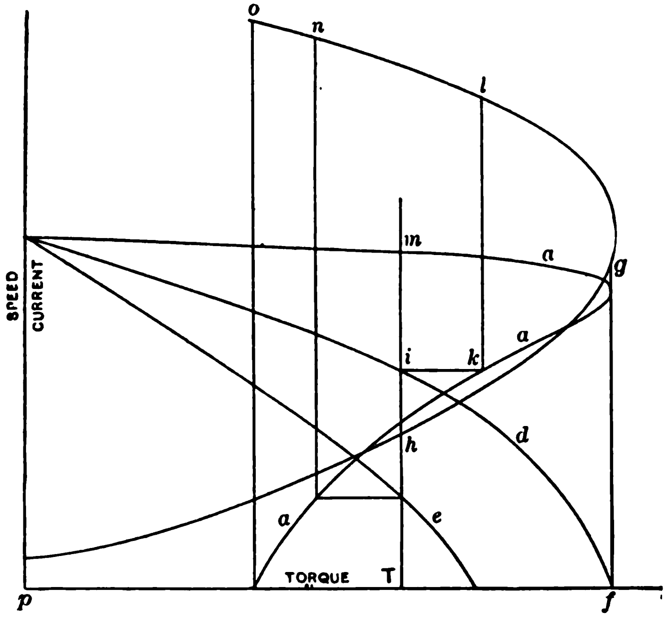


Fig. 298.—Starting Conditions with Variable Secondary Resistance.

gives more torque; *c* takes less current than *b; d* takes less current than *c* and gives the maximum torque at start; *e* takes less current than *d,* and develops less torque; but the current and torque are very nearly in proportion over the whole range. From this we see that a speed-torque curve of the form of *d* or *e* is decidedly better for starting than *a* or *b.* But for running at less than the maximum torque there is no advantage, so far as current is concerned, in curve *d* over curve *a,* and the speed regulation of *d* is poor.

Starting with Variable Secondary Resistance.—Fig. 298 represents the conditions of speed, current, etc., when a variable secondary resistance is used in starting. The motor starts with torque indicated by *f* on curve *d,* and takes current *g.* The current falls to *h,* while the speed rises to *i,* which corresponds to the normal torque *T* at which the motor will run under the given conditions as long as it operates on curve *d,* the speed meanwhile remaining at *i.* If the resistance in the secondary is now short circuited, and the load thus shifted to the speed-torque curve *a,* the torque at the speed *i,* in-

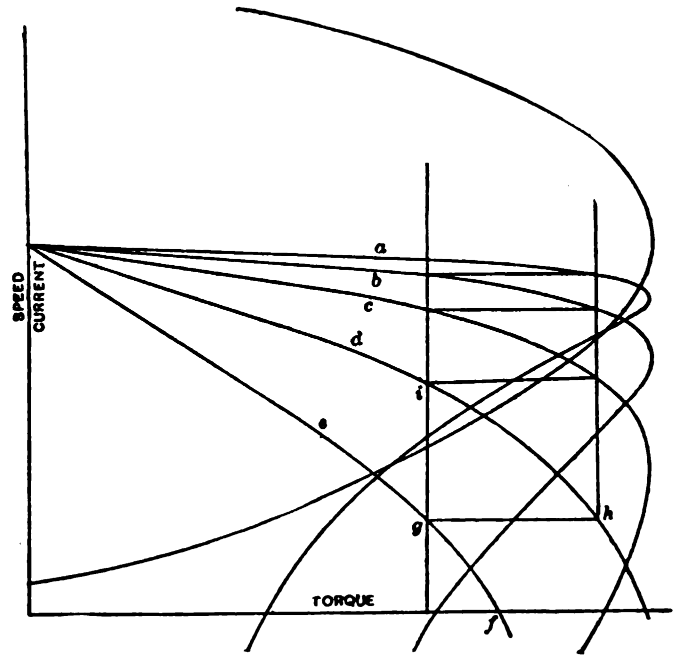


FIG. 299.—**Starting Conditions with Five Secondary Resistance Steps.**

creases to *k* on the torque curve *a.* The current corresponding to this is *l.* As the torque at *k* is greater than the normal torque *T,* the motor speed will increase until normal torque is reached again at *m,* while the current falls from *l* to *h.*

At the moment of cutting out the secondary resistance there was a very considerable increase in the current. By arranging the starting resistance in the secondary so that the motor will start at some curve intermediate between *a* and *d* and thus take more current at start, somewhat less would be required upon switching to curve *a*. If curve *e* is used for starting, and if the torque required when speeding up is greater than that at the point where curves *a* and *e* cross each other, the motor will not pull up because in switching from *e* to *a*, the torque falls, and the motor will stop. The current on switching over increases to *n*, and then rises to *o* as the motor stops. In this case the resistance that gives curve *e* is too great, and a lower starting resistance is required.

By making several steps of the secondary resistance, so that it can be cut out gradually, the motor can be made to pass through a series

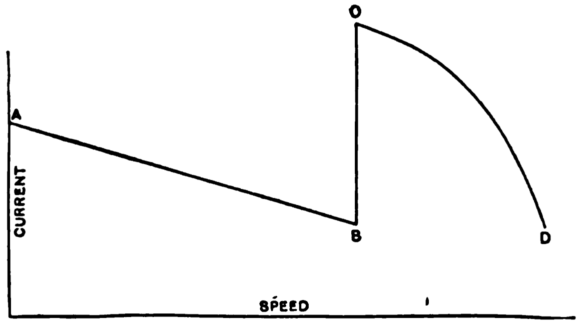


FIG. 300.—Current-Speed Curve for Motor Starting as in Fig. 298.

of speed-torque curves with much smaller variations of current than shown in the preceding diagram.

Fig. 299 shows the condition for starting and speeding up with five speed-torque curves. The motor starts on curve *e* at *f*, and the speed rises to *g*. The motor is then switched to curve *d*, the torque rising to *h* and the speed to *i*. In this way the motor passes successively from *d* to *c*, *b* and *a*, until the full speed is reached. The currents at no time reach very high values.

By plotting the currents in terms of speed, the use of a large number of steps is shown to better advantage. This is shown in Figs. 300 and 301. Fig. 300 shows the same starting conditions as Fig. 298 with curves *d* and *a*. The current starts at *A* and falls to *B*. The resistance is then short circuited and the current rises to *C* and then falls to *D*, which is the same as *B*. If *A* had been higher at start, *C* would have been lowered slightly. But as the time required for passing from *A* to *B* is generally greater than that from *C* to *D*, *C* may be higher than *A*. If the motor is not required to develop such a large torque when pulling up, then *C* can be lowered while *A* is left unchanged.

In Fig. 301, the currents in terms of speed are shown for five steps with the five speed-torque curves of Fig. 299. The starting current *A* is low, and none of the currents, when switching from one curve to another, is large. The dotted lines show the corresponding currents for two steps, as in Fig. 300.

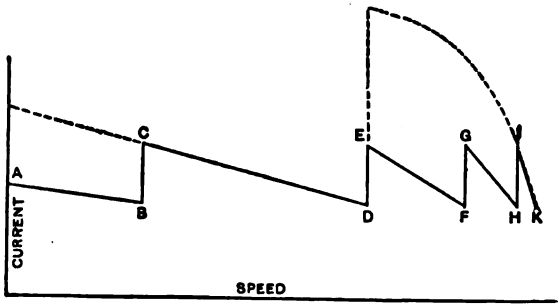


FIG. 301.—Current-Speed Curve for Motor Starting as in Fig. 299. Dotted Lines Show Same Curve as Fig. 300.

Motors for Varying Speed Work.—For varying speed work, such as cranes, elevators, etc., the series of curves in Fig. 297 show one method of regulating the speed. By varying the secondary resistance over a wide range, any speed from zero to maximum can be obtained with any torque up to the maximum. This requires the use of collector rings and adjustable rheostats. The variations in speed are obtained by wasting energy in resistance. For a given torque the same power is expended on the motor whether the speed is zero or maximum. To obtain a given torque at start requires as much power as when running at full speed.

An analysis of the motor shows another way in which the speed-torque curves can be varied. In Fig. 297 all the curves show a certain maximum torque which is the same in all cases; but this is with the condition of constant primary electromotive force. By varying the electromotive force applied to the primary we can obtain a quite different series of curves. By taking, for example, a speed-torque curve of the form *a* in Fig. 302, and applying a higher electromotive force to the primary, a curve is obtained of the same shape as *a*, but with a much higher point of maximum torque. On lowering the applied electromotive force, the maximum torque is lowered. The torques at any given speed are raised or lowered in the same proportion as the maxima are varied. At any given speed the torques are proportional to the square of the electromotive forces applied. This relation holds good for any form of the torque curve, whether of the shape *a, d,* or *e,* shown in Fig. 297.

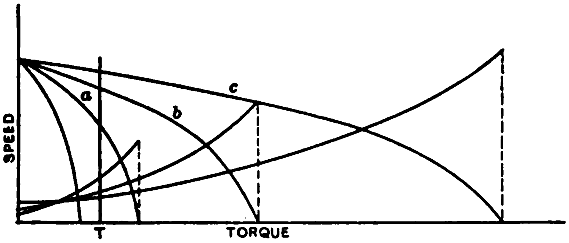


FIG. 302.—Speed-Torque and Current-Torque Curves for Polyphase Motor With Different Voltages Applied.

The current curves are also shown in Fig. 302. They all have the same general shape, but have different maximum values, these being proportional to the electromotive forces applied. The speed-torque curve *a* in Fig. 302 has the same shape as *d* in Fig. 297, which gave too great a drop in speed. In Fig. 302, curve *b,* which is the same form as *a,* gives less speed drop for the same torque. Curve *c* gives less than *b,* and has fairly good speed regulation from no load up to normal torque *T*. But this result is obtained at the expense of increased induction in the iron, and large no-load or magnetizing current due to the higher electromotive force, is required. If it is possible to obtain a speed-torque curve like *c* in Fig. 302 with the normal electromotive force applied, we can obtain good speed regulation from no-load up to the rated torque, and shall be able to start the motor with the maximum torque it can develop. Then, by lowering the applied electromotive force, the same form of speed-torque curve will be retained, but the starting torque and starting current can be lowered to any extent desired.

Varying Speed by Varying Voltage.—Returning to Fig. 296, it was stated that the peculiar shape of this curve, with the torque falling rapidly after reaching a maximum value, was due mainly to magnetic leakage between the primary and secondary windings. But if the motor is so proportioned that the leakage is very small compared with the useful field, the speed-torque curve takes a quite different shape. The maximum torque is increased directly as the magnetic leakage is diminished. This is shown in Fig. 303. Here

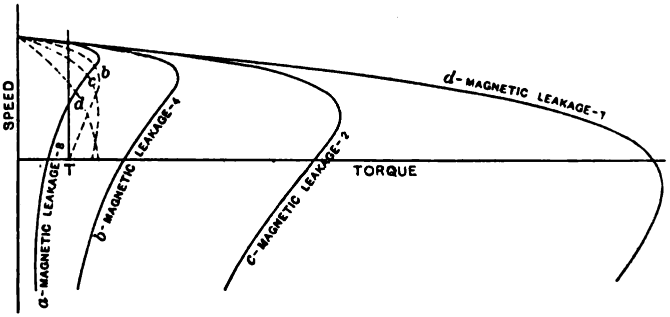


Fig. 303.—Speed-Torque Curves of Polyphase Motor Showing Effect of Magnetic Leakage. Dotted Lines Show Curves *b*, *c*, *d*, With Reduced Voltage.

a is similar in shape to curve *a* in Fig. 297; *b* represents the speed-torque curve with the magnetic leakage reduced one-half; *c* represents it with about one-half the leakage of *b*, and *d* with one-half that of *c*.

In comparing Figs. 297 and 303, it may be noted that *a* in one is the same form as *a* in the other, although drawn to a different scale. In Fig. 303, *b* has the same shape as in Fig. 297, but has a different maximum value. The same is true of curves *c* and *d* in the two figures. By lowering the applied electromotive forces for curves *d*, *c* and *b* of Fig. 303, so that the maximum torques are equal to that of *a*, as shown by the dotted curves, we get practically the same curves as in Fig. 297.

Curve *d* in Fig. 303 gives as good running conditions as curve *a* in Fig. 297, having about the same drop in speed at the normal torque *T*. We have, then, in *d* a curve which starts at the point of the maximum torque, and which also has a small drop in speed at the normal load. The objection to this curve is that the starting current and starting torque, although in the proper proportion to each other, are both much greater than is necessary or desirable. By reducing the applied electromotive force at start, however, lower torques and currents are obtainable. In this way we may combine good starting and running conditions in one motor without the use of starting resistances, and with a secondary that has no resistance except that of its

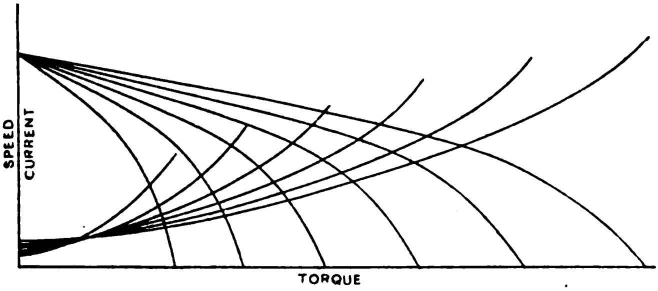


FIG. 304.—Speed-Torque and Current-Torque Curves for Polyphase Motor With Electromotive Force Varied Over a Wide Range.

own windings. Fig. 304 shows the speed-torque and current curves of such a motor with the applied electromotive force varied over a considerable range.

If only one electromotive force is desired for starting and accelerating, and the motor is then to be transferred to the working electromotive force, the speed-torque curves should preferably have the shape shown in Fig. 305. The motor starts with the desired torque at reduced E. M. F., and comes up to almost rated speed before switching over. This is suitable for constant speed work. In Fig. 305 are shown both the starting and running speed-torque curves, and the starting currents both in the motor and the line. The line current is smaller than the motor current in the ratio of reduction of electromotive force in the regulating transformers.

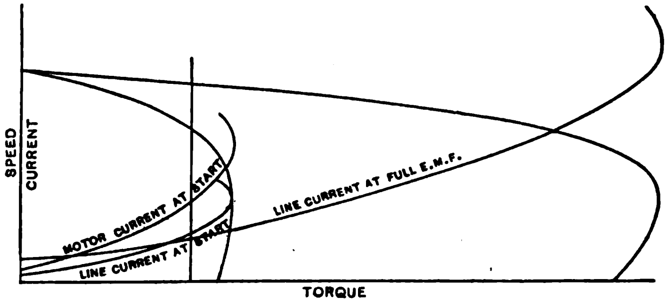


FIG. 305.—Best Shape of Speed-Torque Curve for Motor Started and Speeded up With a Single Reduced Voltage Before Being Transferred to Working Voltage.

Speed-Torque Curves for Varying Speed Work.—For cranes, elevators, and varying speed work in general, curves of the form shown in Fig. 306 are preferable. The line currents are also shown in this figure. This series of speed-torque curves shows that a wide range of speed can be obtained by proper variations of the applied electromotive force. The line currents *A, B,* etc., practically overlap each other. This means that the line current required with this method of control is very nearly constant for any given torque, independent of the speed. The same is true of the method of control by varying the secondary resistance. It may be noted that the current for starting, as on curve *C,* for instance, is slightly greater than that required for running at the same torque on *B* or *A*. This is due to the speed-

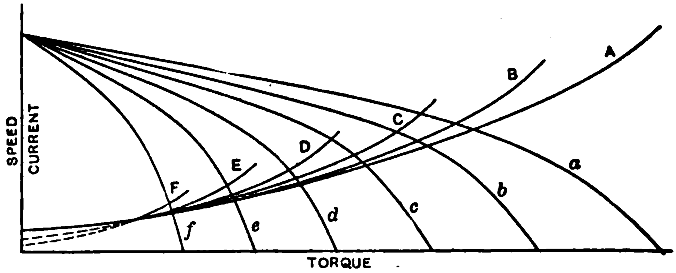


FIG. 306.—Speed-Torque and Current-Torque Curves of Motor for Cranes, Elevators and Similar Variable Speed Work with Voltage Control. Curves *a, b, c, d, e, f* are Speed-Torque Curves with Variable Voltage. Curves *A, B, C, D, E, F* Show Corresponding Line Currents.

torque curve being somewhat curved at its outer end. With a somewhat higher resistance of the secondary the curves are more nearly straight, but the drop in speed is somewhat increased on the speed torque for any given electromotive force. In practice, a compromise is made between the best possible starting condition and a condition of less speed drop.

A comparison of the methods of control by varying the secondary resistance and by varying the applied electromotive force shows that they give practically the same results in regard to starting, speed regulation, etc. But a motor that has been designed for regulation by varying its secondary resistance, will generally give very poor results when an attempt is made to operate it by the variable electromotive force method. A motor must be especially proportioned for small magnetic leakage when this latter method of control is to be used. The proportions and the arrangement of the parts are such as may class this as a practically distinct type of motor.

Efficiency and Power Factor.—We come now to the other characteristics of the polyphase motor, the most important of which are the efficiency and the power factor. The importance of efficiency is generally appreciated, but the question of power factor in most cases appears to be not thoroughly understood or else is entirely overlooked.

The efficiency of a polyphase motor is the ratio of the power developed to the true power expended, as in any other kind of a machine. The power developed may be obtained from the speed-torque curves. If the torques are given for one foot radius, and the speed in revolutions per minute, then the product of any given torque by the corresponding speed, divided by 5250, will give the power developed in horse-power; or torque multiplied by speed, divided by seven, gives the power developed in watts. This power, plus the iron, copper and friction losses, gives the true power expended.

The power factor is the ratio of the true power to the apparent power expended. This apparent power is proportional to the products of the primary currents by the electromotive forces. If there is magnetizing current, and if the motor has magnetic leakage, the primary currents are not in phase with their electromotive forces and their products represent an apparent power which is greater than the true energy expended. The current of each circuit can be considered as made up of two currents, one of which is in phase with the applied electromotive force, representing true energy, and the other at right angles to the electromotive force, representing no energy. This right-angled component is the one that has an injurious effect on the regulation of the generator, transmission lines, transformers, etc.

The size of this component, compared with the useful current, may be shown by a table:

Power Factor	Total Current	Useful Component	90° Component
100	100	100	0.
99	100	99	14.2
98	100	98	19.9
95	100	95	31.2
90	100	90	43.6
80	100	80	60.0
70	100	70	71.4
60	100	60	80.0
50	100	50	86.6
40	100	40	91.6

Effects of Lagging Current.—At 90 per cent power factor, for instance, the current that is lagging 90° behind the electromotive force is equal to 43.6 per cent of the total current flowing. This lagging current reacts on the generator, affecting the regulation.* In an alternating-current generator, a 90° lagging current in the armature coils directly opposes the field magnetization. When delivering a current at 90 per cent power factor there is over 43 per cent of this current opposing the field, and at 80 per cent power factor 60 per cent is opposing the field. If the armature ampere-turns are normally 20 per cent as great as the field ampere-turns, then a load of 80 per cent power factor will give an opposing magnetization in the armature of about 60 per cent of the total armature ampere-turns, or about 12 per cent of the total field, and the armature electromotive force will be lowered approximately that per cent more than with a load of 100 per cent power factor.

The inductive effects of the lagging current in the transmission circuits and transformers are much more serious than those from a

* See pages 406 and 407.

current that is in phase with the electromotive force. The generator, transformers, lines, and motors also have increased losses, due to the large current required when the power factor is low. An 80 per cent power factor in a system means losses due to heating of conductors more than 50 per cent greater than those with 100 per cent power factor. These figures indicate the importance of good power factors in an alternating-current system.

Magnetizing Current and Magnetic Leakage Determine Power Factor.—The lagging, or 90° component, of the current in a motor depends on the amount of the no-load, or magnetizing, current and on the magnetic leakage. Let this lagging component be expressed in per cent of the total current. Also express the magnetizing current in per cent of the total current, and the total magnetic leakage in per cent of the total primary induction. Then the sum of the per cents of magnetizing current and magnetic leakage represents very closely the per cent of the lagging component of the primary current. If, for example, the magnetizing current is 30 per cent and the leakage is 14 per cent, the resulting lagging component is about 44 per cent. From the preceding table, this indicates about 90 per cent power factor. A low leakage and a high-magnetizing current may give the same power factor at full load as a high-leakage and low-magnetizing current; but at half load, the per cent magnetizing current is practically doubled, while the per cent magnetic leakage is halved. Hence, a low-magnetizing current is of great importance in maintaining a high-power factor. If a high value of power factor over a wide range is desired, then both the leakage and magnetizing current must be low.

Voltage Control versus Rheostatic Control.—The method of control by varying the primary electromotive force is dependent on the fact that the motor has low-magnetic leakage. By using certain proportions and arrangements of the windings on the primary and secondary, the magnetizing current can be made comparatively low. Thus both conditions for good power factor are obtained.

With the method of control by varying the secondary resistance, good power factors can be obtained. But the form of secondary winding required when variable resistances are used tends to reduce both the power factor and the maximum torque.

Best Form of Secondary Winding.—An elaborate series of tests was made to determine the best type of winding for the secondary of a polyphase motor. First, two circuits were arranged to give secondary phases 90° apart. The starting, running, and maximum load conditions were determined. Then a three-phase secondary winding was used. This gave a higher pulling-out torque and better power factor than the two-phase. Four phases were tried and were better than three; and six were better than four. Then 12 phases were tried, with a gain over six in maximum torque, but not much gain in efficiency. The power factor was somewhat improved. Finally the winding was completely short circuited on itself, all coils being connected to a common ring. This gave a further increase in maximum torque and power factor over the preceding arrangement, but there was very little gain in efficiency. The same primary was used in all these tests. Each time the number of secondary circuits was increased the power factor was somewhat improved. This was due to the fact that the secondary currents were able to so distribute themselves that the local electromotive forces in the coils, due to leakage, were diminished; or, the magnetic leakage may be considered to have been diminished. This would necessarily give higher pulling-out torques and higher power factors.

Best Form of Primary Windings.—Very complete tests were also made to determine the best form of primary winding, and a certain method of distribution of the coils was found to diminish the primary magnetic leakage very considerably. This somewhat increased the maximum torque and the power factor. Utilizing the arrangements of the primary and the secondary windings just described, and otherwise proportioning for small magnetic leakage, a motor can be obtained that has a comparatively low total induction, and yet has a magnetic leakage of only a few per cent. The low induction allows a small magnetizing current and comparatively low iron losses. The low leakage gives a high pulling-out torque, and thus allows a good speed regulation, and also good starting conditions, by varying the applied electromotive force.

Squirrel-Cage Induction Motors.—Motors adapted for starting by adjusting the applied electromotive forces and for operation with constant secondary resistance must have the special forms of speed-torque curves shown in Figs. 303 to 306, and they may therefore be considered as forming a distinct type, always characterized by low-magnetic leakage and consequent high pulling-out torque. The secondary has no adjustable resistance and all regulation is obtained by varying the electromotive force. The secondary is made the rotating part, on account of the type of winding used, which consists of copper bars placed in tunnels or slots in the core and bolted to two end rings, giving the general form of the wheel of a squirrel cage. There are no bands, and the question of insulation is of very little importance for the maximum secondary electromotive force does not exceed three volts in a 500-horse-power motor and is less with smaller sizes.

Advantages of Squirrel-Cage Motors.—This type of motor possesses several distinct advantages over other forms of polyphase motors. The method of control by varying the electromotive forces applied to the motor, leads to two very important advantages, one of which is mechanical and the other electrical. With this method of control there are no regulating appliances on the motor, which, in consequence, can be of the simplest possible form. The electrical advantage is that the motor can be started and stopped from a distance. Thus it can be placed entirely out of reach of the operator. In elevator service, for example, this is of special importance; squirrel-cage motors in the smaller sizes with high resistance secondaries can be used for elevator operation with no controlling device other than a reversing switch. This switch can be placed near the motor and operated from the elevator cage by means of a rope.

A further advantage lies in the high pulling-out torque. If a heavy overload or a load having great inertia, is suddenly thrown on a motor that has a speed-torque curve like *a* in Fig. 297, the point of maximum torque may be passed for an instant, and the motor will be stopped unless the load is quickly removed. A squirrel-cage motor of proper design would have its speed pulled down for a moment, but this reduction in speed gives an increased torque, thus enabling the motor to carry the overload.

If the electromotive force of the system is lowered, the pulling-out torque of the motors is lowered very materially. A reduction of 20 per cent in the electromotive force will lower the pulling-out torque to about two-thirds of its former value. Even with a temporary drop in the electromotive force, such as would be caused by a momentary short circuit on the lines, this may be sufficient to stop the motor. But a motor that has a pulling-out point several times as large as its normal running torque is very rarely in danger of being shut down from this cause. This type of motor usually has a starting torque larger than the full-load running torque and is thus able to start almost any load within its rated capacity. In practice the starting torque is adjusted to the load to be started by applying a suitable electromotive force.

A very important advantage of the squirrel-cage type of motor is its adaptability for large sizes. The larger the motor of this type, the lower in proportion can be its magnetic leakage and its magnetizing current. In consequence, the power factors are very high. The efficiencies are also very good over a wide range of load. The curves for a 75-horse-power, 6-pole, 3000 alternation motor are given in Fig. 307; also the curves for a 400-horse-power, 2300-volt, 8-pole, 3000 alternation motor in Fig. 308. The power factors of these motors are good examples of what can be obtained on large motors of this type.

Supplement.

The foregoing article is very nearly the same when first published, the only considerable change being the elimination of all reference to type C motors. The descriptive matter formerly applying to type C motors has been retained under the heading "Squirrel-Cage Motors." A few additional explanations regarding some characteristics of polyphase induction motors and methods of speed control may be useful.

Torque.—By full-load torque is meant the turning moment required to develop full-rated output at normal rated speed. The torque T of any motor at any output expressed in pounds at one foot radius (sometimes called pound-feet), can be found by means of the formula $T = \frac{5250 \times \text{H. P.}}{\text{R. P. M.}}$.

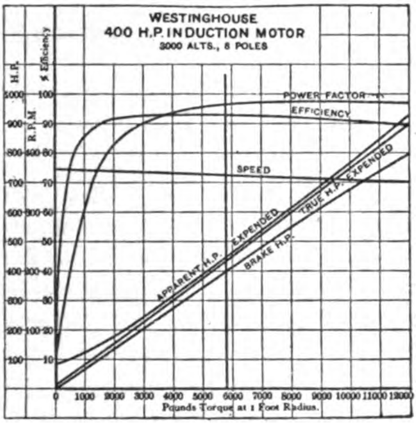


FIG. 307.—**Performance Curve of 75 H. P. Westinghouse Induction Motor.**

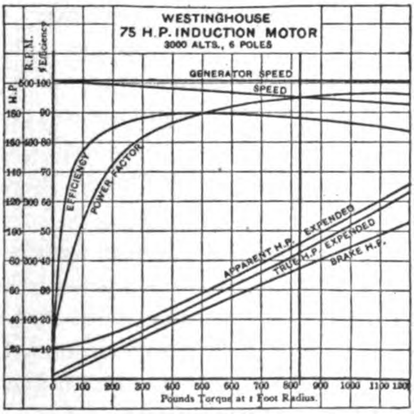


FIG. 308.—**Performance Curves of 400 H. P. Westinghouse Induction Motor.**

Conversely, if the torque in pounds at one foot radius is known the horse-power at any given speed can be determined from the formula $H.P. = \frac{T \times R.P.M.}{5250}$.

The starting torque of an induction motor varies as the square of the voltage applied to the primary; hence, the primary voltage required to produce a given starting torque can be determined by means of the formula

$$V' = V\sqrt{\frac{T'}{T}}$$

where V' and T' signify required voltage and torque, respectively, V the full-rated voltage, and T the starting torque at full voltage. For example: if a squirrel-cage induction motor is required to start with full-load torque only, and if the starting torque at full voltage is 2.5 times full-load torque, the starting voltage should be

$$V' = V\sqrt{\frac{1}{2.5}} = .63V.$$

That is, the starting voltage should be 63 per cent of full voltage.

The maximum starting torque of Westinghouse polyphase induction motors with full primary voltage is in every instance greater than full-load torque, running in some cases as high as three to four times full-load torque. The pull-out torque, or maximum running torque, of phase-wound induction motors is the same as the maximum starting torque; the pull-out torque of squirrel-cage induction motors exceeds the maximum starting torque, in some cases, by as much as 100 per cent.

Starting Current.—Phase-wound motors, when started by means of rheostats in the secondary circuits, can usually be accelerated to full speed with full-load torque with current very little in excess of full-load current. The starting current of squirrel-cage induction motors depends on the starting voltage applied and is independent of the torque required to start the load; the current falls almost immediately, however, to the value corresponding to the required torque and then decreases more gradually as the motor speed accelerates. From this it follows that the starting voltage should be not greatly in excess of that required for the torque.

Changes of Voltage and Frequency.—Some variations from normal voltage and frequency are generally permissible with any induction motor, but such variations are always accompanied by changes from normal performance. With either the voltage or the frequency differing from normal the following performance changes must be expected:

	Power Factor	Torque	Slip
Voltage high	Decreased	Increased	Decreased
Voltage low	Increased	Decreased	Increased
Frequency high	Increased	Decreased	% slip unchanged
Frequency low	Decreased	Increased	% slip unchanged

Usually a variation of either voltage or frequency not exceeding 10 per cent is permissible, and within this limit the efficiency remains approximately unchanged. The voltage and frequency should not be varied simultaneously in opposite directions, that is, one decreased and the other increased. If an induction motor must operate on frequency other than standard, the performance will be better if the voltage is changed in proportion to the square root of the frequency. Thus a 400-volt, 60-cycle motor operating on $66\frac{2}{3}$ cycles will have very nearly its normal operating characteristics if the voltage is raised to $400\times\sqrt{\frac{66\frac{2}{3}}{60}}=442$. Decreasing the voltage much below normal is seldom permissible on account of resulting increased temperature rises.

Loss of Efficiency at Reduced Speeds.—When an induction motor is operated at reduced speeds by increasing the slip, as by increasing the secondary resistance or decreasing the primary voltage, the efficiency is lowered by an amount nearly proportional to the speed reduction, as expressed by the formula

$$E_2=E_1\left(\frac{100-S_2}{100-S_1}\right),$$

in which E_1 is the efficiency of the motor when running at a given torque and a slip S_1; and E_2 is the efficiency when the motor is developing the same torque but with a different slip S_2, efficiencies and slips being expressed in per cent. Thus, suppose a given 60-cycle, 8-pole motor with a synchronous speed of 900 R. P. M. has a normal full-load speed of 855 R. P. M. (slip 5 per cent) and an efficiency of 90 per cent, the efficiency at 810 R. P. M. (slip 10 per cent) with full-load torque will be

$$E_2=90\left(\frac{100-10}{100-5}\right)=90\times\frac{99}{95}=85.2 \text{ per cent.}$$

Speed Control of Polyphase Motors.

The speed of polyphase motors can be controlled by a number of different methods, of which the following are the most important:

I. Adjusting the resistance of the secondary circuit.
II. Adjusting the primary voltage.
III. Using two motor primaries, one of which is capable of being rotated.
IV. Changing the number of motor poles.
V. Operating two or more motors connected in cascade.
VI. Adjusting the frequency of the primary current.
VII. Changing the number of phases of the secondary windings.

The results obtained by the use of these various methods differ widely, so that in selecting a variable speed alternating-current motor careful consideration must be given to the characteristics of the method of control in order to determine its suitability for the service. In many cases a combination of methods is required in order to produce the desired speed changes.

I. Adjusting the Resistance of the Secondary Circuit.—The characteristics of the method of speed control by adjusting the resistance of the secondary circuit are fully discussed on the preceding pages. With constant torque, the speed of the motor increases regularly as each step of the resistor is short circuited and remains constant on any given notch. But with varying torque the motor speed varies also; that is, an alternating-current motor when operating with auxiliary resistance in the rotor circuit is properly classified as a **varying speed motor.** This method of speed control is, therefore, not suitable for service requiring several constant speeds with varying torque, such as machine tool work, etc.

Speed control by means of adjustable secondary resistance is, however, very useful where constant speeds are not essential, for example, in operating cranes, hoists, elevators, and dredges, and also for service in which the torque remains constant at each speed, as in driving fans, blowers, and centrifugal pumps. In service where reduced speeds are required only occasionally and where small speed variation is not objectionable, this method of control can also be used to good advantage. On account of energy loss in the resistors, the efficiency is reduced when operating at reduced speeds, this reduction being greatest at the slowest speeds, as shown in the formula above.

II. Adjusting the Primary Voltage.—As shown elsewhere adjusting the primary voltage of a motor causes speed changes that are similar to those produced by adjusting the resistance of the motor secondary. The voltage variations can be obtained by means of adjustable resistors, auto-transformers, or choke coils in series with the primary.

This method has the disadvantages of poor speed regulation, low efficiency, and unsatisfactory control, especially when the primary

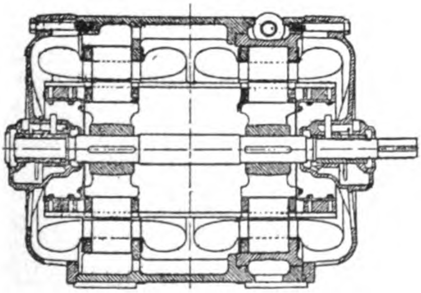


FIG. 309.—Cross-Sectional Diagram of Double Primary Motor.

voltage is high; it is not in general commercial use. Squirrel-cage induction motors are, however, almost invariably started with reduced primary voltage obtained by means of auto-transformers.

III. The Double Primary Motor.—The double primary motor resembles an ordinary squirrel-cage induction motor in construction except that the primary is divided vertically into halves, each with separate core and windings. One-half can be rotated around the rotor by means of a worm screw and rack device. Fig. 309 shows this construction. When the two halves of the primary are placed so that like poles are in line, the rotor windings are subjected to maximum magnetic flux from the primary, and the motor will run with minimum slip and therefore at its maximum speed. By turning the movable half of the primary the flux acting on each rotor bar is gradually reduced, causing increased slip and a corresponding reduction of the motor speed for a given torque.

This operation is equivalent to varying primary voltage and therefore cannot be used with advantage where constant speed with varying torque is desired. The mechanism is, however, self-contained; the speed changes are effected without opening circuits; and the motor, having no brushes, operates without sparking.

IV. Changing the Number of Motor Poles.—The synchronous speed of a polyphase motor is inversely proportional to the number of its poles. Thus, on a 60-cycle circuit a two-pole induction motor has a synchronous speed of approximately 3600 R. P. M., a four-pole motor 1800 R. P. M., an eight-pole motor 900 R. P. M., etc. It is therefore possible to alter the speed of a motor by changing the number of its poles.

This can be accomplished by using two or more separate primary windings, each having a different number of poles, or by using a single winding which can be connected so as to form different numbers of poles. In general only two speeds are possible without great complications, the preferable ratio being 1 : 2.

The rotor should be of the squirrel-cage type as this is adapted to any number of poles, whereas the windings of a wound rotor must be reconnected for the different speeds.

V. Operating Two or More Motors Connected in Cascade.—The operation of two or more motors connected in cascade offers, under some conditions of service, the most convenient and economical method of speed variation. In this arrangement all the rotors are mounted on one shaft or the several shafts are rigidly connected; the primary of the first motor is connected to the line, its secondary, which must be of the phase-wound slip-ring type, to the primary of the second motor and so on. The secondary of the last motor can be either of the squirrel-cage or of the phase-wound type. In practice more than two motors are rarely used. The arrangement is shown in Fig. 310.

Speed changes are obtained by varying the connections of the motors, the following combinations being possible with two motors: Each motor can be operated separately at its normal speed with its primary connected to the line, the other motor running idle; the motors can be connected in cascade so that the rotors tend to start in the same direction (direct concatenation); or the motors can be connected so that the rotors tend to start in opposite directions (differential concatenation). If the first motor has 12 poles and the second four, the following synchronous speeds can be obtained on a 25-cycle circuit:

(1) Motor II (four poles) running single, 750 R. P. M.; (2) motors in differential concatenation (equivalent of eight poles), 375 R. P. M.; (3) motor I (12 poles) running single, 250 R. P. M.; (4) motors in direct concatenation (equivalent of 16 poles), 187.5 R. P. M. By the use of adjustable resistance in the secondary circuits, changes from one speed to the next can be made with uniform gradations.

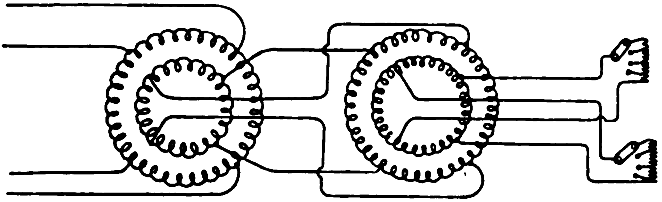


FIG. 310.—Diagrammatic Arrangement of Two Polyphase Motors Connected in Cascade.

A great number of speed combinations are possible by the use of this method; the control is simple and safe, as few leads are required and main circuits are not opened for most of the speeds. The rotors can be made with smaller diameters than is possible with other multi-speed motors, hence the flywheel effect is reduced to a minimum. In general, a cascade set is applicable where speed changes must be frequently made with high horse-power output and primary voltage, and where the speed ratios are other than 1:2.

VI. Adjusting the Frequency of the Primary Current.—Since the synchronous speed of an induction motor is equal to the alternations of the supply circuit divided by the number of poles in each circuit, a change in speed can be effected by changing the frequency of the circuit.

Fig. 311 shows the speed-torque and other curves of a motor when operated at 7200, 3600, 1800 and 720 alternations, per minute, or at 100, 50, 25 and 10 per cent of the normal alternations. The speed-torque curves corresponding to the above alternations are, *a, b, c* and *d*. The current curves are *A, B, C* and *D*. This figure shows that for the rated torque *T*, the current is practically constant for all speeds, but the electromotive force varies with the alternations. Consequently, the apparent power supplied, represented by the

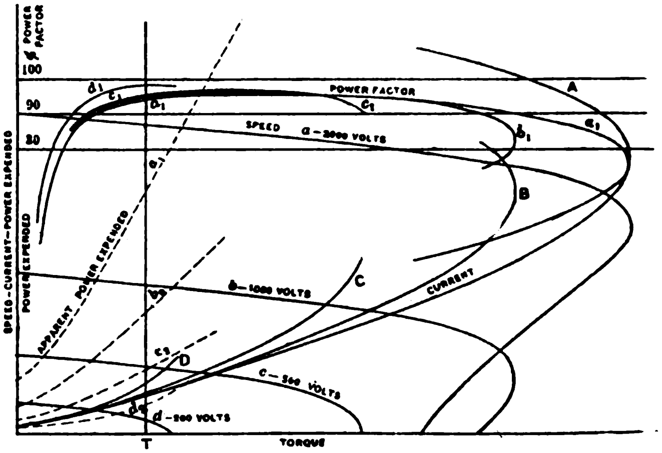


FIG. 311.—Performance Curves of Polyphase Motor with Different Alternations and Electromotive Force.

product of the current by electromotive force, varies with the speed of the motor, and is practically proportionate to the power developed.

In a few cases, where only one motor is operated, the generator speed can be varied. If the generator is driven by a water-wheel, its speed can be varied over a wide range, and the motor speed will also vary. If the generator field is held at practically constant strength, then the motor speed can be varied from zero to a maximum at constant torque with a practically constant current.

Another method of accomplishing this result is by the use of a frequency changer. Fig. 312 shows the arrangement. *C* and *B* are induction motors of the ordinary type; *A* is a direct-current motor directly connected to the rotor of *B*. *C* is the driving motor and *B* the frequency changer. The primary of B is connected to the line, its secondary to the primary of C. The frequency of the current delivered to C depends on the relation of the speed of the rotor B to the synchronous speed of B; the slower the rotation of the rotor the higher the frequency delivered to C and the higher the speed of C.

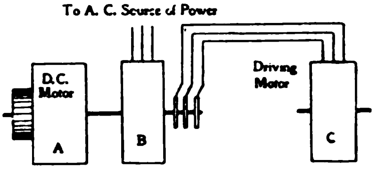


FIG. 312.—Speed Adjustment by Means of a Frequency Changer.

The speed of the rotor B is controlled by adjusting the field of motor A. Motor B must be practically the same size as C; but motor A can generally be relatively smaller, the exact size depending on the maximum and minimum frequency and the power required for motor C.

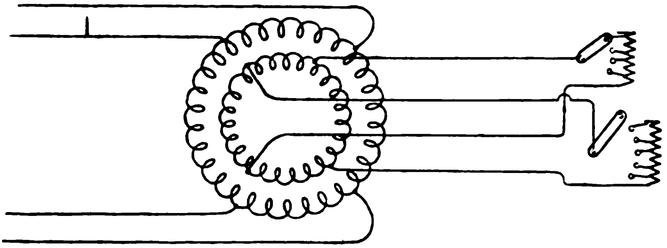


FIG. 313.—Polyphase Motor with Only One Secondary Current Closed.

This method can be applied with special advantage where direct-current motor drive is not desirable.

VII. Changing the Number of Phases of the Secondary Winding.—Phase-wound motors have in almost all cases secondaries with three-phase windings. If only one of the secondary circuits is closed, as in Fig. 313, the motor will run at about half speed, with very low power factor and poor efficiency. This method of speed adjustment is frequently used in experimental work but has no extensive commercial applications.

Miscellaneous Motors.

(4) Chief among these is the repulsion motor. Other motors have been built embodying this repulsion principle combined with the induction principle. At present there is a large number of varieties of A. C. motors involving to a varying degree all of the principles discussed above. Since no one of these stands out and since all together they make up but a small part of the A. C. motors in actual operation, they will not be discussed here.

The characteristics of the motors already described reveal both their advantages and weaknesses. For constant speed work the induction motor is ideal. With an added advantage of moderate speed regulation, it is the most common A. C. motor in use to-day. For variable speed work, except for traction work where the series motor is satisfactory, no A. C. motor can compare with the D. C. motor. The applications of the synchronous motor have already been discussed.

CHAPTER XVII.

STANDARD DEFINITIONS AND CLASSIFICATIONS OF ELECTRICAL MACHINERY.

NOTE.—From Standardization Rules of the American Institute of Electrical Engineers.

Definitions.

NOTE.—The following definitions are intended to be practically descriptive, and not scientifically rigid.

CURRENT, E. M. F. AND POWER.

(The definitions of currents given below apply also, in most cases, to electromotive force, potential difference, magnetic flux, etc.)

A **direct current** is a unidirectional current. As ordinarily used, the term designates a practically non-pulsating current.

A **pulsating current** is a current which pulsates regularly in magnitude. As ordinarily employed, the term refers to unidirectional current.

A **continuous current** is a practically non-pulsating direct current.

An **alternating current** is a current which alternates regularly in direction. Unless distinctly otherwise specified, the term "alternating current" refers to a periodic current with successive half waves of the same shape and area.

An **oscillating current** is a periodic current whose frequency is determined by the constants of the circuit or circuits.

Cycle.—One complete set of positive and negative values of an alternating current.

Electrical Degree.—The 360th part of a cycle.

Period.—The time required for the current to pass through one cycle.

Frequency.—The number of cycles or periods per second. The product of 2π by the frequency is called the *angular velocity* of the current.

Root-Mean-Square or Effective Value.—The square root of the mean of the squares of the instantaneous values for one complete cycle. It is usually abbreviated R. M. S. Unless otherwise specified, the numerical value of an alternating current refers to its R. M. S. value. The R. M. S. value of a sinusoidal wave is equal to its maximum value divided by $\sqrt{2}$. The word "virtual" is sometimes used in place of R. M. S., particularly in Great Britain.

Wave-Form or Wave-Shape.—The shape of the curve obtained when the instantaneous values of an alternating current are plotted against time in rectangular co-ordinates. The distance along the time axis corresponding to one complete cycle of values is taken as 2π radians, or 360°. Two alternating quantities are said to have the same wave-form when their ordinates of corresponding phase bear a constant ratio to each other. The wave-shape, as thus understood, is therefore independent of the frequency of the current and of the scale to which the curve is represented.

Simple Alternating or Sinusoidal Current.—One whose wave-shape is sinusoidal.

Alternating-current calculations are commonly based upon the assumption of sinusoidal currents and voltages.

Phase.—The distance, usually in angular measure, of the base of any ordinate of an alternating wave from any chosen point on the time axis, is called the phase of this ordinate with respect to this point. In the case of a sinusoidal alternating quantity, the phase at any instant may be represented by the corresponding position of a line or *vector* revolving about a point with such an angular velocity ($\omega = 2\pi f$) that its projection at each instant upon a convenient reference line is proportional to the value of the quantity at that instant.

Non-sinusoidal quantities are quantities that cannot be represented by vectors of constant length in a plane, and the following definitions of phase, active component, reactive component, etc., are not in general applicable. Certain "equivalent" values, as defined below, may, however, be used in many instances, for the purpose of approximate representation and calculation.

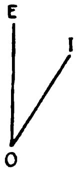
Crest factor or **peak factor** is the ratio of the crest or maximum value to the R. M. S. value. The crest factor of a sine wave is $\sqrt{2}$.

Form factor is the ratio of the R. M. S. to the algebraic mean ordinate taken over a half-cycle beginning with the zero value. If the wave passes through zero more than twice during a single cycle, that zero shall be taken which gives the largest algebraic mean for the succeeding half-cycle. The form factor of a sine wave is 1.11.

Distortion factor of a wave is the ratio of the R. M. S. value of the first derivative of the wave with respect to time, to the R. M. S. value of the first derivative of the equivalent sine wave.

Equivalent Sine Wave.—A sine wave which has the same frequency and same R. M. S. value as the actual wave.

* **Phase Difference: Lead and Lag.**—When corresponding cyclic values of two sinusoidal alternating quantities of the same frequency occur at different instants, the two quantities are said to differ in phase by the angle between their nearest corresponding values, *e. g.*, the phase angle between their nearest ascending zeros or positive maxima. That quantity whose maximum value occurs first in time is said to lead the other, and the latter is said to lag behind the former.



* **Counter-Clockwise Convention.**—It is recommended that in any vector diagram, the leading vector be drawn counter-clockwise with respect to the lagging vector, as in the accompanying diagram, where OI represents the vector of a current in a simple alternating-current circuit lagging behind the vector OE of impressed E. M. F.

* The **active** or **in-phase component** of the current in a circuit is that component which is in phase with the voltage across the circuit; similarly the active component of the voltage across a circuit is that component which is in phase with the current. The use of the term *energy component* for this quantity is disapproved.

* The **reactive** or **quadrature component** of the current in a circuit is that component which is in quadrature with the voltage across the circuit; similarly the reactive component of the voltage across the circuit is that component which is in quadrature with the current. The use of the term *wattless component* for this quantity is disapproved.

* **Refer strictly only to cases where the voltage and current are both sinusoidal.**

* **Reactive factor** is the sine of the angular phase difference between voltage and current, or the ratio of the reactive current or voltage to the total current or voltage.

* **Reactive Volt Amperes.**—The product of the reactive component of the voltage by the total current, or of the reactive component of the current by the total voltage.

* **Non-Inductive Load and Inductive Load.**—A *non-inductive* load is a load in which the current is in phase with the voltage across the load. An *inductive* load is a load in which the current lags behind the voltage across the load. A *condensive* or *anti-inductive* load is one in which the current leads the voltage across the load.

Power in an alternating-current circuit is the average value of the products of the coincident instantaneous values of the current and voltage for a complete cycle, as determined by a wattmeter.

Volt Amperes or Apparent Power.—The product of the R. M. S. value of the voltage across a circuit by the R. M. S. value of the current in the circuit. This is ordinarily expressed in K. V. A.

Power factor is the ratio of the power to the volt amperes. In the case of sinusoidal current and voltage, the power factor is equal to the cosine of their difference in phase.

Equivalent Phase Difference.—When the current and E. M. F. in a given circuit are non-sinusoidal, it is customary, for purposes of calculation, to take as the "equivalent" phase difference the angle whose cosine is the power factor of the circuit. There are cases, however, where this equivalent phase difference is misleading, since the presence of harmonics in the voltage wave, current wave, or in both, may reduce the power factor without producing a corresponding displacement of the two wave forms with respect to each other; *e. g.*, the case of an A.-C. arc. In such cases the components of the equivalent sine waves, the equivalent reactive factor and the equivalent reactive volt amperes may have no physical significance.

Single-Phase.—A term characterizing a circuit energized by a single alternating E. M. F. Such a circuit is usually supplied through two wires. The currents in these two wires, counted positively outwards from the source, differ in phase by 180° or a half-cycle.

* **Refer strictly only to cases where the voltage and current are both sinusoidal.**

Three-Phase.—A term characterizing the combination of three circuits energized by alternating E. M. F.'s which differ in phase by one-third of a cycle; *i. e.,* 120°.

Quarter-Phase, also called Two-Phase.—A term characterizing the combination of two circuits energized by alternating E. M. F.'s which differ in phase by a quarter of a cycle; *i. e.,* 90°.

Six-Phase.—A term characterizing the combination of six circuits energized by alternating E. M. F.'s which differ in phase by one-sixth of a cycle; *i. e.,* 60°.

Polyphase is the general term applied to any system of more than a single phase. This term is ordinarily applied to symmetrical systems.

Per Cent Drop.—In electrical machinery, the ratio of the internal resistance drop to the terminal voltage is called the "*per cent resistance drop.*"

Similarly the ratio of the internal reactance drop to the terminal voltage is called the "*per cent reactance drop.*"

Similarly the ratio of the internal impedance drop to the terminal voltage is called the "*per cent impedance drop.*"

Unless otherwise specified, these per cent drops shall be referred to rated load and rated power factor.

In the case of transformers, the per cent drop will be the primary drop (reduced to secondary turns) plus the secondary drop, in per cent of secondary terminal voltage.

In the case of induction motors, it is advantageous to express the drops in per cent of the internally induced E. M. F.

The **load factor** of a machine, plant or system is the ratio of the average power to the maximum power during a certain period of time. The average power is taken over a certain period of time, such as a day, a month, or a year, and the maximum is taken over a short interval of the maximum load within that period.

In each case, the interval of maximum load and the period over which the average is taken should be definitely specified, such as a "half-hour monthly" load factor. The proper interval and period are usually dependent upon local conditions and upon the purpose for which the load factor is to be used.

Plant factor is the ratio of the average load to the rated capacity of the power plant.

The **demand** of an installation or system is the load which it puts on the source of supply, as measured at the receiving terminals. The demand may be as specified, contracted for, or used. It may be expressed either in kilowatts, kilovolt amperes, amperes or other suitable units.

Maximum demand of an installation or system is its greatest demand, as measured not instantaneously, but over a suitable and specified interval, such as a "five-minute maximum demand."

Demand factor is the ratio of the maximum demand of any system or part of a system to the total connected load of the system, or of the part of system, under consideration.

Diversity factor is the ratio of the sum of the maximum power demands of the subdivisions of any system or parts of a system to the maximum demand of the whole system or of the part of the system under consideration, measured at the point of supply.

Connected Load.—The combined continuous rating of all the receiving apparatus on consumers' premises connected to the system or part of the system under consideration.

The **saturation factor** of a machine is the ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. Unless otherwise specified, the saturation factor of a machine refers to the excitation existing at normal rated speed and voltage. It is determined from measurements of saturation made on open circuit at rated speed.

The **percentage of saturation** of a machine at any excitation may be found from its saturation curve of generated voltage as ordinates, against excitation as abscissæ, by drawing a tangent to the curve at the ordinate corresponding to the assigned excitation, and extending the tangent to intercept the axis of ordinates drawn through the origin. The ratio of the intercept on this axis to the ordinate at the assigned excitation, when expressed in percentage, is the percentage of saturation and is independent of the scales selected for excitation and voltage. This ratio, as a fraction, is equal to the reciprocal of the saturation factor at the same excitation, deducted from unity, or if f be the saturation factor and p the percentage of saturation,

$$p = 100\left(1 - \frac{1}{f}\right).$$

Magnetic Degree.—The 360th part of the angle subtended, at the axis of a machine, by a pair of its field poles. One mechanical degree is thus equal to as many magnetic degrees as there are pairs of poles in the machine.

The **variation in prime movers** which do not give an absolutely uniform rate of rotation or speed, as in reciprocating steam engines, is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution taken as 360°.

The **variation in alternators** or alternating-current circuits in general, is the maximum angular displacement, expressed in electrical degrees (one cycle = 360°), of corresponding ordinates of the voltage wave and of a wave of absolutely constant frequency equal to the average frequency of the alternator or circuit in question, and may be due to the variation of the prime mover.

Relations of Variations in Prime Mover and Alternator.—If p is the number of pairs of poles, the variation of an alternator is p times the variation of its prime mover, if direct-connected, and pn times the variation of the prime mover if rigidly connected thereto in such a manner that the angular speed of the alternator is n times that of the prime mover.

The **pulsation in prime movers**, or in the alternator connected thereto, is the ratio of the difference between the maximum and minimum velocities in an engine cycle to the average velocity.

Capacity.—The two different senses in which this word is used sometimes lead to ambiguity. It is therefore recommended that whenever such ambiguity is likely to arise, the descriptive term *power capacity* or *current capacity* be used, when referring to the power or current which a device can safely carry, and that the term "*capacitance*" be used when referring to the electrostatic capacity of a device.

A **resistor** is a device, commonly known as a resistance, used for the operation, protection, or control of a circuit or circuits.

A **reactor** is a coil, winding or conductor commonly known as a reactance coil or choke coil, possessing inductance, the reactance of which is used for the operation, protection or control of a circuit or circuits.

The **efficiency** of an electrical machine or apparatus is the ratio of its useful output to its total input.

Instruments.

An **ammeter** is a measuring instrument, indicating in amperes.

A **voltmeter** is a measuring instrument, indicating in volts.

A **watt meter** is an instrument for measuring electrical power, indicating in watts.

Recording ammeters, voltmeters, watt meters, etc., are instruments which record graphically upon a time chart the values of the quantities they measure.

A **watt-hour meter** is an instrument for registering watt-hours. This term is to be preferred to the term "integrating watt meter."

A **line-drop voltmeter compensator** is a device in connection with a voltmeter, which causes the latter to indicate the voltage at some distant point of the circuit.

A **synchroscope, sometimes called synchronoscope,** is a device which, in addition to indicating synchronism, shows whether the machine to be synchronized is fast or slow.

Regulation.

Regulation.—The regulation of a machine in regard to some characteristic quantity (such as terminal voltage or speed) is the change in that quantity occurring between any two loads. Unless otherwise specified, the two loads considered shall be zero load and rated load and at the temperature attained under normal operation. The regulation may be expressed by stating the numerical values of the quantity at the two loads, or it may be expressed by the "percentage regulation" which is the percentage ratio of the change in the quantity occurring between the two loads to the value of the quantity at either one or the other load, taken as the normal value. It is assumed that all parts of the machine affecting the regulation maintain constant temperature between the two loads, and where the influence of temperature is of consequence, a reference temperature of 75° C. shall be considered as standard. If change of temperature should occur during the tests the results shall be corrected to the reference temperature of 75° C.

The normal value may be either the no-load value, as the no-load speed of induction motors; or it may be the rated-load value as in the voltage of A.-C. generators.

It is usual to state the regulation of D.-C. generators by giving the numerical values of the voltage at no load and rated load, and in some cases it is advisable to state regulation at intermediate loads.

The **regulation of D.-C. generators** refers to changes in voltage corresponding to gradual changes in load and does not relate to the comparatively large momentary fluctuations in voltage that frequently accompany instantaneous changes in load.

In determining the regulation of a compound-wound D.-C. generator, two tests shall be made, one bringing the voltage down and the other bringing the voltage up between no load and rated load. These may differ somewhat, owing to residual magnetism. The mean of the two results shall be used.

In **constant-potential A.-C. generators**, the regulation is the rise in voltage (when the specified load at specified power factor is thrown off) expressed in per cent of normal rated-load voltage.

In **constant-current machines**, the regulation is the ratio of the maximum difference of current from the rated-load value (occurring in the range from rated-load to short-circuit, or minimum limit of operation), to the rated-load current.

In **constant-speed direct-current motors**, and induction motors, the regulation is the ratio of the difference between full-load and no-load speeds to the no-load speed.

In **constant-potential transformers** the regulation is the difference between the no-load and rated-load values of the secondary terminal voltage, at the specified power factor (with constant primary impressed terminal voltage) expressed in per cent of the rated-load secondary voltage, the primary voltage being adjusted to such a value that the apparatus delivers rated output at rated secondary voltage.

In **converters, dynamotors, motor generators and frequency converters,** the regulation is the change in the terminal voltage of the output side between the two specified loads. This may be expressed by giving the numerical values or as the percentage ratio.

In **transmission lines, feeders, etc.**, the regulation is the change in the voltage at the receiving end between rated non-inductive load and no load, with constant impressed voltage upon the sending end. The percentage regulation is the percentage change in voltage to the normal rated voltage at the receiving end.

In **steam engines, steam turbines and internal combustion engines,** the percentage speed regulation is usually expressed as the percentage ratio of the maximum variation of speed to the rated-load speed in passing slowly from rated load to no load (with constant conditions at the supply).

If the test is made by passing suddenly from rated load to no load, the immediate percentage speed regulation so derived shall be termed the **fluctuation.**

In a **hydraulic turbine**, or other water motor, the percentage speed regulation is expressed as the percentage ratio of the maximum variation in speed in passing slowly from rated load to no load (at constant head of water), to the rated-load speed.

In a **generator unit** consisting of a generator combined with a prime mover, the speed or voltage regulation should be determined at constant conditions of the prime mover; *i. e.*, constant steam pressure, head, etc. It includes the inherent speed variations of the prime mover. For this reason, the regulation of a generator unit is to be distinguished from the regulation of either the prime mover, or of the generator combined with it, when taken separately.

Wires and Cables.

Wire.—A slender rod or filament of drawn metal.

The definition restricts the term to what would ordinarily be understood by the term "solid wire." In the definition the word "slender" is used in the sense, that the length is great in comparison with the diameter. If a wire is covered with insulation, it is properly called an insulated wire. While primarily the term "wire" refers to the metal, nevertheless when the context shows that the wire is insulated the term "wire" will be understood to include the insulation.

Conductor.—A wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

The term "conductor" is not to include a combination of conductors insulated from one another, which would be suitable for carrying several different electric currents.

Rolled conductors (such as bus bars) are, of course, conductors; but are not considered under terminology here given.

Stranded Conductor.—A conductor composed of a group of wires or any combination of groups of wires.

The wires in a stranded conductor are usually twisted or braided together.

Cable.—(1) A stranded conductor (single-conductor cable); or (2) a combination of conductors insulated from one another (multiple-conductor cable).

The component conductors of the second kind of cable may be either solid or stranded, and this kind of cable may or may not have a common insulating covering. The first kind of cable is a single conductor, while the second kind is a group of several conductors. The term "cable" is applied by some manufacturers to a solid wire heavily insulated and lead covered. This usage arises from the manner of the insulation, but such a conductor is not included under this definition of "cable." The term "cable" is a general one and in practice it is usually applied only to the larger sizes. A small cable is called a "stranded wire" or a "cord," both of which are defined below. Cables may be bare or insulated, and the latter may be armored with lead or steel wires or bands.

Strand.—One of the wires or groups of wires of any stranded conductor.

Stranded Wire.—A group of small wires, used as a single wire.

A wire has been defined as a slender rod or filament of drawn metal. If such a filament is subdivided into several smaller filaments or strands and is used as a single wire, it is called a "stranded wire." There is no sharp dividing line of size between a "stranded wire" and a "cable." If used as a wire, for example, in winding inductance coils or magnets, it is called a stranded wire and not a cable. If it is substantially insulated, it is called a "cord," defined below.

Cord.—A small cable, very flexible and substantially insulated to withstand wear.

There is no sharp dividing line in respect to size between a "cord" and a "cable," and likewise no sharp dividing line in respect to the character of insulation between a "cord" and a "stranded wire." Usually the insulation of a cord contains rubber.

Concentric Strand.—A strand composed of a central core surrounded by one or more layers of helically laid wires or groups of wires.

Concentric-Lay Cable.—A single-conductor cable composed of a central core surrounded by one or more layers of helically laid wires.

Rope-Lay Cable.—A single-conductor cable composed of a central core surrounded by one or more layers of helically laid groups of wires.

This kind of cable differs from the preceding in that the main strands are themselves stranded.

N-Conductor Cable.—A combination of N conductors insulated from one another.

It is not intended that the name as here given be actually used. One would instead speak of a "three-conductor cable," and a "twelve-conductor cable," etc. In referring to the general case, one may speak of a "multiple-conductor cable" (as in definition above).

N-Conductor Concentric Cable.—A cable composed of an insulated central conducting core with (N−1) tubular stranded conductors laid over it concentrically and separated by layers of insulation.

Such constructions are usually only two-conductor or three-conductor. Such conductors are used in carrying alternating currents. The remarks on the expression "N conductor" given for the preceding definition applies here also.

Duplex Cable.—Two insulated single-conductor cables twisted together.

They may or may not have a common insulating covering.

Twin Cable.—Two insulated single-conductor cables laid parallel, having a common covering.

Triplex Cable.—Three insulated single-conductor cables twisted together.

They may or may not have a common insulating covering.

Twisted Pair.—Two small insulated conductors twisted together without a common covering.

The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

Twin Wire.—Two small insulated conductors laid parallel, having a common covering.

Specification of Sizes of Conductors.—The sizes of solid wires shall be stated by their diameter in mils, the American Wire Gage (Brown and Sharpe) sizes being taken as standard. The sizes of stranded conductors shall be stated by their cross-sectional area in circular mils. For brevity, in cases where the most careful specification is not required, the sizes of solid wires may be stated by the gage number in the American Wire Gage, and the sizes of stranded conductors smaller than 250,000 circular mils (*i. e.*, No. 0000 A. W. G. or smaller) may likewise be stated by means of the gage number in the American Wire Gage of a solid wire having the same cross-sectional area. Furthermore, an exception is made in the case of "Flexible Stranded Conductors." In **stating large cross-sections**, it is sometimes convenient to use a circular inch (507 square millimeters) instead of 1,000,000 circular mils.

Insulation Resistance.—The insulation resistance of an insulated conductor is the electrical resistance offered by its insulation, to an impressed voltage tending to produce a leakage of current through the same.

Insulation resistance shall be expressed in megohms for a specified length (as for a kilometer, or a mile, or one thousand feet), and shall be corrected to a temperature of 15.5° C. using a temperature coefficient determined experimentally for the insulation under consideration.

Linear insulation resistance, or the insulation resistance of unit length, shall be expressed in terms of the megohm kilometer, or the megohm mile, or the megohm thousand feet.

Switch.—A device for making, breaking, or changing connections in an electric circuit.

Circuit Breaker.—A device designed to open a current-carrying circuit without injury to itself. A circuit breaker may be:

(a) An automatic circuit breaker, which is designed to trip automatically under any predetermined condition of the circuit, such as an underload or overload of current or voltage.

(b) A manually tripped circuit breaker, which is designed to be tripped by hand.

Both types of operation may be combined in one and the same device.

Fuse.—An element designed to melt or dissipate at a predetermined current value and intended to protect against abnormal conditions of current.

NOTE.—The terminals, tubes, etc., which go with the fuse proper are included in the definition.

Fuses shall be rated at the maximum current which they are required to carry continuously and at the normal voltage of the circuit on which they are designed to be used.

They may be divided into two classes:

(1) Those designed to protect the circuit and apparatus both against short circuit and against definite amounts of overload (*e. g.*, fuses of the code which open on 25 per cent overload).

(2) Those designed to protect the system only against short circuits (*e. g.*, expulsion fuses which blow at several times the current which they are designed to carry continuously). The line separating these two classes is not definitely fixed.

Illumination and Photometry.

Luminous flux is radiant power evaluated according to its capacity to produce the sensation of light.

The **luminous intensity** of a point source of light is the solid angular density of the luminous flux emitted by the source in the direction considered; or it is the flux per unit solid angle from that source.

Candle.—The unit of luminous intensity, maintained by the National Laboratories of France, Great Britain, and the United States. This unit, which is used also by many other countries, is frequently referred to as the international candle. The Hefner unit is 0.90 of the international candle.

Candle-Power.—Luminous intensity expressed in candles.

Lumen.—The unit of luminous flux, equal to the flux emitted in a unit solid angle (steradian) by a point source of one candle-power.

Illumination on a surface, is the luminous flux density over that surface, or the flux per unit of intercepting area.

Defining equation:

Let E be the illumination and S the area of the intercepting surface. Then

$$E = \frac{dF}{dS},$$

or, when uniform,

$$E = \frac{F}{S}.$$

Lux is a unit of illumination equal to one lumen per square meter. The C. G. S. unit of illumination is one lumen per square centimeter. For this unit Blondel has proposed the name "Phot." One millilumen per square centimeter (milliphot) is a practical derivative of the C. G. S. system. One foot-candle is one lumen per square foot and is equal to 1.0764 milliphots. The foot-candle is the commonly employed unit of illumination in English speaking countries.

Exposure.—The product of an illumination by the time. Blondel has proposed the name "phot-second" for the unit of exposure in the C. G. S. system.

Brightness, *b*, of an element of a luminous surface from a given position is the luminous intensity per unit area of the surface projected on a plane perpendicular to the line of sight, and including only a surface of dimensions negligibly small in comparison with the distance to the observer. It is measured in candles per square centimeter of the projected area.

Defining equation:

Let θ be the angle between the normal to the surface and the line of sight, and dI the luminous intensity of the element. Then

$$b = \frac{dI}{dS \cos \theta}.$$

Normal brightness, b_0, of an element of a surface (sometimes called **specific luminous intensity**) is the luminous intensity of the element taken normally to the surface of the element, and is expressed in candles per square centimeter.

In practice, the brightness b of a luminous surface, or element thereof, is observed, and not the normal brightness b_0. For surfaces for which the cosine law of emission holds, the quantities b and b_0 are equal.

Defining equation:

$$b_0 = \frac{dI}{dS}, \text{ or, when uniform,}$$

$$b_0 = \frac{I}{S}.$$

Specific Luminous Radiation.—The luminous flux density emitted by a surface, or the flux emitted per unit of emissive area. It is expressed in lumens per square centimeter.

Defining equation:

Let E' be the specific luminous radiation.

Then, for surfaces obeying Lambert's cosine law of emission:

$$E' = \pi b_0.$$

Coefficient of Reflection.—The ratio of the total luminous flux reflected by a surface to the total luminous flux incident upon it. It is a simple numeric. The reflection from a surface may be regular, diffuse or mixed. In perfect regular reflection, all of the flux is reflected from the surface at an angle of reflection equal to the angle of incidence. In perfect diffuse reflection, the flux is reflected from the surface in all directions in accordance with Lambert's cosine law. In most practical cases, there is a superposition of regular and diffuse reflection.

Coefficient of regular reflection is the ratio of the luminous flux reflected regularly to the total incident flux.

Coefficient of diffuse reflection is the ratio of the luminous flux reflected diffusely to the total incident flux.

Defining equation:

Let m be the coefficient of reflection (regular or diffuse).

Then, for any given portion of the surface,

$$m = \frac{E'}{E}.$$

Primary Luminous Standard.—A recognized standard luminous source reproducible from specifications.

Representative Luminous Standard.—A standard of luminous intensity adopted as the authoritative custodian of the accepted value of the unit.

Reference Standard.—A standard calibrated in terms of the unit from either a primary or representative standard and used for the calibration of working standards.

Working Standard.—Any standardized luminous source for daily use in photometry.

Comparison Lamp.—A lamp of constant but not necessarily known candle-power against which a working standard and test lamps are successively compared in a photometer.

Test lamp, in a photometer, a lamp to be tested.

Performance Curve.—A curve representing the behavior of a lamp in any particular (candle-power, consumption, etc.), at different periods during its life.

Characteristic Curve.—A curve expressing a relation between two variable properties of a luminous source, as candle-power and volts, candle-power and rate of fuel consumption, etc.

Mean horizontal candle-power of a lamp—the average candle-power in the horizontal plane passing through the luminous center of the lamp.

It is here assumed that the lamp (or other light source) is mounted in the usual manner, or, as in the case of an incandescent lamp with its axis of symmetry vertical.

Mean spherical candle-power of a lamp—the average candle-power of a lamp in all directions in space. It is equal to the total luminous flux of the lamp in lumens divided by 4π.

Mean hemispherical candle-power of a lamp (upper or lower) is the average candle-power of a lamp in the hemisphere considered. It is equal to the total luminous flux emitted by the lamp in that hemisphere divided by 2π.

Mean zonal candle-power of a lamp—the average candle-power of a lamp over a given zone. It is equal to the total luminous flux emitted by the lamp in that zone divided by the solid angle of the zone.

The **spherical reduction factor** of a lamp

$$= \frac{\text{mean spherical candle-power}}{\text{mean horizontal candle-power}}$$

The **spherical reduction factor** should only be used when properly determined for the particular type and characteristics of each lamp. The spherical reduction factor permits of substantially accurate comparisons being made between the total lumens, or mean spherical candle-powers of different types of incandescent lamps, and may be used in the absence of proper facilities for direct measurement of the total lumens or mean spherical candle-power.

The **specific output of electric lamps** is properly stated in terms of lumens per watt at lamp terminals. The use of the term efficiency in this connection should be discouraged.

When auxiliary devices are employed in circuit with a lamp, the specific output should be referred to lamp terminals, unless otherwise specified.

The **specific consumption** of an electric lamp is its watt consumption per lumen. "Watts per candle" is a term used commercially in connection with incandescent lamps, and denotes, watts per mean horizontal candle-power.

Photometric tests in which the results are stated in candle-power should be made at such a distance from the source of light that the latter may be regarded as practically a point. Where tests are made in the measurement of lamps with reflectors, the results should always be given as "apparent candle-power" at the distance employed, which distance should always be specifically stated.

Basis for Comparison.—Either the total flux of light in lumens, or the mean spherical candle-power, should always be used as the basis for comparing various luminous sources with each other, unless there is a clear understanding or statement to the contrary.

Incandescent Lamps, Rating.—It is customary to rate incandescent lamps on the basis of their mean horizontal candle-power; but in comparing incandescent lamps in which the relative distribution of luminous intensity differs, the comparison should be based on their total flux of light measured in lumens, or on their mean spherical candle-power.

Life Tests.—Similar filaments may be assumed to operate at the same temperature, only when their lumens per watt consumed are the same. Life tests are comparable only when conducted under similar conditions as to filament temperatures.

In **comparing different luminous sources** not only should their candle-power be compared, but also their relative form, brightness. distribution of illumination and character of light.

Radio.*

Damping of a Circuit.—The damping, at a given point, in a circuit from which the source of energy has been withdrawn, is the progressive diminution in the effective value of electromotive force

* The definitions under this heading are not considered as standard but as tentative only.

and current at that point resulting from the withdrawal of electrical energy.

Acoustic Resonance Device.—One which utilizes in its operation mechanical or other resonance to the audio frequency of the received impulses.

Antenna.—A system of conductors designed for radiating or absorbing the energy of electromagnetic waves.

Atmospheric Absorption.—That portion of the total loss of radiated energy due to atmospheric conductivity.

Audio Frequencies.—The normally audible frequencies lying between 20 and about 20,000 cycles per second. (See also Radio Frequencies.)

Capacity Coupler.—An apparatus which electrostatically joins portions of two circuits, and thereby permits the transfer of electrical energy between these circuits through the action of electric forces.

Conductive Coupler.—An apparatus which magnetically and electrically joins two circuits having a common conductive portion (also known as a Direct Coupler).

Counterpoise.—A system of electrical conductors forming one plate of a condenser, the other plate of which is the ground. For alternating current, it may be used to replace a direct connection to ground.

Damping Factor of a Simple Circuit.—The ratio of the effective resistance of that circuit to twice the effective inductance at any frequency. (The reciprocal of a time.) This term applies only to circuits capable of carrying free alternating currents.

Detector.—That portion of the receiving apparatus which, connected to a circuit carrying currents of radio frequency, and in conjunction with a self-contained or separate indicator, translates the radio frequency energy into a form suitable for operation of the indicator. This translation may be effected either by the conversion of the radio frequency energy, or by means of the control of local energy by the energy received.

Electromagnetic Wave.—A progressive disturbance characterized by the existence on the wave front of electric and magnetic forces acting in directions which are perpendicular to each other and to the direction of propagation of the wave.

Forced Alternating Current.—One produced in any circuit by the application of an alternating electromotive force.*

Free Alternating Current.—That produced by an isolated electrical displacement in a circuit having capacity, inductance, and *less* than the critical resistance.†

Critical Resistance of an Oscillating Current Circuit.—Twice the square root of the ratio of the inductance of that circuit to the capacity of that circuit both expressed in practical units. This term applied only to circuits capable of carrying free alternating currents.

Group Frequency.—The number of distinguishable alternating current groups occurring per second in an electrical circuit.

NOTE 1.—The group referred to above is, in general, mainly a free alternating current which is substantially damped to extinction before the beginning of the following group or train.

NOTE 2.—The acoustic pitch of the note in the receiving station is, in general, determined by the group frequency at the transmitting station.

NOTE 3.—The term "Group Frequency" replaces the term "Spark Frequency."

Inductive Coupler.—An apparatus which magnetically joins portions of two electric circuits.

Linear Decrement of a Circuit Containing a Resistance Element Equivalent to a Spark.—The difference of successive current amplitudes in the same direction divided by the larger of these amplitudes. (In circuits containing such an element, not the ratio of successive current amplitudes, but their difference is constant, and characteristic of the damping.)

Logarithmic Decrement.—Logarithmic decrement of a circuit containing inductance, capacity, and constant resistance is one-half the ratio of the electrical energy withdrawn from that circuit during a cycle to the total energy present in that circuit at the beginning of the cycle. It also equals the natural logarithm of the ratio of successive current amplitudes in the *same* direction.

NOTE.—Logarithmic decrements are standard for a complete period or cycle.

* In power applications termed simply an alternating current.

† In power applications termed simply an oscillating current.

Radio Frequencies.—Those above 20,000 cycles per second. (See also Audio Frequencies.)

NOTE.—It is not implied that radiation cannot be secured at lower frequencies and the distinction from audio frequencies is merely one of definition.

A **resonance curve** gives the relation between circuit power, current, or voltage at various frequencies of excitation as a function of those frequencies.

A **wave-length resonance curve** is one wherein the abscissæ are ratios of specified wave lengths to the resonant wave length, and the ordinates are ratios of the energy (or square of the current) at corresponding specified wave lengths to the energy (or square of the current) at the resonant wave length. The scale of ordinates and abscissæ shall be equal.

A Frequency Resonance Curve.—One wherein the abscissæ are ratios of specified frequencies to the resonant frequency, and the ordinates are ratios of the energy (or square of the current) at corresponding specified frequencies to the energy (or square of the current) at the resonant frequency. The scales of ordinates and abscissæ shall be equal.

A **standard resonance curve** unless otherwise specified is assumed to be a wave-length resonance curve.

Selecting.—The process of adjusting an element driven by a plurality of simultaneous impulses, until the ratio of desired response to undesired response is a maximum.

Sustained radiation consists of electromagnetic waves of constant amplitude (such as are emitted from an antenna in which flows a forced alternating current).

Tuning.—The process of securing the maximum indications by adjusting the time period of a driven element. (In transmitter or receiver.)

Wave-Length Meter.—A radio-frequency measuring instrument calibrated to read wave lengths.

Rating.—(1) All radio-transmitting sets shall be rated in actual power output measured in the antenna.

NOTE.—The group or audio-frequency of the note of the station should be stated as well (except for sustained wave sets, where that characteristic should be mentioned).

(2) The over-all efficiency of a radio-transmitting station shall be the ratio of the actual power output as measured in the antenna to the power input supplied to the first piece of electrical machinery which is definitely a part of the radio equipment.

Microphone.—A contact device designed to have its electrical resistance directly and materially altered by slight differences in mechanical pressure.

Relay.—A relay is a device by means of which contacts in one circuit are operated under the control of electrical energy in the same or other circuits.

Resonance.—Resonance of a harmonic alternating current of given frequency, in a simple series circuit, containing resistance, inductance and capacity, is the condition in which the positive reactance of the inductance is numerically equal to the negative reactance of the capacity. Under these conditions, the current flow in the circuit with a given electromotive force is a maximum.

Retardation Coil.—A retardation coil is a reactor (reactance coil) used in a circuit for the purpose of selectively reacting on currents which vary at different rates.

NOTE.—In telephone and telegraph usage the terms "impedance coil," "inductance coil," "choke coil" and "reactance coil" are sometimes used in place of the term "retardation coil."

Skin Effect.—Skin effect is the phenomenon of the non-uniform distribution of current throughout the cross-section of a linear conductor, occasioned by variations in the intensity of the magnetic field due to the current in the conductor.

Telephone Receiver.—A telephone receiver is an electrically operated device designed to produce sound waves or vibrations which correspond in form to the electromagnetic waves or vibrations actuating it.

Classification of Machinery.

The machinery under consideration in these rules may be classified in various ways, these various classifications overlapping or interlocking in considerable degree. Briefly, they are direct current or alternating current, rotating or stationary. Under rotating apparatus there are two principal classifications: *First,* according to the function of the machines; motors, generators, boosters, motor generators, dynamotors, double-current generators, converters and phase modifiers; *Second,* according to the type of construction or principle of operation; commutating, synchronous, induction, unipolar, rectifying. Obviously some of these groups could be rationally included in either classification; *e. g.,* motor generators and rectifying machines.

In the following, the self-evident definitions are for the most part omitted.

Rotating Machines.

FUNCTIONAL CLASSIFICATION OF ROTATING MACHINES.

A **generator** is a machine which transforms mechanical power into electrical power.

A **motor** transforms electrical power into mechanical power.

A **booster** is a generator inserted in series in a circuit to change its voltage. It may be driven by an electric motor (in which case it is termed a motor booster) or otherwise.

A **motor generator** is a transforming device consisting of a motor mechanically coupled to one or more generators.

A **dynamotor** is a transforming device combining both motor and generator action in one magnetic field, either with two armatures, or with one armature having two separate windings and independent commutators.

A **direct-current compensator** or **balancer** comprises two or more similar direct-current machines (usually with shunt or compound excitation) directly coupled to each other and connected in series across the outer conductors of a multiple-wire system of distribution, for the purpose of maintaining the potentials of the intermediate wires of the system, which are connected to the junction points between the machines.

A **double-current generator** supplies both direct and alternating currents from the same armature winding.

A **converter** is a machine employing mechanical rotation in changing electrical energy from one form into another. A converter may belong to either of several types, as follows:

A **direct-current converter** converts from a direct current to a direct current, usually with a change of voltage. Such a machine may be either a motor generator or a dynamotor.

A **synchronous converter** (also called a rotary converter) converts from an alternating to a direct current, or vice versa. It is a synchronous machine with a single closed-coil armature.

A **cascade converter,** also called a **motor converter,** is a combination of an induction motor with a synchronous converter, the secondary circuit of the former feeding directly into the armature of the latter; *i. e.,* it is a synchronous converter concatenated with an induction motor.

A **frequency converter** converts the power of an alternating-current system from one frequency to another, with or without a change in the number of phases, or in the voltage.

A **rotary phase converter** converts from an alternating-current system of one or more phases to an alternating-current system of a different number of phases, but of the same frequency.

A **phase modifier,** also called a *phase advancer,* is a machine which supplies reactive volt amperes to the machine; *e. g.,* induction motor, or to the system to which it is connected. Phase modifiers may be either synchronous or asynchronous.

A **synchronous phase modifier,** sometimes called a synchronous condenser, is a synchronous motor, running either idle or with load, the field excitation of which may be varied so as to modify the power factor of the system, or through such modification to influence the load voltage. The function of a synchronous phase modifier is to supply reactive volt amperes to the system with which it is connected.

CONSTRUCTIONAL CLASSIFICATION OF ROTATING MACHINES.

Commutating Machines.

Direct-current commutating machines comprise a magnetic field of constant polarity, an armature, and a multisegmental commutator connected therewith. These include: Direct-current generators; direct-current motors; direct-current boosters; direct-current motor generators and dynamotors; direct-current compensators or balancers; and arc machines.

Alternating-current commutating machines * comprise a magnetic field of alternating polarity, an armature, and multisegmental commutator connected therewith.

Synchronous commutating machines include synchronous converters, cascade converters, and double-current generators.

Synchronous Machines.

Machines of this class comprise a constant magnetic field and an armature receiving or delivering alternating currents in synchronism with the motion of the machine; *i. e.,* having a frequency strictly proportional to the speed of the machine. They may be subdivided as follows:

An **alternator** is a synchronous alternating-current generator, either single-phase or polyphase.

A **polyphase alternator** is a polyphase synchronous alternating-current generator.

An **inductor alternator is a synchronous alternator** in which both field and armature windings are stationary and in which masses of iron or inductors, by moving past the coils, alter the magnetic flux through them. It may be either single-phase or polyphase.

A **synchronous motor** is a machine structurally identical with a synchronous alternator, but operated as a motor.

Induction Machines.

Under this classification are included apparatus wherein the primary and secondary windings rotate with respect to each other; *i. e.,* induction motors, induction generators, certain types of frequency converters and certain types of rotary phase converters.

An **induction motor** is an alternating-current motor, either single-phase or polyphase, comprising independent primary and

* Definitions of A.-C. commutator motors have not yet been agreed upon. The differences of opinion are fundamental and relate to the whole system to be employed in naming the numerous types. One example of this difference is in connection with the definition of the term "Repulsion motor," some desiring to extend its use to cover all A.-C. commutator motors with short-circuited brushes, and others to substitute more systematic names for the various species of short-circuited brush motors.

secondary windings, one of which, usually the secondary, is on the rotating member. The secondary winding receives power from the primary by electromagnetic induction.

An **induction generator** is a machine structurally identical with an induction motor, but driven above synchronous speed as an alternating-current generator.

Unipolar or acyclic machines are direct-current machines, in which the voltage generated in the active conductors maintains the same direction with respect to those conductors.

SPEED CLASSIFICATION OF MOTORS.

Motors may, for convenience, be classified with reference to their speed characteristics as follows:

(a) **Constant-speed motors,** in which the speed is either constant or does not materially vary; such as synchronous motors, induction motors with small slip, and ordinary direct-current shunt motors.

(b) **Multispeed motors** (two-speed, three-speed, etc.), which can be operated at any one of several distinct speeds, these speeds being practically independent of the load, such as motors with two armature windings, or induction motors with controllers for changing the number of poles.

(c) **Adjustable-speed motors,** in which the speed can be varied gradually over a considerable range, but when once adjusted remains practically unaffected by the load, such as shunt motors designed for a considerable range of field variation.

(d) **Varying-speed motors,** or motors in which the speed varies with the load, ordinarily decreasing when the load increases; such as series motors, compound-wound motors, and series-shunt motors.

CLASSIFICATION OF ROTATING MACHINES RELATIVE TO THE DEGREE OF ENCLOSURE OR PROTECTION.

The following types are recognized:

(1) Open.
(2) Protected.
(3) Semi-enclosed.
(4) Enclosed.
(5) Externally ventilated.

(6) Water-cooled.
(7) Self-ventilated.
(8) Drip-proof.
(9) Moisture-resisting.
(10) Submersible.
(11) Flame-proof.
(12) Flame-proof slip-ring enclosure.

No. 1. An "**open**" **machine** is of either the pedestal-bearing or end-bracket type where there is no restriction to ventilation, other than that necessitated by good mechanical construction.

No. 2. A "**protected**" **machine** is one in which the armature, field coils, and other live parts are protected mechanically from accidental or careless contact, while free ventilation is not materially obstructed.

No. 3. A "**semi-enclosed**" **machine** is one in which the ventilating openings in the frame are protected with wire screen, expanded metal, or other suitable perforated covers, having apertures not exceeding ¼ of a square inch (1.6 square centimeters) in area.

No. 4. An "**enclosed**" **machine** is so completely enclosed by integral or auxiliary covers as to prevent a circulation of air between the inside and outside of its case, but not sufficiently tight to be termed air-tight.

No. 5. An "**externally ventilated**" **machine** has its ventilating air supplied by an independent fan or blower external to the machine.

No. 6. A "**water-cooled**" **machine** is one which mainly depends on water circulation for the removal of its heat.

No. 7. A "**self-ventilated**" **machine** differs from an externally ventilated machine only in having its ventilating air circulated by a fan, blower, or centrifugal device integral with the machine.

If the heated air expelled from the machine is conveyed away through a second pipe attached to the machine, this should be so stated.

No. 8. A "**drip-proof**" **machine** is one provided with ventilating openings, so protected as to exclude falling moisture or dirt.

No. 9. A "**moisture-resisting**" **machine** is one in which all parts are treated with moisture-resisting material. Such a machine shall be capable of operating continuously or intermittently in a very humid atmosphere, such as in mines, evaporating rooms, etc.

No. 10. A "**submersible**" **machine** is a water-proof machine capable of withstanding complete submersion for four hours without injury.

No. 11. A "**flame-proof**" **machine** is a machine in which the enclosing case can withstand, without injury, any explosion of gas that may occur within it, and will not transmit the flame to any inflammable gas outside it.

No. 12. An induction motor in which the slip rings and brushes alone are included within a flame-proof case should not be described as a flame-proof machine, but as a machine "with **flame-proof slip-ring enclosure.**"

Stationary Induction Apparatus.

Stationary induction apparatus changes electric energy to electric energy through the medium of magnetic energy without mechanical motion. It comprises several forms, distinguished as follows:

Transformers, in which the primary and secondary windings are ordinarily insulated one from another.

The terms "**high voltage**" and "**low voltage**" are used to distinguish the winding having the greater from that having the lesser number of turns. The terms "**primary**" and "**secondary**" serve to distinguish the windings in regard to energy flow, the primary being that which receives the energy from the supply circuit, and the secondary that which receives the energy by induction from the primary.

The **rated current of a constant-potential transformer** is that secondary current which, multiplied by the rated-load secondary voltage, gives the K. V. A. rated output. That is, a transformer of given K. V. A. rating must be capable of delivering the rated output at rated secondary voltage, while the primary impressed voltage is increased to whatever value is necessary to give rated secondary voltage.

The rated primary voltage of a constant-potential transformer is the rated secondary voltage multiplied by the turn ratio.

The **voltage ratio** of a transformer is the ratio of the R. M. S. primary terminal voltage to the R. M. S. secondary terminal voltage under specified conditions of load.

The "**current ratio**" of a current transformer is the ratio of R. M. S. primary current to R. M. S. secondary current under specified conditions of load.

The **ratio of a transformer**, unless otherwise specified, shall be the ratio of the number of turns in the high-voltage winding to that in the low-voltage winding; *i. e.,* the "turn ratio."

The "**marked ratio**" of an instrument transformer is the ratio which the apparatus is designed to possess under average conditions of use. When a precise ratio is required, it is necessary to specify the voltage, frequency, load and power factor of the load.

Auto transformers have a part of their turns common to both primary and secondary circuits.

Voltage regulators have turns in shunt and turns in series with the circuit, so arranged that the voltage ratio of the transformation or the phase relation between the circuit voltages is variable at will. They are of the following three classes:

- **Contact voltage regulators,** in which the number of turns in one or both of the coils is adjustable.
- **Induction voltage regulators,** in which the relative positions of the primary and secondary coils are adjustable.
- **Magneto voltage regulators,** in which the direction of the magnetic flux with respect to the coils is adjustable.

Reactors or **reactance coils**, also called **choke coils**; a form of stationary induction apparatus used to supply reactance or to produce phase displacement.

CHAPTER XVIII.

TESTS AND EXPERIMENTS WITH DYNAMO ELECTRIC MACHINES.

The object of testing a completed machine is to determine whether it complies with the specifications under which it was constructed. Further, by actually experimenting with electrical machines a knowledge of their operation and underlying principles may be obtained.

Tests.

A. Preliminary inspection and adjustment.
B. Measurement of resistances.
C. Characteristics.
D. Efficiency.
E. Heating.
F. Miscellaneous tests.

A. Preliminary Inspection and Adjustment.

1. Tabulation of electrical and mechanical points of design.
2. Adjustment and fit of parts.
3. Lubrication.
4. Workmanship and material.
5. Mechanical strength.
6. Balance of armature.
7. Sparking at the brushes.
8. Noise.

1. Tabulation of Electrical and Mechanical Points of Design.—A careful inspection of the machine should be made while it is at rest, and every point connected with the field, armature, commutator, brushes, brush rigging, terminal block, etc., should be noted, so that the facts ascertained can be compared with the specifications, or if none are furnished, the points developed will be of assistance in making a complete description of the machine.

The general form of the field frame, the number of field spools and poles, main and interpole, and the method used to connect the terminals of the windings of one field spool to another should all be noted. The number of the terminals on each spool will indicate the form of field winding; whether series, shunt or compound. If it is a compound machine, it should be noted whether the two windings are separate or whether one is over the other, noting which is outside. An inspection will show whether the pole pieces and magnet core are an integral part of the field frame or whether they are separate and bolted together. The method of ventilation, whether it involves open or enclosed frames and use of fans, should be described.

The construction of the armature will show its type of winding, whether ring or drum, and it should be noted whether the conductors are wound directly on the armature core or are imbedded in slots. The commutator segments should be counted and the method of securing the armature windings to them noted; that is, whether they are clamped, screwed or soldered. The type and number of brushes should be noted and the mechanical design of the brush holders and the means employed to move all the brushes together should be examined. The brushes should be removed and replaced so that familiarity with the various springs and attachments may be acquired. The brushes should be rocked back and forth by the rocker arm and clamped in different positions. The terminal block should be inspected and the different terminals marked so that the series, shunt, armature and equalizer terminals can be readily distinguished. This will also show whether the machine is a long shunt or short shunt if it proves to be a compound machine. The method of connection of the machine to its prime mover or to its load should be noted; as, for example: belt drive, gear drive or direct connected.

The maker's nameplate furnishes important information, such as the power expressed in kilowatts, the revolutions per minute of the armature to produce the required E. M. F., the E. M. F. at the terminals, the current output, type of field winding, etc. This information should be tabulated so that it may be verified by tests and experiments later.

2. Adjustment and Fit of Parts.—The adjustment and fit of all parts should be carefully examined and particular attention should be given to the brush rigging. Brush holders should be accessible for the adjustment and renewal of brushes and springs; also adjustable for tension, generally without tools, and constructed to allow the proper staggering of brushes.

3. Lubrication.—All bearings should be provided with oil wells of sufficient capacity. Inspection should be made to see if any arrangement is provided to prevent oil running along the armature shaft. The best practice requires self-oiling bearings provided with split babbitted bearing linings with oil rings, visual oil gages for determining the amount of oil in pockets and drains for drawing off the oil.

4. Workmanship and Material.—Naturally the materials and workmanship of all parts of any machine should be of the best quality, and notes should be made of any particular part that shows evidence of inferior workmanship, defective or cheap material, and all windings should be carefully observed for any signs of abrasion of the insulation or outside covering. Special attention should be given to the workmanship and material of the brush rigging and springs. The best practice requires all metal portions to be non-corrosive and fitted with flexible connections between brush and holder. Brushes should be carefully examined and their quality should be such as to give perfect contact without cutting, scratching or smearing the commutator.

5. Mechanical Strength.—All the main parts of dynamo electric machines such as the base, field frames, field magnets, armature, shaft, bearings, etc., should be of such strength that they will not spring upon any reasonable force. The strength to resist centrifugal forces due to the armature revolution should be tested by running the armatures at least double their normal speed without load, and series motors should be run at four times their full-load speed. There should be no signs of weakening of any part of the armature when run for at least thirty minutes at these increased speeds.

6. Balance of Armature.—Before commencing any test involving the rotation of the armature, carefully turn it by hand or jack over the engine if direct connected, at the same time looking for any obstruction to free movement. When satisfied that all is clear make ready for the slow turning over of the armature with the motive power available.

In the case of a steam-driven unit, either direct connected or driven by means of a belt, see that the oil service is in working order, and take all the usual precautions in starting an engine: exhaust open, water clear of cylinders, drains and relief valves open, bearings oiled and the cylinders properly warmed. In turning over the armature for the first time be certain that the external circuit is open and that the brushes are raised clear of the commutator.

Open the throttle, let the engine turn slowly, and watch the rotation of the armature, noting whether it revolves concentrically. Be sure that it does not strike the pole pieces at any point; that there is equal clearance between armature and the pole pieces at all points and that it runs smoothly and free from undue vibration. The alignment of the shaft should be noticed. One that is not true soon manifests itself by heated bearings and therefore the bearings must be watched from the time the engine is started.

The perfection of balance of armatures of generators should be tested by running them at least 25 per cent above their normal speed; of shunt motors at their normal speeds; of series motors from normal to double their rated speeds, and of compound motors from normal speed to 50 per cent above normal. In all cases the armatures of well-designed machines should not show the slightest vibration.

7. Sparking at the Brushes.—The causes of brush sparking are given in Chapter XXIII and if any sparking occurs during a test, the cause should be determined and the machine credited with a defect. Modern well-designed generators and motors should show no signs of sparking whatsoever under any load or changes of load within their rated capacity. Generators under ordinary conditions should show no sparking when overloaded 25 per cent, nor should any change in the brushes be required from no load to full load to prevent sparking.

Motors to run open should show no signs of sparking from no load to full load and enclosed motors from no load to 25 per cent over-load, the brushes remaining fixed in position. Variable speed motors should not spark as long as they are running within the speed range indicated by the name-plate.

8. Noise.—All armatures of generators and motors should run at their full rated speed and load practically without noise or humming sounds and without rattling or chattering of the brushes. The causes of noise are given in Chapter XXIII. The hum accompanying the operation of most machines is due to pulsation in the magnetic pull producing vibrations in the frame. An extreme case of this noise may be traced to a weak frame, which yields considerably under the magnetic stresses.

B. Resistance Tests.

The resistance of all parts of the machine should be measured and recorded. These measurements may be classified as follows:

1. Measurement of armature resistance.
2. Measurement of resistance of field windings.
3. Measurement of insulation resistance and dielectric strength.

1. Measurement of Armature Resistance.—Armature resistance may be measured by any of the three methods described on pages 671 to 675 of Chapter XXII. By far the most common method is the volt-ammeter method. In getting the armature resistance by this method, it is very desirable to obtain not only the resistance of the whole armature circuit, but also the separate resistances of leads, brush contacts and armature itself. The brush-contact resistance acts differently from ordinary resistances and ordinarily maintains a nearly constant drop regardless of the current, the drop per brush contact varying from 1 volt in soft brushes to 1½ volts in hard brushes.

2. Measurement of the Resistance of Field Windings—Series Winding.—As this is of very low resistance, any of the methods for low resistances given in the chapter on Measurements may be used.

Shunt Winding.—Either of the two methods given in the chapter referred to may be used, viz., by the testing set or bridge, or by the voltmeter and ammeter method.

In measuring the resistance of the shunt winding, it is usual to measure both the *cold* and *hot* resistance. The voltage applied to the shunt terminals should be the normal working voltage and readings of the voltmeter and ammeter should be taken at regular intervals of time.

Curves plotted with intervals of time as abscissæ and the resistances obtained at the corresponding time as ordinates are instructive. Fig. 314 shows a curve obtained in this manner.

The numbers on the bottom line represent time in minutes and those on the left, resistance in ohms. This shows that the resistance at first increased rapidly with the time, then more slowly and became approximately constant after an hour's time of running, The greatest value is the *hot* resistance. This point will be considered further under Heating.

It is well to measure both the resistance of the winding and the resistance of the rheostat separately.

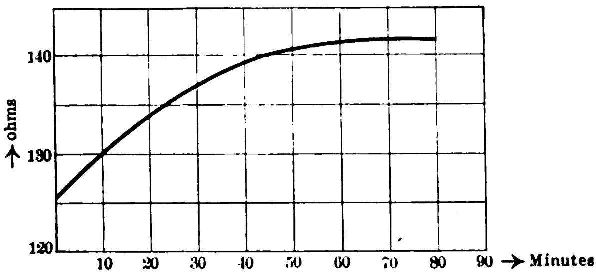


FIG. 314.—Curve of Resistance.

3. Dielectric Strength and Insulation Resistance.—There are three distinct properties which the insulation of a completed machine should possess: first, its ability to withstand the application of a high voltage for a long time without deterioration, that is its *dielectric strength;* second, its ability to offer a sufficiently high resistance to prevent any appreciable leakage of current, therefore, its *insulation resistance;* third, its ability to withstand the highest temperature to which it may be subjected under normal conditions without deterioration of its dielectric strength or insulation resistance.

The insulation of a generator or motor should first be tested by the application of an alternating E. M. F. 5 to 10 times the working pressure of the machine, applied between one of the main terminals and the frame. This insures that all conductors are well insulated from the iron parts of the machine. Naval specifications for generators and motors require the test for dielectric strength to be made at the end of a heat test with pressures of at least 1500 alternating volts to be applied for a continuous period of one minute, the source of power to be either a generator or transformer of at least 5 kilowatts capacity.

Several methods of measuring insulation resistance are given in the chapter on Measurements and also in the chapter on Care of Electric Plant and Accessories, but specifications for modern machines require a testing voltage of at least four or five times the difference of potential ordinarily to be withstood. The insulation resistance between all parts should be at least 1 megohm.

Characteristic Curves.

Characteristic curves of electrical machines have been referred to in the chapter on Generators. The characteristic curves naturally arrange themselves in the following order:

I. All machines.
  (a) Open circuit curve, magnetization curve or no load characteristic.
  (b) Short-circuit characteristic.

II. Generators.
  (a) External characteristic.
  (b) Internal characteristic.
  (c) Armature characteristic.

III. Motors.
  Speed-torque characteristic.

I. All Machines.

(a) Magnetization Curve.—This curve shows the relation between the exciting field current and the resulting E. M. F. produced by the armature at no load.

The diagram of connections is shown in Fig. 315.

The field *F* is disconnected and the voltmeter *V* is connected to the brushes of the armature *D*. The field winding is connected to an outside source of E. M. F. about 50 per cent greater than ordinarily applied to the field. The change of exciting current may be effected in either of two ways and both are given for purposes of instruction. *R,* a variable resistance may be changed, thereby effecting change of current in *F,* or the difference of potential at the terminals of *F* may be varied by the resistance *R'*. This is a resistance of sufficient carrying capacity not to become overheated when permanently connected to the source of supply and also carrying the field current. The field winding is connected to one end of this resistance, *a,* and to a movable point *c,* which slides along *ab.* As *c* is moved towards *a,* the difference of potential between *a* and *c* decreases, consequently decreasing the current through *F.*

Instructions.—Begin with the exciting current zero or very small, by varying either *R* or *R'* or both. Note the simultaneous readings

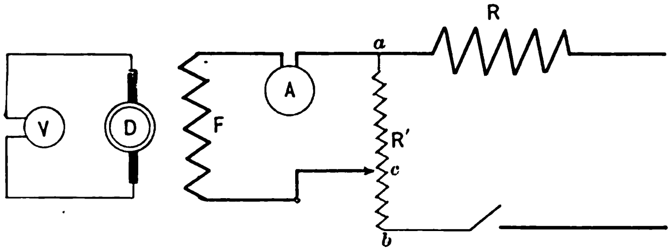


FIG. 315.—Connections for Obtaining Magnetization Curve.

of *A* and *V*. Vary the exciting current as desired and note the readings, and continue this until the maximum currents in *F* is reached. Then decrease the current by steps. For each value of *A* read *V,* and note the speed of *D.* Reduce the readings of *V* to some constant speed from the formula

$$E = \frac{E'n}{n'},$$

where E' and n' are the E. M. F. and observed speed and E the desired E. M. F. and n the normal speed.

With the observed values, plot curves, with current as abscissæ and E. M. F. as ordinates for both ascending and descending values of exciting current. It will be found that this gives two distinct curves, and the failure of the two curves to coincide is due to the *hysteresis* of the magnetic circuit.* The distance apart of the curves will be an indication of the nature of the metal used in the circuit

* See pages 168 and 169.

as regards hysteresis. Soft iron shows little hysteresis while hard iron or steel shows the effect very strongly.

The form of the magnetization curve resembles very closely that of the total circuit curve of the series generator.* This is natural, as the E. M. F. is directly proportional to the magnetization or flux passing into the armature. The flux is nearly proportional to the ampere turns of the field until the iron of the magnetic circuit becomes saturated, and then a given percentage increase of exciting current produces a much smaller percentage increase of flux, and, therefore, voltage.

(b) Short-Circuit Characteristic.—This curve is useful in the study of the comparative strengths of armature and main fields. From this curve the armature reaction in terms of field amperes is deducible. The curve is obtained by connections similar to those of Fig. 315, except that an ammeter is substituted for *V*, the scale being about 1½ times the full load current of the machine. For this test low values of field current are used. With the machine running at rated speed, a series of values of field current and armature current are obtained, which when plotted should yield a straight line. To determine the armature reaction for any particular value of armature current, calculate the armature drop corresponding to this current and look this voltage up on the magnetization curve, obtaining a field current, I_f. Look this same armature current up on the short-circuit curve and obtain a field current I_f'. $I_f' - I_f$ = armature reaction measured in field amperes.

II. Generators.

(a) Series Generators.—Although series generators are practically obsolete, they are considered here primarily for their instructive value.

The curve usually obtained is the external circuit curve. This can be found by connecting up a voltmeter to show the potential of the external circuit, and by an ammeter to show the current in the circuit. The connections are shown in Fig. 316.

* See curve *E* of Fig. 179, page 307.

The voltmeter V is connected to the terminals of the machine (note, not to the brushes) and the ammeter A is included in the main circuit in which there is a variable resistance or load R.

Instructions.—Add resistance in R until both the E. M. F. and current are quite small, and take simultaneous readings of both instruments and record them. Then vary (decrease) R by successive amounts so that successive points on the curve can be obtained. It is generally advisable to make the reading an even number of amperes for convenience in plotting. This operation may be continued either to the safe carrying capacity of the machine or until the machine is short-circuited.

For any given value of current a small change of speed produces an approximately proportional change of E. M. F., so if the speed

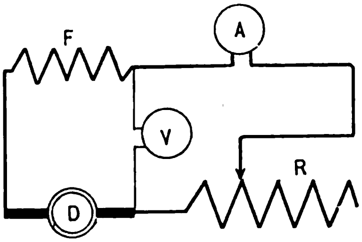


FIG. 316.—Connections for External Circuit Characteristic of Series Generator.

varies, and this should be tested at each reading by a tachometer, the voltmeter readings should be corrected to some convenient constant speed near the mean.

With the data obtained plot the amperes as abscissæ and the potential as ordinates, to some convenient scale, and draw a smooth curve through these points.

Then knowing the resistances of the armature and field, calculate the volts lost in the armature and field for each value of I, by the equation $I(r_a+r_m)$ (see Chapter XIII), and plot the internal resistance line. Then add these values vertically to each of the points on the curve corresponding to the values of I, and these will give a series of points, through which the **total circuit curve** can be drawn. These curves are shown in Fig. 179.

(b) Characteristics of a Shunt Generator—Internal Characteristic.—The characteristic curve of the internal circuit of a shunt generator is obtained by running the machine without load at its rated speed and taking readings of voltage induced at the terminals of the armature against readings of field amperes. This curve differs from the magnetization curve only by the slight armature drop produced by the shunt field current. This is usually quite insignificant since the drop due to the armature resistance is of the order of 5 per cent of the full load terminal voltage, so that with just the field current, which is about 5 per cent of the full load armature current, the armature drop in the case of the internal characteristic is only one-fourth of 1 per cent.

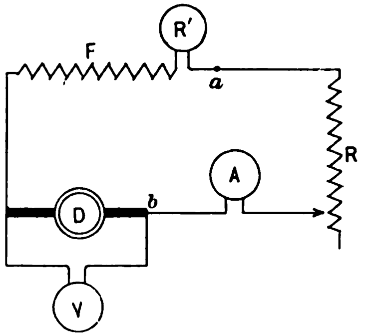


Fig. 317.—Connections for Obtaining Shunt Internal Characteristic.

The connections for the test are as shown in Fig. 317.

Instructions.—Start this experiment with very little magnetization, or with all resistance in the rheostat *R*. When the armature is running at its normal speed, and all the resistance is in *R*, take readings of *A* and *V*. Then vary the resistances till the ammeter shows an even number of amperes and read *V*, checking the speed at the same time, and so on up, until *R* and *R′* are both all cut out. Correct all speeds to that of the rated speed as previously explained.

With the data obtained, the curve can be plotted in the usual way with amperes as abscissæ and volts as ordinates. If the experiment was commenced with low resistance or high magnetization and the current stepped down, the resulting curve would lie above the curve obtained as above, due to hysteresis.

External Shunt Characteristic.—The connections for obtaining the necessary data for this curve are shown in Fig. 318.

There are no changes in the connections of the machine itself, but the variable resistance or load *R* is introduced in the external circuit in series with an ammeter.

Instructions.—Adjust the regulator in the field so that the generator at normal speed will give the normal E. M. F. at rated full load. This gives one point on the curve, full load current and E. M. F. Do not change the regulator resistance during this experiment.

Vary *R* for a new value of *A* and note the simultaneous readings keeping the speed constant.

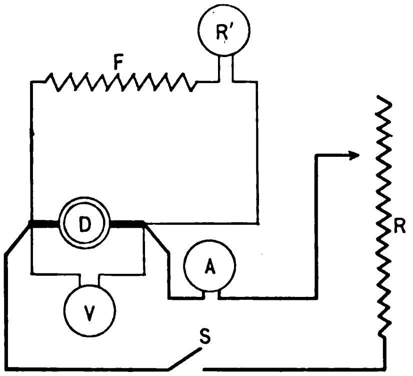


FIG. 318.—Connections for Obtaining Shunt External Characteristic.

The general form of the curve is shown in curve 1 (Fig. 181) with the method of obtaining the other curves from this one.

Precautions.—In order to imitate operating conditions the shunt-field circuit should be warmed up before the test by impressing on it its rated voltage for several hours. After setting the field current to give rated voltage at rated load, this should not be changed. In addition to constant field rheostat setting, both the brush setting and the speed must be kept constant. In taking the curve the changes in load should preferably be in the same direction to avoid hysteresis effects, which, as a matter of fact, usually have very small effect on the load characteristic. Sudden changes in load should be avoided especially in large machines owing to the resulting shock. The load characteristic should be carried as far as the heating or commutation limit of the machine will allow. In the smaller machines the load may be carried beyond the "break-down" point * where the voltage drops off very rapidly and where further decrease

* See point 1 on curve 1 of Fig. 181, page 310.

of external resistance produces a decrease of load current. (See Fig. 322.

(c) Armature Characteristic.—This is a curve that shows the relation between the external current and the field current when the difference of potential at the terminals is kept constant. When the terminal voltage tends to drop, the field current is increased to bring it back to its original value. Armature current is plotted as abscissæ and field current as ordinates. This curve is very useful in studying the compounding of a generator, as the departure of the curve from a straight line shows the change in the field ampere turns necessary to compensate for the voltage drop of the machine. Know-

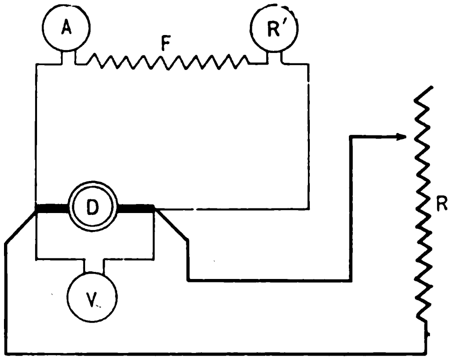


FIG. 319.—Connections for Obtaining Armature Characteristic.

ing the number of shunt turns, the number of series turns for flat compounding may be determined.

The connections for making the test are shown in Fig. 319.

An ammeter is connected in the field circuit and the usual variable resistance *R* in the external circuit.

Instructions.—With the external circuit open adjust the E. M. F. at the brushes to the value at which the test is to be made. Then close the external circuit through the maximum resistance, adjust the field regulator so as to give the same E. M. F. as before and then read *A* and *V*. Change the resistance *R* slowly, adjust the E. M. F.

to its constant value, and read A and V. The curve will have the general form shown in Fig. 320.

To use this curve for changing this shunt generator to a compound generator, the number of turns on each shunt-field coil should be known. If this be taken as N_f, then the extra field current, $I_f = 1\text{-}2$ (see Fig. 320), multiplied by N_f gives the extra ampere turns $N_f I_f$ which the series field must supply to maintain approximately con-

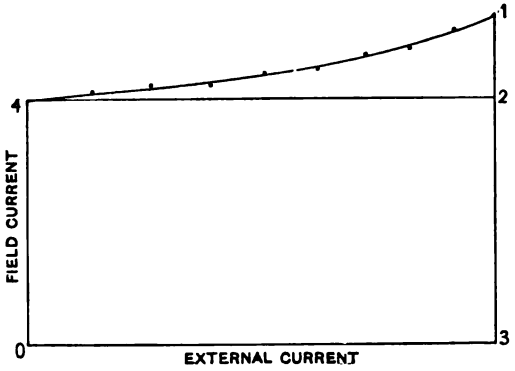


FIG. 320.—Armature Characteristic.

stant voltage. If the external current be $I = 0\text{-}3$ and the generator is to be short shunt, then $\frac{N_f I_f}{I}$ will be equal to the number of series turns per pole required to produce a flat compound external characteristic.

Characteristics of a Compound Generator.—The compound machine, being merely a shunt generator with the addition of a series field of a few turns, may be used as a shunt generator by leaving out the series coils. The connections are made and the *external* and *internal* characteristics are then obtained as previously described under the shunt generator.

To obtain the series characteristic, the shunt field is disconnected and the procedure is the same as given under the series generator.

Compound Characteristic.—The connections for obtaining the data for plotting the compound characteristic curve is shown in Fig. 321.

This shows a "long shunt" machine with the voltmeter V connected across both armature *D* and series field *F'* and the ammeter in the external circuit.

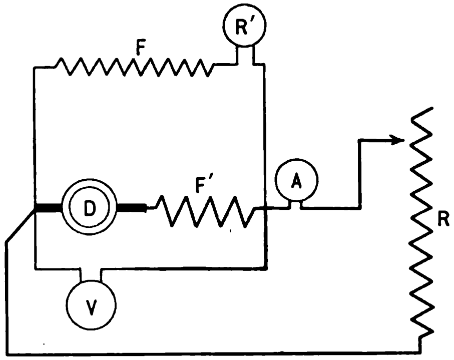


FIG. 321.—Connections for Obtaining Compound Characteristic.

Instructions.—Before closing the external circuit adjust the E. M. F. to the same value as that for the external shunt characteristic, so the two curves will start from the same point on the ordinate axis. When the field regulator is once adjusted to give the proper voltage do not change it during the experiment.

Close the external circuit through a resistance that will give a small current and take simultaneous readings of *A* and *V*, and at same time take the speed to reduce the voltage to the normal speed. Proceed by small changes in the resistance *R* and obtain values for *A* and *V*. If the voltage drops very rapidly, the series turns are probably "bucking" the shunt field and the series field should be reversed.

By disconnecting the series coils and connecting them so that the current through them is reversed, the **differential curve** is obtained. As the field is weakened by the increase of current in the series coils, which oppose the shunt, the curve drops more rapidly than the external shunt and the maximum current is much smaller.

Curves showing the relative differences between the characteristics of a compound generator are shown in Fig. 322.

The degree of compounding in a compound generator is adjusted by the *diverter,* which is a resistance designed to shunt away from the series field part of the main current. The adjustment of the diverter to produce a specified voltage at full load can be checked by this compound characteristic.

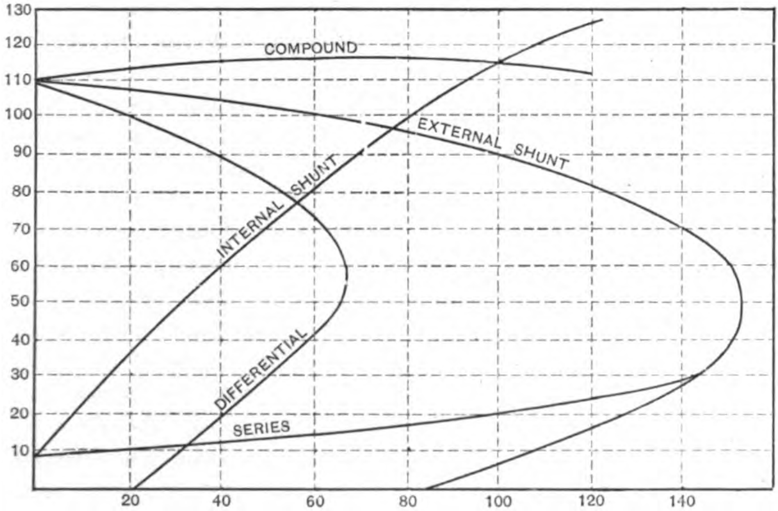


FIG. 322.—Characteristic Curves of a Compound Generator.

III. Motors.

(a) Series Motor Characteristics.—The speed-torque curve of a series motor is obtained by running the motor at its rated voltage, and absorbing the power by a brake. The connections are shown in Fig. 323. Readings of torque against speed are recorded. The speed should not be allowed to exceed four times rated speed. The motor under a moderate load to prevent its running away is started by cutting out resistance with the controller, *R*. The load should be gradually reduced by adjusting the brake until the maximum safe speed is reached. At this point the speed and torque should be recorded. Then the load should be increased step by step, taking simultaneous readings of speed

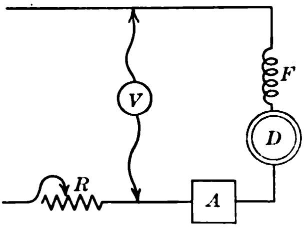


FIG. 323.—Connections for Obtaining Speed-Torque Curve.

and torque. The load should be increased until either the motor stops or the current exceeds the heating limit of the motor, which for a few minutes may be taken as two or three times the normal full-load current. For this reason an ammeter should be placed in the circuit so that the test may be stopped when the current limit is reached. The voltmeter is required to make certain that the impressed voltage remains constant and equal to the rated voltage. When the readings of speed are plotted against torque, the resulting curve is of the nature of a rectangular hyperbola.

(b) Shunt Motor Characteristics.—After the motor has been started by the ordinary starting box, the brake is adjusted to absorb no power and the speed of the motor measured. Then the load is increased, step by step, until the maximum safe overload or breakdown torque is reached. The overload limit is often fixed by excessive sparking at the brushes.

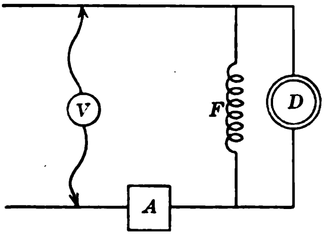


FIG. 324.—Connections for Obtaining Shunt Motor, Speed-Torque Curve.

When the readings of speed are plotted against torque, a curve, similar to the curve marked "external shunt" in Fig. 322, will be obtained, full load occurring for example at 100 and corresponding to a speed regulation of $\frac{110-90}{90} = \frac{20}{90}$ or 22 per cent.

(c) Compound Motor Characteristics.—Compound motors may be so connected that the series field acts in conjunction with or in opposition to the shunt field. The former is called cumulative compounding, the latter differential compounding. The speed torque curves, obtained just as described in (a) and (b) above, will be as in Fig. 325.

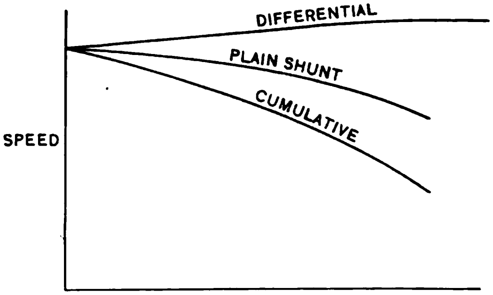


FIG. 325.

Torque.—Cumulative compounding is used to give motors a strong starting torque, while differential compounding is used to improve the speed regulation. The motor of the motor-alternator set used in radio work is differentially compounded so as to give constant speed at all loads.

Variation of Speed.

The allowable variation of armature speed of electric machines under different conditions of load and temperature depends on the kind of work for which they are designed. Modern well-designed machines should show very close regulation of speed. As illustrative of the amount of variation considered to be allowable, the specifications for machines used on ships of the navy are quoted.

For main generators the speed variation must not exceed 2½ per cent when the load is varied between full load to 20 per cent of full load, gradually or in one step, engine running with normal steam pressure and vacuum. A variation of not more than 3½ per cent is allowed when full load is suddenly thrown on or off the generator, with constant steam pressure, either normal or 20 per cent above normal. A variation of not more than 3½ per cent is allowed when 90 per cent of full load is suddenly thrown on or off the generator, with constant steam pressure at 20 per cent below normal; exhaust in both cases to be either into condenser or atmosphere.

For shunt-wound motors, the variation in speed from no load to full load is not allowed to be more than 12 per cent in motors of less than 5 horse-power and not more than 9 per cent in motors of 5 horse-power and above. Series and compound-wound motors must make their rated outputs at their rated speeds. The motor must be designed to give its rated speed when hot, with atmospheric temperature of approximately 25° C. and the speed actually obtained at the end of a heat run must be within 4 per cent of the rated. The variation in speed due to heating should not exceed 10 per cent.

For motor generators of a speed of about 2000 revolutions per minute, such as are used for gun-elevating equipment, the speed variation between no load and full load and from full load to no load should not exceed 10 per cent of normal. For those of about 1500 revolutions per minute, used in turret-turning equipment, the variation between no load and full load and from full load to no load should not exceed 6 per cent of normal.

For motors driving machine tools, the variation in speed from no load (hot) to full load (hot) shall not be more than 9 per cent in motors of less than 5 horse-power and not more than 7 per cent in motors of 5 horse-power and over. For all motors the variation from their rated speeds at full load (hot) must not exceed 5 per cent and the variation in speed due to heating must not exceed 10 per cent. For variable speed motors these conditions must be met at any set speed throughout the range.

Efficiency.

The question of efficiency of generators has been treated in the chapter on Efficiencies and Losses of Generators and of motors in the chapter on Motors. The efficiency of generating sets should be as high as practicable and still consistent with good design, reasonable cost and the specific requirements. Where thorough reliability and freedom from danger of breaking down are the first requisites, as in motors for turning turrets, elevating guns, hoisting ammunition, hoisting boats, etc., maximum efficiency is often sacrificed to reliability. Since poor efficiency means large losses and since the lost watts go over into heat, low efficiencies and low temperature rise are incompatible. Therefore the specification of low temperature rise makes for an efficient but expensive machine.

The commercial efficiencies required for the main generators installed on ships of the navy are given in the following table:

K. W.	Loads.			
	1½. Per Cent.	1. Per Cent.	¾. Per Cent.	½. Per Cent.
2.5	78	78	76	73
5	80	80	78	75
8	83	83	81	77
16	87	87	86	84
24	88	88	87	85
32	88	88	87	85
50	89	89	88	86
100	90	90	89	87
200	91	91	90	88
300	92	92	91	89

The commercial efficiency is defined as the product of the mechanical efficiency of the engine-generator set and the electrical efficiency of the generator.

Commercial Efficiency of Generators.—The commercial efficiency is determined by finding the ratio between the power utilized in the external circuit and the total power supplied to the engine driving the generator.

The methods used for determining the efficiency are of two kinds:

(1) Methods in which the driving power and the electrical output are both measured. These are called *direct* methods.

(2) Methods in which the losses in the generator are determined by electrical measurements. These losses added to the output gives the power supplied to it. These are called *indirect* methods.

Direct Method.—For any given load the power utilized in the external circuit is found by inserting an ammeter in the circuit and connecting a voltmeter to the terminals of the machine. Indicator cards are taken from all cylinders at the same time and the revolutions of the engine are taken.

From the indicator cards, the mean effective steam pressure is found, and with the area of piston, length of stroke and number of revolutions, the indicated horse-power is found from the formula

$$\text{H. P.} = \frac{2\,plan}{33{,}000}, \qquad (1)$$

where p = mean effective pressure in pounds per square inch,
l = length of stroke in feet,
a = area of piston in square inches,
n = number of revolutions per minute.

Dividing the product of the volts and amperes of the external circuit by 746 expresses the external energy utilized in horse-power, thus

$$\text{H. P.} = \frac{EI}{746}, \qquad (2)$$

and the commercial efficiency $= \dfrac{(2)}{(1)}$.

Indirect Method.—In this method the losses in the generator set are found and the efficiency is calculated from the formula

$$\text{efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{losses}}.$$

The full load output is obtained from the name-plate of the machine. The losses are partly calculated and partly found by experiment.

The calculated losses are those due to power spent in overcoming the field and armature resistances. In each case and for each particular part, the loss in watts is equal to the square of the current multiplied by the resistance, or

$$\text{watts} = I^2R.$$

Thus, for the

armature loss, $W = I_a^2 r_a$;
series-field loss, $W = I_m^2 r_m$;
shunt-field loss, $W = I_s^2 r_s$.

The losses found by experiment are those due to

Friction of the bearings, brushes, engine parts, air friction.
Eddy currents in the armature core and pole shoes.
Hysteresis losses in the armature core.

These losses can be determined by running the generator as a motor with no load, separately exciting the field at its normal value and supplying the armature with current sufficient to make it run at the same speed it did when running as a generator; or, in other words, sufficient to impart to the armature terminals an E. M. F. equal to the *total* E. M. F. generated when run as a generator.

When the generator is run as a motor with no load and separately excited, then

$$\text{input} = \text{losses}.$$

The losses now are the watts lost in the armature, due to the current producing the speed and the other losses referred to. The current and the armature resistance both being so small, the $I_a^2 r_a$ is so extremely small as to be negligible, so the input is equal to the losses due to friction, hysteresis and eddy currents.

The input is measured by a voltmeter connected to the armature terminals and an ammeter connected in the armature circuit.

Swinburne's Test.—The following indirect method of finding the efficiency is known as Swinburne's test.

Connections are made as in Fig. 326, in which

L_1L_2 are the supply mains,
D the armature of the machine under test,
F the shunt-field coils,
R_1 adjustable resistance for varying voltage at armature terminals,
R_2 adjustable resistance for regulating exciting current,
V voltmeter connected across armature,
A ammeter for measuring armature current,
A_F ammeter for measuring field current,
SR starting rheostat.

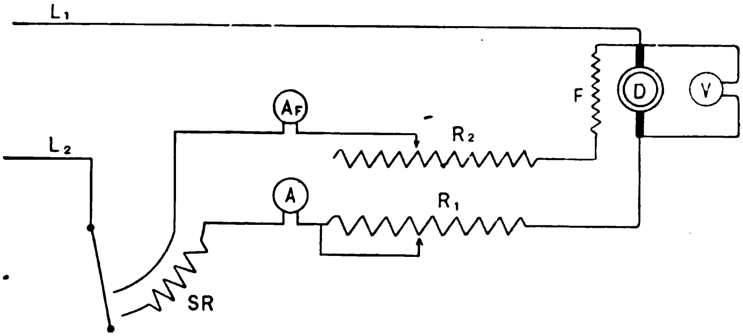


FIG. 326.—Connections for Swinburne's Test.

Instruction.—With the resistance in R_2 all out, close the switch of *SR*. This throws in the shunt field and excites it and at the same time sends current through R_1 and the armature *D*, starting it.

Adjust the resistance in R_1 until the voltage shown on *V* is equal to that produced when running as a generator. (Note that this E. M. F. must be the total E. M. F. produced, calculated for a shunt generator from $E=e+I_a r_a$, or $E=e+(I+I_s)r_a$. The voltage thus obtained should be increased a few per cent to account for the extra loss due to distortion as a result of the armature reaction on the field.) Measure the speed. If it is not the rated speed, adjust R_2 until the rated speed is obtained.

When running at the proper speed and the voltmeter shows the proper E. M. F. read *A*, and call the reading I_0.

With the data known from running as a generator as e, I, r_a, r_s, the calculation of losses is as follows:

$$I_s = \frac{e}{r_s},$$

$$E = e + (I + I_s) r_a + (0.01 \text{ to } 0.02) e,$$

$$I_a = I + I_s.$$

Loss in armature $= I_a^2 r_a$,

" shunt $= I_s^2 r_s$,

" driving $= E \times I_0$.

Total losses $= I_a^2 r_a + I_s^2 r_s + EI_0$.

Output $= eI$,

Input $= eI + I_a^2 r_a + I_s^2 r_s + EI_0$.

$\therefore$ Efficiency $= \dfrac{eI}{eI + I_a^2 r_a + I_s^2 r_s + EI_0}$.

This method is applicable to shunt, series or compound generators, the only difference being in the calculation of the losses in the armature and field, as the current flowing in them will be different in each class of machine.

This indirect method can best be illustrated by an example.

A *short*-shunt compound generator maintains a difference of potential at the terminals of 150 volts at a certain speed and supplies 20 amperes to the external circuit. The resistances are

Armature,	.18 ohm,
Series winding,	.07 ohm,
Shunt winding,	95 ohms.

Solution: The fall of potential in the series winding $= 20 \times .07 = 1.4$ volts; therefore, the difference of potential at armature terminals $= 150 + 1.4 = 151.4$ volts.

$$\text{Shunt current} = \frac{151.4}{95} = 1.59 \text{ amperes},$$

$$\text{Armature current} = 20 + 1.59 = 21.59 \text{ amperes}.$$

The fall of potential through armature $= 21.59 \times .18 = 3.9$ volts.

Taking the correction for armature reaction as 2.1 volts, the total E. M. F. corresponding to a terminal voltage of 150 is 156. At this voltage, $I_0 = 0.754$ ampere.

Loss in armature	$= 21.59^2 \times .18$	$= 84.8$	watts.
" shunt	$= 1.59^2 \times 95$	$= 240.3$	"
" series	$= 20^2 \times .07$	$= 28.0$	"
Other losses	$= 153.9 \times .754$	$= 116.0$	"
Total losses		$= 469.1$	"
Output	$= 20 \times 150$	$= 3000.$	"
Input	$=$	3469.1	"

$$\therefore \text{Efficiency} = \frac{3000}{3469} = 86.4 \text{ per cent.}$$

Commercial Efficiency of Motors.—The commercial efficiency of a motor is the ratio of the mechanical output of the motor to the electrical power supplied to it.

The electrical power supplied to the motor is expressed in watts and is found from the readings of a voltmeter and ammeter properly connected to the supply circuit.

The mechanical power is usually expressed in terms of horse-power, 1 horse-power being 33,000 foot-pounds per minute or equal to 746 watts.

The ordinary mechanical means of measuring the power given out by a motor is by some form of brake, or by dynamometer.

Brakes.—Brakes may be of several kinds, the ordinary ones being the *band* brake and *arm* brake.

In the **band** type, the brake is applied directly to a rotating pulley on the motor armature shaft, the pull exerted by the brake being on the surface of the pulley and tangential to it.

In the **arm** brake, the brake is connected to an arm and the pull is exerted at the end of the arm, the brake itself being on the surface of the pulley. Fig. 327 shows the type of arm brake in use in the Dynamo Laboratory of the Naval Academy.

Formula for Brake Horse-Power.—Power is the rate of doing work, or the rate of overcoming a force in a given distance.

In the case of a brake, the force overcome is that exerted at the surface of the pulley, due the friction of the brake band, and is overcome by the turning moment of the armature and pulley.

Let f = force in pounds exerted by the brake,
d = diameter of pulley in feet,
n = number of revolutions per minute.

The distance per revolution is πd feet, and the work done in n revolutions is $fn\pi d$ foot-pounds, and the power exerted is $\frac{fn\pi d}{33,000}$ horse-power.

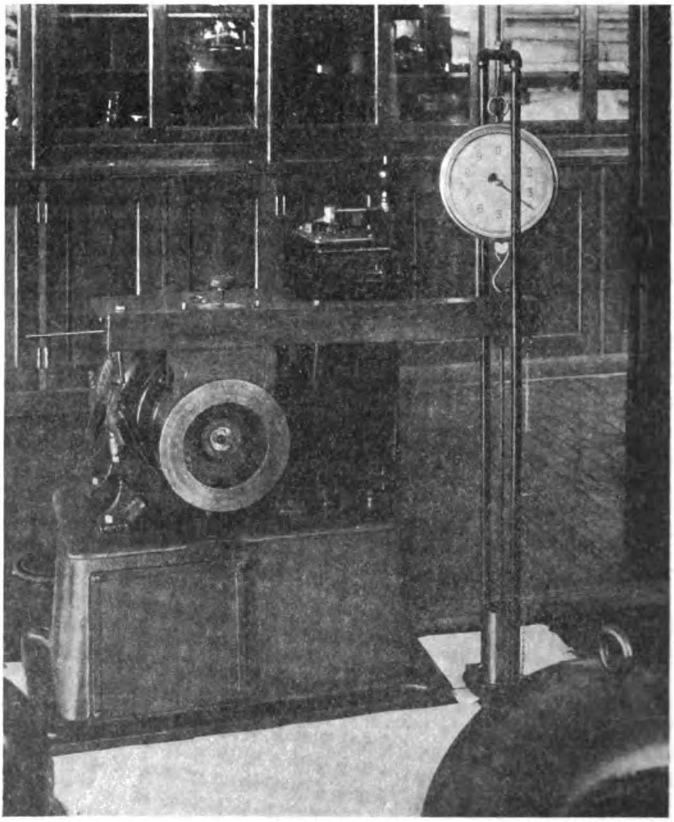


FIG. 327.—Prony Brake used at the U. S. Naval Academy.

If the arm brake is used, the force exerted by the brake at the end of the arm is fl, where l equals the length of arm in feet; and the horse-power is $\frac{fln\pi}{33,000}$.

Dynamometers.—In all types of brakes, the power which is to be measured is absorbed at the brake, going into heat at that point. The heat is usually carried away by converting water inside the brake into steam. Dynamometers are arranged to measure torque without absorbing energy.

The torque is the force exerted at the rim of a pulley on the motor shaft and measures its tendency to turn round its axis. Numerically it is equal to the force × the radius of the pulley.

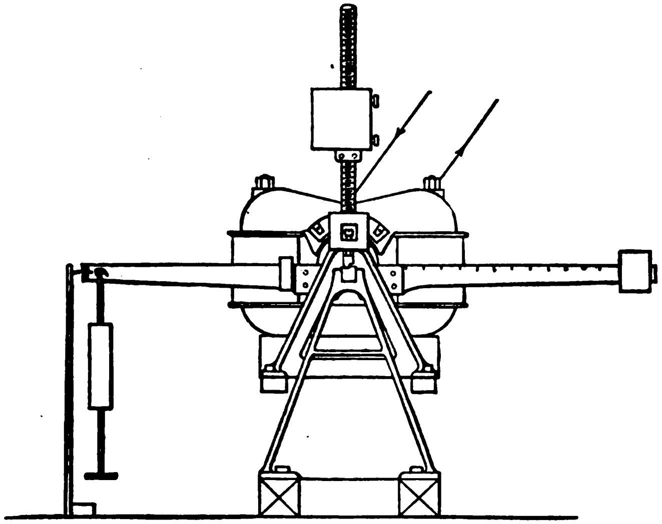


FIG. 328.—Brackett's Cradle Dynamometer.

The power given out is the product of the torque and speed. The speed is $2\pi n$ feet per minute and the power is

$$fr2\pi n \text{ or } fdn\pi \text{ foot-pounds per minute.}$$

Dynamometers are of two general kinds, **transmission** and **absorption** dynamometers.

Brackett's Cradle.—A form of absorption dynamometer is shown in Fig. 328.

The motor is bolted to a small platform which is suspended on a pair of knife edges fixed in a frame, one at each end of the cradle in line with the center of the motor shaft when the latter is properly placed. The cradle has a swinging motion about the axis of the knife edges but is otherwise rigid.

The cradle is fitted with lugs to which may be secured a graduated arm, on which slide known weights. On the cradle are upright screws on which work different weights, fitting eccentrically on the screw shafts, and by these, the center of gravity of the system may be made to coincide with the axis of suspension, and the cradle can be accurately balanced.

If necessary a belt or cord may be passed around the motor pulley and drawn taut, so as to produce a braking effect to reduce the revolutions, but without tending to disturb the balance on the knife edges.

Measuring the Output.—When the motor is accurately balanced with the weight at the zero of the scale, current may be supplied to the motor. The field will tend to rotate relative to the armature, due to the drag on the armature conductors, and this drag will pull the motor around. It can be brought back to its level position by moving the weight out on the arm, or different weights may be used at different distances to produce the balance.

The torque is equal to the product of the weight and the distance it is from the center of the shaft, or in case more than one weight is used, it is the sum of the products of each weight by its own distance.

As shown above the power exerted, or given out by the motor, is

$$\frac{fdn\pi}{33,000} \text{ horse-power,}$$

where f = weight on the arm in pounds,
d = distance of weight from center in feet,
n = revolutions of armature per minute.

It is not necessary that the weight shall be at zero when the motor is balanced, but it should be noted where it is, and then knowing the distance it has to be moved to obtain a balance, the torque is the product of the weight and the distance it has been moved.

It is also not necessary that the zero of the scale should coincide with the center of the shaft, for when the first balance is effected.

the moment of the weight about the center is counterbalanced by the adjusting weights, so the zero mark of the scale can be placed at any convenient place on the arm.

Determination of Losses.

In the preceding remarks regarding efficiency, it was shown that the difference between the input and output of dynamo electric machines was due to the losses in the machine. The losses are ordinarily grouped into two classes. The first class includes all I^2R or copper losses, occurring in armature or field circuits. These armature and series field losses increase in proportion to the square of the load current. In contrast with these are the practically constant losses, including the iron loss in the armature and pole shoes and the friction loss at the brushes and bearings. The iron loss in turn may be subdivided into hysteresis and eddy current losses. With the friction loss should be placed the windage loss, which in all but large high-speed machines is a very small quantity.

The separation of these losses is of the greatest importance to the designer, and an analysis of the losses tells him how he can best reduce the total loss. Excessive hysteresis shows inferior quality of iron and large eddy currents show poor lamination in the core. Large friction losses show inferior lubrication or excessive brush pressure.

The separation of the iron and friction losses from the total loss is given here for purpose of experiment, as such work is of great help in producing a sound understanding of the principles governing the construction of electric machines.

Determination of Iron and Friction Losses.—For this experiment make connections as shown in Fig. 326, the machine under test to be run as a motor without load. Under these conditions there are no copper losses except the extremely small loss due to the current necessary to drive the armature, which may be neglected, and all the losses are those due to iron and friction.

The experiment is similar to that for finding the efficiency of a generator (the indirect method), but more observations are taken.

Instructions.—Run the machine for some time (one or two hours) to get everything running smoothly and to allow the conductors to attain their normal temperature.

Excite the field to its normal value; that is, with the same current it would have when running at normal speed as a generator. By means of the adjustable resistance R_1 (Fig. 326) drop the voltage at the armature terminals to some small value and with the field current constant, take readings of the armature voltage, armature current and speed.

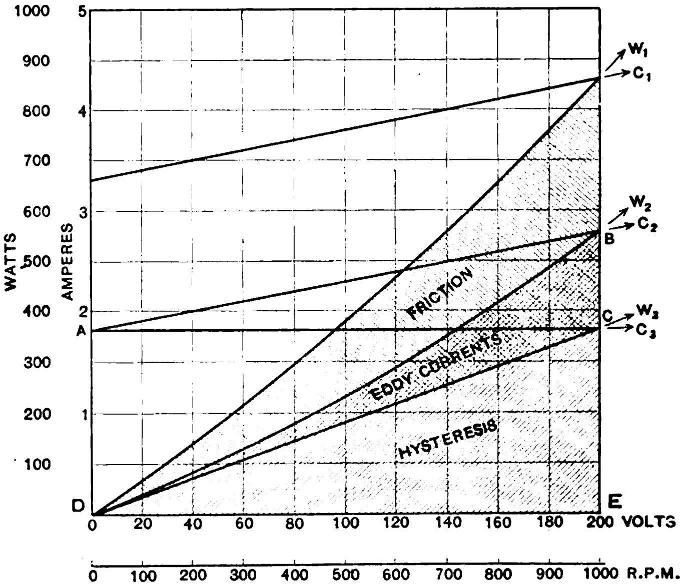


FIG. 329.—Curves Showing Separation of Losses.

Always keeping the field current constant, increase the armature voltage and take the same readings as before. Do this for gradually increasing voltages until the full voltage is obtained.

Construction.—With the two variable quantities, armature voltage and armature current, plot points to some convenient scale, making volts as abscissæ and amperes as ordinates and draw a curve through the points so determined.

Such a curve is shown in Fig. 329 marked C_1.

Since the speed and voltage are very nearly proportional with a constant excitation and no load, a scale of revolutions per minute may be added. In the example assumed 1000 revolutions per minute correspond to 200 volts.

The iron and friction loss, or **no-load loss curve** can now be plotted. This is done by plotting the volts as abscissæ and the product of volts and amperes as ordinates, a scale of watts being marked to a convenient scale on the left. Thus for volts equal to 40, the current is 3.5 amperes, and the watts $40 \times 3.5 + 140$. This is plotted with 40 as abscissa and 140 as ordinate. Similarly other points on the curve are plotted and the curve W_1 drawn through them.

The ordinates of this curve for any speed will show the "no-load" loss at that speed.

Determination of Friction Losses.—The loss due to friction of the brushes and of the bearings increases in direct proportion to the speed of the armature, while the air-friction loss varies almost as the square of the speed.

If the armature could be run without any field, there would be no iron losses, and the only loss would be that due to friction. Therefore, if a curve showing the relation between total loss and field current at constant speed be plotted, and the loss curve be extrapolated to zero field current, this intercept upon the watt axis represents total friction loss.

This curve may be obtained by running the machine light as before (Fig. 326). Start at some predetermined value of speed with R_1 all cut out. Read field current, armature current and armature volts. Increase the value of R_1 and as this drops the speed, bring the speed back to its original value by increasing R_2. Continue this operation until the armature ceases to rotate. Each time record the field current, armature current and armature volts.

This operation should be repeated for several other values of speed. The observations with low field current should be taken close together.

For each set of observations, one set for each speed, find the watt curve, or the product of armature volts and amperes. Since at constant speed, the armature volts are a function of the field current only, and the armature volts become zero when the field current becomes zero, the curve is plotted with armature volts as abscissæ, rather than field current. This facilitates the separation of losses when the friction losses are subtracted in Fig. 329. For each speed plot a series of points with watts as ordinates and armature volts as abscissæ, and through these points draw representative curves.

The ordinates of these curves for any armature voltage will give the "no-load" loss for the different speeds.

These curves are continued until they cut the axis of watts at zero voltage, and the intercepts on the watt axis will give the friction losses for those speeds.

Remembering that the curve W_1 (Fig. 329) represents the total no-load loss, the friction losses found from the curves on Fig. 330 can be transferred to it, and subtracting the friction losses from the total loss for the corresponding speed, the remainder will be the total iron losses. This will give curve W_2, the ordinates intercepted between curves W_1 and W_2 being the friction losses for the different speeds or different armature voltage.

From curve W_2, which is the **watt curve of iron losses**, the current curve C_2 can be plotted by dividing each ordinate (watts) by the corresponding abscissæ (volts), using for points on the curve, volts for abscissæ and amperes for ordinates.

Where the curve C_2 cuts the axis of watts, draw a horizontal line C_3. This line divides the ordinates of the current line C_2 into two parts, the portion below the horizontal line representing the current required to overcome the hysteresis loss, and the portion intercepted between the horizontal line and curve C_2, the current required to overcome eddy-current losses.

The area of the triangle $ABC = \frac{1}{2}BC \times AC$,

$$\frac{BC}{AC} = \tan a, \therefore \text{area} = \tfrac{1}{2}AC^2 \tan a,$$

and is therefore proportional to the square of the voltage and consequently to the square of the speed. Since eddy losses increase in proportion to the square of the speed, the area must represent the power necessary to overcome them. The area $ACED$ is proportional to DE, $\therefore$ to the voltage and to the speed, and as hysteresis is proportional to speed, this area represents the power necessary to overcome the hysteresis loss.

From the last curve C_3, find the watts spent in overcoming hysteresis, by multiplying the current ordinate by any voltage within the limits of experiment, and drawing a straight line through this point to the origin.

The losses are now completely separated and are as shown in Fig. 329. The friction losses are represented by the ordinates for any voltage (or speed) between the two curves W_1 and W_2; the eddy-current loss by the ordinates between W_2 and W_3 and the hysteresis loss by the ordinates between W_3 and volt line, and the sum of course equals the total friction and iron loss for any voltage.

Example.

The foregoing separation of losses may be made clearer by an example with assumed values to illustrate the experiment, the values taken being those used to plot Fig. 329.

In the first part of the experiment, keeping the exciting current constant and varying the voltage, the following values were obtained in columns I and II.

I. E (volts).	II. I (amperes).	III. EI (watts).
40	3.5	$40 \times 3.5 = 140$
80	3.7	$80 \times 3.7 = 296$
120	3.9	$120 \times 3.9 = 468$
160	4.1	$160 \times 4.1 = 656$
180	4.2	$180 \times 4.2 = 756$

Curve C_1 was plotted with the values given in columns I and II, and curve W_1 with values in columns I and III.

In the second part of the experiment, the friction loss, the following data were obtained by keeping the speed constant for a series of readings and observing the armature volts and amperes, the observed data being given in the second and third columns of the four tables, *A, B, C* and *D*.

A				B			
I. Revs.	II. E.	III. I.	IV. EI.	I. Revs.	II. E.	III. I.	IV. EI.
900	160	3.6	576	700	160	3.6	576
900	120	3.8	456	700	120	3.6	432
900	80	4.5	360	700	80	4.2	336
900	40	7.5	300	700	40	6.5	260

C				D			
I. Revs.	II. E.	III. I.	IV. EI.	I. Revs.	II. E.	III. I.	IV. EI.
500	120	3.3	396	300	80	2.6	208
500	80	3.1	248	300	40	3.0	120
500	40	4.5	180				

The four curves of Fig. 330 were plotted from the data of columns II and IV.

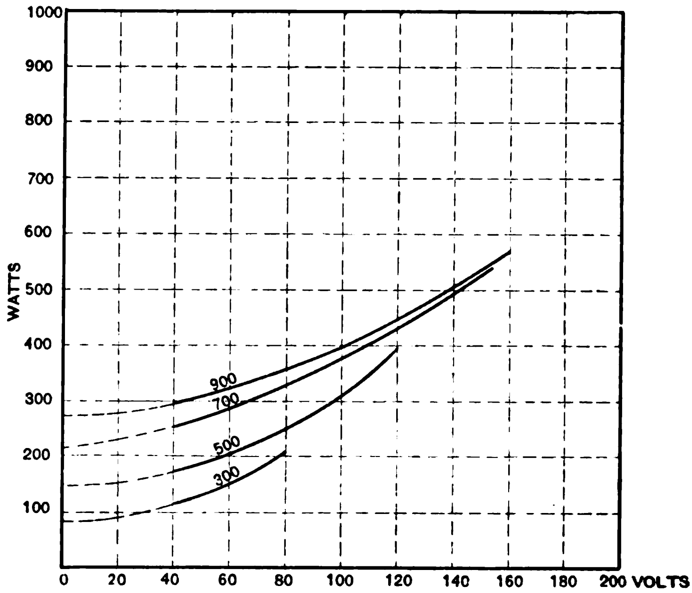


FIG. 330.—Curves of No-Load Loss.

These curves were then prolonged until they cut the vertical axis, the ordinates of which give the friction loss in watts. These values are from the curves:

Revs.	Friction watts.
900	270
700	210
500	150
300	90

To Plot Curve W_2.—On ordinate corresponding to speed of 900 revolutions subtract the friction loss for that speed, thus

For 900	revolutions	(180 volts)	756 − 270 = 486
700	"	(140 ")	560 − 210 = 350
500	"	(100 ")	380 − 150 = 230
300	"	(60 ")	215 − 90 = 125

With the values in the last column of the above table and volts corresponding to the speed of the first column, plot curve W_2.

To Plot Curve C_2.—Divide the values in the last column of the above table by the voltage corresponding to the speed, thus

EI.		E.		I.
486	÷	180	=	2.7
350	÷	140	=	2.5
230	÷	100	=	2.3
125	÷	60	=	2.1

With the values of E and I of the above table, plot curve C_2. This will be a straight line parallel to C_1 for the differences of their ordinates is a constant quantity; thus ordinate of C_1 corresponding to 180 is 4.2, to 140 is 4.0, to 100 is 3.8 and to 60 is 3.6. The differences of the ordinates is then

$$4.2-2.7=1.5$$
$$4.0-2.5=1.5$$
$$3.8-2.3=1.5$$
$$3.6-2.1=1.5$$

To Plot Curve C_3.—This has already been explained.

To Plot Curve W_3.—The ordinate of C_3 is the difference between that of C_1 for zero voltage and the differences of the ordinates of C_1 and C_2, or $3.3-1.5=1.8$ amperes.

For 20 volts then the watts are equal to

	20×1.8	amperes	= 36	watts,	
and	40×1.8	"	= 72	"	
"	60×1.8	"	=108	"	
"	80×1.8	"	=144	"	
"	100×1.8	"	=180	"	etc.

As there is a constant difference the line is straight and can be determined by taking any convenient voltage, finding the watts, and plotting the point with volts and watts and drawing a straight line to the origin.

Heating.

The energy which goes to supply the losses of an electric machine eventually reappears as heat. In the armature iron and pole shoes we have core loss and in the field and armature windings we have copper loss. The heat is at first produced at the seat of the loss and, if not dissipated there, flows to other cooler parts of the machine until finally all parts of the machine reach a steady temperature. Different types of machines are allowed different temperature limits, 30° C. to 60° C. rise above room temperature after a four- to eight-hour run being the generally allowed temperature rise. Enclosed motors are ordinarily allowed a 10° C. greater rise.

For generators used in the navy the maximum allowable rise in degrees C. is armature 33⅓°, commutator 40°, field coils 33⅓° above a standard room temperature of 25° C.

Rise of Temperature.—It is usual to measure the rise of temperature in the armature and field coils by means of the change of their resistances due to the heat produced and in the commutator and other parts by means of a thermometer.

By Thermometer.—In using the thermometer great care should be used to see that the bulb is well protected by waste or some such covering to prevent radiation and that the highest temperature is taken. It is obviously impossible to measure the temperature of coils by a thermometer with any degree of accuracy, as the inner layers, which are the hottest, cannot be reached by ordinary thermometers. Difficulty would also be found in getting the hottest part of outside layers as some parts would be cooled by the moving armature more than others.

The thermometer should have a long thin bulb and be placed flat against the surface with as much bearing surface as possible, and well covered with some non-conducting material and if possible should be read in this position.

By Resistance Method.*—This method consists in the measurement of the temperature of windings by their increase in resistance, corrected * to the instant of shut-down when necessary. In the application of this method careful thermometer measurements must

* From the Standardization Rules of the American Institute of Electrical Engineers, 1914.

also be made whenever practicable without disassembling the machine, in order to increase the probability of revealing the highest observable temperature. Whichever method yields the higher temperature, that temperature shall be taken as the "highest observable" temperature and a hottest-spot correction of 10° C. added thereto.

In the case of resistance measurements, the temperature coefficient of copper shall be deduced from the formula $\frac{1}{234.5+t}$. Thus, at an initial temperature $t=40°$ C. the temperature coefficient or increase in resistance per degree centigrade rise is $\frac{1}{274.5}$ $=0.00364$. The following table, deduced from the formula, is given for convenience of reference:

Temperature of the winding, in degrees C, at which the initial resistance is measured.	Increase in resistance of copper per ohm per °C.
0	0.00 427
5	0.00 418
10	0.00 409
15	0.00 401
20	0.00 393
25	0.00 385
30	0.00 378
35	0.00 371
40	0.00 364

In **field coils of low resistance,** where the joints and connections form a considerable part of the total resistance, the measurement of temperature by the resistance method shall not be used.

In connection with the above method, the following instructions should be carefully observed:

(a) The temperature t should be taken by a thermometer placed directly on the coil, at the time the cold resistance is taken, and has nothing to do with the cold-room temperature. In taking this cold-coil temperature care should be taken that the coil has not been recently brought from a much colder or hotter place than that in which the test is being made.

(b) The room temperature T, above which the temperature rise of the machine is calculated, must be very carefully determined.

The temperature of the room should be read from a thermometer placed in such a position that it fairly represents the temperature of the air surrounding the machine. If the room temperature remains constant during the run there will be no question as to the final room temperature; if the temperature varies, however, as is usually the case, for a short run of two hours or less, the average of the entire run should be taken; for a run of six hours or more the average of the last three hours should be taken. Conditions should be such that the room temperature will not vary greatly during the tests, and a variation in room temperature of over 10° C. during a heat run of six hours, or a proportionate change for runs of shorter duration, should in no case be exceeded. If, however, the temperature is very irregular throughout the run, or changes rapidly at the end, the test should be made over, especially if the machine is near the heating limits of the specifications.

To prevent the sudden fluctuation of room temperature due to the opening of doors, etc., it is recommended that the bulb of the thermometer registering the room temperature be inserted in a hole drilled in a small iron block, the hole to be filled with cylinder oil or mercury. This block can be conveniently made of about the following dimensions: Three inches in length, 2 inches in diameter, with a ½-inch hole, drilled 1½ inches in depth. Care should be taken that the machine under test is not exposed to drafts of air.

When measuring the field resistance for temperature use, the drop across the field copper, and not that across the rheostat, should be measured. The voltmeter leads should be connected inside the rheostat.

When measuring the armature resistance for temperature rise, the drop between the segments under the brushes, and not that across the brushes, should be measured. In order that the same path through the armature be measured each time, the two segments between which the drop is measured should be marked, preferably with a center punch.

In multipolar, lap-wound machines, the current distribution through the armature, when it is at rest, is determined by the individual brush and contact resistance. Therefore, the resistance path through the armature may be different when the cold and when the hot resistance measurements are made. To eliminate this error, all but two brushes should be insulated by the insertion of paper, or some insulating material as shown in Fig. 331. In a four-pole machine, the drop is measured between segments 90° from one another. In a six-pole machine the drop may be measured between opposite brushes, and in an eight-pole machine it may be measured between brushes 135° apart. Less current for a given drop is required under these conditions. The connections for a four-pole machine are shown in Fig. 331. It must be remembered that the drop measured this way is not the true resistance of the armature under working conditions, but serves merely to determine the temperature rise.

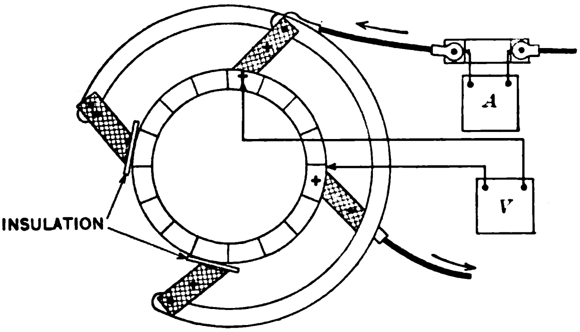


FIG. 331.—Connections for Measuring the Copper Resistance of an Armature.

Determination of E. M. F. Around Armature.

The object of this test or experiment is to show the distribution of potential around the armature. If the difference of potential is measured between the negative brush and successive bars of the commutator it will be found that in a well-designed machine the difference of potential increases regularly, though not equally, in both directions, becoming a maximum when the position of the positive brush is reached and decreasing symmetrically as the return is made to the negative brush.

Another way of determining the potential distribution is to measure the voltage induced in the coils connected between individual pairs of commutator segments at different points around the circumference. There are two methods in general use for making these measurements, depending on the relative position of the individual pairs of commutator segments to which the measuring instrument is connected.

Two-Brush Method—S. P. Thompson Method.—If the difference of potential between successive segments is required the simplest method is to use two small brushes insulated from each other and connected to a low-reading voltmeter. The connections are shown in Fig. 332.

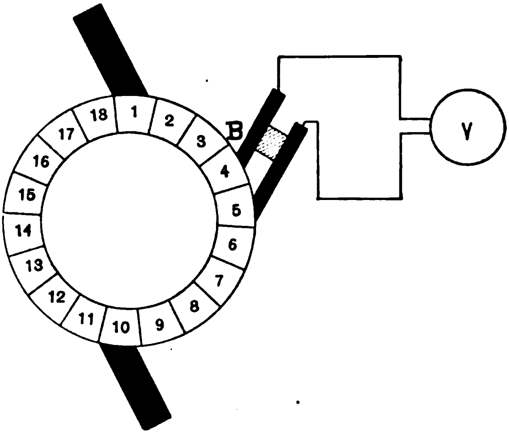


FIG. 332.—Exploring E. M. F. Around Armature.

By moving the small auxiliary brushes *B* around the commutator a difference of potential is measured on the voltmeter *V* which is proportional to the flux density at that point.

The results may be plotted in the form of a curve which will show the total difference of potential between brushes or between one brush and any particular segment as well as the difference of potential between successive segments. Such a curve is shown in Fig. 333.

In Fig. 333 the position of the negative brush is shown at 1 and the positive brush at 10, and the commutator segments are numbered consecutively from 1 to 18. If the exploring brushes are pressed against segments 1 and 2, the resulting E. M. F. would be plotted, according to some convenient scale, as an ordinate equal to $2-A$. If connected to 2 and 3, the resulting E. M. F. is plotted as $3'-B$. To this must be added that due to $1-2$, which is $3-3'$. In other words, following consecutively around the commutator, the resulting E. M. F. should be added to the total E. M. F. up to that point, and in this way the whole curve is constructed. After leaving the positive brush, the resulting differences of potential will be subtractive from the preceding one.

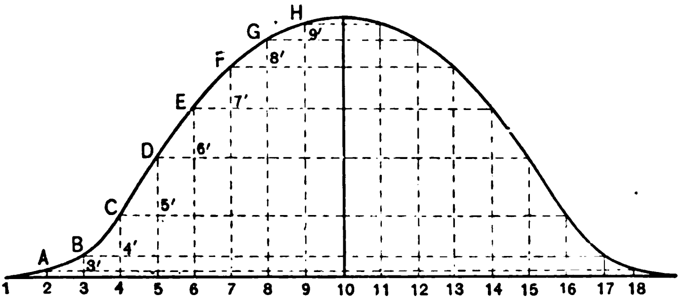


FIG. 333.—Curve of Total Difference of Potential.

To obtain the flux distribution curve, it is only necessary to plot the actual measurements ($2-A$, $3'-B$, $4'-C$, etc.), as ordinates, rather than the sums or differences, as in Fig. 333.

Single-Brush Method—Mordey's Method.—Another method of attaining the same result is to use only one auxiliary contact brush, to which the terminal of the voltmeters is connected, the other terminal being connected to one of the main brushes of the machine. By moving the auxiliary brush from one segment to another, the difference of potential is measured from the main brush to the segment, and to obtain the difference between any two segments it is only necessary to subtract the differences of potential between the main and auxiliary brushes, when the latter is connected to consecutive segments.

In using two auxiliary brushes, the voltmeter may be a low-reading one, as the greatest difference of potential is only that between two successive coils, but the single-brush method requires a voltmeter to register the complete voltage of the armature.

The results obtained by the single-brush method can be plotted in a curve exactly similar to that shown in Fig. 333. When the auxiliary brush is connected to segment 2 the resulting voltage can be plotted as $A-2$; when on segment 3 as $3-B$, etc.

To obtain the difference between any two consecutive segments, or in fact, any two segments, it is only necessary to subtract the ordinates corresponding to the segments desired.

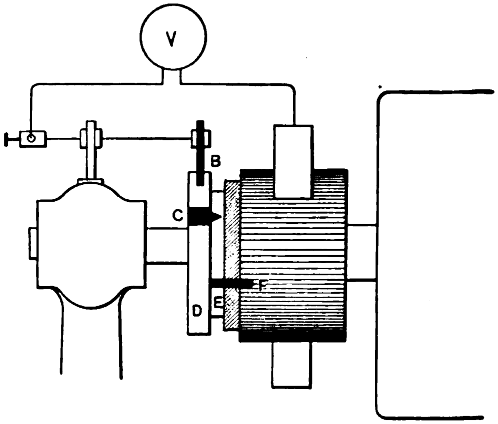


FIG. 334.—Illustrating Joubert's Method of Exploring E. M. F.

Practical Arrangement of a Single-Brush Method—Joubert's Method.—A practical method devised by Joubert for examining the E. M. F. induced at successive points on the commutator is shown in Fig. 334.

D and *E* are two wooden discs fitted around the armature shaft and can be secured in any position relative to each other. One of these is fixed to the shaft and the other is carried by it. The disc *E* is fitted with a continuous metal rim to which is connected a small spring *F* which presses against the commutator. Let into the rim of *B* is a contact plate *C* which has a small tongue which is in contact with the metal rim of *E*. The auxiliary brush *B* is fixed and rubs against the rim of *D*, making contact with *C* once in each revolution.

When *C* passes under the brush *B,* the circuit is completed through the voltmeter *V*. By shifting *D* and *E* relatively to each other, *C* and *F* are brought relatively nearer together or further apart, so connection can be made between any two segments of the commutator. This device can be so arranged that when *C* is passing under *B, F* makes contact with the adjoining segment to that under the main brush of the machine, so the voltage obtained will be that between the main brush and its adjoining segment. By shifting *F* ahead the angular distance of one segment at a time, the voltages will be measured consecutively around the commutator from the common brush.

Owing to the fact that the contact of the brush *B* with the contact piece *C* is momentary and intermittent, an ordinary voltmeter would oscillate rapidly, or if it was absolutely dead beat, it would indicate a mean lower voltage than that corresponding to the voltage at the instant of contact. For accurate results, it is better to use an electrostatic voltmeter with a condenser connected in parallel, as the voltmeter would probably have so small a capacity that it would discharge itself too rapidly to affect the slow-moving needle. A hot-wire voltmeter specially calibrated can be used to good advantage.

In making the test, it is well to connect another voltmeter to the machine terminals, and by means of a regulator in the shunt field, keep the voltage of the machine constant during the test.

One experiment can be made with no load on the machine and another with full load, and the differences in the resulting curves of E. M. F. will show the effect of the armature current on the field distribution.

Fall of Potential Around a Stationary Armature.—In the above methods, the fall of potential around the commutator has been measured by the current produced by the armature itself, but to test the similarity of windings in the different sections of an armature, an ouside source of current can be used and the fall of potential due to the resistance of the armature windings can be tested.

Connections are made as in Fig. 335.

The brushes of the stationary armature *D* are connected to an outside source of current and a strong current is sent through the armature and a voltmeter *V* connected to the brushes will show the total fall of potential through the armature windings. Another voltmeter *V'* is shown connected one terminal to one brush, the other to any segment of the commutator.

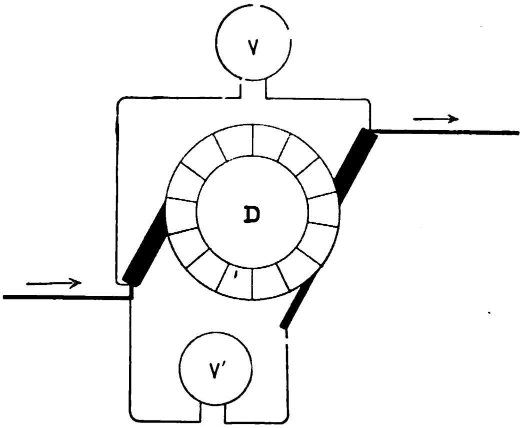


FIG. 335.—Fall of Potential Around Armature.

If the armature is sound and the windings similar there should be the same fall of potential from the leading-in point to segments each side equally distant from it, and the fall of potential should be the same from one segment to another. If it is not, it indicates a fault of some kind in the winding, and this method can be used to locate short-circuits, as a short-circuited coil would show no change of difference of potential from its adjoining coil. See page 731.

CHAPTER XIX.

INCANDESCENT LAMPS.

An incandescent electric lamp might be described as consisting of a filament or light-giving substance enclosed in a glass bulb from which the air has been exhausted. As will be described later, instead of having the inside of the glass bulb a vacuum, it may be filled with certain inert gases. The light from an incandescent lamp is due to the heating of the filament to incandescence by a current of electricity flowing through it.

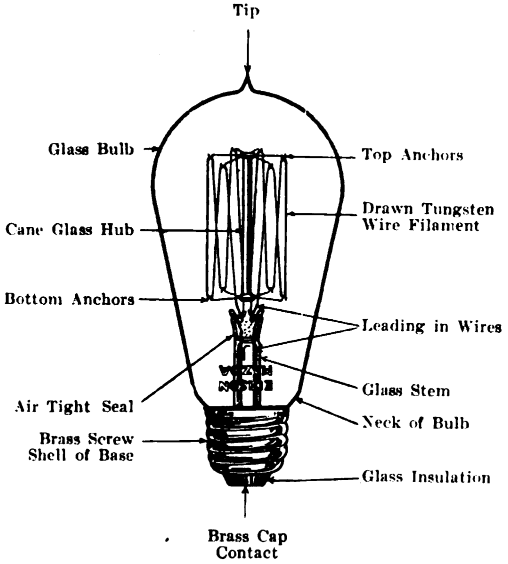


FIG. 336.—Edison Mazda Lamp.

A brass shell screw base is usually cemented to the neck of the bulb and connected to the filament by means of the leading-in wires, which, passing up through the stem and an air-tight seal, are joined to the filament. The base provides a convenient method for connecting the lamp to an electric circuit. Fig. 336 shows in detail the different parts of a Mazda lamp.

Filaments.

There are a number of different substances used for filaments of incandescent lamps. The principal requirements for an incandescent lamp filament are as follows:

1. High melting point.

2. High vaporizing temperature; that is, it must be possible to raise the filament to a very high temperature before vaporization of the filament takes place, as it is generally the vaporized particles which discolor the bulb, thereby shortening the life.

3. Selective radiation. This property in the filament means that a large proportion of the energy radiated from the filament is within the visible spectrum; that is, at the same temperature one filament has a greater selective radiation than another filament, when it radiates more energy in the form of light.

In the selection of a suitable substance for filaments the following qualities are given consideration:

1. Efficiency or the relative amount of electrical energy consumed.

2. Cost of manufacture.

The following substances have been used for the manufacture of filaments: Platinum, osmium, iridium and alloy of platinum and iridium, carbide of titanium, tantalum, tungsten and carbon. Of these substances only tungsten and carbon are now used to any extent.

While tungsten does not have as high a melting point as carbon, the temperature at which it vaporizes is much higher and it has a greater degree of selective radiation and consumes only about one-third the energy per candle-power.

Incandescent lamps, known as "Carbon" lamps, have filaments of carbon. This filament is obtained by mixing cotton in chloride of zinc solution, squirting the cellulose thus formed through a die, producing a thread which is shaped in the desired form, usually an oval, and then carbonized in a similar manner to the making of charcoal.

Lamps with carbon filaments were used almost exclusively for illuminating vessels of the navy. They have been practically replaced by tungsten lamps, although carbon lamps are still used in portables and near machinery where excessive vibration is experienced, and in dressing cables for ships' illuminating sets.

Lamps known as " Gem " lamps have a metallized filament, being a carbon filament which has taken further treatment in the electric furnace, making a filament of more metallic characteristics, and higher efficiency.

Tantalum lamps (see Fig. 337) were made with filaments of the metal "Tantalum." This metal was found sufficiently ductile to be drawn into wire of diameter fine enough for filaments for commercial lamps. The Tantalum lamp, however, has been superseded by the Mazda lamp.

The Mazda (tungsten) lamp at the present time is made with a filament of drawn tungsten wire. Inasmuch as the tungsten lamp has practically replaced all other incandescent lamps, the different processes in the manufacture of a lamp of this type will be described.

FIG. 337. The Tantalum Filament Incandescent Lamp.

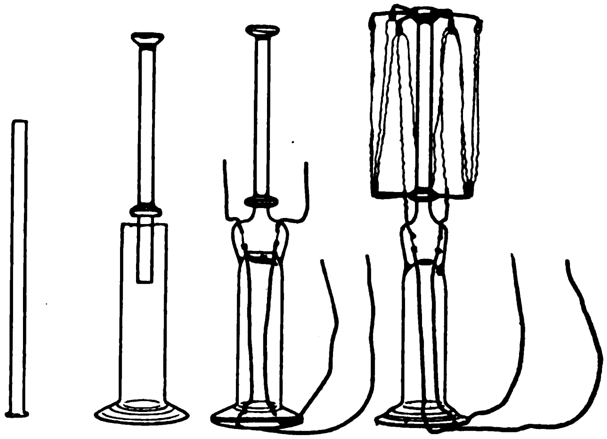
Manufacture of the Mazda Lamp.

The early Mazda lamps had filaments known as " pressed tungsten." As it was considered impossible to make the tungsten powder ductile it was mixed with a binding material resulting in a paste, which could be squeezed through dies, forming a thread from which the binding material could be reduced electrically. The completed filament consisted of hairpin loops welded together, but this construction was naturally fragile.

A method was then discovered in the laboratories of the General Electric Company by which the pure tungsten powder could be compressed into the form of rods and then passed through swedging machines, and with each passage made more workable until the tungsten rods became of sufficiently small diameter to draw through diamond dies; each succeeding die being smaller in diameter. In this manner the tungsten rods were eventually reduced to fine wires of proper diameters for different sizes of filaments.

This wire is now mounted in one continual piece in the lamp being draped on supporting anchors, resulting in a filament which is sufficiently strong to withstand all ordinary usage as it has no rigid joints and the wire itself has sufficiently high tensile strength.

Taking the different steps in the process of manufacture in order and referring to Fig. 338 the hub on which the anchors for holding the filament are placed is made from cane glass on which two beads are formed to receive the anchors; the hub is then welded to



(*a*) (*b*) (*c*) (*d*)

FIG. 338.—Illustrating the Manufacture of a Mazda Lamp. (*a*) Cane glass for hub. (*b*) Hub and stem tube. (*c*) Complete glass stem. (*d*) Completed mount.

the stem tube, one end of the latter having a flare, as shown, to which the neck of the bulb is welded. The leading-in wires are welded in the stem by means of an air-tight seal, as shown. The anchors are then inserted in the hub at the beads or buttons, and the filament is draped on these anchors and clamped at the ends to the leading-in wires, which come through the glass seal, thus forming a complete mount.

The glass bulb, as shown in Fig. 339, is received from the glass factory with a long neck and no provision at the rounded end for exhaust. The bulb is tubulated, that is a glass tube is welded to the end, leaving an air passage through which the air is later exhausted, also the superfluous glass at the neck is cut off. The completed mount is then inserted through the neck of the bulb and the neck of the bulb is welded to the flare of the stem. The lamp is now ready for exhaust.

The exhaust tube of the lamp is connected to a vacuum pump and all the air sucked out, at the same time the bulb being sufficiently

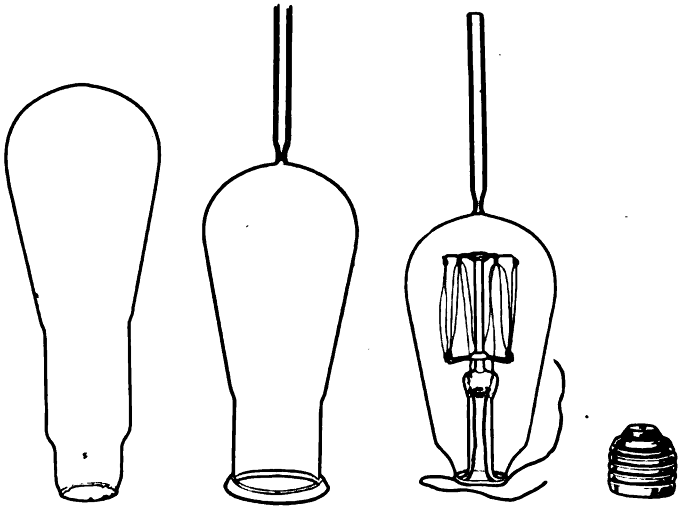


FIG. 339.—Illustrating the Manufacture of a Mazda Lamp. (*a*) Mold-blown bulb. (*b*) Tubulated bulb. (*c*) Completed mount sealed in bulb. (*d*) Edison shell brass screw base.

heated to drive out all moisture. After the bulb is properly exhausted the exhaust tube is cut off by a bunsen flame, forming a tip.

The last process is basing. The base is fastened to the neck of the lamp by cement and the leading-in wires soldered to the base at the proper point, one leading-in wire being soldered to the brass cap at the end of the base, which cap is insulated by glass from the screw shell; the other lead wire is soldered to the edge of the brass shell.

The base usually supplied is called the "medium screw base" and is shown in Fig. 339. A larger base of the same type known as

MAZDA LAMP TABLE.

Volts.	Size of lamp in watts.	Efficiency W. P. C.	Type and size bulb.	Diam. bulb.	Maximum over all, length.	Base regularly supplied.
STRAIGHT SIDE.						
				Inches.	*Inches.*	
105 to 125	10	1.30	S-17	$2\frac{1}{8}$	$4\frac{5}{8}$	Med. Screw.
	15	1.15				
	20	1.10				
	25	1.05	S-19	$2\frac{3}{8}$	$5\frac{1}{4}$	Med. Screw.
	40	1.03				
	60	1.00	S-21	$2\frac{5}{8}$	$5\frac{1}{2}$	Med. Screw.
	100	.95	S-30	$3\frac{3}{4}$	$7\frac{7}{8}$	Med. Sc. Sk.
	150	.90	S-35	$4\frac{3}{8}$	$8\frac{3}{4}$	Med. Sc. Sk.
	250	.90	S-40	5	10	Med. Sc. Sk.
	200	.80	S-30	$3\frac{3}{4}$	$7\frac{7}{8}$	Med. Sc. Sk.
	300	.78	S-35	$4\frac{3}{8}$	$8\frac{3}{4}$	Med. Sc. Sk.
	400	.75	S-40	5	10	Mog. Screw.
	500	.70	S-40	5	10	Mog. Screw.
	750	.60	S-46	$5\frac{3}{4}$	13	Mog. Sc. Sk.
	1000	.55	S-52	$6\frac{1}{2}$	$13\frac{3}{8}$	Mog. Sc. Sk.
220 to 250	25	1.30	S-19	$2\frac{3}{8}$	$5\frac{1}{8}$	Med. Screw.
	40	1.20	S-19	$2\frac{3}{8}$	$5\frac{3}{4}$	Med. Screw.
	60	1.20	S-21	$2\frac{5}{8}$	$5\frac{1}{8}$	Med. Screw.
	100	1.10	S-30	$3\frac{3}{4}$	$7\frac{7}{8}$	Med. Sc. Sk.
	150	1.05	S-35	$4\frac{3}{8}$	$8\frac{7}{8}$	Med. Sc. Sk.
	250	1.00	S-40	5	10	Med. Sc. Sk.
ROUND.						
105 to 125	15	1.15	G-25	$3\frac{1}{8}$	$4\frac{3}{4}$	Med. Screw.
	25	1.05	G-25			
	40	1.03	G-25			
	60	1.00	G-30	$3\frac{3}{4}$	$5\frac{1}{2}$	Med. Screw.
	100	.95	G-35	$4\frac{3}{8}$	$7\frac{1}{4}$	Med. Sc. Sk.
	400	.90	G-56	7	$10\frac{7}{8}$	Mog. Sc. Sk.
	500	.90	G-64	8	12	Mog. Sc. Sk.
220 to 250	25	1.30	G-25	$3\frac{1}{8}$	$4\frac{3}{4}$	Med. Screw.
	40	1.20	G-25	$3\frac{1}{8}$	$4\frac{3}{4}$	Med. Screw.
	500	1.00	G-64	8	12	Med. Sc. Sk.
TUBULAR.						
105 to 125	25	1.05	T-10	$1\frac{1}{4}$	$5\frac{7}{8}$	Med. Screw.
	25	....	T-8	1	12	Med. Screw.
	40					

"mogul screw base," requiring a special socket, is used with lamps of 400 watts and over. Another type of base as illustrated in Fig. 337 is called the "medium skirted base."

A recent departure in the manufacture of Mazda lamps of certain sizes has been in the introduction of an inert gas in the bulb; the filament is then operated in the presence of this gas, the function of the gas being to prevent rapid departure of particles from the filament and also carrying any particles that are evaporated to the upper part of the bulb, making a deposit at the neck where this deposit cuts off very little useful light.

The tungsten filaments used in lamps of this description are of a closely coiled construction; that is, the filaments are wound in a spiral coil similar to a door-spring, but of very small diameter, and this coil is mounted on supporting anchors; the purpose being to concentrate the filament sufficiently to prevent too rapid cooling by convection currents of the gas.

The efficiencies at which these lamps are operated run much higher, for example the 1000-watt 105-125-volt lamp would have an efficiency of .55 of a watt per candle, nearly twice as efficient as lamps of previous construction. The light emitted by lamps of this description is a much closer approach to daylight. This type is now made in 100-watt sizes.

Rating of Lamps.

Incandescent lamps for standard multiple circuits are rated by watts to indicate their different sizes. The table given above shows the different sizes and types available for 105-125 and 210-250 volts. The voltage of lamp is the voltage or electric pressure at which the lamp should operate to give most economical results and should correspond as nearly as possible to the actual voltage at the lamp socket.

Lamps are also made in different shaped bulbs, the most common one being the pear shape, known as the straight side bulb shown in Fig. 336. For decorative purposes round bulbs are used. Tubular bulbs are used where the conditions do not permit of using a bulb with a large diameter.

The letters used by the manufacturer to designate the shape of bulb are: "S," straight side; "G," round or globular; "T," tubular. The manufacturers use a number after the letter designation, which shows the size of bulb; this number expresses the number of eighths of an inch in the maximum diameter. For example, S-19 used with the 25- and 40-watt lamps is a pear-shaped bulb having straight sides, the greatest diameter of the bulb being nineteen-eighths of an inch, or 2 3/16 inches.

Efficiencies.*

Efficiencies of incandescent lamps are expressed at the present time in the watts per candle. Therefore, the approximate candle-power of a given lamp can be determined by dividing the watts by the watts per candle.

The efficiencies of Mazda lamps have been continually improved, that is the watts per candle have been lowered numerically until the present values are as shown in the table. Roughly speaking, the relative efficiencies of different classes of lamps are as follows:

Carbon ....3.00 watts per candle.
Gem ....2.50 watts per candle.
Mazda ....1.00 watt per candle.

The recent lamps having bulbs filled with gas, as described above, operate at efficiencies approaching half a watt per candle.

Lives of Lamps.

Most of the Mazda lamps used on standard multiple circuits have rated lives of 1000 hours; this is considerably longer than that for carbon or gem. The figures given for lives of lamps represent average values rather than individual. In this connection the lives of lamps may be compared to the lives of human beings as, while a few may fail early in life, these early failures are compensated for by those that live much longer than the average. The life of any lamp is usually the number of hours the lamp will burn before the candle-power given out has depreciated by 20 per cent due to discoloration of the bulb. In some cases, of course, the filament of the

* See pages 491 and 492.

lamp may fail before the lamp has discolored this amount. Lamps which have blackened sufficiently to be noticeable should theoretically be removed from service, as the efficiency of the blackened lamp is sufficiently less than that of the new lamp which replaces it to justify its being thrown away.

The efficiencies of Mazda lamps are so high, and the lamp has been so perfected as to be used under all conditions, that there has resulted a material increase in the standard of artificial illumination; it being practical now to obtain economically the best lighting effects for all different requirements.

Inspections and Tests.

Incandescent lamps for the navy are inspected and tested by the Bureau of Standards. The method of conducting this test is as follows:

(a) From each lot of lamps there is selected at random about 5 per cent for the purpose of determining the mechanical and physical characteristics of the lamps, the individual limits of voltage and finally the life and the candle-power maintenance. The manufacturer may present for initial test tungsten (or Mazda) lamps which have not been sufficiently burned, or aged, to have reached stable values of wattage or candle-power. The manufacturer shall arrange for the proper "aging" of such lamps as are selected for the initial limits test.

(b) **Rejection for Mechanical and Physical Defects.**—The test quantity of lamps selected from any lot of lamps shall be inspected for physical defects; and when so inspected, if a number of the lamps show physical defects incompatible with good workmanship or good service the entire lot of lamps from which test quantity was selected may be rejected without further test.

(c) **Rejected for Defective Rating.**—Lamps shall be tested at a rated voltage, current or candle-power and, when so tested, if the number of lamps in any lot falling beyond the limits allowed equals or exceeds the percentage or quantity necessary for rejection, the entire lot of lamps from which the test quantity was selected may be rejected without further test.

(d) **Selection of Lamps for Life Test.**—For the purpose of selecting lamps for life test, accepted packages containing 100 lamps or less may be grouped to aggregate not more than 250 lamps. From such groups and from accepted standard packages containing more than 100 lamps each, at least one sample shall be selected which approximates most closely to the average of the test quantity. The lamp thus selected shall be designated as the life-test lamp, and will be subjected to a life test. A second or duplicate lamp may be reserved to replace this life-test lamp, in case of accidental breakage or damage during life test.

(e) **Life-Test Voltages.**—Life-test lamps shall be operated on the life-test rack at voltages (or current) corresponding to the test watts per candle specified.

(f) **Candle-Power Measurements.**—During life test, carbon and metallized filament (gem) lamps shall be read for candle-power and current at the test voltage at approximately 50 hours, and at least every 100 hours thereafter until the candle-power shall have fallen 20 per cent below the initial candle-power or until the lamp breaks, if within that period. Tungsten (or Mazda) lamps shall be read for candle-power and current at the test voltage at approximately one-twentieth of the test-life period corresponding to the test watts per candle, and thereafter at such intervals as shall afford approximately five determinations until the average candle-power shall have fallen 20 per cent below the initial candle-power or until the lamp breaks, if within that period.

(g) **Test Life.**—The number of hours each lamp burns until the candle-power has decreased to 80 per cent of its initial value, or until the lamp breaks, if within that period, is known as the test life. Lamps which are accidentally broken, but not burned out on test, shall not be counted to diminish the average performance. In case any life-test lamps are broken or damaged before the life test is completed, the average performance of all lamps of the same class, size, etc., tested under the same contract, shall be assigned to the package represented. On all life tests for determining test life and candle-power, each package or group of packages which will be affected by the results of the test shall have at least one lamp on such test.

(h) **Voltage Regulation.**—Accurate recording voltmeter records shall be obtained during the life test on lamps to show the variation of the voltage on the circuit. Variations of voltage are not to exceed one-quarter of 1 per cent above and below the test voltage.

(i) **Conditions for Rejection.**—The failure of the lamps to conform to the specifications as to mechanical and physical characteristics, or to initial limits may cause their rejection. Any group of the lamps initially inspected may be rejected, provided such group is represented on the life test by at least four lamps which give an average test-life value less than the test-life value specified.

Illumination.

Illumination is the amount of light falling upon some unit of area, as a square foot, of the surface to be lighted and is independent of the nature of the surface, and the light may be either reflected, absorbed or transmitted. The illumination depends upon (1) the quantity of light from the source and (2) the distance between the body illuminated and the source. The unit of illumination generally accepted is the *candle foot,* being that amount of light falling upon a body at a distance of one foot from a standard candle. The intensity or amount of light per unit area also varies inversely as the square of the distance from the source of light. The question of the kind and location of incandescent lamps for general illumination on board ship is one that presents few difficulties; but one that creates at times considerable criticism. One candle foot is a convenient illumination for reading. For the ordinary heights on shipboard, one 16-candle-power lamp will illuminate well about 50 square feet of surface. As a matter of efficiency, pure and simple, that is to get the greatest amount of light from a given power, it would appear that all lamps installed should have naked, clear glass bulbs; but other questions than efficiency, especially on shipboard, arise, such as personal taste, structural details and the effect on the eye in reading, writing or working.

Before the introduction of the present prismatic fixtures it was usual to use frosted globes in cabins and staterooms. It was considered desirable to use these, though some of them absorb as much as 60 per cent of the light emitted. This loss of light seems a great waste, but the loss of efficiency is not as much perhaps, as would seem on first glance. The filament in a frosted globe is invisible and the whole bulb looks as though it were the source of light, and the luminous area being thus enlarged, there is less contrast between the source of light and the objects lighted. In realty, the frosted globe is a better dispenser of light than the clear globe, each little particle of the rough glass acting as a prism, refracting the rays in all directions. A room with a naked gas flame appears poorly lighted compared to the same flame surrounded by a globe, although the light emitted is certainly less in the latter case. It is often a question whether for reading or desk work a clear bulb high up or a frosted one low down will give the best results; the amount of light received being not far from the same in both cases; the clear one losing in intensity due to its distance away. It seems perfectly proper not to use clear globes when they come within direct and constant range of the eye, as the pupil of the eye will involuntarily contract at the dazzling light, and it is doubtful if more rays actually enter the eye than in case of the frosted globe.

Prismatic reflectors are now used in ceiling fixtures, electroliers and bracket fixtures for desk lights. These reflectors diffuse and disperse light rays and have made a great improvement in the general illumination on board ship.

Overhead lighting seems to be best adapted for ship's use for standing lights in open spaces where men are not berthed, and side lighting where they are. In store-rooms and passageways, it is usual to place the lights where they are least in the way of movables, general illumination only being required.

Simply as a matter of illumination and uniform distribution of light, a small number of low candle-power lamps is better than one lamp of the combined candle-power, thus four 16-candle-power lamps would give a better general effect than two 32's, although no more power is absorbed.

The question of color of sides or ceiling of a room has a great deal to do with the lighting effect. Dull and dark surfaces absorb as much as 80 per cent of the light incident on them; while clean, white surfaces will reflect that much, adding to the general effect. With fairly white walls, a rule which allows two watts for every square foot of floor area, is one that would give more than ample illumination.

The Nernst Lamp.

Although the Nernst lamp has not been used in the naval service, it is of interest on account of the principles involved in its construction and of the high efficiencies obtained.

This lamp differs from the ordinary incandescent lamp in that it is not enclosed in a vacuum, and instead of the filament being made of carbon or tungsten, it is made of some highly refractory oxides "rare earths," such as zirconia, thoria or yttria, in the form of little rods and mounted on platinum wires by means of a paste of the refractory oxides. The lamp is operated in air and is protected by the very high melting point of the filament. This filament is a non-conductor when cold, but becomes a conductor when heated and its resistance decreases as the temperature increases. This is corrected by a steadying resistance in series with the filament, and including this resistance, the efficiency varies from .8 to 1.8 watts per candle-power. The steadying resistance, containing hydrogen at low pressure, is enclosed in a glass tube consisting of a coil of fine iron wire to protect the wire from oxidation. The resistance of iron wire increases greatly at a temperature near redness and if the lamp is so constructed that the temperature of the steadying resistance is just below this critical point when the lamp is operating normally, any tendency of the lamp to take excessive current due to the decrease in the resistance of the filament is prevented by the sudden increase of resistance in the iron wire.

In order to make the filament a conductor, its temperature is raised by what is called a *heating resistance* in shunt with the filament and close to it. The heater consists of one or more clay tubes wound with high resistance and covered by fire-clay. When the filament commences to conduct, a cut-out disconnects the heater.

This lamp operates more efficiently with alternating current than with direct current. The Nernst lamp was used to some extent for outside illumination and for illuminating large interior spaces. It is now becoming obsolete due to the higher efficiency and numerous advantages of high-powered incandescent lamps having filaments of drawn tungsten.

CHAPTER XX.

ARC LIGHTS.

The arc light is the oldest form of electric light known. Until recently it found no practical use for lighting on shipboard, but now it is used in large spaces for general illumination as in the fire-rooms of large modern vessels. Arc lights are used on board some of the later battleships to supply the necessary illumination for coaling ship at night. The application of the arc light to the focus of a reflecting mirror, spherical or parabolic, in an enclosure to give a beam of reflected light gives the search-light.

General Principles.—If two carbon points, forming part of a closed circuit in which a current is flowing, be separated sharply a short distance and the current is strong enough, a spark will jump from one to the other. If the electromotive force across the terminals of the arc is high enough, a series of sparks will continue to jump from one to the other and if the distance between them is not too great, a flame will soon form, and this flame gives out light and heat. The explanation is as follows: The current passing from one carbon to the other is suddenly arrested when the carbons are separated, or more properly speaking, the current meets with a greater resistance, that of the air between the points, and the first spark is due to the high E. M. F. of self-induction. The effect of this sparking across is to reduce the resistance of the air gap by filling it with the volatilized vapor from the carbon and the current continues to flow through this resistance, the result of which in a short time is to heat the air gap, to such degree that it becomes incandescent.

The incandescent flame produced between the points of the carbons has a violet appearance, and from the fact that the original source of E. M. F. was a voltaic battery, it is commonly called the "voltaic arc." The word arc is a corruption of "arch," which was originally used to designate the shape of the flame.

Production of the Arc.—The operation of producing an arc by first bringing the carbons in contact and then separating them is commonly known as "striking the arc." The reason for this preliminary contact is that it would require a very high E. M. F. in the circuit to start an arc across even the thinnest filament of air between the carbons. When the carbons first touch and current flows between them, the junction gets very hot owing to the resistance of the imperfect contact, and when separated the high induced electromotive force breaks down the air resistance and volatilizes some of the carbon, which lowers the resistance sufficiently to allow the current to continue to flow.

Electrodes.—The choice of electrodes used with the arc is practically limited to carbon in some form or other. The intensity of light depends on the temperature at which volatilization takes place, and most metals have a low temperature of volatilization compared with carbon, and their temperatures of incandescence are very near their melting points. Carbon cannot be melted into a liquid state, but passes direct from the solid into the gaseous state, or volatilizes, only at a very high temperature.

Form and Temperature of the D. C. Arc.—The result of the great heat formed in the arc is to heat the carbon the current leaves, the positive carbon, and this heat produces a carbon vapor that is projected across to the negative carbon. The vapor helps to form a conductor for the current and becomes incandescent. This incandescent vapor is not the chief source of light, for solids are better radiators than gases, and the carbon tips are much hotter than the vapor. The temperature is so high that the positive carbon actually boils, and this glowing portion is the chief source of light.

The vaporization goes on most intensely in the center of the positive carbon, lessening as the distance is increased from the center, and this burns a hollow-shaped cavity in the positive carbon forming what is known as the **crater.** This crater is the source of most of the heat and light, very little coming from the arc, and scarcely any from the negative carbon.

As the carbon vapor is projected across to the negative carbon, part of it condenses and builds up this carbon to a conical point, though the carbon as a whole burns away.

The positive carbon is supposed to be at a temperature between 5000° C. and 6000° C., while the negative carbon is probably between 2000° C. and 3000° C. On account of this difference in temperature, the positive carbon wastes away faster than the negative one, and, as it has been said, part of the vapor from the positive carbon condenses on the negative one.

The above considerations are only true for arc lights produced by continuous currents. If the arc is produced by alternating currents, the electrodes are acted upon alike in every particular, for one is positive at one instant and negative at the next; and they will be consumed at equal rates and will assume the same shape at their tips.

In continuous currents, the rate of consumption of the positive carbon is about twice as great as that of the negative one, and the rate of consumption depends also upon whether the arc is enclosed or not.

Resistance of the Arc.—When the arc is in operation the relation existing between its terminal electromotive force current and resistance is not given by Ohm's law. If the current is kept constant the value of the electromotive force is given by the equation $E=A+BL$ where A and B are constants for the same conditions and L is the length of the arc. When the length of the arc remains constant the electromotive force is given by the equation $E=m+\frac{n}{I}$ where m and n are constants for the same electrodes and I the value of the current. The value of A or m in the above equations is about 39 volts. It thus appears that a minimum E. M. F. of about 39 volts is required before the arc can operate and that the total E. M. F. is the sum of this E. M. F. and a variable factor, which is a function of the current and the length of the arc. From the above equations it is evident that the resistance of the arc increases with an increase of length, but decreases with an increase of current. There have been many theories advanced to account for the action of the arc, but it is generally considered to be due to the thermal effect and the initial drop of about 39 volts is believed to measure the energy required in volatilizing the carbon.

An arc lamp has one length of arc with which it will act best, and a lengthening of it will produce *flaring* of the flame, and the flame will leave the tips and burn around the edges, while a shortening will produce violent hissing and sputtering. With the proper length of arc the flame will burn quietly and smoothly.

Carbons.—The carbons used for arc lights are generally made from graphite, a powdered form of carbon, deposited on the inside of the retorts used in the manufacture of coal gas. It is powdered, mixed with a syrup to make the particles adhere firmly and then molded in the proper form and baked hard. They are made with an inner core of softer carbon, having less resistance than the outside, thereby tending to hold the current near the center of the carbon, facilitating the first formation of the crater in the center and keeping it there. The finished carbons are given a thin electroplated coating of copper which increases the original conductivity of the carbons, besides adding to its duration from 30 to 40 per cent.

The size of the carbons depends on the current used, one for 50 amperes, as a search-light, requiring a diameter about $\frac{22}{32}$ to $\frac{24}{32}$ of an inch. On account of the boiling of the positive carbon, it wears away about twice as fast as the negative one, this last losing by the incandescent particles of carbon being thrown against it, tearing and wearing it away. The negative carbon is smaller in diameter than the positive as it does not lose as much as the positive. The lengths depend on the time they are required to burn, one 12 inches long will burn from 7 to 12 hours in an open arc, but in a closed arc, a pair of ordinary carbons will sometimes last 150 hours.

Regulation of the Arc.—While the arc lasts, the carbons are quickly consumed, and the air gap widens until a point is reached when the resistance is so great that the current will no longer maintain the arc and the flame or arc is extinguished. To relight, the carbons must be touched again and at the instant the current flows must be separated the proper distance.

The lamp of an arc light must then automatically (1) *cause the regular and gradual approach of the carbons towards one another, or one toward the other;* (2) *produce the initial spark by bringing the carbons in contact and separating them the proper distance at the instant current is established;* (3) *hold the carbons at a certain distance, called the length of arc, previously determined for the current used and the intensity of light required.*

The lamp of a search-light must satisfy the above three conditions and in addition must (4) *provide means by which the arc is kept continually in the focus of the mirror,* as the positive carbon wears away faster than the negative one. All four of the above conditions are satisfied in the construction of the search-light lamp, partly by mechanical and partly by electromechanical means.

Principles of Regulation of Search-Light Arcs.

Arc lights, used as search-lights on board ships, require from 45 to 65 volts between the carbons to produce and maintain a steady arc depending on the current, about 39 volts being absorbed in doing the work of vaporizing the carbon. As search-lights are worked in parallel with incandescent lamps, requiring a higher voltage, a dead resistance must be inserted in each search-light circuit to cut the voltage down to the required difference of potential between the carbons. As the light given out by the arc depends on the number of watts absorbed, both the voltage and amperage may be varied, the former, however, within very narrow limits.

We have thus two electrical factors to vary, volts and amperes, the varying factors being the length of arc and the resistance in the circuit. These four are intimately connected, a variation in either the length of arc or of the resistance producing changes either in the difference of potential or current or in both.

For a certain maximum length of arc, the least difference of potential between the carbons is fixed, and with this length of arc the current may be varied by changing the dead resistance. If from any cause the length of arc becomes smaller the difference of potential decreases, but the current increases without any change in the dead resistance. So, if a certain difference of potential is decided on, the current may be varied by a change in the dead resistance.

If a certain current is decided on, it can be obtained by changing the length of arc, or if that is fixed, by changing the resistance, or both may be changed.

If both the differences of potential and current are fixed, the former can be regulated by giving the maximum length of arc, and then the current can be obtained by varying the dead resistance. This last condition is the one generally adopted in actual practice, the difference of potential or maximum length of arc, being adjusted by the tension of a spring acting against the mechanism which feeds the carbons together, and this then being a fixed quantity, the desired current is obtained by one certain fixed resistance. This presupposes that the lamp is perfectly automatic, that is, it keeps the arc constantly at the same length, and if such were the case, it would require no further attention.

However, no lamp is perfectly automatic, and any consequent change in the arc may be corrected, while the lamp is working, by varying the resistance.*

In the earlier lamps, there was no provision made for feeding the carbons apart, if by any chance they approached too close; and while they were naturally wasting away, the current had to be controlled by the dead resistance. Later designs provide for feeding the carbons in both directions.

Action of the Dead Resistance.

Fig. 340 shows the action of the dead resistance in the circuit in causing the necessary drop in potential, R being the resistance introduced in series with the main current and R' representing the resistance of the arc.

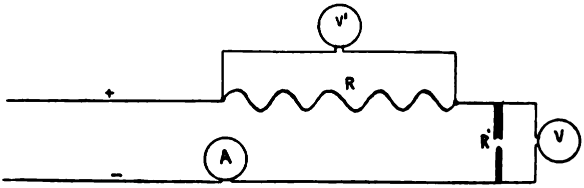


FIG. 340.—Action of Dead Resistance.

If the carbons are far apart, so that R' is practically infinite, a voltmeter connected as shown at V would indicate the full voltage of the circuit and one connected to the terminals of the resistance R would not indicate, the current through it being negligible.

* In practice, however, difficulties regarding excessive current consumption, improper voltage, etc., are generally corrected by a very slight adjustment of the spring that controls the position of the carbons.

If the arc is once struck so that the resistance of the main circuit is very much lowered, and a large current flows through R', V will then indicate the difference of potential at the carbons, or the fall of potential through R', and V' will indicate the fall of potential through R. Knowing the current desired and the necessary drop through R', R may be calculated to give the proper conditions. When the current is flowing the sum of the two readings of V and V' will be the same as that indicated on V when no current was flowing through R'.

The figure shows a typical search-light circuit, ammeter A being inserted in the circuit, V' connected as shown, V may be omitted, as the difference of potential at the carbons can be obtained by subtracting the reading of V' from that of the switchboard voltmeter.

The Necessity for Using a Ballast Resistance when Operating Arc Lights from Constant Voltage Mains.—By referring to the equations given in a preceding paragraph on the resistance of the arc it will be apparent that an arc light cannot be operated from constant potential mains without a dead resistance in series with the arc. Take the equation $E = m + \frac{n}{I}$ and suppose that the arc is operating successfully from a constant potential main. If for any reason there should be a slight decrease of current, the electromotive force required to maintain the arc would be greater than that available and this would result in a further decrease and the arc would go out almost instantly. If on the other hand the current should increase slightly this would reduce the E. M. F. required to maintain the arc and this would further increase the current which would increase almost immediately to an excessive value. There is no mechanism which would act quickly enough to obviate this difficulty. By using a dead resistance in series with the arc, sudden excessive variations of the current are avoided and a mechanism can be devised to control the arc. A resistance used in this manner as illustrated in Fig. 340 is called a ballast resistance. The ballast resistance is so designed that when the arc is supplied with the normal current the electromotive force across the terminals of the arc will be that which is theoretically required to maintain the arc under the given conditions.

Calculation of Ballast Resistance.—Suppose a search-light is to be worked at 50 volts, and to be sufficient size to absorb 50 amperes, then the resistance of the arc would be, $R = \frac{E}{I}$ or $R = \frac{50}{50} = 1$ ohm. If the full voltage was 80, the fall through the resistance R' must be $80 - 50 = 30$ volts. The current through R' being 50 amperes, by Ohm's law $E = IR$ or $R = \frac{E}{I}$, $R = \frac{30}{50} = \frac{3}{5}$ ohm.

The total resistance then in circuit is $\left(1 + \frac{3}{5}\right)$ ohms. $I = \frac{E}{R}$ where E and R represent total E. M. F. and total R,

or $$I = \frac{80}{1 + \frac{3}{5}} = 50 \text{ amperes.}$$

This is also arrived at as follows:

CD is the fall through the arc and DE is the resistance of arc, AB is total fall and x is the resistance to be inserted, then by similar triangles (Fig. 341),

$$\frac{AB}{CD} = \frac{1+x}{1} \text{ or } \frac{80}{50} = 1 + x \text{ or } x = \frac{3}{5}.$$

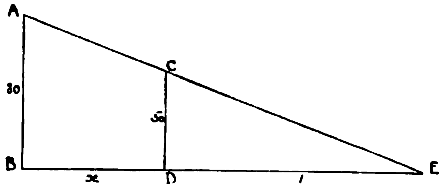


FIG. 341.

Horizontal Lamp.

Having now shown what a good automatic lamp should be capable of doing as explained under regulation of the arc, a description of two horizontal lamps now used in the service will be given.

Fig. 342 is intended to show the general working mechanism of the single feed lamp and the action of the current in making it automatic. Current is brought to the lamp from slide contacts in the projector, these contacts receiving current from the mains through a switch in the pedestal of the projector. When the lamp is placed in position in the barrel of the projector, the terminals of the lamp press against the slide contacts, making sliding connection, to enable the lamp to be moved in and out from the mirror for the purpose of focusing. The negative lamp terminals is shown at *a*. The corresponding positive terminal is not shown in the figure. From the positive terminal, the current flows around an electromagnet *b* in series with the main current; the end of the magnetiz-

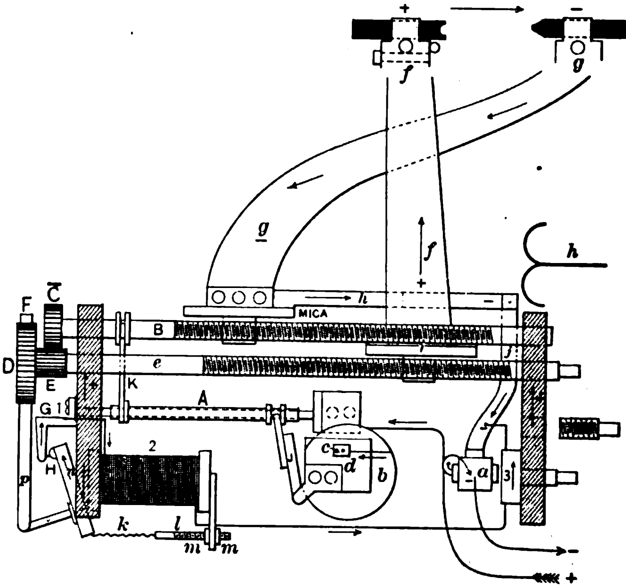


FIG. 342.—Horizontal Lamp.

ing coil being secured at *c*, on the iron piece *d*, which in turn is secured to the core of the electromagnet. The iron piece *d* is in contact with the metal framework of the lamp, the sides of the frame being shown removed. Any part or point of the frame may be considered as the positive terminal of the arc, as it is in direct metallic connection with the main current.

From the piece *d* in contact with the frame, current finds its way through the end pieces of the framework, through the screw spindle *e*, through the two upright supports of the positive carbon *f*, through the positive to the negative carbon, down the two uprights *g*, through the connecting piece *h* to *j* and down the latter to the negative terminal of the lamp. The uprights *g* are insulated from the rest of the framework, thus allowing all the framework to be of the same potential. Current also finds it way from the side at *i* to the positive uprights, the uprights *f* being provided with flanges sliding in slots in the side of the frame.

For the automatic working of the lamp, there is a shunt circuit controlling the automatic mechanism. The positive terminal of this shunt circuit may be considered as any part of the framework, such as the point where the armature *n* of the electromagnet 2 is pivoted to the frame. The shunt current from here flows through the armature *n*, through the flat copper spring, *H*, which acts as a contact breaker, through the contact point on the bracket *G*, through the bracket *G* which is insulated from the frame, through and around the electromagnet 2, to the automatic switch 3 and to a point on *j*, acting as the negative terminal.

The two uprights *f* are connected at the bottom by a cross-piece to which is secured a lug with a thread cut in it and through which screws the spindle *e*. A rotary motion given to *e* causes the uprights carrying the positive carbon to move along the spindle. Motion is given to the uprights *g* carrying the negative carbon in a similar manner by the rotation of the spindle *B*. This spindle also has a lengthwise motion through its bearings in the ends of the frame, allowing the uprights to be moved a short distance without a rotary motion of *B*. This provision is made in order to strike the arc, and to do this one carbon must move independently of the other, thus necessitating a flexible connection. In striking the arc, the two uprights *g* move and they are connected to the upright *j*, a rigid solid conductor, by a conductor of flexible copper ribbon, of a shape shown on the right at *h*, so when *g* is moved to the right or left, the copper ribbon bends back or unrolls on itself.

The spindles *B* and *e* are connected to each other through the gear wheels *C* and *E*, and if the spindle *e* is turned the carbons are either brought closer together or further apart, the threads being right-handed and of equal pitch. To make provision for the positive carbon wasting away faster than the negative one and in order to keep the arc always in the same place, the gear wheel *C* is twice the size of *E*, so a motion given to *E* will only cause half the motion in *C*, or in other words, any rotary motion given to the spindle *e* will cause the positive carbon to either approach or recede from the negative one at a rate twice as great as the negative carbon moves.

The uprights have clamps to hold the carbons. The upright for the positive carbon is fitted with tangent screws, by which the end of this carbon may be slightly raised or lowered, or turned to the right or the left so as to accurately center the arc, and make the carbons burn evenly.

The movement of the spindle *B* in striking the arc is controlled by the electromagnet *b*, through the armature *J*, sleeve spindle *A* and rod *K*. *J* is the armature of the series magnet, pivoted as shown, and when attracted towards *d*, communicates its motion through a connecting piece with an end clutch to *A*, which slides on a rod, carrying *K* which has a forked arm, engaging the clutch on *B*. When *J* moves to the right the negative carbon moves the same way, the positive one remaining stationary. The amount of motion of *A* to the left is determined by a screw stop-pin through the left-hand end-piece and to the right by *J* bringing up against the armature *d*, so the initial separation of the carbons is limited.

When magnet 2 is energized, the armature *n* is attracted, pulling the copper spring contact away from the contact pin, breaking the circuit. The piece *o* pivoted to *p* is rigidly connected to *n*, and when *n* is attracted to the magnet, *p* is pushed up, turning an arm, not shown, carrying a pawl *F* which engages the teeth on *D* connected to the spindle *e*. When the circuit is broken, *n* is pulled back in place by the spiral spring *k*, hooked to a small screw spindle *l*, and in doing so, *p* is pulled down, the pawl *F* revolving the wheel *D*, which sets in motion the spindles *e* and *B*, feeding the carbons together. As soon as the contact spring *H* comes in contact with the point, the circuit is re-established and the same motions repeated. This make and break gives an alternating movement to the feeding pawl as long as current flows through the shunt magnet. There is a stop on the left not shown which regulates how many teeth the pawl *F* engages, so the feeding may be fast or slow.

The tension of the spring *k* regulates the difference of potential at which the carbons will feed, for the greater the tension, the stronger must be the current; or, in other words, the higher the voltage necessary to attract the armature *n*. The tension of the spring *k* is regulated by two stop nuts *m, m*.

Suppose the tension on the spring *k* has been regulated to give the difference of potential at which it is required the carbons will feed and the carbons are just touching. The main switch at the base of the projector is turned, and immediately the whole current flows through the series magnet, the circuit being completed through the carbons. At this instant, the series magnet *b* is energized and the armature *J* attracted, and as has been explained the negative carbon is drawn away from the positive, striking the arc. The resistance of the arc at this time is such that all the current flows through the carbons, there not being enough difference of potential between the carbons to cause enough current to flow through the shunt magnet to overcome the tension of the spring *k*. The carbons gradually burn away, and as they do, the resistance of the arc increases, the difference of potential increases to the amount for which the spring *k* was set and current flows through the shunt magnet. This starts the feeding mechanism as explained and the carbons are fed together again, the difference of potential gradually falling until the spring overcomes the shunt current and the feeding stops. This arrangement constitutes the automatic working of the lamp. If by any chance the carbons approach too close, there is no provision made for feeding them apart and they must burn away.

If it is required to work the lamp by hand, the automatic switch 3 is turned by a wrench on the right-hand end, and this simply breaks the shunt circuit, when the carbons can be fed by a wrench on the end of the spindle *e*.

In order that the arc may be accurately put in the focus of the mirror, there is a screw spindle, projecting through the projector which screws into a screw thread cut in the face of the lamp frame, and turning this moves the lamp towards or from the mirror.

In horizontal lamps, there is a tendency for the flame to ascend, due to the heated air, and to prevent this, and to center the arc and make it burn evenly, a ring of magnetic material surrounding the arc has been used. The use of this magnetic ring has been discontinued in the recent types of lamps.

The Double Feed Lamp (Motor Control).

Fig. 343 shows a modern double feed lamp in which the carbons are fed in both directions. The power for feeding the carbons, as

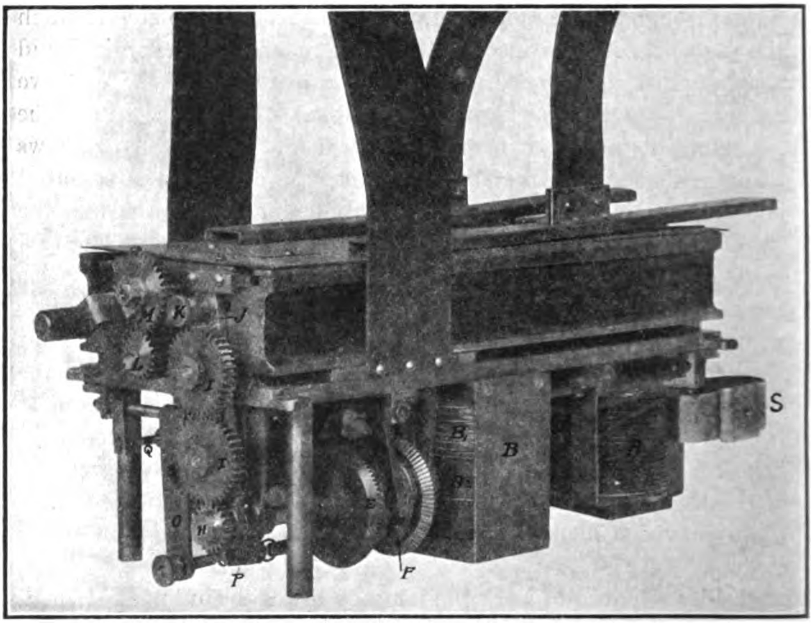


FIG. 343.—Type H, Form M, Class 36″, Projector Lamp, General Electric Co.

well as the regulation of the feeding, is controlled by a special form of motor.

Referring to the figure, which is lettered, the current enters the lamp through the contact shoes, *S*, of which one is shown at the rear of the lamp. The starting magnet *A* is similar to the usual magnet, being in series with the arc current and its function is to separate the carbons when striking the arc.

The motor is designated as B, B_1 being the series field in series with the arc, and B_2 the shunt field in shunt with the arc, the armature being also in shunt. The two fields are connected accumulatively, consequently the excitation of the motor is the sum of the ampere turns of both fields. The object of this winding is to provide a large speed change of the motor for a small change of arc conditions.

The motor shaft by means of worm operates a bevel gear (not shown in figure) which drives two bevel gears E in opposite directions; and by means of differential gearing the two-toothed rings F are rotated in opposite directions and the gearing is so arranged that when both of the two-toothed rings are free to rotate the shaft H remains stationary, and also when either one of the two is locked the shaft H will have a direction of rotation depending upon which ring is stationary.

The locking of either of the rings F is by means of the detent G which forms part of the regulating mechanism and which will be described later.

The shaft H, by means of a pinion on its end, rotates the feed screws L and M by means of the intermediate gears I, carried on the swinging lever J. The gears can be thrown out of engagement with the feed screws by means of the spring catch K to permit separating the carbon supports for re-carboning.

The motor shaft also drives a special governor which operates the lever O, and the regulation of the point of feeding of the arc is by means of the spring P connected to the end of the lever O.

The lever O, by means of the reach rod Q and the cross shaft to which it is connected, operates the detent G, swinging it into engagement with either of the two rings F or holding it out of engagement with either.

The winding of the motor is such that its excitation is greater with a long arc than with a short arc. This, combined with the fact that the potential of the armature is also greater with a long arc than with a short arc, makes possible a large speed variation per volt change of arc.

The operation of the lamp is as follows:

With the carbons separated, upon closing the main switch in the search-light circuit, due to the fact that no current is flowing through the series resistance, there will be full potential at the lamp terminals and the motor will have full potential at its brushes and the shunt field will be excited, the latter, however, having less ampere turns under normal conditions than the series field. Due to the potential at the armature brushes and the weak field of the motor, the governor is rotated at its highest speed, moving the lever *O* outward and throwing the detent *G* into engagement with one of the rings, causing the carbons to be fed toward each other.

Upon completion of the circuit, due to the contact of the carbons, the potential at the lamp is decreased, due to drop in potential in the series resistance. The motor conditions are then different from those already described inasmuch as the potential at the brushes and the shunt field is much lower, but a high current through the series field provides a very strong resultant field and a combination of all the conditions reduces the speed of the motor to its lowest speed and the governor on this account moves the lever *O* in the opposite direction and the detent *G* is moved by it into engagement with the opposite ring, causing the carbons to be fed apart until the speed of the motor, which then gradually increases, becomes such that the detent *G* is held between the two rings and in engagement with neither. This is the normal position of the mechanism when the arc is normal, and a change in the arc conditions causes the detent *G* to swing either of the two ways, feeding the carbons together or apart as may be required.

Alternative Methods of Controlling the Arc.

The introduction of a dead resistance in the leads of a search-light arc to reduce the generator voltage to that required to sustain the arc results in the expenditure of energy that does not appear as light. This loss is not so great when the arcs take small current and the search-lights are few in number, but as both the size and number increase the waste energy becomes a matter of great importance.

In the example given, the energy consumed is $80 \times 50 = 4000$ watts, of which the arc only consumes $50 \times 50 = 2500$ watts, a waste of 37.5 per cent, and numerically 2 horse-power. This loss takes place in the dead resistance and is dissipated in the form of heat, the I^2R loss being $50 \times 50 \times \frac{3}{5} = 1500$ watts.

Several methods have been devised to reduce this loss and some of these methods have been tried on board vessels of the navy, but were not entirely satisfactory and the ballast resistances were retained as being more reliable under all conditions of service. As many interesting electrical principles are involved in the design of machines used to replace the ballast resistances, a brief description of some of these machines is given below.

The Balancer.

This machine is similar in appearance to a motor generator, with the field of the motor in series with the armature while the genera-

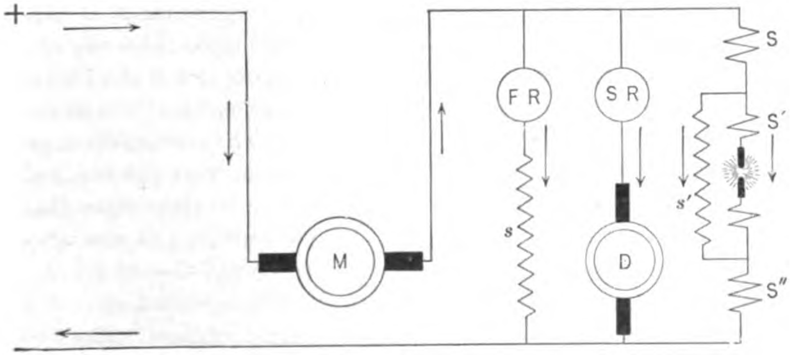


FIG. 344.—Elementary Connections of the Balancer.

tor field is differential wound. Its action will be understood by reference to Fig. 344, which shows the method of connection to the leads.

The arc leads are marked + and − (Fig. 344), with the motor M connected in the line, and S is its series field. D is the generator connected directly across the line with its shunt field *s*; *FR*, field rheostat, and *SR* a starting rheostat. *S''* is the series field of *D* wound differentially with respect to *s*. *S'* is the series winding and *s'* the shunt winding of the lamp-regulating mechanism.

When the carbons are separated and the main switch closed, current flows as indicated by the arrows. Under this condition, *D* acts as a motor under the action of the constant field due to *s* and drives *M*. The current through *M* is small, as the carbons are separated, and the resistance of *s'* is high. From the fact that the current is small, the field of *M* through *S* is but feebly energized, consequently the counter E. M. F. of *M* is low, and the fall of potential through *M* is also low, being equal to $I_a r_a$ of *M*. The terminals of the lamp shunt *s'* receive practically the full voltage of the line and the shunt current acts to feed the carbons together.

As soon as the carbons touch and current flows through them, the entire condition is changed. The field of *M* is now fully energized and *M* now acts as the prime mover, driving the armature of *D*. This current flowing through *S''* reduces the field of *D*, as the fields are oppositely wound, and reduces the excitation. *D* acts as a generator and the current through it is reversed. The counter E. M. F. of *M* increases as the field is strengthened, and the excess of line voltage over that required for the maintenance of the arc is represented by the counter E. M. F. developed. The current through *M* varies with the difference of potential at the carbons, the counter E. M. F. and the armature resistance, and it may be lower than that required to actuate the arc, in which case the deficiency is made up by that generated by *D*. This represents the saving effected by this device as the current is not drawn from the main generator.

As the carbons burn apart and the resistance increases, the field current of *M* decreases and the armature speeds up. This decrease of current decreases the series effect of *D*, and both causes, the increase of speed and field, result in an increase of the difference of potential at the lamp shunt terminals and the carbons are fed together.

If the carbons get too close together the increased current causes *M* to slow down, and also decreases the field of *D* which causes it to lower the voltage at the carbon terminals.

Generators for Projectors.

In supplying power for projectors an alternative means for the control of the arc is found in the use of specially designed generators. These generators must have a more or less drooping characteristic of voltage with respect to current and must be capable of standing a short circuit. Upon the steepness of the drooping characteristic or the rate of change of potential at the lamp terminals with reference to the current depends the regulation of the current.

The means taken in one type of generator to obtain the desired characteristic consist essentially in short circuiting what in an ordinary dynamo would be the service brushes, and in placing the actual service brushes on the commutator, midway between those of the first set. The field cores are designed for a much higher degree of saturation than is usually the case in an ordinary dynamo and the pole pieces are of different shape and of greater size.

The elementary principles upon which the action of the machine is based may, perhaps, be better understood by reference to Fig. 1, which is intended to show a resolution of the magnetic fluxes into the directions of their respective magnetomotive forces.

This diagram represents a bipolar dynamo, with the armature revolving in a counter-clockwise direction between the pole pieces, marked *N* and *S*. The magnetic flux, which may be conceived of as emanating from the pole *N* and entering the pole *S*, is indicated in the diagram by the solid lines *NS*, and for the sake of explanation will be termed as "primary flux."

Under these conditions of rotation and field, the electromotive force induced in the armature conductors produces a current which flows toward the observer in the upper half of the armature winding and away from the observer in the lower half. This current flowing around the armature and through the short-circuited brushes creates a "secondary flux" at right angles to the primary and indicated by the lines $N'S'$.

The current resulting from the conductors cutting this secondary flux creates a tertiary magnetomotive force at right angles thereto in the direction of the broken lines $N''S''$, that is to say in direct opposition to the primary flux. This current is collected by the brushes *BB* and supplies the external circuit.

With this explanation the action of the machine becomes at once apparent: it is, in effect, in a state of magnetic balance; any increase in current immediately increasing the tertiary magnetomotive force opposing the primary flux, with the result that the current produced by this flux is diminished, the secondary flux reduced, and finally the terminal voltage of the machine. It is evident from this, that at constant speed the generator will have a drooping voltage characteristic and may be designed to give a practically constant output.

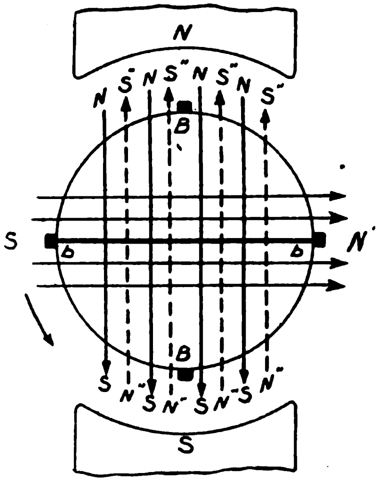


FIG. 345.

It will be noted that there are three magnetomotive forces involved: one due to the main excitation on the poles, a second due to the short-circuited current, and the third which opposes the main flux from the fields.

This forms a basis of another type of generator which also gives the necessary drooping characteristic. In this type of generator there is a separately excited shunt field, a self-excited shunt field, and a series field whose flux opposes that of the other two. In the case of a shunt machine with straight line saturation there is an instability due to the fact that any voltage in its range can be generated without a change of field excitation; in other words, without changing a field rheostat. It therefore becomes necessary to bring in some stabilizing factor. This is accomplished in the addition of the separately excited winding.

In order to produce the drooping characteristic it is necessary to augment the armature reaction by a differentially connected series field, as in this type we do not have the short-circuited brushes. The separately excited field is of such a value that its magnetomotive force offsets the effect of the armature reaction and the differentially connected series field at normal rating of the machine; so that the flux due to the self-excited winding is producing the actual voltage.

With this arrangement it will be seen that a decrease of current will, of course, cause a decrease of armature reaction and bucking series field, so that there will be a tendency for the voltage to rise and thus maintain the same current. As stated above, rapid and undesirable fluctuations are prevented by the combination of the separately excited shunt field and the bucking series.

A modification of the above is found in the use of a commutating field somewhat stronger than necessary for good commutation alone, and a shift in the brushes of the machine from the full-load neutral position. This allows the commutating flux to replace the bucking series in augmenting the armature reaction and producing the drooping characteristic.

Search-Light Projectors.

The projector carrying the lamp consists of a fixed pedestal surmounted by a turntable carrying the projector proper. The pedestal is arranged so that it can be securely bolted to the deck or platform and fitted to contain the electrical connections.

The turntable is so designed that it can be revolved in a horizontal plane freely and indefinitely in either direction or clamped rigidly if desired.

The drum is trunnioned on two arms bolted to the turntable and has free movement in a vertical plane of 70° above and 30° below the horizontal. The drum can be rotated on its trunnions by hand or clamped rigidly in any position, and while clamped may be given a slow movement in altitude by turning a small handle in the axis of the pedestal. The drum is fitted with peep sights for observing the arc in two planes, in the side by a colored piece of glass and in the top by reflecting prisms. The drum is designed to contain a parabolic mirror.

The mirror is of the best quality of glass and should be free from all flaws and holes, with its surface ground to exact dimensions. The back is silvered in such a way as to be unaffected by heat. The glass is mounted in a separate metal frame lined with a non-conducting material to allow for expansion due to heat, and to prevent injury from concussion.

The front of the drum is provided with a glass door composed of strips of clear plate glass.

The lamps produce the best results when taking current as follows:

12-inch	18 to 20 amperes.
18-inch	30 " 35 "
24-inch	40 " 50 "
30-inch	70 " 80 "
60-inch	150 " 200 "

The 18-inch projector is supposed to project a beam of light of such intensity as to render plainly discernible, on a dark night with a clear atmosphere, a light-colored object 10×20 feet in size, at a distance of not less than 4000 yards, the 24-inch projector at a distance of not less than 5000 yards and the 30-inch projector at a distance of not less than 6000 yards.

For the care and management of search-lights see Chap. XI, Vol. II.

Enclosed Arc Lamps.

Enclosed arc lamps are now being used on shipboard to some extent where a large area requires general illumination. They are especially well adapted for supplying the illumination for coaling ships, at night. These lamps differ from ordinary arc lights in that the arc is surrounded by a small glass globe which fits the carbons so closely that the air inside the globe can only slowly change. One effect of this is to reduce the rate of combustion of the carbons which also lessens the work of the feeding mechanism. The enclosed air becomes a source of light, so that the whole globe seems to glow, thus increasing the apparent amount of light.

Enclosed arc lights require a higher voltage than open arcs, 60 volts being about the minimum, and take from 2 to 10 amperes.

Lamps are furnished to operate on voltage of 80, 110 or 125 volts with a normal current of 4.5 amperes. The arc is enclosed by an inner opal globe, which is surrounded by a clear globe protected by a composition guard. The guard and outer globe are removed together and so held by supporting chains that the inner globe may be removed to renew the carbons.

Carbons are ½ inch in diameter and have a life of 120 hours without trimming.

Each lamp contains the proper resistance for reducing the line voltage to that required for the best regulation of the arc, an average of about 85 volts.

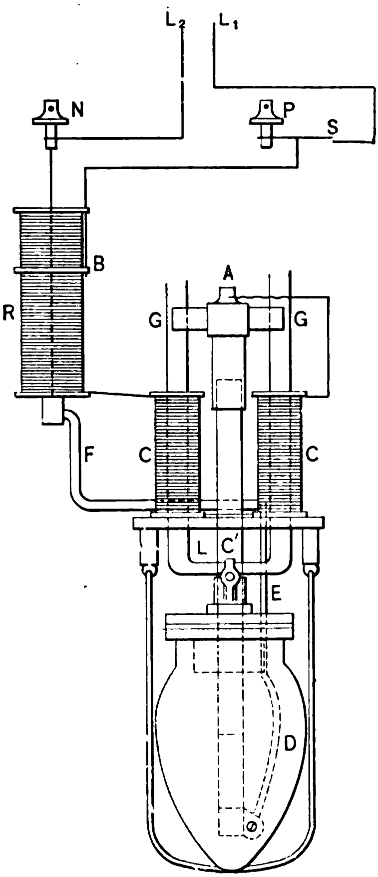


FIG. 346.—Form 12 Arc Lamp General Electric Company.

A commercial form of lamp that meets the required specifications is made by the General Electric Company and is shown diagrammatically in Fig. 346. L_1 and L_2 are the line leads, and are wired in multiple from the lighting mains. L_1 is connected to the positive terminal of the lamp *P*, through the switch *S*, on top of the lamp. From the positive terminal, the circuit leads to the edgewise wound rheostat *R*, through the sliding contact *B*, which can be moved up or down along the rheostat. This throws more or less of the resistance of *R* into circuit and acts as the dead resistance previously described. From the rheostat the circuit leads to the electromagnets C, C, and thence to the terminal A, which is a part of the support holding the upper, positive, carbon of the lamp. Current flows from the positive carbon to the lower, negative, carbon, then to the curved conductor D, vertical conductor E and curved conductor F, up through the center of the rheostat to the negative terminal N of the lamp and thence to the line lead L_2.

The positive carbon is held by a clutch C'' through a bell crank arm and acts to grip the carbon and raise it when the support is raised; but on lowering when the clutch comes against the top of the inner globe support, the clutch opens and allows the carbon to fall until it brings up against the negative carbon, so at all times the lamp is ready for operation.

Before current is switched on the carbons touch, but as soon as the electromagnets are energized, the plunger L is sucked into the core of the solenoid, and at the same time the clutch grips the positive carbon, raising it, and thus strikes the arc. As the carbons burn away and the length of arc increases, the resistance increases; consequently, the current through the arc lessens and the plunger is not held so strongly in the magnets and it drops, until the increased current is sufficient to hold it at the proper distance for the voltage across the arc.

The working mechanism of the lamp is protected from dust and dirt by a sheet-copper casing, and there should be no occasion to remove this as the rheostat is properly adjusted and should not be changed.

Candle-Power of Arc Lights.

The candle-power of arc lights is rather a deceptive means of determining how much light an arc is producing. For instance, a so-called 2000-candle-power arc light does not give more than 1400 candle-power in the direction of greatest intensity. The same considerations hold for arc lights as for incandescent lights regarding their mean spherical candle-power; that is, it is the average candle-power on the surface of a sphere with the light at the center. However, there is a great difference between the horizontal candle-power and the maximum candle-power, the latter being found in vertical DC arcs with the + carbon uppermost on a line making approximately an angle of 45° with the horizontal. This is due to the fact that the crater of the positive carbon is the chief source of light and the rays of light are therefore projected downward.

An empirical rule for finding the mean spherical candle-power is to add one-half the mean horizontal candle-power and one-quarter of the maximum candle-power.

It is very evident that for a search-light to give out the most light, the carbons should be so placed that the maximum amount of light will be included in the solid angle of aperture consistent with their position at the focus of the reflecting mirrors. In other words, the carbons should be horizontal, with the positive carbon farthest from and pointed towards the mirror, and this is the case with all present designs of search-lights.

The practical method of determining the candle-power is to find the power in watts absorbed to produce it. The mean spherical candle-power can be determined by using the arc in connection with the photometer, finding both the horizontal and maximum candle-power; and at the same time by properly connecting a voltmeter and ammeter, the number of watts absorbed can be found. When the arc is used as a search-light, and the product of the volts and amperes show a value equal to that found when the candle-power was being tested then the arc is producing its rated candle-power. Different shaped carbons or different adjustments may vary the intensity or direction of the maximum ray, but with the same number of watts, the *mean* candle-power remains practically the same.

The maximum candle-power can be determined by connecting a voltmeter and ammeter in circuit, and varying these quantities until their product is a maximum. The range of voltage is practically limited to a few volts, the greatest current consistent with steadiness of arc, proper length of arc and the carrying capacity of the carbons may be found. When a light is being used under the conditions determined for maximum candle-power, or the product of the two variables is the same, then it may be certain that the arc is giving its maximum mean spherical candle-power.

Enclosed Flame Arc Lamp.

In the old style carbon arc lamp, most of the light obtained is entirely dependent upon the temperature of the carbon tips and not upon the arc stream. A later type of lamp, the enclosed flame arc lamp has been designed which involves the principle of the arc stream and which produces a highly luminous and efficient arc. In this type of lamp, practically no light is obtained from the carbon tips themselves, their temperature is not so material and, therefore, larger diameter carbons can be used enabling long life, and without decreasing the efficiency. To obtain high efficiency with the old style carbon arc lamps, it was essential to have carbons of as small a diameter as possible in order to lessen the heat conductivity from the carbon crater.

Flame carbon electrodes are composed mainly of carbon impregnated or mixed with certain salts, usually calcium fluoride for producing a yellow light and cerium fluoride when a whiter light is desired. These salts are volatilized at a comparatively low temperature and become luminescent as they pass into the carbon vapor stream. The carbon electrodes are $\frac{7}{8}$ inch in diameter and 14 inches long and have a life of from 120 to 140 hours.

The introduction into the electrode of calcium fluoride or other mineral salts from which the arc receives its luminosity, causes a gas to be emitted during operation, which on cooling condenses in the form of a fine white powder. This powder, if not suitably disposed of, will form a coating upon the globe immediately surrounding the arc in a comparatively short time. This coating obstructs the light rays in proportion to the density of the deposit.

These gases, however, when emitted by the arc, rise by natural convection until their progress is arrested by the pocket formed in the condensing chamber. Here the lower temperature causes the finely divided particles of calcium or cerium fluoride to deposit upon the upper and lower surfaces of the chamber. These gases are very rich in fluorine, which has a great affinity for water, forming hydrofluoric acid. Sufficient water condenses in the inside of the enclosing globe chamber and to prevent the action of this acid on the glass, slabs of lime are placed in the condensing chamber to absorb all moisture which may collect in either the globe or chamber.

Before current is switched on the carbons are in contact with each other, but as soon as the electromagnets are energized, the carbons are separated, thus striking the arc. The proper arc length is maintained by the use of properly designed operating magnets.

Lamps of the flaming arc type are furnished to operate in series or in multiple on both alternating and direct current voltages and are particularly valuable for illuminating shops, armories, drill grounds, dry docks, wharfs and other large areas. In addition to the high efficiency of the light production the natural distribution, which is practically horizontal, makes it possible to utilize scientifically designed reflecting devices to obtain distribution adapted to every requirement.

Luminous Arc Lamp.

Another type of lamp which obtains its light from the arc stream and not from the carbon tips is the magnetite arc lamp of the luminous type. This lamp, like the enclosed flame lamp, is of high efficiency.

The electrodes used in this lamp are of two different kinds: the top, or positive electrode consisting of a copper rod of such diameter that its surface acts as a baffle to the rapidly ascending vapor currents. The lower, or negative electrode, is a composition of iron and titanium oxide and chromium and it is this electrode which determines the characteristic of the arc. These light-giving materials are fed into the arc and carried through the arc stream by electro-conduction. The copper electrode is practically non-consuming and has a life of from 2000 to 8000 hours. The negative, or magnetite electrode has a life varying between 125 and 350 hours, depending upon the current at which they operate.

This production of light by the magnetite arc is accompanied by fumes, which, if permitted to condense on the globe, would soon give a dirty appearance. It is therefore necessary to provide means for removing the products of combustion from the vicinity of the arc and electrodes. Since these vapors are carried upward by natural convection currents, a central chimney, with its lower opening surrounding the positive electrode, supplies the simplest means of disposing of these fumes.

In this type of lamp the electrodes are not in contact when the current is cut off. This may be explained by stating that in the case of a magnetite arc the tip of the electrode is in the form of a molten pool, and if the electrodes were to be brought in contact with each other immediately the current was cut off, they might "freeze" together upon cooling. Furthermore, as the surfaces of the electrodes are not first-class conductors when cold, it is desirable to bring them into forcible contact in order to insure satisfactory starting. By means of contacts operated by properly designed magnets the negative electrode is allowed to drop back by gravity, whereby the arc is struck.

This lamp, while designed originally for street and large area lighting, has also met with great success for ornamental purposes and there has resulted the design and standardization of three new forms. These are known as the great white way lamps, consuming 520 watts at 6.6 amperes, and 320 watts at 4 amperes; the residential district lamp, consuming 300 watts at 4 amperes; and the parkway lamp designed for operation at both 4 and 6.6 amperes, 300 and 500 watts, respectively.

Mercury Vapor Lamps.

A mercury vapor lamp consists simply of a highly exhausted glass tube containing mercury, and fitted with an electrode at each end. The tube contains some vapor of mercury at all times. Ordinarily the tube hangs in a slanting position so that the mercury collects in a reservoir at its lowest end around the negative electrode and forms part of it. To start the lamp, it is raised, either by hand or automatically, to a horizontal position, when the mercury runs out of the reservoir and into and along the tube to the positive electrode. This establishes a current, and upon breaking the stream of mercury by allowing the tube to fall into its normal slanting position an arc jumps across the gap, and the volatilized mercury conducts the current, being heated to incandescence thereby and giving out light. Mercury is continually vaporized, is condensed upon the cooler portions of the tube and trickles back to the reservoir.

As usual when the conductor is gaseous, the current does not obey Ohm's law in its simple form and hence it is necessary to have a ballast resistance in series with the lamp.

When a mercury lamp is to be used on ordinary line voltages, 110 to 125 volt circuits, some means must be provided to produce the high E. M. F. necessary for starting. This is obtained by placing an inductance coil in series with each lamp, which, during the operation of starting, at the break of the mercury stream, causes a high induced E. M. F. which is sufficient to break down the air gap and to strike the arc, after which the line voltage is sufficient to maintain it.

Operating Circuits.—Some mercury vapor lamps are made to tilt themselves automatically in starting, others are started by tilting by hand. A wiring diagram of an automatic lamp is shown in Fig. 347. This shows two lamps operated in series. The automatic tilting is accomplished as follows: When current is switched on, a path is provided for it from the + line through a shunt circuit and a pivoted contact to the coils of an electromagnet to the − line through the ballast resistance. This energizes the electromagnet, which draws up a plunger to which the tube is connected, one portion of the tube remaining fixed. This raises the tube and allows the mercury to run along its length, which provides a path for the current through the lamp. This current flows from the + line and the two inductance coils in series to the + terminal of the lamp, across the mercury to the − lamp terminal and through the ballast resistance to the − line.

The inductance coil now acts as an electromagnet, attracting an armature which lifts the pivoted contact of the shunt circuit, breaking the circuit, upon which the lamp falls back to its original position, and on the mercury stream being broken, the high E. M. F. induced by the inductance coils on the break, is sufficient to break down the air resistance, and the arc is established.

The adjuster resistance shown on the left is for the purpose of regulating the voltage of the lamp to that of the line voltage.

Electrical Characteristics.—The ordinary voltages for which these lamps are designed to work vary between 100 to 240 volts. On the 120-volt circuit two Type H lamps of the Cooper Hewitt make are installed in series to avoid the long length of one tube, although if but one tube is used the same energy is consumed as when the two lamps are in series. The average current consumed per lamp is 3.5 amperes at 110 volts, giving 600 candle-power for the double lamp, or an efficiency of .64 watt per candle-power, which is about ¼ of the power used in a carbon filament. To a cer-

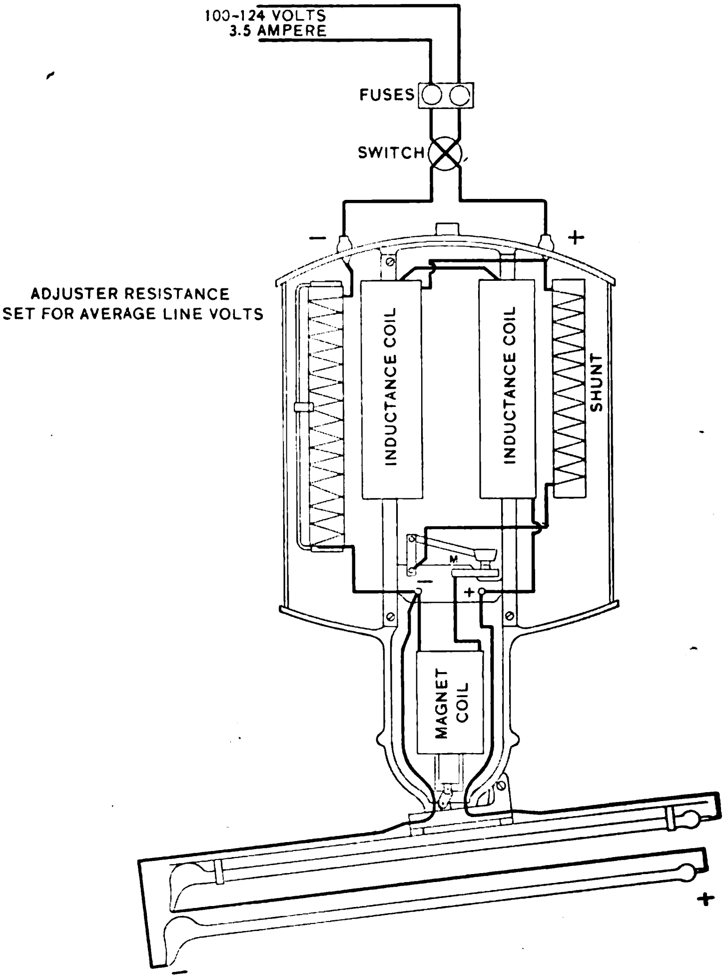


FIG. 347.—Wiring Connections of Type H Automatic Mercury Vapor Lamp.

tain extent the candle-power of the lamp is controlled by the diameter of the tube.

This lamp gives off a greenish light of very high intensity. The spectrum shows practically an absence of all red rays. The color of the light is unpleasant and its efficiency is no greater than the nitrogen-filled incandescent lamps having tungsten filaments.

Distant Control for Search-Lights.

It is very desirable to fit the search-lights on board ships with some efficient means of controlling the direction of the beam from some point distant from the light. Various electrical and hand devices have been installed for this purpose. A late type of hand control, which is being manufactured at the Navy Yard, Norfolk, is proving very efficient. An electric control manufactured by General Electric Co. has been supplied to several vessels and will be described.

36″ Electric Control, Form " N " Projector General Electric Co.

The exterior of this projector is similar to previous projectors of this type manufactured by the General Electric Co. with a few minor differences. The main differences in the interior are found in the lamp mechanism and in the method of control, this type being fitted for both hand and electric or " distant " control.

The electric control is effected by two motors in the base and on the turntable of the projector, one for training in azimuth and one for training in altitude, connected to a portable controller by flexible cable. The controller is provided with a sight bar * which is arranged to move synchronously with the projector beam through the agency of hand wheels on the controller which operate the motors and which are so geared to the sight bar that the movements of it in altitude and azimuth correspond to the movements of the beam.

The Training System.

On the controller there are two separate hand wheels, one for each plane of control. By means of shafts connected to these wheels they rotate simple commutating devices which are so arranged that the direct current of the supply is split up into currents having three-phase relation. Two leads, one of positive potential and one of negative, are led to each commutator from which three leads are taken and the current is so commuted that two of them have the same potential, while the third has the opposite. This will be understood by a consideration of Fig. 348.

* This sight bar has been omitted in later types of controllers.

The commutating segments are shown as R_1 and R_2, to which are connected respectively the line leads $+L$ and $-L$. Three brushes, B_1, B_2 and B_3, press against the commutator segments and they are connected respectively to the leads 1, 2 and 3. In the position shown, lead 1 would have + potential and leads 2 and 3 − potential. If the commutator is turned to the left through 60°, the brushes remaining stationary, 1 and 2 will be + and 3 will be −; if turned through 120°, 1 and 3 will be −, 2 will be +, etc.

The three leads 1, 2 and 3 from the commutator segments are led to a system of magnet coils, six in number, symmetrically ar-

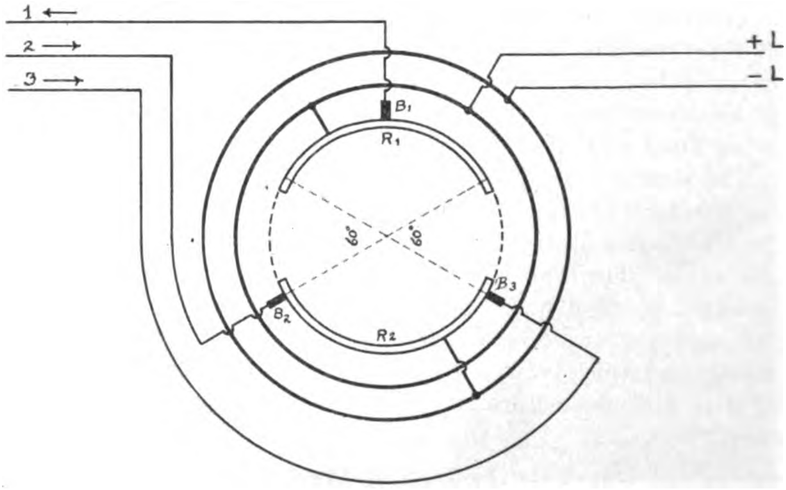


FIG. 348.—Commutating Device, Distant Control Search-Light.

ranged in a circle. These coils are fitted with pole pieces which project inwardly towards the center of the circle in which they are arranged. A developed view of these coils is shown in Fig. 349, and a sectional view of Fig. 350.

Within the space formed by the inwardly projecting pole pieces are fitted two field pieces at right angles to each other which are free to revolve. The ends of one of these field pieces are always of positive polarity, and those of the other end of negative polarity, produced by currents which always flow in the same direction in the coils which are wound on them.

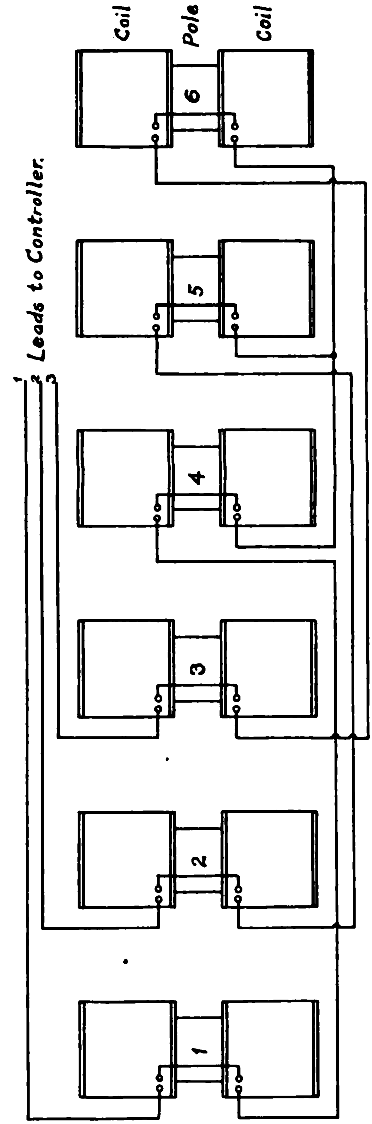


FIG. 349.—Developed View of Magnet Coils and Poles.

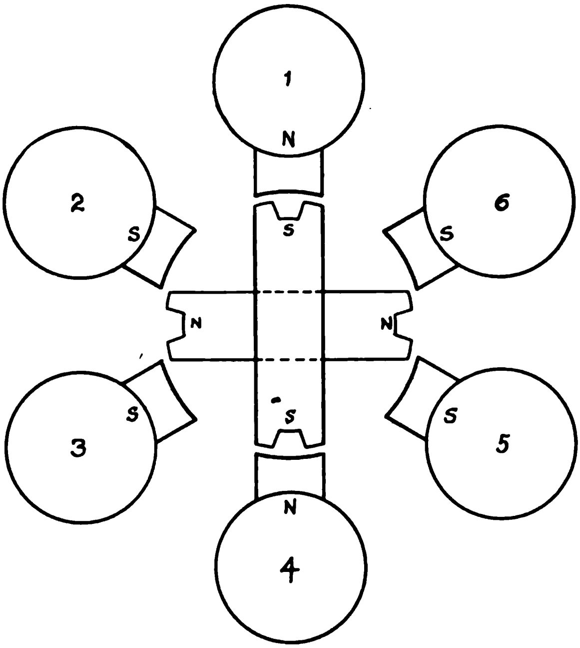


FIG. 350.—Sectional View of Magnets and Revolving Field Pieces.

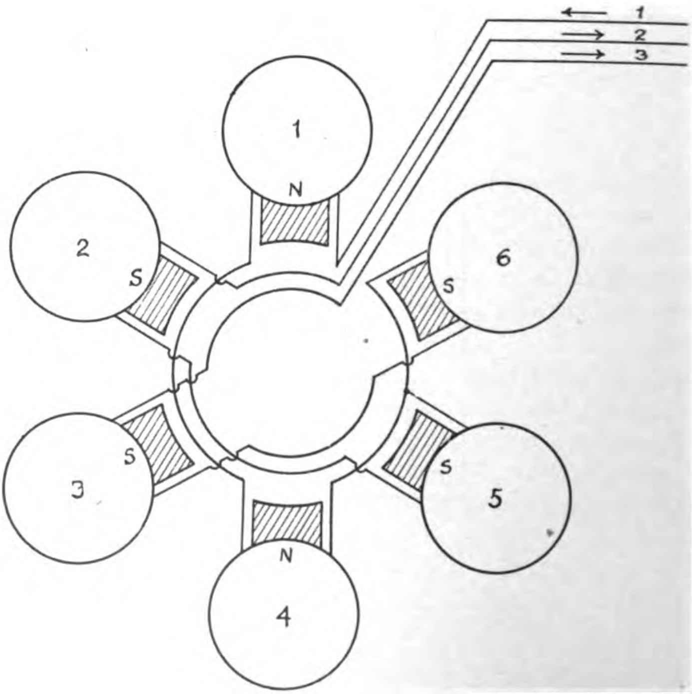


FIG. 351.—Sectional View of Magnet Coils and Poles.

Suppose the magnet coils are so wound that current flowing to the coil by the right-hand terminal and leaving by the left-hand one (facing the coil from the center), makes the pole of the coil of north polarity, and in the opposite direction makes it south polarity. Then if the current flows in the leads 1, 2 and 3 as indicated by the arrows in Fig. 351 it will be seen that coils 1 and 4 produce north polarity and coils 2, 3, 5 and 6 produce such polarity. If leads 1 and 2 have current flowing to the left, or they are of positive potential, and lead 3 has current flowing to the right, or is of negative potential, coils 1, 4, 2 and 5 will produce north polarity and coils 3 and 6 will produce negative polarity.

As the commutator rings are turned, the currents in leads 1, 2 and 3 change in direction as previously described; consequently the polarities of the magnet coils change. As the polarity changes, the field pieces take new positions, turning with each change of polarity. Fig. 350 represents the zero position of the field pieces with the polarity of the coils due to the currents shown in Fig. 351. If the commutator is now turned 60° to the left, coils 1, 2, 4 and 5 will be of north polarity and coils 3 and 6 of south polarity and it will thus be seen that the field piece will turn through an angle of 30° to the left, bringing the north poles of the field pieces directly opposite the south poles of coils 3 and 6, and the south poles midway between the north poles of coils 1 and 2, and 4 and 5. Each turn of 60° of the commutator thus causes the field piece to revolve 30°.

The table on page 594 shows the direction of current through leads as determined by the commutator, the polarity of the armature poles and the position of field poles.

Each position of the field poles in this table represents 30°, and after the 12 positions, or 360°, the operation is repeated.

The combination of the magnet coils and field pieces described above is called a *pilot motor* and in future, reference to it will be by that designation.

The pilot motor for the training system is mounted on the turntable of the projector and the leads from the commutating device in the controller are brought to it by means of wires made up into a flexible cable.

Direction of Current through Leads Nos.			Polarity of Armature Poles Nos.						Position of Field Pole Nos.
1	2	3	1	2	3	4	5	6	
+	—	—	N	S	S	N	S	S	1
+	+	—	N	N	S	N	N	S	2
—	+	—	S	N	S	S	N	S	3
—	+	+	S	N	N	S	N	N	4
—	—	+	S	S	N	S	S	N	5
+	—	+	N	S	N	N	S	N	6
+	—	—	N	S	S	N	S	S	7
+	+	—	N	N	S	N	N	S	8
—	+	—	S	N	S	S	N	S	9
—	+	+	S	N	N	S	N	N	10
—	—	+	S	S	N	S	S	N	11
+	—	+	N	S	N	N	S	N	12

The full horizontal training mechanism is shown in Fig. 352. Rotating the horizontal training handwheel on the controller through 180° causes the revolving field piece of the pilot motor *D* in the projector to rotate through 90°. The field piece is connected to a cam cylinder *E* through the spur gears *F, G, H* and *I* and the bevel box gearing *J, K* and *L; K* engaging with *J* and *L*, though not shown in the sectional view. This gearing is so designed that 90° revolution of the field piece produces about 15° revolution of the cam cylinder.

The movement of *E* operates the contact fingers *M* which connects the line current to the training motor *N*. The motor operates the projector through the worm *O* attached to the motor shaft, the worm wheel *P*, spur gears *R* and *S* and pinion *T*, connected to *S*, which engages in the circular rack on the turntable of the projector. Connected to the shaft *U*, which connects the gears *S* and *T*, is the bevel gear *V*, which also drives the cam cylinder *E*, but in a direction opposite to that produced by the pilot motor. The cam cylinder *E* which makes the circuit between the line and the training motor thus has a motion which is dependent upon the relative

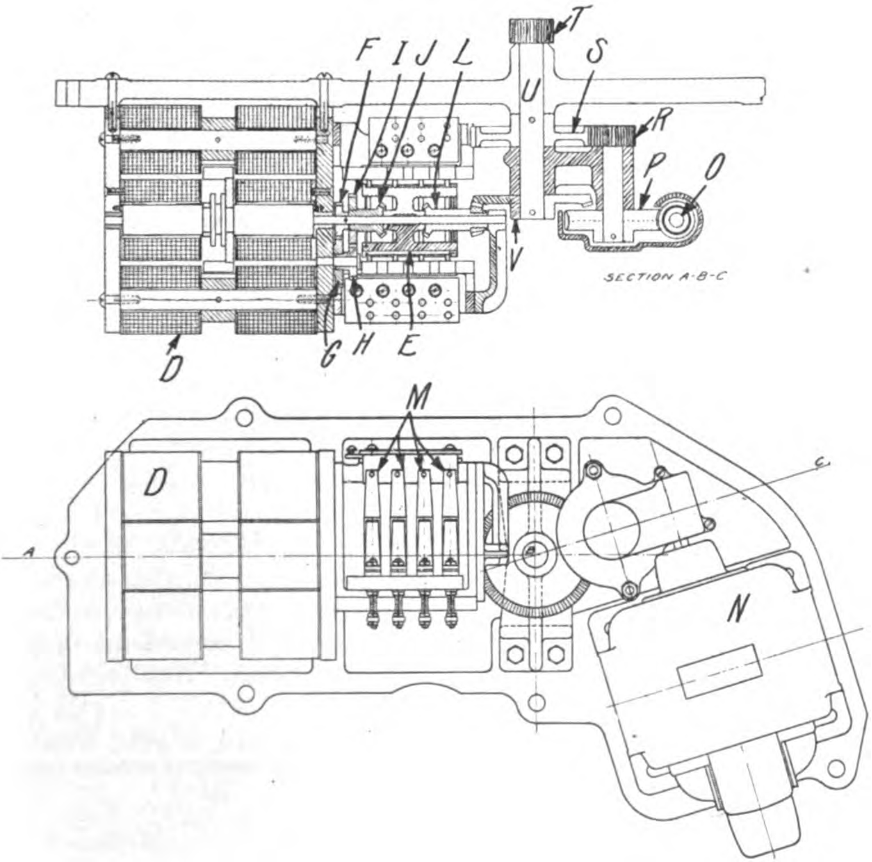


FIG. 352.—Assembly of Horizontal Training Mechanism of 36″ E. C. Projector.

motions of the pilot motor and training motor, the equivalent of which is always equal to zero. As soon as *E* begins to rotate, due to the rotation of the pilot motor, the projector begins to rotate and in so doing tends to revolve it back to its original position.

The effect of this is to repeatedly make and break the line connection to the training motor, which trains the projector by a series of steps, and this will continue as long as the controller handwheel is rotated. One-half turn of the controller handle turns the pilot motor 90°, the cam cylinder 15° and the gearing is so proportioned that the projector revolves 1°. To turn the projector 10°, it is only necessary to turn the controller handle through five complete revolutions. Reversing the direction of the controller handle causes the cam cylinder to make connections such that the training motor receives current in the opposite direction and the direction of rotation of the projector is reversed. The connections are such that turning the controller handle to the right, the projector turns to the right and vice versa. A slow motion of the controller handle produces a slow motion of the projector and a rapid motion produces a rapid motion of the beam. For the slow movements the motor is connected through resistances, which are short circuited for the faster speeds of training. If the rotation of the controller handle is relatively faster than the rotation of the projector, there will be a slight lag, but it will catch up and stop at the proper place corresponding to the position in which the controller handle is left.

Vertical training is accomplished in the same manner as the horizontal, through the agency of a handwheel on the controller and a pilot motor and motor for vertical training. This mechanism is mounted in a watertight case on the turntable and the driving pinion engages a segment of a circular rack which is connected by brackets to the body of the projector.

In addition to the electric control, the projector is fitted with both vertical and horizontal wheels for hand control.

The Controller.

The mechanism of the controller is contained in a watertight case which is of such weight and dimensions as to be easily portable. It contains the *commutating devices,* the *operating wheels,* a *locking magnet,* the *sight bar* and the gearing by which the sight bar is moved synchronously with the projector beam. The same motion of the control wheels that operates the commutating devices serves to move the sight bar by means of a system of gearing which is readily seen by an inspection of Fig. 353.

Locking Magnet.—This is for the purpose of locking the operating wheels when current on the training motors fails and the wheels cannot be moved when the magnet is de-energized. This is to pre-

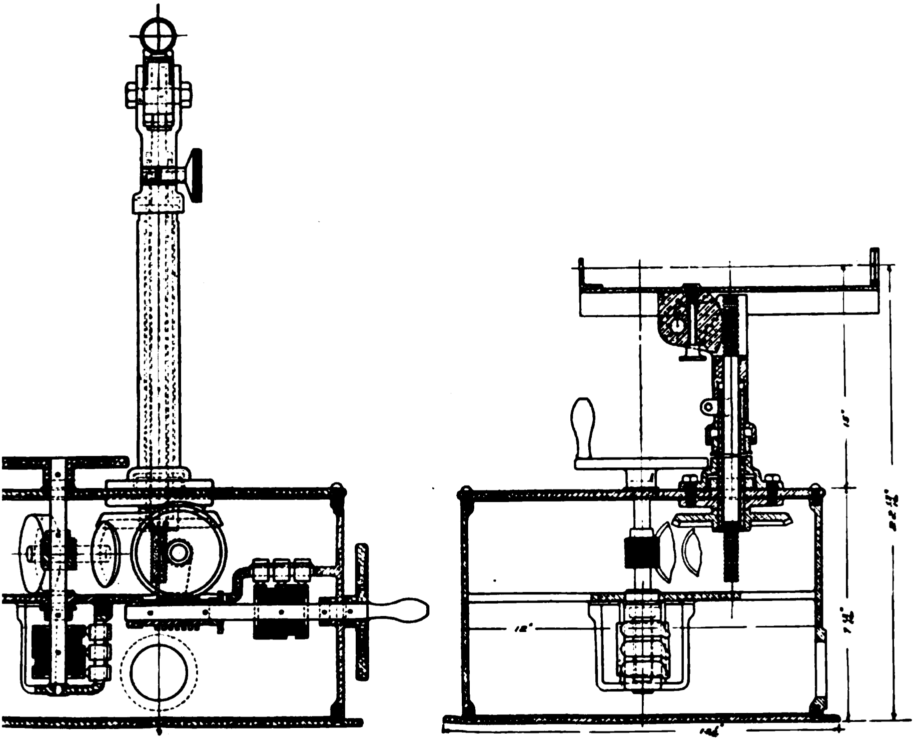


FIG. 353.—Form N Projector Controller.*

vent any motion of the sight bar without a corresponding motion of the beam and tends to preserve the orientation of the sight bar and beam. In case the rotation of the handwheels is relatively greater than the speed of the beam, the locking magnet circuit is broken by

* The details of construction of the later type of controllers are not as given in the above figure owing to the omission of the sight bar and its mechanism.

the opening of its circuit through one of the cam fingers operated by the pilot motor and the wheels remain locked until the beam can catch up. An inspection of Fig. 354, showing the wiring diagram, will show how this is accomplished, the magnet receiving its positive potential from the left-hand finger on the cam through terminal No. 9 in couplings and in the controller.

Orienting.—The projector beam and line of sight are conveniently oriented by bringing them on a common object at some distance and then clamping the projector to the electric control. The hand-wheels are provided with clutches for this purpose and any slight variation in alignment may be corrected by thumb screws on the controller.

Lamp.

The lamp originally supplied with this type of projector differed from those which have been previously described. The series magnet provided for striking the arc was dispensed with and the carbons were caused to approach or recede from one another according to the arc voltage by separate feeding magnets. Each feeding magnet operated a feeding screw, one feeding the carbons together, the other feeding apart.

Fig. 354 shows the working principle of the lamp. The two feeding magnets are shown connected in series directly across the line, and though they operate under the ordinary arc voltage, they must be designed for the full line voltage which exists before the arc is established. They are equipped with two armatures, and each armature controls the mechanism for feeding in one direction. These armatures of the feeding magnets are selectively operated by a pilot magnet which has two armatures connected by means of links to steel latches which lock or unlock the armatures of the feeding magnets.

The pilot magnet is differentially wound by two windings, one a shunt winding across the terminals of the arc, the other in series with the arc and carrying the whole arc current.

Lamp Operation.—Assuming that the carbons are in place and some distance apart, the operation is as follows: When the main line switch is closed, the shunt winding of the pilot magnet receives full line voltage and a maximum flux is caused through the magnet. This causes both the right- and left-hand armatures of the pilot

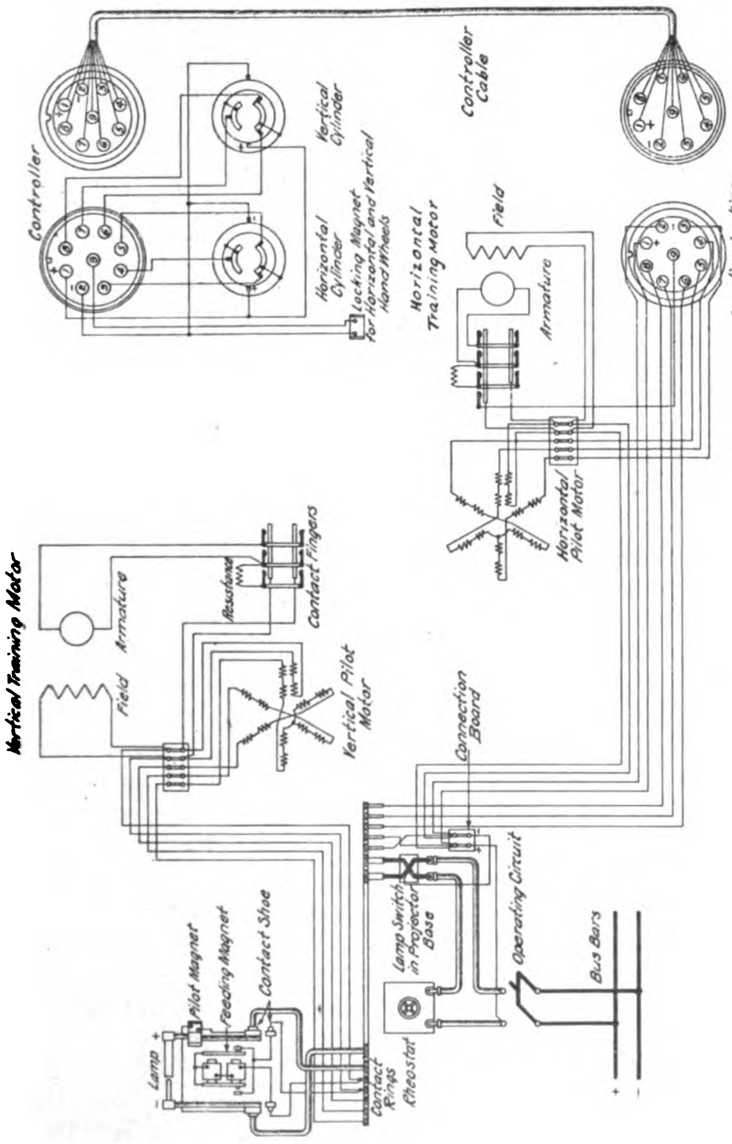


FIG. 354.—Connections of Electric Control Projectors 36″ Form N. Gen. Elec. Co.

magnet to be attracted. The right-hand armature releases one of the armatures of the feeding magnets and the left-hand armature locks the other armature of the feeding magnet. The released armature, through its make and break and pawl and ratchet, as in the previous type of lamps, acts on one feeding screw and the carbons are fed together. When the carbons touch, current passes through the series winding of the pilot magnet, and owing to the differential winding, and to the fact that the voltage at the shunt-winding terminals is reduced to about 30 volts when the carbons first touch, the flux is reduced to a minimum. At this reduced flux both pilot magnet armatures are released, with the result that the right-hand armature now locks the one that was at first released, and the left-hand armature releases the one that was at first locked. This released armature, through similar mechanism to the other, acts to feed the carbons apart.

As the carbons are fed apart, the voltage gradually increases and the current decreases, and with this type of lamp when the arc voltage is about 60 volts and current 110 amperes, the flux through the pilot magnet has increased a sufficient amount to attract the left-hand armature of the pilot magnet. This locks the feeding-apart armature and under these normal conditions of voltage and current both feeding magnet armatures will remain locked and the carbons will cease to be fed.

As the arc burns away the carbons, the current is reduced and the voltage is increased and the flux through the pilot magnet increases to such an extent that the right-hand pilot magnet armature is attracted. This releases the feeding-together armature, and the other being locked, the carbons are again fed towards one another until normal conditions are reached. Any increase in arc voltage above normal increases the pilot magnet flux and releases the feeding-together armature, and any decrease reduces the pilot magnet flux and releases the feeding-apart armature, and the feeding continues until normal conditions are reached at the arc.

Adjustment.

In adjusting the lamp, the feed-apart armature of the pilot magnet should be adjusted by means of its controlling spring so that it will be released when the arc voltage has reached 45 volts, feeding apart until it is attracted at 52 volts.

The feed-together armature of the pilot magnet should be adjusted by its spring so that it will be attracted at 62 volts, feeding together until 54 volts have been reached.

In adjusting either of these pilot magnet armatures, the other should be held in a position where it will lock its feeding magnet armature.

The jaws of the locking latches should be kept clean and occasionally a small amount of clock oil should be used on them. All parts of the lamp mechanism should be kept clean and free from carbon dust and the points of the feeding magnet contact screws especially should be kept bright.

CHAPTER XXI.

MEASURING INSTRUMENTS.

There are many laboratory methods for measuring electrical quantities and testing electrical machines, but on shipboard measurements are limited by the instruments furnished; these only being sufficient in a most general way for measuring the three electrical quantities of resistance, difference of potential and current.

The instruments ordinarily furnished to ships for electrical measurements are voltmeters, ammeters, testing sets and magnetos. In addition, on some ships may be found ohmmeters, whose principle and use will also be described.

Types of Instruments.

Electricity manifests itself in four ways, *i. e.*, by electrostatic forces, by electromagnetic forces, by heating effects and by electrochemical action. Of these the electromagnetic force forms the basis for the instruments furnished on shipboard.

Electrostatic Effect.—In these instruments the voltage is measured by the attraction or repulsion of two electrified bodies. If one is freely suspended while the other is immovable, the suspended one in approaching the other may be made to operate a pointer which will indicate the difference of potential. Voltmeters made on this principle have an advantage in that they absorb no power, and on D. C. take no current.

Electrostatic voltmeters are well adapted to measuring kilovolts, but they are not suitable for measuring currents or small voltages. Such voltmeters operate equally well on alternating or direct current circuits. For low voltages, however, a multicellular type has been successfully developed.

Heating Effect.—If a current, I, is passed through a wire of resistance, R, energy will be expended at the rate of I^2R watts, and the temperature of the wire will rise above the temperature of the surroundings until the energy dissipated per second equals I^2R. This rise of temperature causes a change in length of the wire and this change in length has been used to actuate the needle of voltmeters and ammeters. The voltmeter of Major Cardew was the first of this type, but has now given place to the more compact instruments which operate as shown in Fig. 355.

The sag of the wire AB is taken up by CD, H and F, moving to the left and rotating the needle drum clockwise. Voltmeters of this type require from 0.3 to 0.1 ampere to give full deflection while ammeters require a drop in the shunt of 0.2 to 0.5 volt.

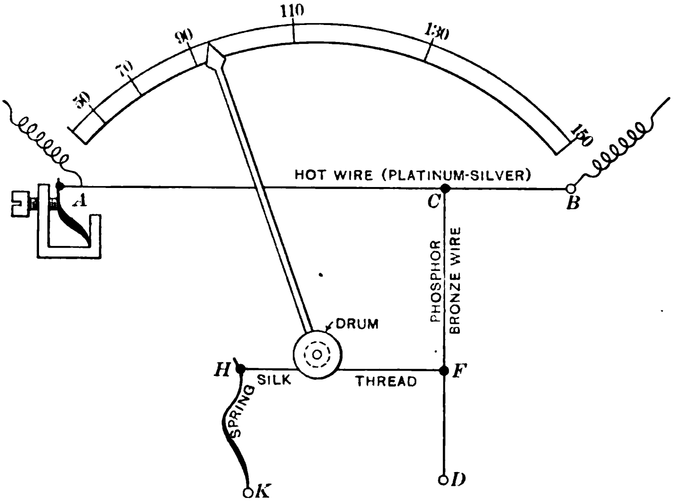


FIG. 355.—Mechanism of Hartmann and Braun's Hot-Wire Instruments.

The hot wire ammeter has been found to be a useful accessory in wireless telegraphy. It is equally accurate with direct or alternating current, and is not affected by stray fields.

Electrochemical Effect.—When a direct current passes through a salt solution, the electrode where the current enters the liquid is gradually carried into the solution, and at the same time material is carried out of the solution and deposited on the electrode where the current leaves the liquid. If the electrodes and the electrolyte are prepared according to some standard specifications, the same current in the same time will always liberate the same amount of matter. This change in weight of electrodes can be measured and therefore the current determined. This effect is very accurate and is used to some extent as a standard for measuring currents (see Ampere).*

Magnetic Effect.—Several classes of instruments are made depending upon magnetic or electromagnetic effect. Some depend on the mutual attraction or repulsion of conductors carrying current due to the magnetic fields set up around them; others depend upon the reaction between a magnetic field due to some outside source and the magnetic field set up around a conductor carrying a current lying in that field; and still others depend upon the attraction between a conductor carrying a current and the field induced by it in some soft-iron core.

I. Measurement of Current and Voltage.

A. Siemens' Dynamometer.—The well-known Siemens' electrodynamometer is an example of the class of instruments based on the mutual attraction or repulsion of conductors carrying a current. It is of interest because it is often used as a standard. It is adapted to be used as a voltmeter, an ammeter, or a watt meter and either for D. C. or A. C. This dynamometer consists of two coils at right angles to each other, one of which is stationary and the other is free to revolve. The movable coil hangs from a thread secured to a spiral spring, which in its normal condition allows the coil to remain at rest perpendicular to the stationary coil. Current is sent through the two coils in series and the magnetic fields set up around the conductors tend to move the two coils so as to make their planes parallel. This tendency causes the movable coil to rotate against the tension of the spiral spring, and it comes to rest in a position determined by the relative strengths of the fields and that of the spring. The amount of twist given the spring in order to bring the movable coil back to its zero position is a measure of the current in the coils. The spring is twisted by means of a milled head which carries a pointer travelling over a scale, the current being proportional to the square root of the angle through which the pointer has turned.

If both coils are made of a large number of turns of fine wire, it can be used as a voltmeter by connecting a high resistance in

* See page 23.

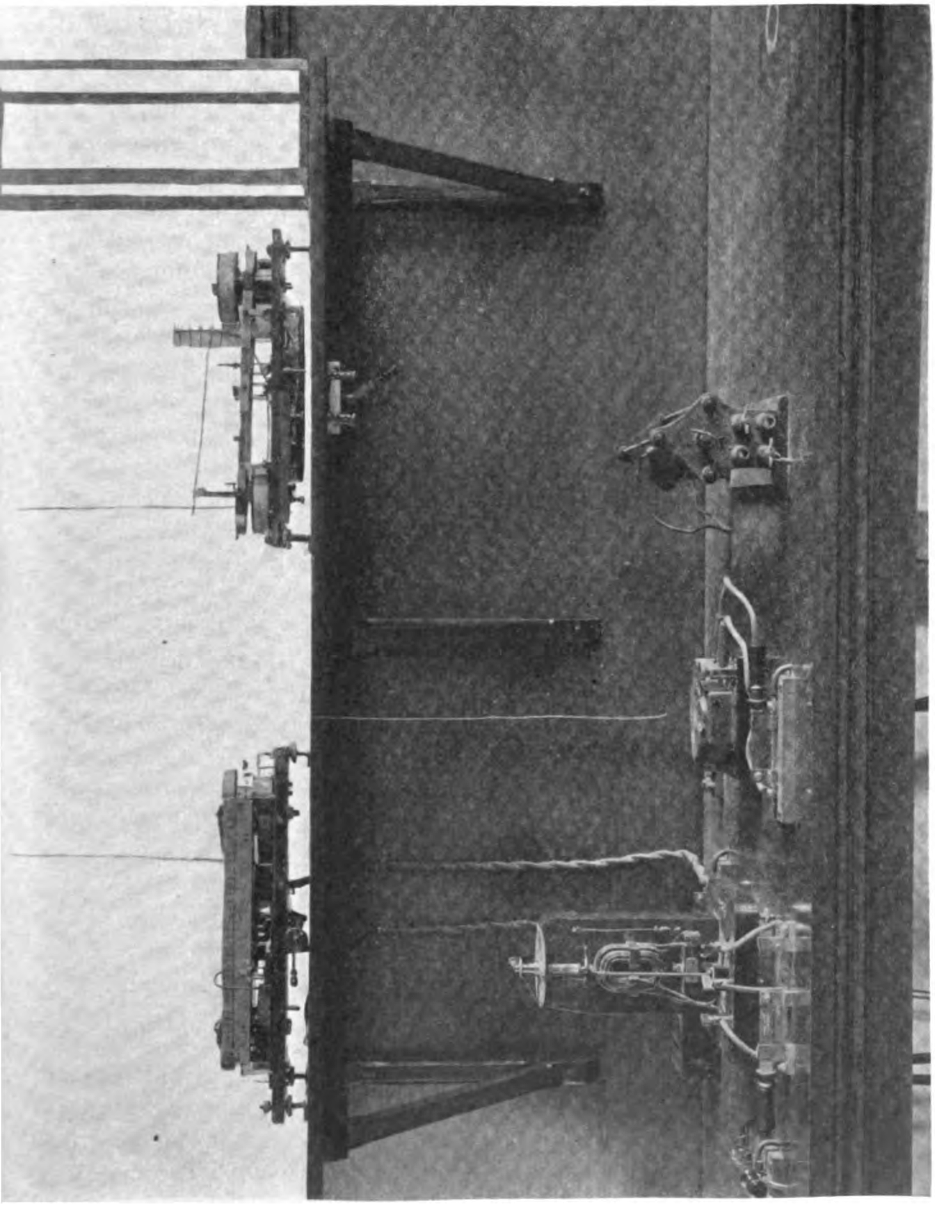


FIG. 356.—Kelvin Balances and Siemens' Dynamometer, Standardizing Laboratory, U. S. Naval Academy.

series with it. It still measures the current, but this is proportional to the E. M. F. at the terminals and the force is a measure of the E. M. F.

This form of instrument could not be used on board ship, for it must be carefully leveled; as it is not direct reading, it requires time and very careful handling, and it is of not much use if the current fluctuates. It is of special value as a transfer standard for calibrating other instruments, and its permanence and reliability depend only on the spring, which experience has shown to be practically unchangeable.

Another instrument depending on this principle is the Kelvin current balance. In Fig. 356 are shown the Siemens' dynamometer and Kelvin Balance as set up in the Standardizing Laboratory of the U. S. Naval Academy.

B. The Tangent Galvanometer.—This is an instrument for indicating and comparing currents, not to measure them, except in an indirect way. One of the most delicate instruments for showing the effect of an electric current is an ordinary magnetic compass needle. It will be remembered that the definition of the ampere was based on the effect that a current produced on a magnetic pole. It will be well here to repeat the definition. If a conductor 1 unit in length (1 centimeter) be bent into an arc of a circle 1 unit in radius (1 centimeter) and a unit magnetic pole be placed at the center, then the current through such a conductor will be 1 unit of current if it acts on the unit magnetic pole with a force of 1 dyne. The effect of the current is inversely proportional to the square of the distance, r the radius, from the magnetic pole. Evidently there could be no closed circuit in such a conductor, and to make one complete turn around the pole, there would have to be a conductor in length equal to $2\pi r$. The force then in dynes which a current I would exert on a unit pole due to one complete turn would be expressed by the equation $\frac{2\pi r I}{r^2}=f$, and if the coil consisted of n complete turns, would be

$$\frac{2\pi n I}{r}=f.$$

If such a coil surrounds a magnetic needle, each unit of strength of the needle will be acted on by a force of f dynes. The needle is held in the magnetic meridian by the horizontal force of the earth's magnetism, this force designated by H acting on each unit of strength of the magnet. If the needle is acted upon simultaneously by these two forces it will take a position at an angle δ from the meridian that will represent the resultant of the direction of the two forces. If the coil is in the meridian, the force due to the current acts at right angles to it, and the force due to the earth acts in the meridian. Fig. 357 represents the forces acting on the needle, NS being the meridian, δ the angle of deflection, H the horizontal force of the earth tending to hold the needle in the meridian and f the force due to the current flowing in a coil in the meridian over the needle. It is evident, then, that

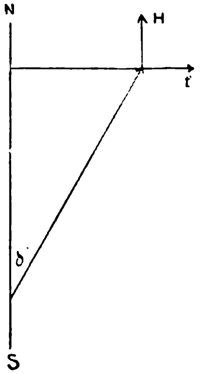


FIG. 357.
Forces Acting on Needle in Tangent Galvanometer.

$$f = H \tan \delta,$$

or

$$\frac{2\pi n I}{r} = H \tan \delta.$$

These quantities all being known, it follows that I in C. G. S. units $= \frac{r}{2\pi n} H \tan \delta$, or I is proportional to $\tan \delta$. This is the principle of the tangent galvanometer. The tangent galvanometer, however, is not used for taking accurate measurements, since it depends on H which varies in a capricious way even in the laboratory.

C. Weston Voltmeters.—The general form invariably used in the service on shipboard is that of the Weston type, being a development of the early d'Arsonval galvanometers. Two forms are usually supplied, one the station type for use on permanent switchboards, and the other a portable instrument for measurements about generators, motors, or measurements for resistance or fall of potential in different parts of a circuit. They are constructed on the same principle, already quoted under the second class of instruments given under the heading *magnetic effect*.

The permanent magnetic field is produced by a permanent steel magnet of peculiar form, half circular, half horse-shoe (see Fig. 377); the outside form of the face of the portable instrument being often the shape of the magnet. The form of the pole pieces is such that the deflecting coil moves in a constant uniform field, and therefore the deflections follow the proportional law. In the annular air gap of this permanent magnet is pivoted on very sharp points resting on jeweled bearings, a light rectangular coil of wire, as shown in Fig. 358. The motion of this coil is restrained by two fine spiral springs, each something like the hair-spring of a watch, one at the top and one at the bottom, through which the current is led into and out of the pivoted coil. The two springs are coiled in opposite directions so that temperature changes, tending to change the zero are neutralized.

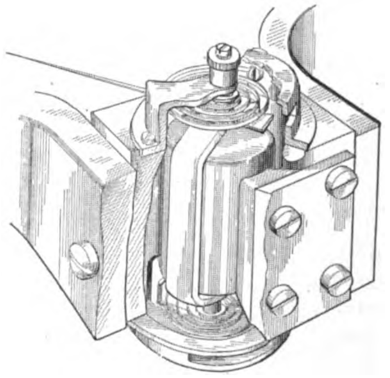


FIG. 358.—Coil and Poles of Weston Instruments.

The index that registers the reading on the face is a long thin aluminum pointer and is secured to the top of the coil, moving with the coil as it is deflected. When no current is flowing, the action of the springs keeps the coil at the zero position.

Within the movable coil is a central cylindrical core of soft iron, this tending to strengthen the magnetic field of the permanent magnet, or rather tending to reduce the reluctance of the permanent magnetic circuit. The movable coil is wound on a light copper or aluminum frame, which in addition to serving as a support for the coil acts as a magnetic brake, moving as it does in an intense magnetic field and having currents induced in it opposing its motion. This makes the instrument practically "dead beat." As soon as current flows, the pointer at once takes a position to indicate the voltage and there is no "hunting" or fluctuating of the pointer.

The movable coil has a resistance of about 60 ohms and a full deflection is produced when a difference of potential of about .6 volt is applied to the coil. When measuring higher voltages than this, it is necessary to insert resistances in series with the coil, the added resistance being proportional to the maximum difference of potential to be measured. The inserted resistance must be calculated for a resistance of $\frac{60}{.6}=100$ ohms for each scale division. To measure 100 volts would require a total resistance of $\frac{60}{.6}\times 100 = 10{,}000$ ohms, or 9940 ohms additional. This resistance is usually a coil of platinoid or manganin wire placed inside the instrument case. As this alloy has a very low temperature coefficient, the temperature error is inappreciable and the instrument may be left in circuit continuously. Because of the high resistance of the instrument, the power loss is very small.

When this voltmeter is connected to the two points of different potential, there is a temporary magnetic field set up around the movable coil, and the coil experiences a pull on one side and a push on the other tending to make it rotate, until it takes a position dependent on the resultant of the forces due to the two magnetic fields and the tension of the springs. The same current always produces the same field and the same deflection, so by proper calibration or comparison with other standards, the proper number of volts may be marked off on the scale.

As the coil moves in a practically uniform field, the subdivisions on the scale are very nearly equal.

The portable voltmeters are usually calibrated for and marked with two scales, one for high reading, and the other for low reading. The low-reading scale is made available and effective by placing properly wound resistance coils in series with the movable coil, this arrangement necessitating a third terminal on the instrument.

D. Weston Ammeters.—The ammeters furnished for ships' use are generally of the Weston type (see Fig. 359), and their governing principle and construction are exactly similar to that of the Weston voltmeter, the scale being marked to register amperes in place of volts. In some of the earlier forms it was usual to lead the whole current to be measured to and through the ammeter,* in the inside of which was a resistance slightly greater than that of the leading wires, and the current that flowed through the ammeter coils was shunted from the ends of this resistance. Only a portion of the main current flowed through the instrument coils, which acted in all respects exactly as a voltmeter measuring the difference of potential between the points to which it was connected.

FIG. 359.—Weston Portable Ammeter.

E. Ampere Shunt.—In order to obviate the necessity of leading the heavy wires to the instrument on the panel board, a later practice is to insert the resistance that was formerly placed in the instrument directly in the leads in some convenient place on the switchboard. Such a resistance is called the **ampere shunt,** and it consists of a resistance slightly greater in value than the main conductors in which it is inserted. A general form of this resistance is shown in Fig. 360.

Two copper terminals, *a, a,* are soldered to the ends of the main conductor *b, b.* Between these copper terminals are strips of metal alloy, *c,* soldered in place to the terminals; the resistance being in strips to better allow for ventilation. The leads to the ammeter

* Such is the case in Fig. 359.

terminals *d, d,* are brought to the copper terminals and clamped at *e, e.*

The metal strips have their resistance so proportioned as to shunt a small current of the magnitude of 0.01 ampere through the ammeter, which thus practically measures the difference of potential between the ends of the resistance. This being proportional to the main current flowing, by proper calibration, it measures the whole current.

It is very necessary that the shunt should have a practically constant resistance as it may carry constantly varying currents

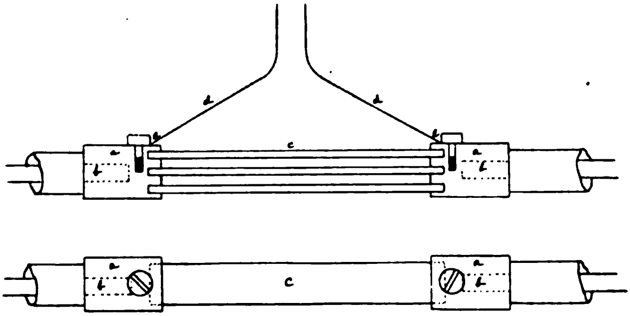


FIG. 360.—Ampere Shunt.

and this is effected by using an alloy of low temperature coefficient, such as platinoid or manganin.

It must be remembered that the ammeter is calibrated with a certain resistance in the leading wires from the terminals of the resistance to the instrument, and the resistance of these wires must not in any way be changed by splicing or cutting, for the main resistance remaining constant, it is evident that the resistance of the leading wires must also remain constant if the instrument is to record correctly.

There must be perfect electrical connection between the shunt terminals and the main conductor and also between the shunt and the ammeter leads. Any resistance due to a bad contact in the former case would cause undue heating, in the latter case the instrument would read low.

The coil of the instrument is the same for all ranges and the full deflection of the needle is obtained when the difference of potential at the terminals is .06 volt. The resistance of the shunt is such that this difference of potential, about .06 volt, exists when the shunt is carrying the maximum current and the resistance of the shunt is varied by changing the number of strips of alloy in it, their lengths remaining the same.

F. Voltmeter Series Resistances or Multipliers.—The same instrument may be used either as an ammeter or a voltmeter by the use of resistances properly constructed and connected in circuit with it. If the deflecting coil has a resistance of 60 ohms and a full scale deflection is produced when .6 volt is applied at its terminals, .01

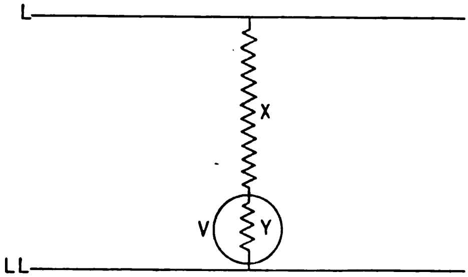


FIG. 361.—Resistance for Voltmeter Connections.

ampere would flow through the coil. To measure any potential difference greater than .6 volt, resistance must be added in series with the deflecting coil.

Suppose it was required to have the full scale deflection represent 150 scale divisions or to indicate 150 volts, a resistance of 14,940 ohms would have to be added in series with the 60 ohms of the deflecting coil. This is determined as follows:

In Fig. 361 Y represents the deflecting coil to which the deflecting needle of the voltmeter V is secured. The added resistance is X, and X and Y are connected in series across the line L, LL, across which the potential difference is required. In reality X is enclosed by the voltmeter case.

If the potential difference across the line is 150 volts, the current through the resistances X and Y is

$$\frac{150}{X+60}. \qquad (1)$$

The fall of potential across Y is .6 volt and across X is $150-.6 = 149.4$ volts. The current through X is

$$\frac{149.4}{X}. \qquad (2)$$

As the current is the same in both instances $(1)=(2)$, or

$$\frac{149.4}{X}=\frac{150}{X+60},$$

or $X=14{,}940$ ohms.

If the potential difference across the line is 100 volts, the current through the resistances X and Y is $100 \div 15{,}000$ amperes, and the drop across the deflecting coil is $(100 \div 15{,}000) \times 60 = \frac{6}{15}$ volt. If .6 volt represents 150 scale divisions, $\frac{6}{15}$ volt would represent $\frac{6}{15} \times \frac{150}{.6} = 100$ scale divisions. 100 volts would then produce a scale deflection of 100 divisions, and if 150 scale divisions represented 150 volts, 100 scale divisions would represent 100 volts.

The value of the series resistances, referred to above, runs from 10 ohms per volt in cheap instruments to 150 ohms per volt in standard instruments.

G. Shunts.—To have the scale of the instrument indicate directly in amperes, it is necessary to add a shunt resistance in parallel with the deflecting coil.

Suppose the deflecting coil had a resistance of 20 ohms and a full scale deflection was produced when a potential difference of .2 volt existed at its terminals, then .01 ampere would flow through the coil. Suppose it is required to have 100 amperes represented by a full scale deflection, then a certain resistance must be connected as a shunt to the deflecting coil and through which the current to be measured must flow.

In Fig. 362 the main current whose strength is to be measured flows in *L, L,* in which is inserted the shunt resistance *S,* to which the terminals of the deflecting coil of the instrument are connected. For a full scale deflection, the potential drop across *S* and *Y* (neglecting the resistance of the connecting wires) is .2 volt, and if a current of 100 amperes, which is to be represented by a full scale deflection, is flowing, the resistance of *S* must be $.2 \div 100 = .002$ ohm. With this resistance, different currents through *S* would produce different potential drops across *Y*. Thus 50 amperes would give a drop of $50 \times .002 = .1$ volt, and as .2 volt gave full scale deflection, .1 volt would give half scale deflection, and if full scale deflection represented 100 amperes, half scale deflection would represent 50 amperes, which was the amount flowing.

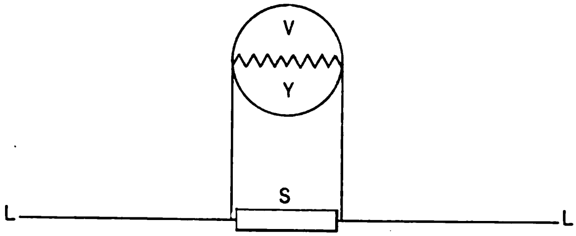


FIG. 362.—Shunt Resistance for Ammeter Connections.

H. Millivoltmeters.—If the scale in the above instrument had been marked in volts instead of amperes, the full scale deflection would be marked $100 \times .002 = .2$ volt or 200 millivolts. If 50 amperes were flowing, the potential drop across *Y* would be $50 \times .002 = .1$ volt or 100 millivolts, and the half scale deflection would represent 100 millivolts. Thus a millivoltmeter with a shunt resistance may be used to indicate amperes directly by marking the scale in amperes rather than in millivolts. By using different values of shunt resistance, the same throw of the pointer in a millivoltmeter may represent different current values, and the scales may be marked according to the value of the shunt used.

Thus, suppose a .001 ohm shunt was used, a full scale deflection would represent $.2 \div .001 = 200$ amperes, and a .004 ohm shunt would represent $.2 \div .004 = 50$ amperes. Thus the instrument, instead of being marked in millivolts, could have the same scale marked for three different current values; the maximum in each case being 50, 100 and 200 amperes.

I. Iron Vane Instruments.—A shunt cannot be accurately used with alternating current ammeters because of the inductance in the instrument, and it is difficult to carry the entire current to be measured into a moving coil. Consequently, for practical work, the so-called "iron vane" class of instruments, of which the Weston instruments and the G. E. inclined coil instruments are examples, have been introduced. The pointer is fastened upon a pivoted shaft to which only a small, soft iron vane and springs are attached. This sets in a solenoid in which the current to be measured flows. The iron vane tends to set itself in line with the magnetic field, and, in so doing, turns the shaft and needle against the action of the springs. Voltmeters are also made on this principle, the solenoid being wound with a large number of turns of fine wire. Such instruments cannot be accurately standardized with direct current, owing to hysteresis and the changing permeability of the iron. They are, however, accurate to 1 per cent with direct current.

J. Potentiometer.—A potentiometer is an instrument by means of which voltages are measured in comparison with a standard cell, or by which E. M. F.'s of cells are compared with one another. It can also be used for accurate measurements of currents, voltages and resistances and for the calibration of measuring instruments. With it, voltages from a fraction of a millivolt to several thousand volts can be accurately compared with the E. M. F. of a standard cell, and currents ranging from a small fraction of an ampere to many thousand amperes may be measured.

The principle of the potentiometer is illustrated in Fig. 363.

CD is a uniform conductor of such size that its resistance will not be materially changed by the heat which is produced by the current flowing in it. It is shown as being divided into 16 equal parts, 15 to the left of the point marked 0 and 1 to the right. It is immaterial what the resistance of each of these parts may be, but it is absolutely essential for accurate measurements that the resistances of all parts be equal. The ends of this wire are connected to the terminals of a battery *B* and in series is joined a regulating rheostat *R*. The battery should preferably be a storage cell or one that gives a continuous steady current.

Assuming that each portion of the wire is of 5 ohms resistance, and neglecting for the present the connections at *M* and *M'*, the potential difference at the end of the wire *CD* is $I(16\times 5)=80I$. Assuming that this potential difference is 1.6 volts, the current flow-

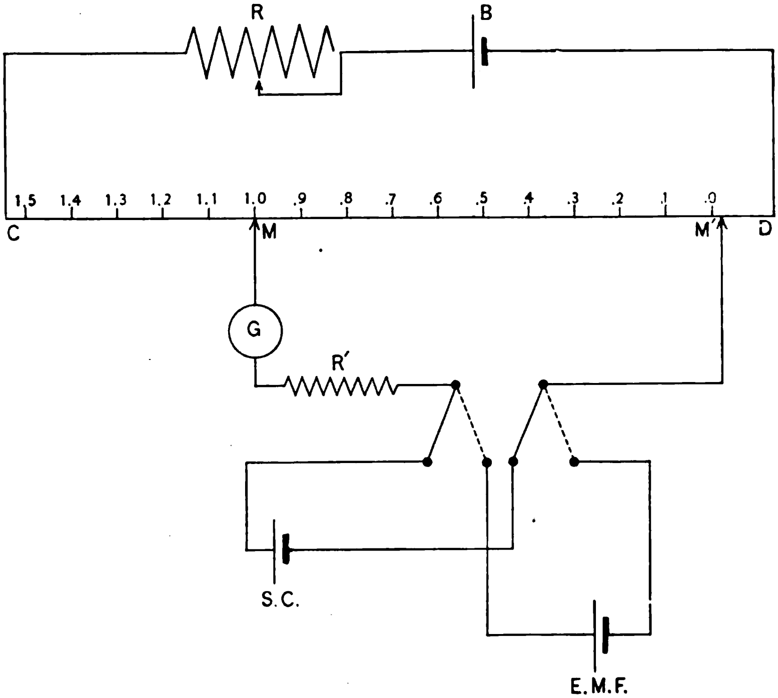


FIG. 363.—Connections of Potentiometer.

ing through it would be $1.6\div 80=\frac{1}{50}$ of an ampere. The drop of potential between the terminals of any one of the 16 equal parts would be $\frac{1}{50}\times 5=\frac{1}{10}$ volt, and over the whole wire $\frac{1}{50}\times 80=1.6$ volts. The equal parts of resistances can then be marked to represent volts as shown in the figure by the numbers .1, .2, .3, etc. The part to the right of the 0 is divided into tenths, so the drop across each of these parts is .01 volt. By dividing this portion still more minutely, the potential drop can be measured to thousandths or ten-thousandths, depending upon the accuracy with which this portion of the resistance can be divided.

Connected at M and M' to the resistance wire is a circuit which contains a galvanometer G, a protecting resistance R' and through the double-throw switch a standard cell SC, which should be so connected that its current opposes that of B. This is diagrammatically shown in Fig. 364.

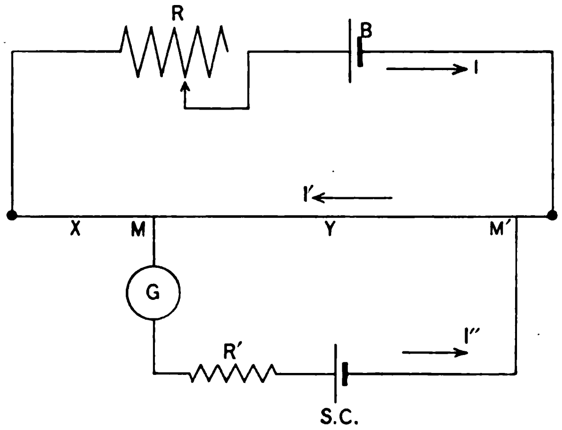


FIG. 364.—Elementary Connections of Potentiometer.

Calling E = E. M. F. of cell B,

e = E. M. F. of cell SC,

X = resistance to left of M,

Y = resistance between M and M',

R'' = all resistances in B's circuit except Y,

R''' = all resistances in SC's circuit except Y,

and the currents as indicated, we have

$$E = IR'' + I'Y,$$

$$e = I''R''' + I'Y.$$

When M and M' have such positions that the galvanometer shows no deflection, $I''=0$ and $I'=I$, or

$$e = IY. \qquad \text{(a)}$$

Similarly if another cell is substituted for *SC* another position of *M* and *M'* can be found that will give no galvanometer deflection, and similarly

$$e' = IY'$$

or

$$\frac{e}{e_1} = \frac{Y}{Y'}.$$

Y and *Y'* are known and the E. M. F.'s of the two cells can be compared, and if the value of one is known, the other readily follows.

Suppose $\frac{1}{50}$ of an ampere was flowing through *CD,* Fig. 363, when *M* and *M'* are connected as there shown, and no deflection of the galvanometer took place, then $\frac{1}{50}$ of an ampere would also be flowing in the portion between *M* and *M'* and the drop of potential between those points would be $\frac{1}{50}(10\times5)+\frac{1}{50}(.2\times5)=1.02$ volts. Conversely if the terminal *M* was set at 1 and *M'* at .02, and *R* *regulated until no deflection occurred,* it is evident that $\frac{1}{50}$ of an ampere was flowing and the voltage of *SC* must be 1.02 volts. This then indicates the manner by which the current of $\frac{1}{50}$ is assured. If the E. M. F. of the standard cell is 1.02 volts, it is only necessary to set *M* and *M'* at their proper values on the resistance and regulate *R* until no deflection in the galvanometer takes place. When this is the case, substituting in equation (a) the known values of *e* and *Y,* a balance having been established, we have

$$1.02 = I(10\times5+.2\times5) = 51I,$$

or

$$I = \tfrac{1}{50}.$$

To measure the E. M. F. of another cell, it is now only necessary to throw the switch so as to connect the cell in circuit with the galvanometer, and *without changing the resistance in R,* so move *M* and *M'* that a balance is again obtained. Suppose when this took place *M* was at 1.2 and *M'* at .03, then the fall of potential between them would be $\frac{1}{50}\,(12\times5+.3\times5)=\frac{1}{50}\times61.5=1.23$ volts, or the E. M. F. could be read directly from the positions of *M* and *M'*, 1.2 for *M* and .03 for *M'*.

It is evident that the E. M. F. of *B* must be of such a value that the potential drop between *C* and *D* will be greater than the E. M. F. of the standard cell or of the cells to be compared.

The function of *R′* is to protect the galvanometer from excessive current when far from the balancing position and to prevent the standard cell from becoming polarized. As the balancing position is approached the resistance should be cut out in order to make the galvanometer more sensitive.

In actual construction, the resistance units are made up in a dial form, over which moves a sliding contact, so that *M* may be readily placed in any position. The part to the right of *O* has the same resistance as any one of the other portions. By making it in the form of a spiral of ten turns of the proper diameter it is readily divided into tenths, and by a sliding contact each tenth can be so divided that the potential drop can be read to ten-thousandths.

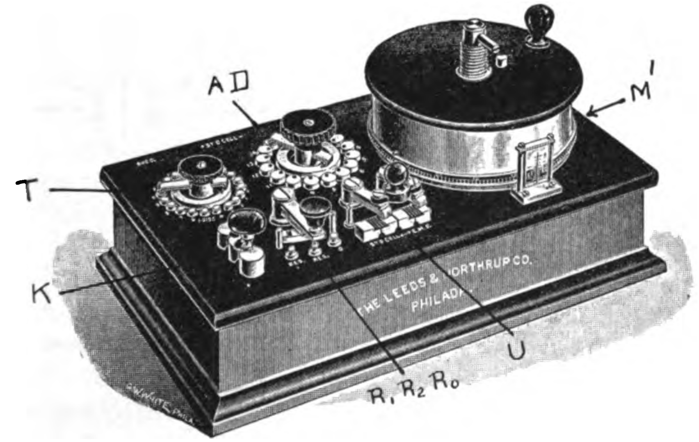


FIG. 365.—Leeds and Northrup Potentiometer.

The L. and N. Potentiometer.—Fig. 365 shows a cut of the Leeds and Northrup potentiometer which is used to large extent in this country. Fig. 366 shows the diagram of connections. Such portions of Fig. 365 as are shown in Fig. 366 are marked with corresponding letters.

The essential part of the instrument consists of 15 five-ohm coils *AD*, adjusted to equality to a high degree of accuracy, connected in series and having in series with them an extended wire *DB*, the resistance of which from 0 to 1000 on its scale (the entire scale reading from 0 to 1100), is also 5 ohms. A contact point *M* is arranged so that it can make contact between any two of the 5-ohm coils and a contact point *M'* so that it can make contact at any point on the extended wire *DB*. Current from the battery *W* flows through these

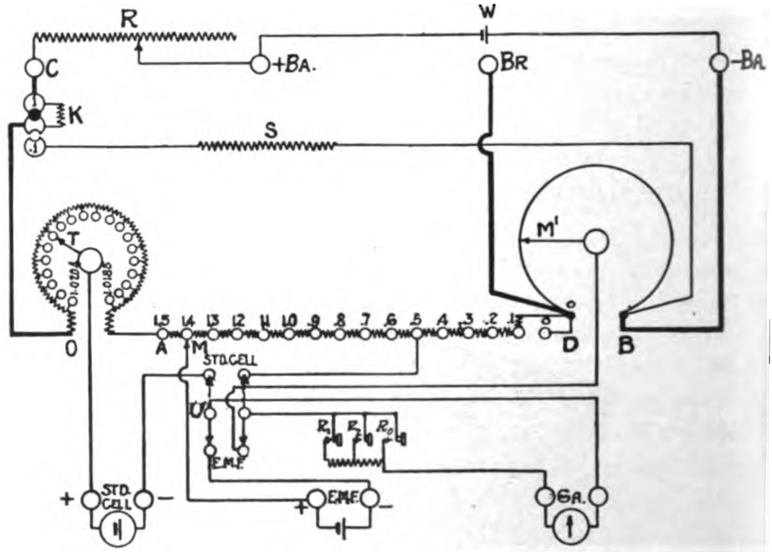


FIG. 366.—Wiring Diagram, Leeds and Northrup Potentiometer.

resistances and by means of the regulating rheostat *R*, it is so adjusted as to be exactly $\frac{1}{50}$ of an ampere. The fall of potential across any one of the coils *AD* is consequently $\frac{1}{10}$ of a volt and that across the extended wire *DB* is .11 volt. By placing the contact point *M'* at zero and by moving the contact *M*, the electromotive force between *M* and *M'* may be varied by steps of $\frac{1}{10}$ of a volt, from 0 up to 1.5 volts. The wire *DB* is divided into 1100 equal parts. By moving the contact point *M'* from 0 to 1100, the electromotive force between *M* and *M'* may be varied by extremely small fractions of a volt. To measure an unknown electromotive force it is introduced in series with a galvanometer between the points M and M' and in opposition to the fall of potential along AB. The contact points M and M' are then adjusted until the galvanometer shows that no current is flowing, and then the value of the unknown electromotive force can be read from the position of the points M and M'. In the diagram, the connections show the unknown electromotive force introduced at the binding posts marked E. M. F., the galvanometer at the point *Ga,* and in series with these, three keys marked R_1, R_2 and R_0. When the key R_1 is depressed the circuit is closed through a high resistance; when R_2 is closed the circuit is closed through a lower resistance, and when key R_0 is closed the circuit is closed through zero resistance. The purpose of keys R_1 and R_2 is to protect the galvanometer against excessive deflections when the opposing electromotive forces are not approximately balanced.

Ordinary Methods of Applying the Standard Cell.—To regulate the current flowing through the wire AB and make it exactly $\frac{1}{50}$ of an ampere, a standard cell may be introduced at the binding posts E. M. F., the points M and M' set at the electromotive force of the standard cell and the regulating resistance R adjusted until the galvanometer shows a balance.

There is always a possibility that the current will change between the adjustment of R and the completion of a measurement. To provide against this, the current should be checked against the standard cell after each measurement. This usually involves the necessity of resetting the points M and M' after a measurement has been made. This resetting takes considerable time and results in a corresponding loss of accuracy and convenience. To obviate this defect an improved method of applying the standard cell has been introduced.

Quick Method of Applying the Standard Cell.—At the point .5 on the series of resistances AD, a lead wire is permanently attached which leads to one point of the double-throw switch U. Between A and O there is a series of 19 resistances with a sliding contact T. The resistance between .5 and A is exactly that which corresponds with the electromotive force of 1 volt, and that between A and 1.0185 a sufficient addition to make the resistance between .5 and this point correspond to an electromotive force of 1.0185 volts. Between this and the end of the series of resistances there are 19 coils, which increase the corresponding electromotive force by steps of .0001 to 1.0204 volts. This range corresponds with the variations in different cadmium cells and the circuits are so connected that the two points T and .5 may be thrown in series with the galvanometer and the keys R_1, R_2 and R_0. In this circuit are also the two binding posts marked standard cell, to which the standard cell is to be connected. To adjust the current $\frac{1}{50}$ of an ampere throw over the double-throw switch U to the position indicated by the dotted lines. Set the point T to correspond with the electromotive force of the standard cell and regulate R until the galvanometer shows no deflection. The unknown electromotive force may then be measured as before with the contact points M and M', the double-throw switch having been placed in the position indicated by the full lines. After a balance has been obtained, the current may be checked by simply changing the position of U and touching the contact key R_0. A galvanometer balance shows that no change has occurred. A slight deflection calls for a slight readjustment of R and a corresponding readjustment of M'.

The Extended Wire and Contact *M'*.—The wire *DB,* indicated in the diagram by a single turn, corresponds, in the instrument, to 11 turns on a cylinder 6 inches in diameter. It is, consequently, about 207 inches long and each turn represents .01 of a volt. The final divisions, representing $\frac{1}{100}$ of a turn, are about 4 millimeters apart and are subdivided with a short line indicating half divisions. It is, consequently, quite easy to estimate these divisions to tenths. A vertical scale shows the number of turns and the fraction of a turn is read from a circular scale.

It has sometimes been found inconvenient to measure an E. M. F. which is fluctuating between points where one must quickly turn the contact M' (Fig. 366) through 10 turns, and readjust M, in order to follow the voltage change. For instance, if the voltage is .695, and goes to .705, the slider M' must be turned through 990 divisions, and the point M reset to .7. To obviate this difficulty, an extra turn of wire has been added to the slide wire, making the whole 11 turns instead of 10. It will be seen that by this arrangement, small fluctuations not exceeding .01 volt slightly overlapping the 10 turns, may be followed with ease.

The contact point is mounted inside of an aluminum hood and moves up and down with this hood on a heavy screw projecting from the center of the marble cylinder. When it is screwed down the hood entirely covers the extended wire, thus protecting it. The lower periphery of the hood carries the scale on which the fractions of a

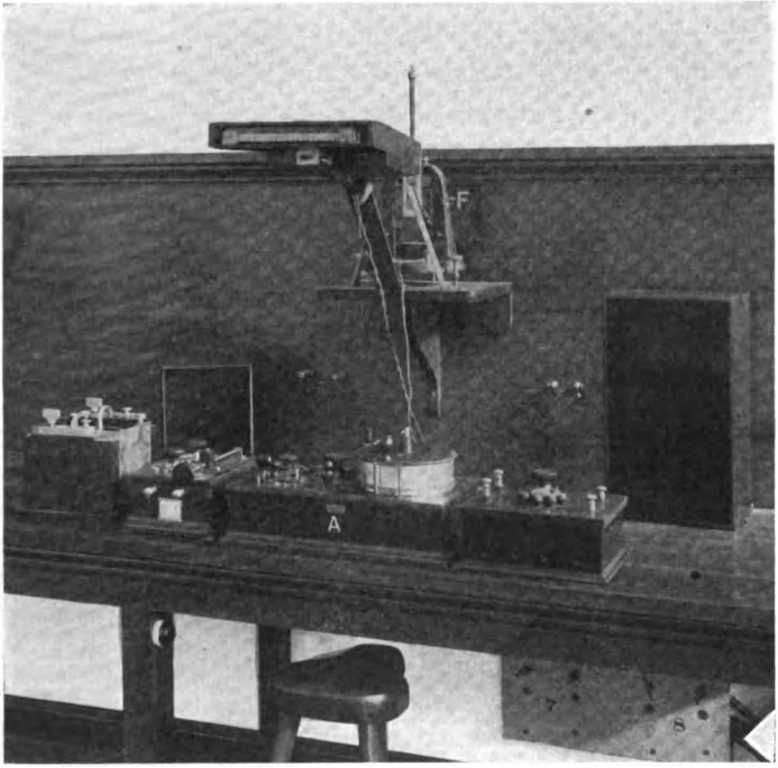


FIG. 367.—L. and N. Potentiometer and Accessories, in the Standardizing Laboratory, U. S. Naval Academy.

turn are marked, and a glass scale immediately in front of it has a vertical line which serves as the index and a horizontal scale which shows the number of turns.

In the figure are shown the various pieces of apparatus, found necessary in potentiometer measurements at the U. S. Naval Academy.

A = that part of the apparatus corresponding to Fig. 365,
B = resistance R,
C = standard cell,
D = volt box or volt multiplier,
E = ampere shunt,
F = wall galvanometer.

II. Measurement of Resistance.

A. The Testing Set.—The testing set for measuring and comparing resistances ordinarily consists of a battery of a few cells, a galvanometer, and a combination of resistance coils of known value. The principle of all resistance testing sets is that of the Wheatstone bridge.

B. The Wheatstone Bridge. The Theoretical Bridge.—The bridge (Fig. 368) consists of four arms 1-2, 2-3, 3-4 and 4-1, in three of which are variable coils of known resistance, and in the fourth, the unknown resistance X is placed. A battery B of a few cells is connected to 1 and 3, and a galvanometer G is connected to 2 and 4.

Let A, B, C and X represent the four resistances and I_a, I_b, I_c and I_x the currents in those resistances at any time.

A and B usually contain coils of resistance varying by multiples of 10, as 1, 10 and 100, and 10, 100 and 1000, and they are called the *balance* ratio, or bridge arms. The arm C contains numerous coils of resistance of such values that any whole integer may be made, and this is called the *rheostat* arm.

The current from the battery divides at 1, flows through A and C, B and X to 3 and thence back to the battery. When there is a difference of potential between 2 and 4, current will also flow in that branch, either towards 2 or towards 4, depending on the relative resistances of A and B. If current does flow through the galvanometer, it will be shown by the needle being deflected, but if there is no difference of potential between 2 and 4, no current will flow in that branch and the needle will remain at rest. When this happens a *balance* is said to be established between the four arms, and as this condition always exists in making a measurement, it is called a *null* method. There are keys in the battery circuit and in the galvanometer circuit, so current only flows when making a test.

When current is flowing, there is a certain absolute potential at 1 and a lower potential at 3 in order that current should flow in that direction; and there is also a certain potential at 2 and a certain potential at 4. In order that there may be no *difference of potential* between 2 and 4, the fall of potential from 1 to 2 must equal the fall in potential from 1 to 4, although the currents and resistances in these branches may be different. Similarly the fall

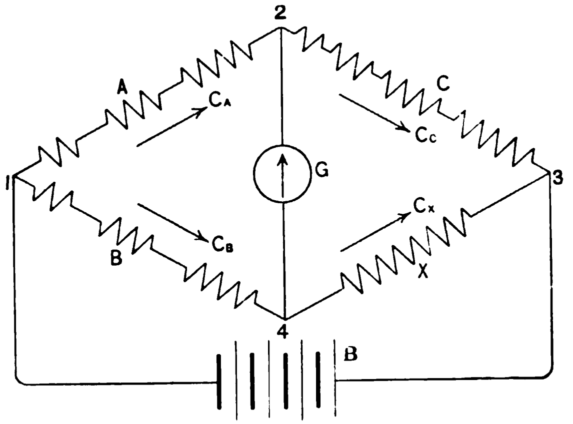


FIG. 368.—Connections of Theoretical Wheatstone Bridge.

in potential from 2 to 3 must be the same as from 4 to 3. In other words, by Ohm's law

$$I_aA = I_bB \text{ and } I_cC = I_xX.$$

When there is no difference of potential between 2 and 4 the current in A is the same as in C because no current flows through the galvanometer; and in B the same as in X, or

$$I_a = I_c \text{ and } I_b = I_x.$$

Therefore,

$$I_aA = I_bB \text{ and } I_aC = I_bX$$

and dividing one by the other

$$\frac{A}{C} = \frac{B}{X} \text{ or } X = \frac{BC}{A}$$

from whence A, B and C being known, X is readily calculated.

If the resistances in the balance arms A and B are equal when a balance is obtained, then the unknown resistance X is equal to the resistance found in C. If B is greater than A, the resistance in C must be multiplied by the number of times B is greater than A, and similarly if smaller than A, divided by the number of times it is smaller.

Resistance Coils.—The resistance coils are usually made of German silver, platinoid, or manganin wire as their resistance is affected very little by a change of temperature. In order to prevent the effects of self-induction due to the current and of induction due to stray fields in the neighborhood of the coils, it is necessary that the wire be doubled back on itself. The wire should be either wound on the bight as in Fig. 369, or, if there are to be many turns, the first layer should be wound right handed and the next left handed and so on, each layer being secured so as not to unwind when the next layer is wound. Then again the bobbin on which the wire is wound may be divided into halves, the upper half being wound right handed and the lower left handed.

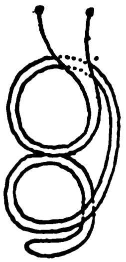


FIG. 369. Winding of Resistance Coils.

After the coils are wound they are dipped into melted paraffin, so on cooling every portion is covered, being protected mechanically and electrically.

The rheostat arm of the bridge may be used as a separate resistance, and if so used, care must be taken that too great current is not sent through coils, as they are delicate and are easily burnt out. Resistance coils ordinarily found in bridge boxes will carry about 0.02 ampere. The same precaution is necessary in using the galvanometer as a separate instrument, as the coils of that instrument cannot stand too heavy a current.

Silver Chloride Cell.—As has been stated this form of cell is ordinarily used in testing sets, and in order to use the set intelligently a short description of the cell is given. The positive electrode is a zinc rod and the negative electrode consists of a silver rod surrounded by silver chloride melted into a cylinder upon the rod. The electrolyte is sal ammoniac, but in the dry cell, as used with testing sets, the water is replaced by some gelatinous substance which differs in its composition according to the maker, it generally being a paste containing zinc oxide, zinc chloride, sal ammoniac, lime and water.

When the cell generates current the chlorine in the ammonium chloride (sal ammoniac) is displaced by the zinc and the ammonium set free displaces the chlorine in the silver chloride, leaving metallic silver deposited on the silver electrode. There will be no free gas given off unless the cell is worked too hard. This cell gives under ordinary conditions about 1.1 volts.

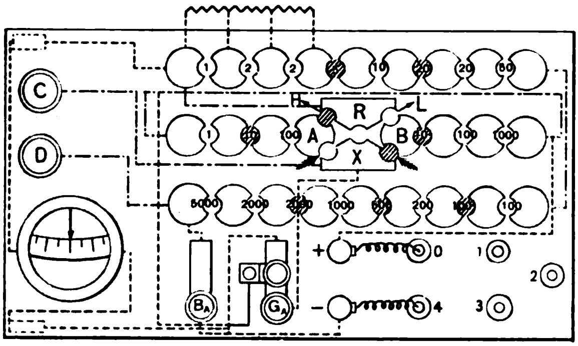


FIG. 370.—Queen-Acme Testing Set.

C. Service Testing Set.—One form of Wheatstone bridge furnished to ships is that made by Queen & Co., called the Queen-Acme Portable Testing Set. The bridge, battery and galvanometer are all placed in a compact box of seasoned mahogany fitted with lock and key.

The upper face of the set is shown in Fig. 370, the full lines and circles showing the connections, binding posts, keys and terminals on the outside of the box and the dotted and broken lines the connections under the face which is of hard rubber.

The Coils.—The coils are wound of platinoid wire carefully seasoned to prevent gradual changing of the resistance with time. The wire has a low temperature coefficient and the endeavor is to have corresponding coefficients for all the coils. The rheostat coils are adjusted to an accuracy of $\frac{1}{8}$ of 1 per cent and the bridge coils to an accuracy of $\frac{1}{10}$ of 1 per cent. The rheostat coils are 16 in number, their combined resistance being 11,110 ohms. In each bridge arm there are three coils of 1, 10, 100 ohms and 10, 100, 1000 ohms respectively. The commutator admits of a ratio of 1 to 1000 on either bridge arm, and the theoretical range is from .001 to 11,110,000 ohms, though for resistances above 1,000,000 ohms, additional battery power is required.

The Galvanometer.—This is of the d'Arsonval type, similar in principle to Fig. 358. The moving element consists of a rectangular coil of wire about 2 centimeters wide by 5 centimeters long and turning in the annular air gap of a permanent magnet. The central core of this magnet provides a support on which to pivot the coil. To adapt this galvanometer to null methods, the springs shown in Fig. 358 are omitted so that a current of a few microamperes passing through the coil is sufficient to produce a deflection.

The Battery.—This consists of four dry cells, one or more of which may be used as desired. They maintain a steady E. M. F. and are good until exhausted. The cells have a very low resistance and with care will last for months even though the set may be used daily. These cells are designated 1, 2, 3, 4, in the lower right-hand corner of Fig. 370.

The Keys.—There are two single contact keys. The left-hand key is a single contact key in the battery circuit. The right-hand one is in the galvanometer circuit and is a short-circuit key. When depressed it closes the galvanometer circuit and when released it short-circuits the galvanometer, bringing it to rest by electrical damping.

Connections and Circuits.—The connection and circuits are readily understood by referring to Fig. 370. The top row of blocks is connected to the bottom row by a heavy copper bar joining the right-hand blocks. These two rows together constitute the rheostat. Any resistance from 1 to 11,110 ohms may be obtained in this rheostat by removing the proper plugs. The lower left-hand block of the rheostat is connected to the lower line post *D*. The upper line post *C* is connected to block *X*. This block *X* has no other permanent connection excepting that it is joined to one end of the galvanometer key. The block *R* is connected to the upper left-hand block of the rheostat and otherwise has no connection excepting by plugs. The end blocks of the middle row are connected by a heavy copper bar. Each half of this row constitutes a bridge arm, designated *A* and *B* respectively. Starting from the lower line post *D*, the circuit is continuous from there through the rheostat and then through first one bridge arm and then the other back to the other line post *C*.

The function of the commutator is to transpose the two bridge arms *A* and *B* so that they are passed through in reverse order. All of the above connections are in circuit with the resistance being measured and are made sufficiently heavy to add no appreciable resistance to the circuit.

The two battery terminals + and – are connected, one directly to the common junction of the two bridge arms, the other through the battery key to the rheostat.

The two galvanometer terminals are connected, one directly to the block *R*, while the other connects through the galvanometer key to the block *X*. The blocks *A*, *B*, *R* and *X* are joined by plugs as shown by the shaded circles between the blocks.

The Commutator.—This consists of the blocks *A*, *B*, *R* and *X* and two plugs. When these two plugs are in the position shown in the figure, the bridge arm *A* is connected to the rheostat and the bridge arm *B* to the line. In this position the following relation holds

$$\frac{A}{B} = \frac{R}{X},$$

and the bridge is in a position for measuring high resistances, indicated by the arrow marked *H*.

If the plugs have the opposite position, the bridge arms are reversed, the one that was connected to the rheostat now being connected to the line, and the one to the line being joined to the rheostat. In this position, the following relation holds

$$\frac{A}{B} = \frac{X}{R},$$

and the bridge is in a position for measuring low resistances, indicated by the arrow marked *L*.

Uses of the Set.—This testing set may be used to measure resistances, either high or low, insulation resistance, to compare E. M. F. of batteries, to check a voltmeter, to measure battery resistances, to check an ammeter and to make what is known as the Varley Loop Test. These will be described in Chapter XXII.

D. Standard Portable Testing Set.—The testing set that has been adopted as the standard for ship board use consists in general of a Wheatstone bridge, rheostat, galvanometer, battery and keys, all properly arranged in a hard-wood carrying case. The theoretical range of the instrument is from .001 ohm to 10 megohms. The rheostat is arranged on the *decade* plan, and consists of the proper number of coils to permit a range of from 1 to at least 9999 ohms in steps of 1 ohm. The terminals of the coils are labeled in a manner permitting the value of the resistance coil to be readily determined, and each row marked for denomination, *i. e.,* for units, tens, hundreds and thousands.

The ratio coils are arranged on the plug-in plan.

Blocks are provided so that connections can be quickly made for locating faults by both Murray and Varley loop tests.

The galvanometer is of the d'Arsonval type and approximately dead beat, with an adjustment lever for the needle, so that it can be adjusted to the center of the scale and indicate zero.

E. Magneto.—This is an instrument used in testing electrical circuits and in a limited degree for measuring resistances. It can be used to detect an open circuit, to detect a ground or to locate a fault in an open circuit, and within limits to measure resistance.

In its most common form, it consists of two parts, a small dynamo or generator and a bell. The connections are shown in Fig. 371.

The field of the generator is furnished by two or more permanent steel magnets. Between the poles is rotated a small closed armature, usually a simple rectangular coil wound on an iron core.

There is a small crank on the outside of the case containing the generator to which is attached a toothed wheel which engages a smaller wheel connected directly on the armature shaft, so one revolution of the crank gives a great many to the armature. Connected in series with the armature is the bell circuit, and when connected for testing an outside circuit, that circuit is also in series with the armature and bell circuit. Current from the armature is led around an electromagnet, between the legs of which and on the end opposite the yoke, is pivoted an iron armature. This armature has secured to it at right angles an arm terminating in a striker for the bell. This striker projects through the case, and has motion between two bells, striking them alternately as it vibrates.

When the armature is revolved and the armature turned in the field of the permanent magnets, alternating currents are induced

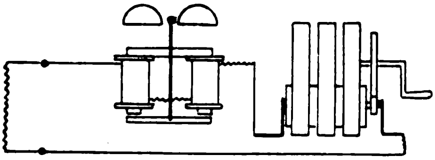


FIG. 371.—Magneto.

in the armature circuit and this being in series with the electromagnet causes alternating currents which cause an alternating change of polarity, causing the armature to be attracted first to one leg and then the other. This causes the striker to vibrate and to ring the bell. This can only happen, however, when the armature circuit is complete through some outside circuit.

The E. M. F. produced in the armature depends to a great extent on the speed with which it is turned, but a good magneto should develop from 50 to 100 volts. For certain purposes, as will be illustrated later, it is necessary to know the maximum resistances that current can be forced through, and these data are usually stamped on them, varying from 3000 to 100,000 ohms.

F. Electric Fault Finder.—As the name implies, this is a device for locating faults in electric circuits, such as leaks, grounds, fractures, short-circuits, open circuits, etc. It will perform all the functions of the magneto and has the advantage of requiring but one person to perform the tests. The vibrating bell of the magneto is replaced by a telephone receiver and the absence or presence of sound in it, or the relative intensity of sound is a measure of the state of leak or ground.

An inspection of the wiring diagram in Fig. 372 will show the connections of the fault finder as made by the Electric Controller

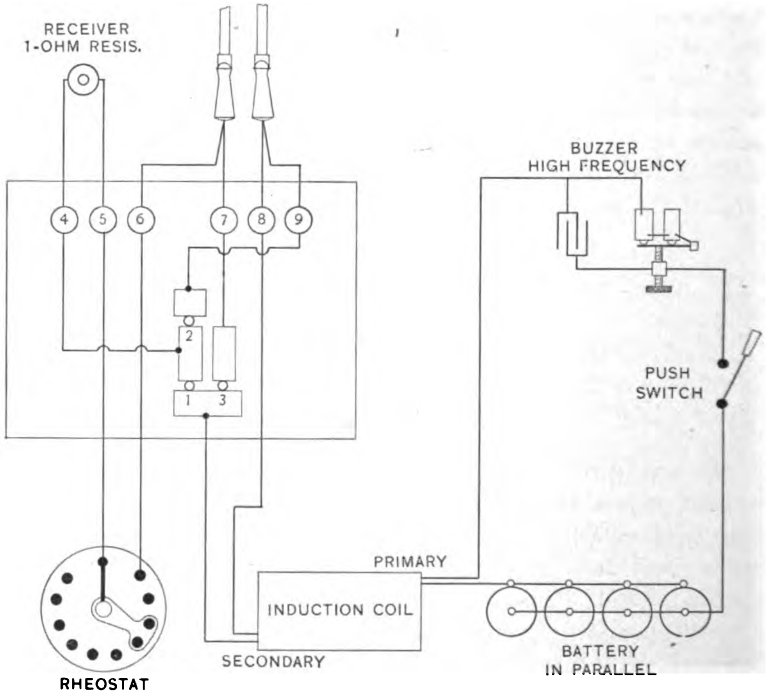


Fig. 372.—Wiring Connections of Electric Fault Finder.

and Supply Co. This shows an induction coil in which the primary is energized by four cells in parallel, and in the circuit of which is a high frequency buzzer for making and breaking the circuit. The alternating currents induced in the secondary flow, by properly arranged switches, through a telephone receiver and the circuit under test. Thus it will be seen that, if the primary circuit is made and switch 1 is closed, the circuit through the receiver is only complete when there is some connection between the external terminals. With this combination, it is seen that the device will perform as an ordinary magneto, sound being produced in the receiver when the external terminals are closed, and the relative intensity of the sound is a measure of the resistance between the terminals in the same manner that the loudness of sound of the bell in the magneto is a measure of the resistance.

The use of the electric fault finder is explained in the latter part of Chapter XXII.

G. Ohmmeter.—This instrument as its name signifies is for measuring resistance, and the value of the measured quantity may be read directly in ohms on the scale of the instrument. In testing for faults or testing the soundness of the insulation used in an electric light installation, it is necessary that an E. M. F. at least as great as that under which the plant is to work, should be used. Such a high E. M. F. would be too great for use with the ordinary Wheatstone bridge testing set, so the ohmmeter is designed to be used with a small magneto giving the desired E. M. F., and then the resistance can be read directly from the instrument. This instrument is of particular value in measuring insulation resistance, and affords the most ready and rapid means of measuring it, its practical application will be shown later.

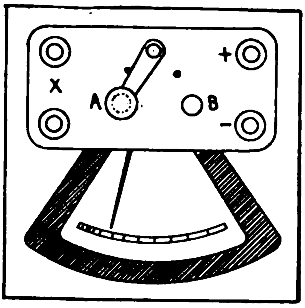


FIG. 373.—Ohmmeter.

Fig. 373 shows the general outside appearance of an ordinary ohmmeter. The two right-hand terminals are for the leading wires from the source of supply (generally a small magneto machine). They are marked + and −. The two left-hand terminals are for the wires leading to the unknown resistance to be measured. There are two contacts in the middle marked *A* and *B*, corresponding to the two scales on the face. If the switch is on *A*, the outer scale is to be used, and if on *B*, the inner scale.

Fig. 374 shows the interior construction, it being a half section through the coils as viewed from beneath. There are three coils, the two outer ones, *a, a,* being placed with their planes parallel and connected in series; the third, *b,* is placed between them with its plane and magnetic axis at right angles to those of *a, a.* There is a small steel needle pivoted in the center of the coil *b* with its magnetic axis lying in the common axis of *a, a.* To this needle is attached the pointer and the coil *b* is so cut away as to allow a wide range for the travel of the pointer. Underneath the pivoted needle is a small weak bar magnet to counteract the earth's magnetism, so the needle only acts under the influence of the coils when current flows through them.

Any current flowing through *a, a,* tends to keep the needle in its zero position with its length in the common axis of *a, a.* In this position the needle is parallel to the plane of *b* and any current through *b* tends to deflect it, and the needle will take a position depending on the relative strength of the current in the coils.

The coils *a, a,* of high resistance are connected only to the source of E. M. F., but the coil *b* which is connected to the same source of E. M. F. is also connected in series to the high resistance to be measured. The current through the deflecting coil *b* is inversely proportional to the resistance and directly proportional to the E. M. F., while the current through the magnetizing coils *a, a,* is directly proportional to the same E. M. F. Any variation of the E. M. F. affects equally both the magnetizing and deflecting currents, so the deflection of the needle is simply inversely proportional to the resistance to be measured, the resistance of *b* being small.

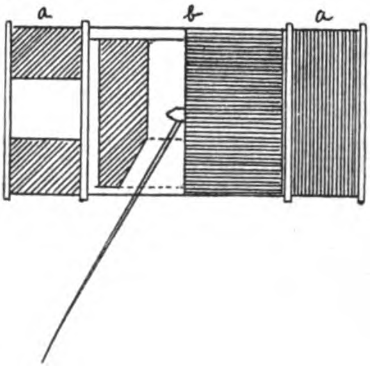


FIG. 374.—Coils of Ohmmeter.

If the resistance to be measured is infinite no current flows through *b* and there is no deflection of the needle. As soon as the resistance is at all lowered a certain small current flows producing a small deflection, and by simple calibration the scale can be marked to indicate directly in ohms the value of the unknown resistance.

H. The Evershed Testing Set.—The ohmmeter described in the preceding section is known as the Evershed ohmmeter, but a later form of this instrument is now made, known as the Evershed Testing Set. This instrument is made by Queen & Co., and the description and use of this instrument has been furnished by the makers.

The electrical principle involved is the same as in the case of the ohmmeter, but the arrangement of the coils is slightly different. This is shown in Fig. 375. The leads from the magneto are secured to the terminals marked $A(+)$, $B(-)$, and the unknown

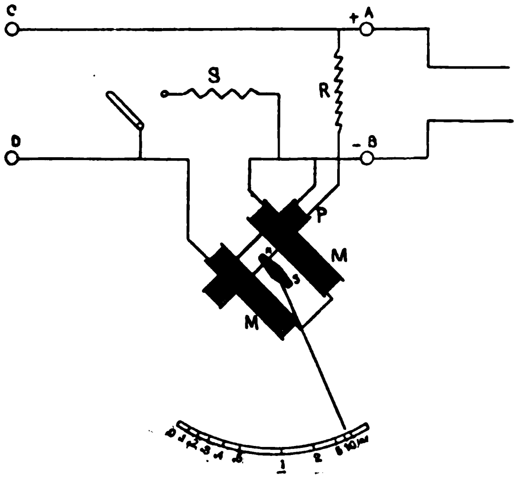


FIG. 375.—Connections of Evershed Testing Set.

resistance to terminals C and D, one of which is marked "Earth" and the other "Line." For testing insulation the conductor under test is connected to the earth terminal, and the other terminal is grounded.

Inside the terminals A and B, the current divides, part flowing through the coil P, called the pressure coil, through a constant resistance R, and part through the unknown resistance and through the coils MM in series, these coils being known as the current coils. The action of the pressure coil is to keep the axis of the needle NS perpendicular to its own coil and that of the current coils to deflect the needle. This needle carries the pointer traveling over a graduated scale from points marked 0 to infinity.

When there is no leakage on the line, there is no current through *MM* and consequently the needle remains at rest, with the pointer indicating infinity, showing an infinite resistance on the line. When the line resistance is so low as to be negligible, the current flowing through the current coils depends on the voltage and the resistance of the coils, and the needle will be deflected to a position in which the turning moments of the two coils *P* and *MM* are balanced. This point on the scale is marked 0 and for any given resistance in the line the pointer will come to rest at a point between 0 and infinity. The position of the pointer will not be changed by altering the voltage of the magneto, for the currents in the coils will be increased or decreased together, so their ratio remains unchanged.

The scale is marked in tenths and units of megohms, thus indicating directly the resistance measured.

Magneto.—In the latest pattern of this testing set, the magneto is built after the fashion of a modern continuous-current generator. It has a tunnel-wound armature with a finely laminated core built from stampings of best iron of "transformer" quality, a special form of commutator with elastic roller brushes and roller bearings for the armature axle. The armature is driven by double gearing by a winch handle so hinged that it may be turned into a recess in the box when not in use. A flexible double conductor connects the magneto to the ohmmeter.

Needle.—The ohmmeter has a very finely pivoted astatic needle system, magnetized by the magneto current. The needle system is automatically lifted off the jewel bearing and clamped by the action of shutting the lid of the box. The current coils *MM* are wound with an enormous number of turns of the finest wire so as to secure the maximum sensibility. A one-ninth shunt *S* is provided so as to reduce the sensibility ten times when low insulation resistances are being tested.

Instructions for Use.—Adjust the ohmmeter until the bubble is in the center of the spirit level.

Place the generator not less than 18 inches away from the ohmmeter and couple its terminals to the marked terminals on the ohmmeter.

Couple the mains to be tested to the *line* and *earth* terminals of the ohmmeter. Turn the generator handle steadily in either direction at any speed above 60 revolutions per minute and the ohmmeter index will point to the resistance under test.

I. The Evershed Megger.—A megger is a name applied to an instrument for measuring very high resistances, the indicating scale being marked in megohms. The Evershed Megger is a modified form of the Evershed Testing Set previously described. It differs from it in that the testing set is constructed on the principle of the reaction exerted between current carried in *stationary coils* and a *movable magnet* while the megger is of the d'Arsonval type of instruments and is constructed on the principle of the reaction exerted between current carried in *moving coils* and a *stationary magnet.*

The operating features are contained in one case and the power is obtained from a hand-driven magneto. This is made in different sizes and E. M. F.'s of 100, 250, 500 or 1000 volts may be generated for 100 R. P. M. of the crank. The coils are separately connected to commutators of a peculiar disc form and against these spring disc brushes roll, making light but sure contact.

The electrical and magnetic circuits are shown in Fig. 376.

N and *S* represent the *permanent* magnets of the system. Between one set of poles, the armature *G* is revolved by the hand crank. Between the other set of poles is secured a C-shaped iron piece *C,* in order to produce a uniform field for the region in which the pivoted coils move. This gathers up the lines of force due to the pole pieces and causes the flux to be very evenly distributed between it and the pole faces.

There are two sets of moving coils, the *current* coil *A* and the *pressure* coil *B',* with an auxiliary coil *B* in the same plane as *B'* and secured to it. All these three coils are rigidly connected together and *B'* carries the pointer which moves over the graduated scale.

These coils are shown as they appear looking down on them and they all are suspended together on vertical pivots at the top and bottom over and under the center of the C-shaped piece. Their terminals are brought to slender copper strips which press lightly against circular rings on the vertical shaft to which the current leads are secured. Coils *B* and *B'*, called the pressure coils, are connected in series and directly across the generator leads in series with a resistance *R'*. Coil *A*, called the current coil, is in series with the resistance to be measured through a resistance *R*.

When the terminals *T* and *T'* are not closed and the armature is turned, current flows through coils *B* and *B'* and they would take

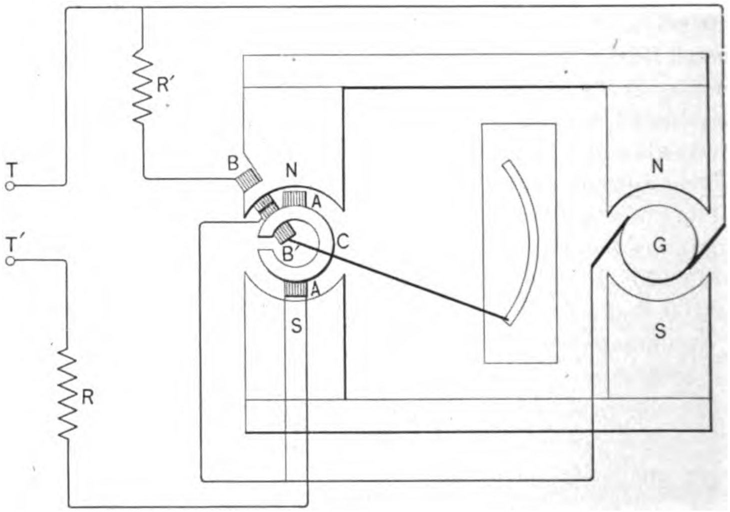


FIG. 376.—Electrical and Magnetic Circuits of Megger.

a position at right angles to the direction of the magnetic flux, which would be opposite the gap in the C-shaped piece, and as all the coils are connected, *A* would be carried with them, *A* at this time having no current. In this position the pointer would be at the other end of the scale from that shown and would indicate infinity. If a resistance is connected to the terminals and the crank turned, the E. M. F. would cause current to flow through *A* and the resistance. The current is so led through *A* that it would be urged to a limiting position at right angles to the flux, but in tending to assume this position it would move in the opposite direction to that in which B' moved, as the current is led to it in an opposite sense. Its limiting position fixed by mechanical considerations is that shown in the figure. The same E. M. F. urges B and B' in one direction and A in the opposite direction, and B and B' exert a stronger and stronger restraining torque as A moves. The coil of B is so wound that the polarity of its face nearest the pole of the permanent magnet is the same as that of the pole, which acts as a restraining force acting against the movement of A. The resistance connected to the terminals, in conjunction with the E. M. F., determines the amount of current through A, and consequently the distance the system of coils moves and the distance the pointer is carried. If the terminals are short-circuited, the excess of current in A will cause it to take its limiting position which would be marked zero on the scale.

Any change in E. M. F. due to difference of R. P. M. of the armature affects the currents in all coils alike and the resulting difference of torque between the coils is always the same for the same resistance and the pointer will remain steady.

One terminal is marked "line" and the other "earth." To measure the insulation resistance of a conductor to ground, it is only necessary to connect the conductor to the terminal marked "line" and the other terminal to "ground." On rapidly turning the armature the resistance will be indicated by the pointer.

III. Measurement of Speed.

Electric Tachometers.—The basis of most of the electric tachometers is the magneto-voltmeter principle. If a coil of wire be revolved in the magnetic field, set up by a permanent magnet as in the case of a magneto, the voltage induced will be in direct proportion to the speed. Consequently, if a voltmeter be connected across the terminals of the magneto armature it will be found that if speed in revolutions per minute be plotted against corresponding voltmeter readings a straight line will be obtained. From this line may be obtained the constant of the magneto in volts per 1000 R. P. M., and also the information necessary for supplying the voltmeter with a scale to read directly in revolutions per minute.

Since the d'Arsonval direct current voltmeter is by far the most permanent of voltmeters and least affected by temperature or stray fields, this type of instrument is ordinarily used. To suit this condition it becomes necessary to build direct current magnetos. The magneto can be arranged for portable service for attachment at will to the center of any revolving shaft, or it may be arranged with a base for stationary service for mounting in close proximity to any shaft, and to be gear-driven, belt or direct connected to the shaft.

Principle of Operation.—The Hopkins Electric Tachometer consists of a small direct-current magneto generator and an indicating electrical voltmeter. The two parts of the system are connected by a duplex (two-wire) insulated cable. The instrument is manufactured in many forms as a portable instrument for laboratory and general speed indicating service, or it may be of the switchboard type for mounting upon a wall or switchboard, or it may be in the form of a special waterproof cast brass case with an adjustable bracket for mounting on the dashboard of a motor car or the bulkhead of a motor boat.

The magneto can be arranged for portable service for attachment at will to the center of any revolving shaft, or it may be arranged with a base for stationary service for mounting in close proximity to any shaft, and to be gear driven, belted or direct connected to the shaft.

Description of Instrument.—The voltmeter used in connection with this magneto-voltmeter method of speed measurement is of the d'Arsonval type described on page 608. Since the voltage induced is proportional to the speed, the scale of the instrument can be marked in R. P. M. instead of in volts.

There is nothing about this instrument to get out of order. There is no mechanical wear on it; there are no joints or parts to wear and cause lost motion; the accuracy of the system is unaffected by changes in temperature, and furthermore by using the permanent magnet type of instrument the tachometer gives absolutely steady readings at all speeds.

Construction of Instrument.—A phantom view of the instrument used with Model MB, Hopkins Electric Tachometer, is shown in

Fig. 377. All instruments used are of this same principle and general construction.

The system is composed of a permanent magnet *B* carrying the pole pieces *C*, between which the moving element *F* turns, mounted in the sapphire bearing *H* above and below.

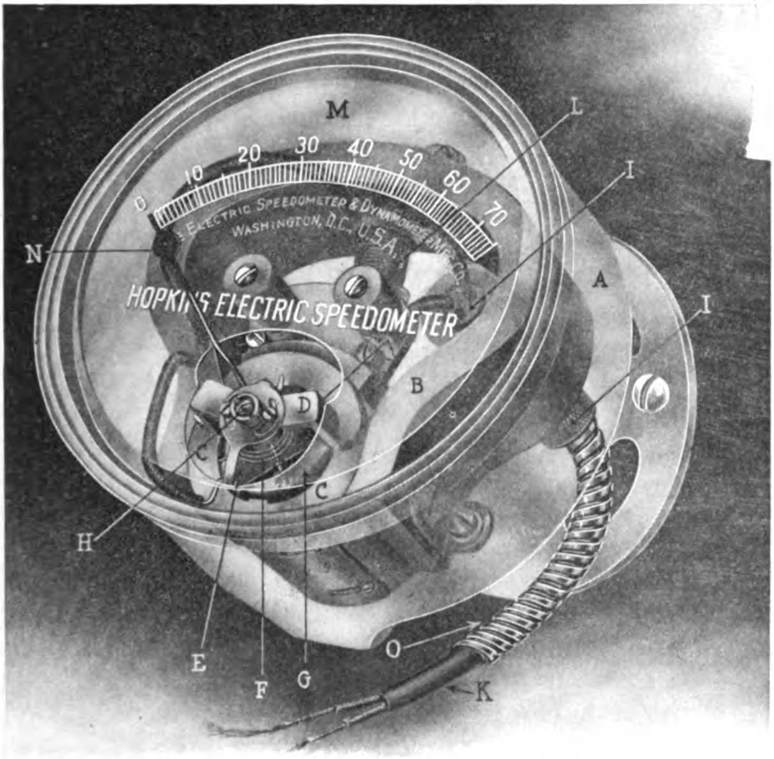


FIG. 377.—Internal Construction of d'Arsonval Electrical Voltmeter used with Hopkins Electric Tachometer.

This moving element consists of an aluminum frame pivoted and carrying a light electrical winding and an aluminum pointer or indicating hand *N*. The scale plate, *M*, shown in the illustration, is an etched dial having uniform graduations throughout its entire length.

The small spool *L* carries a very fine resistance wire of zero temperature coefficient.

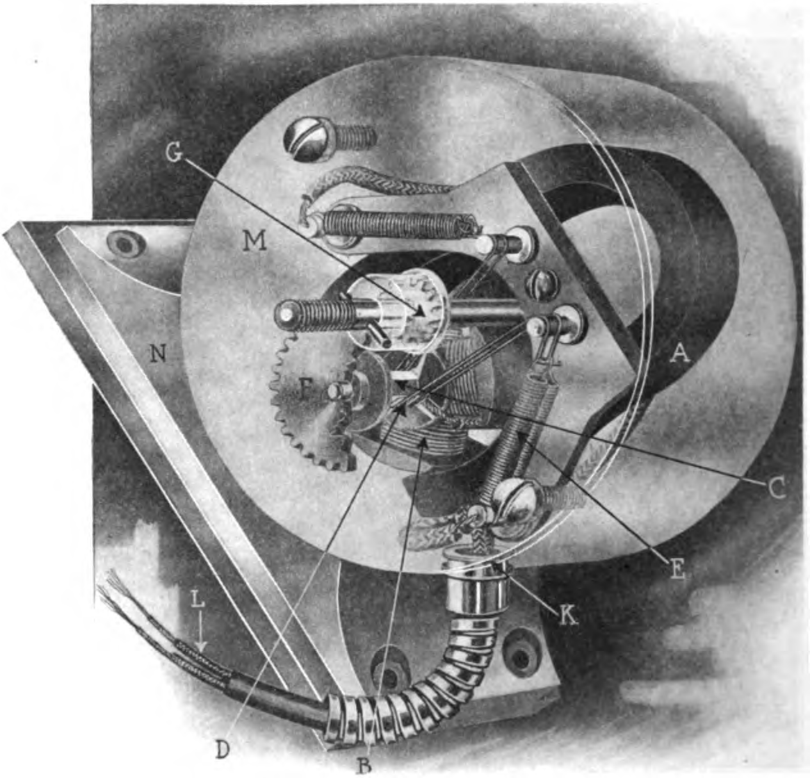


FIG. 378.—Internal Construction of Hopkins Magneto.

A separable junction box, shown at *I*, screws into the back of the instrument, provides for the wires *K* which lead from the magneto generator and are enclosed in a waterproof brass armor *O*; this construction is used on all stationary type tachometers.

The entire instrument mechanism is enclosed in a brass waterproof case *A*, having a beveled plate-glass front. This type of instrument is attached to its support through the adjustable bracket and the instrument is adjustable to any convenient angle.

Description of Hopkins Magneto.—The Hopkins magneto is of the direct current type. It consists of a three-coil armature rotating between the poles of a permanent horseshoe magnet. The current generated in the armature is sent to the line through a commutator of three parts. The rotating bars are of platinum and the brushes or contactors of 20-karat gold.

Because of the use of gold brushes and platinum commutator bars no variation in the resistance of the circuit occurs, as there are no oxidation changes nor insulating salts formed.

The magneto armature is gear driven from the main or external shaft by spur gears.

By using internal reduction gears remarkably high speeds can be measured with precision without exceeding the practical bounds of commutation. In addition the internal reduction gears minimize the commutator and brush wear.

Construction of Magneto.—In Fig. 378 is shown a phantom view of the internal construction of the Hopkins magneto.

A is a magnet between the poles of which rotates the small armature *B*, the commutator of which is composed of three platinum bars *C*, and the brush gear, which consists of four small gold brushes *D*, acting upon the commutator and held in position by the long flexible bronze springs *E*.

The driving of the armature is accomplished by internal gears, the pinion gear *G* on the main shaft, and the armature gear *F*. The wires *L* are led out through the flexible brass armor *K* in the stationary type, while in the portable type they are connected within the containing case of the magneto to the binding posts.

The entire generating mechanism is enclosed in the cast phosphor bronze water-tight case *M*, having in the stationary type a base *N* for ready installation.

Portable Tachometer.—This instrument consists of a d'Arsonval voltmeter of the portable type, and a portable magneto with binding posts, a diamond-shaped point and a wooden handle. These two parts of the tachometer, the indicating instrument and the magneto, are connected with a pair of flexible leads of sufficient length to allow the instrument to be placed upon a suitable table, a stand near the shaft whose speed is being indicated.

The instrument used with the portable tachometer is of exactly the same type and principle as that shown in Fig. 377, except that it is mounted in a mahogany case having a large leather handle for easy transportation. The scale is fitted with a mirror and the indicating pointer is of the hair-line type moving above this mirror and scale so that precise indications can be observed, eliminating parallax errors.

The portable tachometer has in circuit a rheostat of wire of zero temperature coefficient, with a moving contact of non-oxidizing metal so that calibration can be adjusted at any time. This rheostat is operated by a suitable screw on the face of the instrument, as shown in Fig. 377. In double scale tachometers each scale has an independent rheostat.

In the portable magneto a ball thrust bearing is inserted in the main bearing next to the handle so that the magneto may be held against a revolving shaft with any degree of pressure without in any way injuring or impairing the operation of the magneto.

To recalibrate the tachometer at any time, check its indication upon a slow speed shaft and if possible upon one giving uniform rotation, with a revolution counter and stop watch and adjust the instrument for this speed with the rheostat for that particular scale. The tachometer should then read accurately throughout its entire range. To raise the reading turn the rheostat clockwise. To lower the reading turn the rheostat counter-clockwise. When the tachometer is being calibrated its indication is perfectly steady and uniform, the shaft upon which it is being calibrated is revolving at an absolutely uniform rate.

Stationary Tachometers.—Stationary tachometers are furnished with a zero center scale and calibrated "ahead" and "astern" in order to indicate not only the speed of the propeller shaft in either direction, but to give information that signals from the bridge have been correctly received and executed.

The magneto is driven from the propeller shaft by a split gear which engages with the gear on the magneto shaft while indicators may be mounted on the bridge, in the conning-tower, central station, engine-rooms or other desired stations.

This type has been installed on ship board to meet the demands of an engine revolution indicator. The pointer shows at all times the direction of revolution of the main shaft as well as the number of revolutions per minute being made.

A shaft speed indicator consisting of a small two-phase alternator with a permanent magnet rotating field is being used on board ship for indicating the propeller shaft speed directly. The voltage induced by the generator is proportional to its speed and is read by an induction type voltmeter. With this type of instrument the speed in R. P. M. and whether the speed is ahead or astern is indicated. (See Bullard, Vol. II.)

Magnetic Type Speedometer.—This type of speedometer, of which the Stewart and Warner are examples, is based upon the principle of magnetic induction. If a magnetic field is drawn across a conducting body, currents are induced, which, acting in conjunction with the field producing them, tend to chase this field. The torque developed is proportional to the speed, if the flux and resistance of the material remain unchanged.

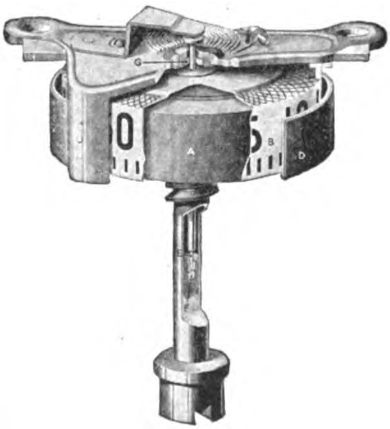


FIG. 379.—Stewart Speedometer.

Fig. 379 shows a Stewart speedometer. The rotating part *A* consists of a hard steel ring *A*, which is driven by flexible shafting. *A* is also a permanent magnet with the lines of force running in an axial direction, vertical in this case. These lines of force thread the light aluminum cup *B*, which contains the scale. *B* turns on the polished steel shaft *E*, which rests in the jewel bearing *F*. The upper bearing passes through the jewel *G*, so friction is practically eliminated. *C* is the restraining spring against which *B* must turn. *D* is a bimetallic temperature compensating device which acts directly on the spring *C*. The flux produced by *A* threads this aluminum scale, and rotating exerts a torque on it proportional to the speed. *B* is restrained from moving by spring *C*. The instrument may be graduated directly in R. P. M. There being no mechanical connection between the rotating and indicating devices, this instrument is undoubtedly the most reliable of any tachometer.

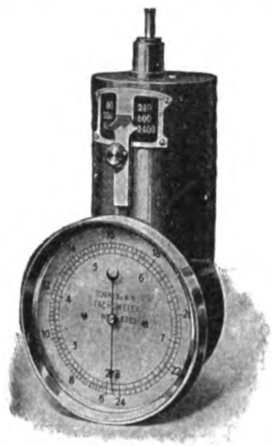


FIG. 380.—Ja-Ga-Bi Hand Tachometer.

The "Ja-Ga-Bi Hand Tachometer," shown in Fig. 380, depends upon a centrifugal device for its operation. It is very convenient and is practically deadbeat. The speed is read directly upon a graduated dial. By simply moving a stop on the shank of the instrument, three or four different scales may be obtained. This tachometer is as reliable as such mechanical devices usually are, but it should be frequently checked with a speed counter if dependable results are desired.

The "Ja-Ga-Bi Hand Tachoscope" is shown in Fig. 381. It consists of a stop watch and a speed counter mounted together. If the tip of the instrument is inserted in the countersink of the shaft, and no pressure exerted, neither instrument is operative. As soon as pressure is exerted, however, both the stop watch and speed counter start simultaneously. Also they stop simultaneously when the pressure is removed. This instrument gives the exact speed of a shaft, since the personal element is entirely eliminated, and it is recommended where an accurate measurement of speed is desirable.

FIG. 381. Ja-Ga-Bi Hand Tachoscope.

IV. Measurement of Power.

Watt Meters and Watt-Hour Meters.—A watt meter is an instrument for measuring the electric power developed in a circuit. Power in a direct current circuit is equal to the product of the current delivered times the voltage at which it is supplied. This power may be obtained at any time by taking simultaneous readings of a voltmeter and ammeter connected in circuit and taking their product. A watt meter so constructed as to show the product of instantaneous values of volts and amperes is called an **indicating** watt meter. One so constructed that will graphically record the product of volts and amperes is called a **recording** watt meter. It is generally desired to know the power used during a certain interval of time, and an instrument that will allow the product of power times the time to be found is called a **watt-hour** meter. Another form of meter which measures the product of current alone and the time is called the **ampere-hour** meter.

Practically all watt-hour meters are of the motor type, a small motor being arranged to revolve at a speed proportional to the rate at which energy is passing through it. The number of revolutions of the motor may be recorded on a dial, and by calibration a constant may be found, which, when multiplied by the number of revolutions, will give the energy used in watt hours. The shaft of the motor which drives the indicating mechanism is generally geared to it in such a manner that the indications are read directly in kilowatt hours.

The current that passes through the motor armature is taken from a circuit shunted from the main circuit, in which case it is proportional to the line voltage. The field is energized by the line current, and under these conditions the attraction between the field and armature currents, and also the speed, are proportional to voltage times current, or proportional to the power flowing, provided that the retarding torque is proportional to the speed. The retarding is ordinarily accomplished by an aluminum or a copper disc rotating between the poles of fixed magnets. Currents thus generated in the disc reacting with the flux, retard the disc. The main current may be led through the armature and the field energized by the line voltage, producing a similar effect, and the revolving armature may be geared to a counting mechanism that will allow the energy to be read directly in kilowatt hours.

A type of watt meter that has been installed on ships' switchboards is that known as the Sangamo meter, a description of which follows.

A. Sangamo Meter.—The principle of operation of the Sangamo

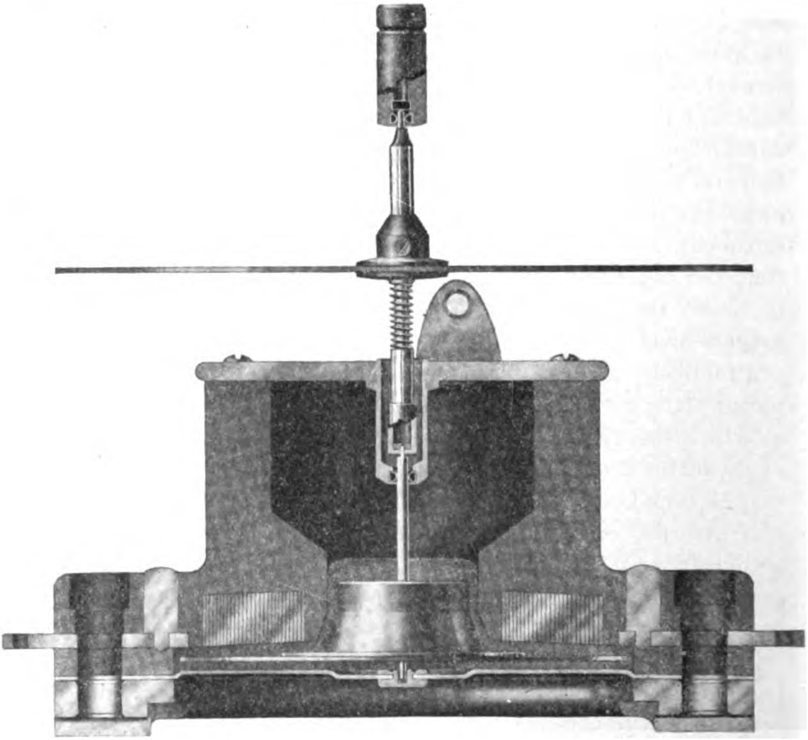


FIG. 382.—Cross-Sectional View of Sangamo Meter.

meter depends upon the fundamental law of motors that current passed at right angles through a magnetic field is urged in a direction at right angles both to the current flow and the field. The motor element of the meter, as it is called, is shown in Fig. 382. It consists of a molded insulation receptacle with a thin pressed metal bottom, held to the receptacle by means of a heavy brass clamping ring; the very shallow circular space between the inside of the receptacle and the metal bottom contains the armature. The armature consists of a thin copper disc and it is completely immersed in mercury which is plainly indicated in the figure. The current terminals, shown at each side to the right and left, are nickel-plated copper ears, which are deeply imbedded in the insulating material, and serve to lead current into and out from the mercury and the copper armature. Inside the molded insulation piece above the armature is shown as sectioned at two points a laminated steel ring. This acts as a part of the magnetic circuit for the magnetic lines emanating from a U-shaped laminated steel yoke which is bolted to the brass ring, the poles coming just under the laminated steel ring. In the direct current type a pair of fine wire shunt coils is carried on the arms of the yoke and receives current from the line supply.

With the field energized by the line voltage and the line current flowing through the armature, the latter is urged in a direction at right angles to the field and revolves at a speed which is proportional to the torque, developed by the reaction between the armature and field currents. A damping effect is produced by the revolution of a disc carried by the operating spindle between the poles of permanent magnets.

Secured to the armature by means of a disc and a float above it is the spindle which actuates the indicating mechanism, which is shown in Fig. 383, showing a switchboard watt meter with a four-cycle integrating train.

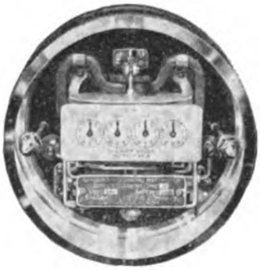


FIG. 383.—Sangamo Switchboard Meter.

In this type of meter, the armature *floats* in the mercury in which it is immersed, the necessary lifting effect for the weight of the entire moving system, including the armature, operating spindle, clamping disc, etc., being obtained by the small, solid, non-metallic float riveted to the center of the copper disc. The buoyancy is such that a very slight pressure is exerted in the jewel bearing at the top, thus rendering these meters absolutely proof against jars and shocks of severe service and reducing friction to a minimum.

The mercury chamber is designed somewhat like an inverted ink well, so it is impossible to spill the mercury, no matter in what position the meter may be turned or placed.

Operation with Shunts.—The maximum rated full-load current through the armature of the direct current meter is 10 amperes, so that in capacities above 10 amperes the meter is operated from shunts, similar to an ammeter and its shunt, with the difference that the leads from the shunt terminals to the instrument must always be large enough to carry 10 amperes. Every Sangamo meter of whatever capacity is simply a 10-ampere meter properly adjusted

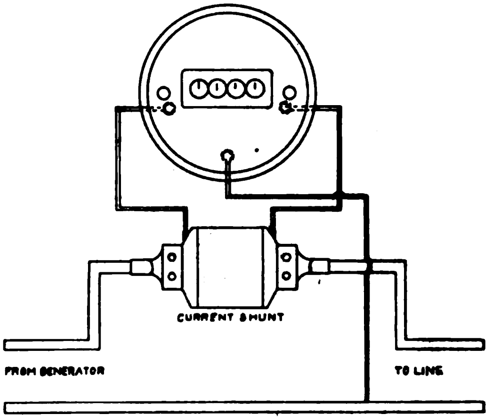


FIG. 384.

for drop with respect to the shunt and with a recording train so geared as to read directly in kilowatt hours for the actual total energy passed through the shunt and meter. If the meter is correct as a 10-ampere meter and is correct for drop through the cables and meter, the combination with the shunt must be right.

The method of connecting the Sangamo meter in circuit with a shunt is shown in Fig. 384.

Speed Adjustments.—The heavy load adjustment consists of a soft steel disc above the permanent damping magnets, shown in Fig. 383, arranged so that it can be screwed up or down to shunt more or less of the field of these magnets, varying the retarding effect and the speed of the motor as required without moving the magnets.

The light load adjustment consists of a small clamp on a pair of parallel wires at the bottom of the meter in front. The movement of this clamp to the left or right varies a small initial or starting current through the armature. This adjustment is of wide range, is easily obtained and absolutely positive.

In addition to the above adjustments, there is a sliding series adjustment for the purpose of setting a meter for correct resistance or drop, with respect to the shunt with which it is to be used. This adjustment is the small clamp just to the right of the laminated magnet. It is seldom that it is necessary to alter this adjustment unless the meter has suffered some accidental injury.

Light Load Compensation with Thermo Couple.—Behind the shunt coils is a thermo couple compensating device for light load; this being two strips of dissimilar metal joined together and surrounded by a heating winding of resistance wire in series with the shunt coils of the meter. The purpose of the thermo couple is to pass a low potential current through the armature in order to give a slight initial torque to overcome the unavoidable bearing friction, slight as this may be. The thermo couple is so arranged that the current set up in it will always pass from left to right through the armature chamber, no matter which way the heating current passes in the winding surrounding the couple. Thus it is necessary to connect the meter in circuit so that the load current will always flow through the armature in the same direction as the current set up by the thermo couple. This necessitates having the incoming terminal to the meter *positive* in order to get the correct light load compensating effect, for if current passes through the meter the other way, even though the shunt field is also reversed, giving proper direction on heavy load, the effect of the thermo couple will be in opposition, causing the meter to be very slow on light load.

B. Sangamo Ampere-Hour Meters.—These meters are designed for use in circuits in which the power used is obtained from storage batteries, and as the name implies, the indicating mechanism registers in ampere hours. The operating mechanism is entirely similar to that described for the kilowatt-hour meter, with the exception that the field is produced by permanent magnets. This makes the motor speed independent of the line voltage, as voltage is not a factor entering into the quantity to be indicated. The indicating mechanism, driven by the armature is such that the number of ampere hours is directly read off from one circular dial.

As used on the switchboards of submarine vessels using storage batteries as their propelling power, Sangamo meters are designed for the control of the cycles of charge and discharge. The equipment of submarines consists of two meters for the forward battery and two for the after battery. One of these is a watt-hour meter equipped with a duplex train, having two rows of circles. One row records the charge and the other the discharge, proper arrangements being made by detents in the wheel train to prevent the charge wheels from moving on discharge and vice versa. The other meter is in series with the watt-hour meter and is a standard circular dial ampere-hour meter. Both of these meters operate with a single shunt of 1800 amperes capacity. These meters have the special feature of thermo couple compensation which acts on discharge only. The charging of the batteries is done at a practically constant voltage and current value, but on discharge, both current and voltage values vary greatly and the meters are so arranged that they are able to stand the large discharge rates while underway and will also register with a fair degree of accuracy in port when the propelling power is off.

A diagram of the circuits of Sangamo meters as installed on submarine vessels is shown in Fig. 385. With the aid of the description given above, the connections should be easily traced and understood.

C. Thomson Watt-Hour Meter.—In this watt-hour meter, the load current is led through the coils, *C*, thus producing a magnetic field perpendicular to the plane of the page. In this field is placed a light globe-shaped armature, *A*. This is connected in series with a high resistance directly across the line.

The armature current is then proportional to the load voltage. Thus, neglecting friction, the torque of the motor armature is directly proportional to the load watts. On the armature shaft is attached an aluminum disc, *D*, which acts as a brake when revolving

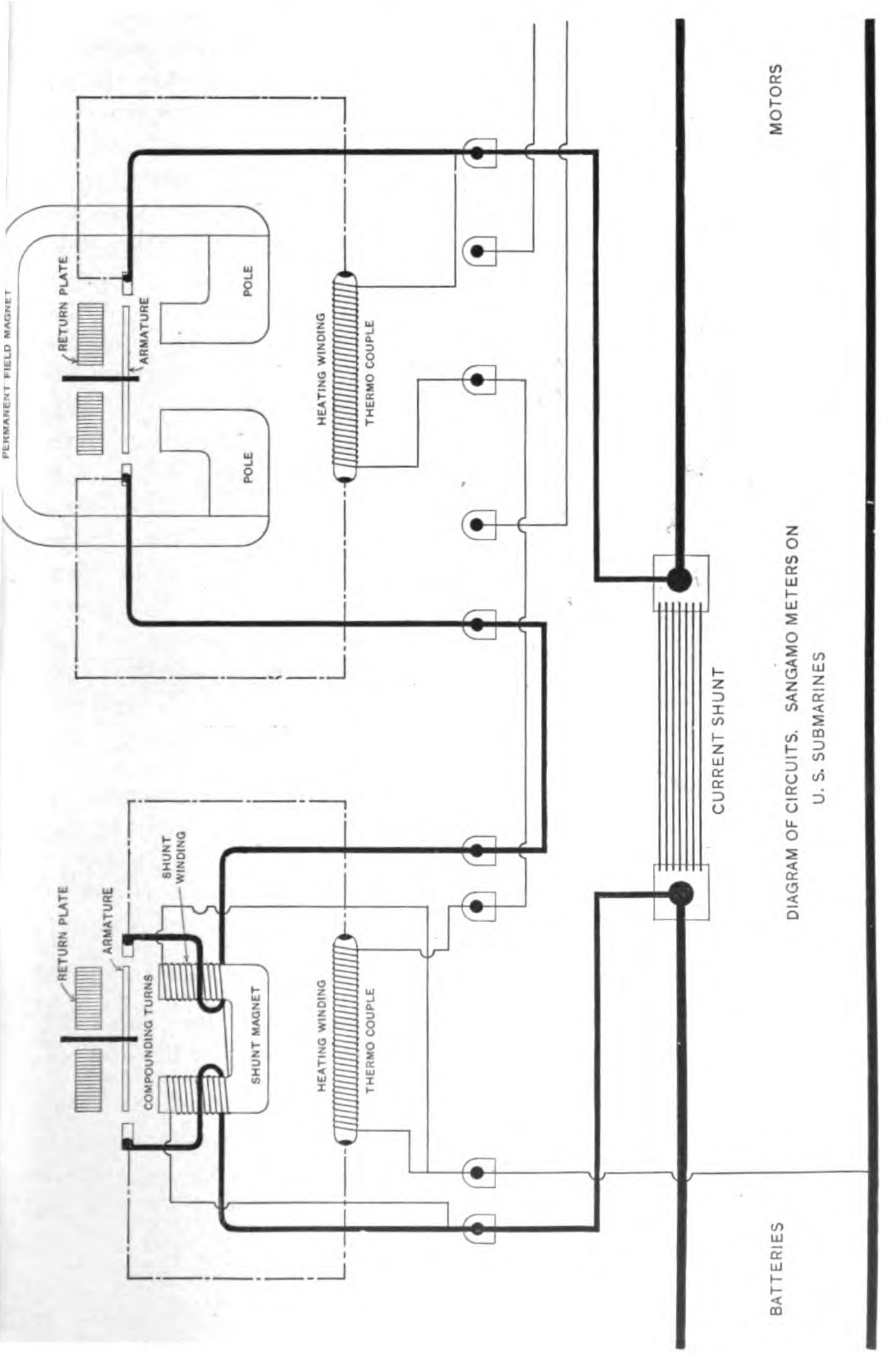


DIAGRAM OF CIRCUITS. SANGAMO METERS ON U. S. SUBMARINES

FIG. 385.

in the magnetic field produced by the magnets, *M*. This magnetic braking is directly proportional to the speed, so that when the revolving element reaches a constant speed, the braking torque of the disc must equal the driving torque of the armature. Consequently, if the brake torque is proportional to the speed and equal to the driving torque, the driving torque also must be proportional to the speed. Since the driving torque is proportional to the watts, then must the speed be proportional to the watts.

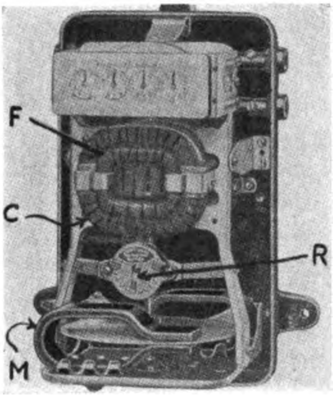


FIG. 386.

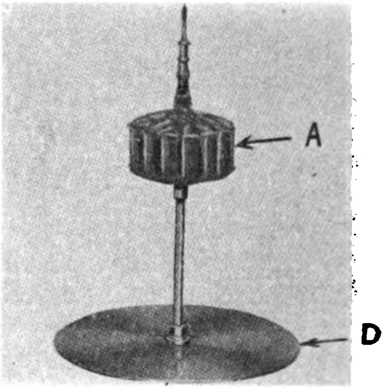


FIG. 387.

The coil *F* is connected in series with the armature, and assists the main coils *C*. The number of turns in circuit can be varied by the small arm and contacts *R*. This coil compensates for the friction of the meter, which is proportionately large at light loads. In some types of instruments the adjustment is made by moving coil *F* nearer or further away from the armature, and thus changing its influence on the armature.

To calibrate the meter, a load is applied and the load measured with a calibrated voltmeter and ammeter from which the average true watts may be calculated. From the formula:

$$W = \frac{K \times N \times 3600}{t},$$

the average watts of the meter may be calculated.

When W = average watts of the watt-hour meter,
K = meter constant, usually marked on the disc,
N = total revolutions of the disc,
t = time in seconds.

N may be counted and the time measured with a stop watch. If the meter is fast it may be slowed down by moving the permanent magnets nearer the periphery of the disc, and if slow, the magnets should be moved nearer the center. The meter should be adjusted at its rated load by means of these magnets and at 5 per cent load by means of the compensating coil **F**.

CHAPTER XXII.

MEASUREMENTS.

The measurements explained in this chapter will involve the voltmeter, ammeter, testing set, magneto, ohmmeter and standard resistances, all of which pieces of apparatus are available on board ship. A number of other tests are explained which involve apparatus found only in the testing laboratories of universities or large manufacturing companies. The laboratory of the U. S. Naval Academy is equipped to perform tests of this latter description.

The Use of Voltmeters and Ammeters.

An ammeter, as its name implies, measures current, and a voltmeter measures voltage or difference or fall of potential. Ammeters and voltmeters are identical in their mechanical details, but electrically they differ. An ammeter is provided with a shunt, whereas a multiplier is used in connection with a voltmeter.

The ammeter shunt is a very low resistance, across which is shunted the moving coil of the instrument. Thus, but very little of the current being measured passes through the measuring instrument, all but a fraction of 1 per cent going through the shunt. Likewise, in the voltmeter, provision must be made to ensure that a very small current passes through the moving coil. This is done by connecting in series with the moving coil circuit a high resistance. When this resistance is in a separate case from the measuring instrument it is called a *multiplier*. In this chapter where reference is made to the resistance of an ammeter, it means the equivalent resistance of the combination of the moving coil and shunt and where reference is made to the resistance of a voltmeter the total resistance of the coil and series resistance or multiplier is intended.

An ammeter measures directly the strength of the current flowing through its coils. In order that the current flowing in a circuit may not be altered by the introduction of the instrument which measures it, the ammeter should have as little resistance and therefore consume as little power as possible.

A voltmeter measures the difference of potential between two points, and as little of the total current as is necessary for the proper sensitiveness of the instrument should be diverted through the voltmeter. Therefore the voltmeter should have a very high resistance both for the sake of economy and in order that it may not change the circuit conditions. If a high resistance is connected in series with a sensitive ammeter designed to measure small currents, then the current passing through this circuit will be proportional to the circuit voltage and the instrument will constitute a voltmeter.

The current flowing through an ammeter is proportional to the difference of potential at the terminals of the instrument, and from this it might appear that the difference of potential between two points might be measured by simply joining an ammeter between the two points, recording the number of amperes flowing and from the resistance of the ammeter compute the difference of potential between the points. But if such a low resistance as that of an ammeter be connected between the two points, the ammeter because of its low resistance would take a very large current, hence disturb circuit conditions very materially.

For instance, if an ammeter were used in the place of a voltmeter in order to obtain the voltage of a battery, so large a current would be drawn from the battery by the ammeter that the voltage of the battery would fall very materially, and the product of the resistance of the ammeter and its reading would indicate an E. M. F. much below the true battery E. M. F. If the battery already has a resistance connected across its terminals and it be attempted to get the battery E. M. F. for this condition by an ammeter, the insertion of the ammeter as a voltmeter will so alter the original current in the circuit that the ammeter reading will be meaningless. The less current, then, that is absorbed by the instrument measuring difference of potential, the more accurate it is, and it is seen that as the ammeter has more and more resistance it develops into a voltmeter.

Further reasons for the peculiar construction of voltmeters and ammeters and the objects to be attained by them may be illustrated by a simple example.

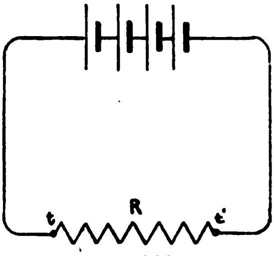


FIG. 388.

In Fig. 388 is represented a typical battery circuit, consisting of a few cells, leading wires and a resistance R joined between the terminals t and t'. If the E. M. F. of the battery is constant, there will be a constant current flowing in all parts of this circuit, the same through the battery, through the connecting wires and through R; this current depending on the E. M. F. of the battery and the resistances of the several parts. Suppose the E. M. F. of the battery and all the resistances are accurately known, then the current flowing in any portion of the circuit will be known, and the difference of potential may be calculated for any two selected points.

Let

$E=12$, the E. M. F. of the battery;
$r=2$ ohms, internal resistance of the battery;
$r'=1$ ohm, resistance of leading wires;
$R=3$ ohms, resistance between t and t';

then I, the current flowing in any portion of the circuit, by Ohm's law $=\frac{12}{1+2+3}=2$ amperes.

By the same law, also, the difference of potential between t and t' is $2\times 3=6$ volts.

Now when it is wished to measure these values by instruments, the question arises where should they be placed in circuit or how should they be connected in order that the values already known to be correct should not be materially changed. It has already been shown that to measure a current, the current must pass through the instrument, and in order that the existing current may not be changed, the ammeter must necessarily have a very low resistance and be directly connected in series with the circuit. If the resistance is not low but still connected in series, the current value would be materially changed. If the resistance is low, but not connected in series, but as a shunt between two points, the external resistance will be reduced, thus increasing the battery current.

To measure the difference of potential between two points, the instrument must be joined as a shunt to those points, and in order that the current between them may not be greatly changed, the resistance of the voltmeter must be very great.

The connection of the instruments for measuring the battery current, and the difference of potential between t and t' is shown in Fig. 389.

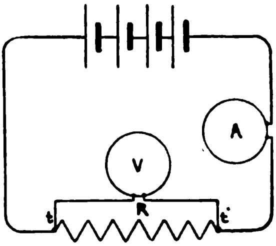


FIG. 389.

A represents the ammeter and V the voltmeter. A is connected for measuring the total battery current, and V for measuring the difference of potential between t and t'. Suppose A had a resistance of .01 ohm and V a resistance of 15,000 ohms. If V had been inserted in A's place to measure the current, the value of I would be

$$I = \frac{12}{1+2+3+15,000} = .0008 \text{ ampere.}$$

If A had been used to measure the difference of potential between t and t', I would be

$$I = \frac{12}{1+2+\frac{3\times .01}{3+.01}} = 3.98 \text{ amperes,}$$

and the difference of potential between t and t' would be $3.98\times$ (.0099 = joint resistance between t and t') = .0394 volt.

If A were put in V's place and V in A's, I would be

$$I = \frac{12}{1+2+\frac{3\times .01}{3+.01}+15,000} = .00079 \text{ ampere}$$

and the difference of potential between t and t' would be

$$.00079\times(.0099 = \text{joint resistance}) = .0000078,$$

figures which do not bear any resemblance to the real values, and which show the effect of connecting up the instruments wrong.

If they are connected as in the figure, I would be

$$I = \frac{12}{1+2+\frac{3\times 15{,}000}{3+15{,}000}+.01} = 1.9963$$

and the difference of potential between t and t'

$$1.9963 \times (2.9994 = \text{joint resistance}) = 5.9877,$$

results which differ slightly from the values known to be correct.

With this arrangement the fall of potential around the circuit would be

	Through the battery	$2\times 1.9963=$	3.9926	volts.
	" " wires	$1\times 1.9963=$	1.9963	"
	" wire t, t'	$3\times 1.9963=$	5.9889	"
	" A	$.01\times 1.9963=$	.0199	"
or	Total fall		$=11.9977$	"

Measurement of Battery E. M. F.—The E. M. F. of a cell may be measured directly by means of Sir Wm. Thompson's absolute electrometer, which draws no current whatever from the cell. The principle of this instrument is that of a condenser with one fixed and one movable plate. If these two are connected to two points of an electric circuit, between which there exists a difference of potential, the movable plate tends to move so as to increase the electrostatic capacity of the condenser, and it is moved with a force proportional to the square of the difference of potential by which the force is produced. The force produced is measured by balancing it against known weights. An ordinary condenser with a galvanometer and key in circuit may replace the electrometer, when comparing the cell with some standard cell.

There are many laboratory ways of comparing electromotive forces, all of them requiring some standard cell, or cell whose E. M. F. is accurately known, certain known resistances and a galvanometer. Galvanometers are not furnished on board ship, but a very good substitute may be found in a double reading voltmeter furnished on some ships as a ground detector, and the resistances of the Wheatstone bridge may be used. These will be described later, and having these, one method will be described showing how the E. M. F. of a cell may be compared with one whose E. M. F. is known.

The two batteries or cells to be compared are joined up as shown in Fig. 390, and their opposite poles are connected by leading wires and resistances *R* and *r* inserted in one side of the connections. The points *A* and *B* are connected by a galvanometer or the double reading voltmeter. If the resistance *R* is fixed, then *r* is adjusted until the voltmeter shows no deflection; or, in other words, *A* and *B* are at the same potential. When this condition holds then

$$E_1 : E_2 :: R : r$$

from which the E. M. F. of either cell may be found in terms of the other.

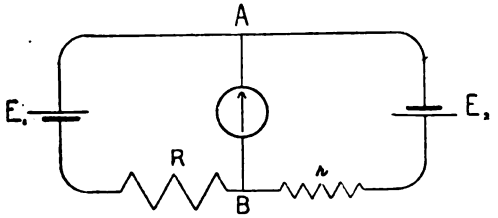


FIG. 390.—Connections for Comparing E. M. F. of Cells.

The resistances of the leading wires are supposed to be inappreciable and the resistances of the cells small in comparison with *R* and *r*, but if not, they must be added to *R* and *r*.

This method is easily arranged and comparison of cells may be made in a very short time. For all practical purposes, however, the E. M. F. of a cell is sufficiently determined by connecting its terminals to the binding posts of a low-reading portable voltmeter. The small current flowing from the cell is inappreciable owing to the high resistance of the voltmeter, so that the lost volts in the cell are extremely small and the E. M. F. as measured is very near the total E. M. F. of the cell.

Care in Using and Connecting Voltmeters and Ammeters.—The result of using a voltmeter for an ammeter or an ammeter for a voltmeter has already been illustrated. Further, there should be no difficulty in distinguishing one from the other, for they are usually marked, and the scales are also marked either volts or amperes. The binding posts of an ammeter, except for very low range instruments, are of heavy construction * and made of bare metal. On the other hand, the binding posts of voltmeters are made very light and the exposed metal parts covered with hard rubber.

If an ammeter were used for a voltmeter on a high potential circuit, due to the very low resistance of the ammeter, a very large current would flow which would not only injure the instrument, but also damage other apparatus in the circuit. If a voltmeter were used as an ammeter, very little current would flow, because of its high resistance, unless the E. M. F. was very high, and in this case the delicate coils of the voltmeter might be burnt out.

Ordinarily it does not injure voltmeters or ammeters to connect them with the wrong polarity, as the pointer simply indicates in the wrong direction. An excessive current sent suddenly through an instrument may throw the pointer violently against its upper stop and bend it. More current than the instrument is designed for may cause the coils to heat dangerously and burn or destroy the insulation of the conductors, or it may heat the phosphor bronze spiral springs sufficiently to draw their temper.

In making connections with a voltmeter or ammeter, it is better to make the connections on the instruments first, and to the circuit last, and it is still better to have a switch in the circuit, so all connections may be made without danger of injuring the terminals by the arc which might otherwise be formed.

Instruments should be used with care and judgment at all times. The best ones are made with great care and have small pivots and jewel bearings. Rough handling may dull the pivot points, crack the jewels, or weaken the permanent magnet in instruments like those of the Weston type.

Instruments should not be placed near a running generator or motor, because of the danger of having the magnetic fields distorted by the stronger fields, nor should instruments with permanent magnets be placed close to one another, *i. e.*, within a foot or so. Stray fields in the neighborhood of heavy bus bars are often responsible for inaccuracies in instrument readings.

* See Fig. 359, page 610.

To Measure Current.

Current is measured by connecting an ammeter directly in the circuit through which the current is passing.

To Measure Current without Opening the Circuit.—This can be done where there is a convenient switch in the line, for the ammeter may be connected around the switch, and the switch then opened, when the full current will pass through the ammeter.

To Measure Current by Resistance and Voltmeter.

By Ohm's law the fall of potential through a conductor equals the product of its resistance and the current then flowing. By knowing the resistance and measuring the difference of potential between its ends, the current is at once obtained. Fig. 391 shows how the connection should be made.

R is the standard resistance and *V* the voltmeter, which in this case should be a low-reading one, ordinarily a millivoltmeter.

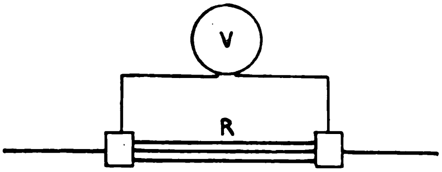


FIG. 391.—Connections for Measuring Current with Resistance and Voltmeter.

To Measure E. M. F.

E. M. F. is measured by connecting a voltmeter to the two points between which the difference of potential is required.

Calibration of Instruments.

Calibration is the process of determining the value of the current or voltage required to move the indicator to any or all parts of the scale. This may be done when making a new scale or in checking an instrument that has been in use. For example, suppose that an instrument has a resistance of 10,000 ohms, and that .001 ampere causes the pointer to move an inch from its zero point. By Ohm's law $E=I\times R$ or $E=.001\times 10{,}000=10$ volts, so that point on the scale 1 inch from the starting point might be marked either

10 volts or .001 (1 milliampere). When this instrument is connected between two points and current flows through it so that the pointer takes this position, it is then known that a current of .001 ampere is flowing through it, or that the difference of potential between the points is 10 volts. In a similar way the value of any other point on the scale may be determined.

All voltmeters and ammeters should be calibrated from time to time by comparison with some standard instruments. To be accurate they should be compared with absolute standards, but as they are not available on shipboard, it is usual to compare all instruments with some secondary standard, which in turn might be calibrated on shore by reference to absolute standards.

Calibration of Ammeters.—To compare an ammeter with a standard they are connected in series and the same current is sent through

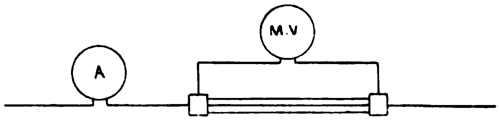


FIG. 392.—Connections for Calibrating Ammeters.

both. The ammeter under calibration and the standard are then read simultaneously. If the instrument being calibrated, is correct, the readings should be the same.

The instruments should be placed far enough apart so that the magnetic field of one does not affect the other, and the instruments should be in their normal position, that is, level or vertical, as the case may be.

If a standard ammeter is not at hand, a standard resistance and a millivoltmeter may be used, and the current flowing through the resistance calculated, and this should be the value indicated on the ammeter under test. The connections are shown in Fig. 392.

The instruments may be compared with increasing and then decreasing currents to see how far the instrument is affected by friction.

Calibration of Voltmeters.—Voltmeters are compared with a standard voltmeter by connecting all in multiple, so that all are subjected to the same voltage. The voltage is then changed to different values and the reading of the voltmeters is compared with the standard.

To Obtain Different Voltages.—In order that voltmeters can be compared throughout the range of the instrument, some means must be adopted of varying the voltages. A good method of doing this is to connect across the mains of a constant potential circuit, such as the lighting mains on ship, a piece of wire that will allow a small current to pass. A conductor of German silver wire is especially adapted for this, as its resistance per unit of length is uniform, so the fall of potential will be uniform. As a specific example, 75 to 100 feet of resistance wire of material such as to give 3 ohms per foot for No. 30 B. & S., is suitable for 125 volts.

By connecting the voltmeters in multiple along this wire any difference of potential may be obtained, and comparisons with the standard made. It is well to have one common terminal secured to one of the mains, and another common terminal may be moved along the wire. The connections are made in Fig. 393.

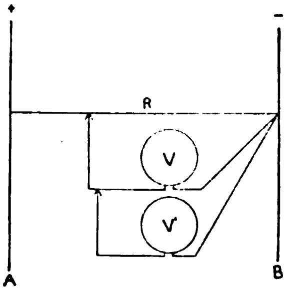


FIG. 393.—Connections for Calibrating Voltmeters.

A and *B* represent the mains and *R* the German silver resistance, *V* the standard voltmeter and *V′* the one under comparison.

To Connect Voltmeters to Increase their Range.—It may be desirable to measure a voltage that is beyond the range of the voltmeter at hand. The range of the voltmeter may be doubled by placing it in series with a resistance equal to its own. If the voltmeter reading to 150 volts has a resistance of 15,000 ohms, it will read to 300 volts when it is connected in series with an added resistance of 15,000 ohms or another voltmeter of the same resistance. This results from the fact that if the resistance of the circuit is doubled, twice as much pressure is required to send the same current through. If these two voltmeters are connected between two points whose difference of potential is 300 volts, each instrument will register 150 volts, the fall of potential through each being 150 volts. The total fall of potential will be the sum of the potential drops in each instrument.

To Connect Voltmeters to Decrease their Range.—Most portable voltmeters are provided with two resistances, by means of which two scale readings are available, one for high and one for low differences of potential, and separate terminals are provided for putting these resistances in the circuit. It frequently happens, however, that a high-range voltmeter is the only means at hand for measuring voltages, and it may be necessary to measure a small difference of potential. Weston voltmeters are marked in single volts, but frequently they are not accurate within the first few divisions on the scale of the high-reading instruments. In this case it is better to connect the points between which the E. M. F. is required in series with the voltmeter and connect them both across high potential mains.

Suppose it was required to measure the E. M. F. of a battery with a voltmeter whose range was 150 volts. Connect the battery in series with the voltmeter and connect them both across the lighting mains, say an 80-volt circuit. If the voltmeter showed 78.5 or 81.5 volts, it would indicate that the battery had added or subtracted 1.5 volts, depending on how its poles were connected, and therefore the E. M. F. of the battery must be 1.5 volts.

Uses of Potentiometer.

One of the primary uses of a potentiometer, that of comparison of E. M. F.'s of electric cells with that of a standard cell has been mentioned under the description of the instrument in the preceding chapter. Some of its other uses will be considered.

To Measure High Voltages.—It is evident that the instrument as previously described will not measure voltages higher than 1.6 volts and to measure higher values than this recourse is had to so-called "volt boxes." A volt box consists of a single high resistance from which are taken off taps, these taps being placed so as to include known portions of the whole resistance, as $\frac{1}{10}$, $\frac{1}{100}$, $\frac{1}{1000}$, etc., as illustrated in Fig. 394.

AB represents a high resistance with taps taken off from points representing $\frac{1}{10}$, $\frac{1}{100}$, $\frac{1}{1000}$, of its value. These are connected to contacts over which a contact arm moves by which these tap-off points are connected to the potentiometer by means of the leads *a* and *b*. The leads between which the potential difference is sought are connected to the extremities of *A* and *B*.

The standard cell is connected in place, see Fig. 363, setting the contact points, *M* and *M'*, to the certified value of its E. M. F. With

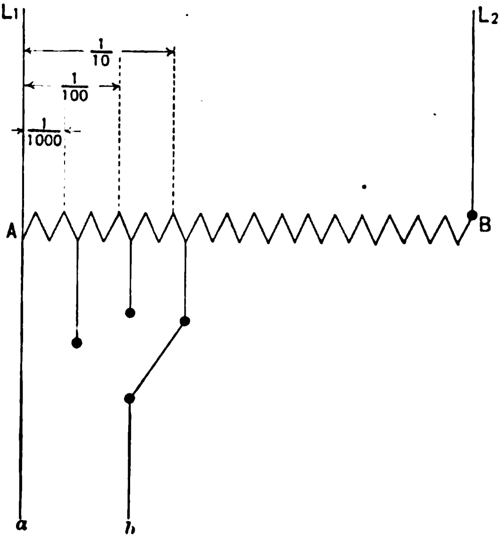


FIG. 394.—Connections of Volt Box for Potentiometer.

all the protecting resistance *R'* in series with the galvanometer, its circuit is closed and the current is regulated by the resistance *R* in series with the power cell until the galvanometer shows no deflection. The protecting resistance is gradually cut out and when all is out and the balance is still maintained, the standard cell is cut out and the potentiometer E. M. F. terminals are connected to the leads *ab* of the volt box. In doing this it is necessary to see that the positive side of the line is connected to the same terminal that the positive terminal of the standard cell was connected. After the points *ab* are connected to the potentiometer a balance is again obtained by moving the contact points, M and M', without disturbing the regulating resistance R, and the voltage is read off from the position of the contact points. If the lead b is connected to the $\frac{1}{10}$ tap-off point, the voltage read off is multiplied by 10 to obtain the difference of potential between the lines L_1 and L_2. The actual measurement gives the potential difference across $\frac{1}{10}$ of the whole resistance of the volt box, and assuming the resistance to be uniform, the whole would be 10 times this value. It must be remembered, however, that the volt box ratio only holds true when no current flows through the lead b (Fig. 394). It can only be used in connection with a null method, if the ratios marked on the box are to be used.

To Calibrate Voltmeters.—In the above connections for measuring high voltages, the true potential difference between L_1 and L_2

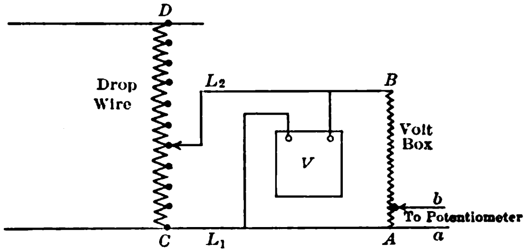


FIG. 395.—Drop Wire and Volt Box Connections.

is obtained. If a voltmeter is connected across them, a certain value will be indicated, and if it is not the same as the value found by potentiometer measurement, it must be in error by the amount of the difference.

To calibrate a voltmeter over a considerable portion of its scale requires a means of producing potential differences along its whole scale at more or less regular intervals. Thus to calibrate a 150-volt instrument on a 220-volt circuit, a resistance should be used across the line that would give a suitable small current, say 5 amperes. If one end of this resistance be called C (Fig. 395) and ten taps be led off from this resistance at equal intervals, then by connecting both the voltmeter under test and the high voltage side of the volt box, one lead to C and the other to any one of the ten taps, any desired voltage may be impressed simultaneously on both potentiometer and voltmeter under test.

To Measure Current.—Current can readily be measured by means of the potentiometer and standard low resistances, such as .1, .01 or .001 ohm. As the resistances are so small, the fall of potential across them is also small, and this difference of potential can readily be measured by connecting the terminals of the resistance directly to the E. M. F. terminals of the potentiometer and connecting the resistance in series with the current circuit and ammeter under test. Knowing the difference of potential and the resistance, the current is at once known.

To Calibrate Ammeters.—To do this, it is only necessary to make the connections above described and connect the ammeter in the current line with a suitable resistance for varying the current. The potentiometer and ammeter readings are taken at the same time, the true current calculated and compared with that shown by the ammeter.

To Measure Resistances.—With the aid of the apparatus used to measure current, the resistance of conductors may easily be measured. One of the standard resistances is connected in series with the resistance to be measured and both are included in a circuit containing one or more secondary cells to give a steady current. The difference of potential across the standard resistance is then measured by the potentiometer and also that across the resistance to be measured. As the current through each resistance is the same, the resistances are proportional to the differences of potential.

If the resistance to be measured is large, it may be that the drop of potential across it will have to be measured by the aid of the volt box and both resistances connected to high voltage lines in order to get a suitable current. If the current value times the value of the standard resistance is greater than the direct reading capacity of the potentiometer, the volt box will also have to be used to measure the drop across this resistance.

To Measure Resistances.

High resistance may be measured by a voltmeter, by the testing set or by an ohmmeter.

Low resistance may be measured by an ammeter and voltmeter, or by a voltmeter and standard resistance.

To Measure a High Resistance with a Voltmeter.—To do this requires a voltmeter of known resistance and a source of constant potential, as a running generator. The difference of potential across the mains of the generator is first measured and then the resistance to be measured is connected in series with the voltmeter, and the fall of potential through these two is measured across the mains whose difference of potential is constant. This is represented in Fig. 396.

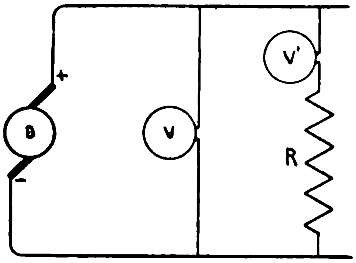


FIG. 396.—Connections for Measuring Resistance with Voltmeter.

Suppose E is the reading of the voltmeter when connected directly across the mains and E' the reading when it is connected up with R, the unknown resistance in series with it. Let X be the resistance of the voltmeter and I the current through E' and R, then by Ohm's law $E=I(X+R)$ and $E-E'=IR$.

Subtracting one from the other,

$$E'=IX \text{ or } I=\frac{E'}{X},$$

also

$$I=\frac{E-E'}{R}.$$

$$\therefore \qquad R=\frac{(E-E')\times X}{E'},$$

all of which quantities are known.

This method is available for high resistances and is particularly adapted for measuring insulation resistance as described farther on.

To Measure Resistance of a Voltmeter.—This is just the converse of the above, requiring a source of constant potential and a high resistance. The connections and readings are made as before, when the resistance of the voltmeter would be equal to the other resistance multiplied by the second reading and divided by the difference of the readings.

The resistance of most voltmeters is marked on the box or case, but the above would be available in case it was unknown.

With a Weston 150-volt range voltmeter using the above method satisfactory resistance measurements can be made from 500 ohms up to 1 megohm, the most accurate being for resistances about equal to that of the voltmeter.

To Measure Resistance with an Ammeter and a Voltmeter.—To do this it is only necessary to connect up the resistance in series with the ammeter and connect a voltmeter at the terminals of the resistance. Then, by Ohm's law, the resistance is at once calculated. From above $R=\frac{E}{I}$ (Fig. 397). This method is adapted to resistances from 0.01 to 500 ohms.

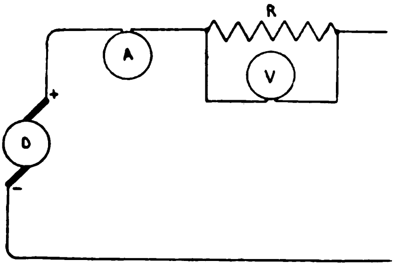


FIG. 397.—Connections for Measuring Resistance with Voltmeter and Ammeter.

Precautions when Measuring Resistance with Ammeter and Voltmeter.—See that the instruments are far enough apart so that neither will be affected by the other, and use a value of current large enough to give a good reading, but not so large as to heat the circuit under test. See that all connections are good, and especially those of the voltmeter. For low resistances it is better to connect the ammeter outside the voltmeter, for the error will be less if the ammeter measures the slight current through the voltmeter than if it were connected so that the voltmeter recorded in addition the fall of potential through the ammeter. For high resistances it is better to connect the ammeter inside the voltmeter, for the voltmeter current may be appreciable compared with the ammeter reading.

To Measure Resistance with a Voltmeter and Standard Resistance.—The circuit whose resistance is to be measured is connected in series with the standard resistance and a steady current sent through both. The voltmeter is connected around the standard resistance and then around the unknown resistance. The current being the same through both resistances, the differences of potential are directly proportional to the resistances. A typical connection is shown in Fig. 398 for measuring the resistance of an armature.

A few cells are connected up in series with the standard resistance and the armature whose resistance is to be determined. A voltmeter is connected to the terminals of the resistance and when current is established through the circuit, the fall of potential through the resistance is noted. When the same current is flowing, the voltmeter is connected to the brushes of the armature or

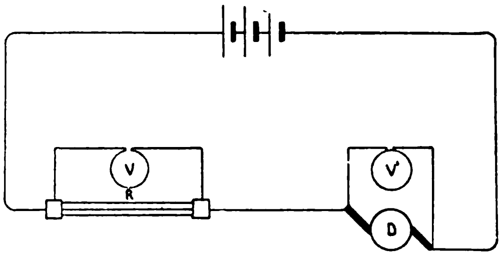


FIG. 398.—Connections for Measuring Resistance with Voltmeter and Standard Resistance.

to two opposite segments of the commutator, and the fall of potential noted. Calling R and D the resistances and E and E' the readings of the voltmeter, then the current I through R and D is, by Ohm's law,

$$I = \frac{E}{R} = \frac{E'}{D} \text{ or } D = \frac{E'R}{E},$$

whence D is readily calculated.

In this measurement, the standard resistance should be capable of carrying considerable current without heating, and for this the "ampere shunt" resistance can be used to advantage. The current should be steady, and the resistance of the voltmeter high, and the voltmeter itself low reading.

Standard Resistances.—If no resistances are available, they can readily be made on board ship. Knowing the resistance required and the current to be carried, from the resistance data of the available wire the necessary diameter and length can be determined, see pages 27-29. Its calculated resistance should be checked by actual measurement by some of the methods given.

Measurement of Armature Resistance by Comparison of Deflections.*—This depends on the following general principle: If two resistances have the same current flowing in them, the differences of potential at their ends is proportional to their resistances.

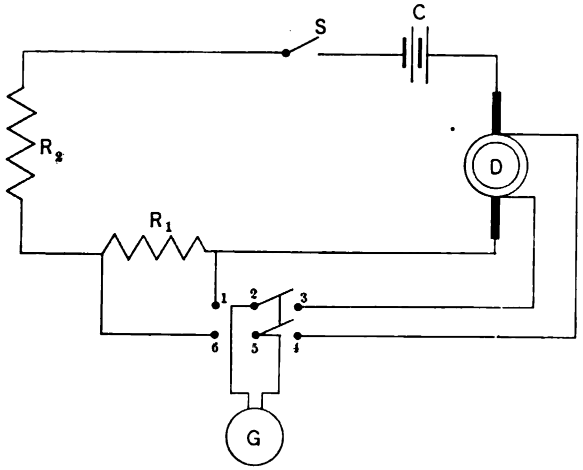


FIG. 399.—Measurement of Armature Resistance.

In Fig. 399

D is the armature resistance,
R_1 standard resistance, approximately equal to that of *D*,
R_2 variable resistance,
C one or two cells (preferably storage cells),
G galvanometer,
S switch,
1, 2, 3, 4, 5, 6 terminals of a double-pole, double-throw switch.

The leads of the circuit containing the cells are connected to the brushes, disconnecting the field windings. The wires from the

* This is similar to the method of page 672, except that a galvanometer replaces the voltmeter.

armature to the galvanometer are connected between the brushes and the commutator, making sure that the wires press on opposite segments and make contact with one segment only.

The galvanometer should have a uniformly divided scale and its reading should be proportional to the deflecting current. If it is a very sensitive one, it may be necessary to use a shunt, or a resistance in series with it will often give the desired result.

The resistances of the leading wires to the galvanometer do not affect the accuracy of the measurement as they are so very small compared with that of the galvanometer, and the latter may be far removed from the machine where it will be free from any influences other than the deflecting current.

Instructions for Test.—Close the switch S and by means of the switch hinged at 2 and 5 connect the galvanometer to 1 and 6, so that it is connected to the circuit containing the standard resistance. Adjust resistance R_2 to get a good readable deflection. Note the deflection on the scale of the galvanometer. Reverse the switch to 3 and 4, connecting to armature and note the deflection. Reverse the switch and repeat the first reading, and repeat the whole operation five or six times.

Let d_1 be the mean of all the deflections when connected to R_1,
d_2 be the mean of all the deflections when connected to D,
E_1 the fall of potential through R_1,
E_2 the fall of potential through D.

Then

$$\frac{d_1}{d_2} = \frac{E_1}{E_2},$$

and by the principle stated above

$$\frac{E_1}{E_2} = \frac{R_1}{D},$$

or

$$\frac{R_1}{D} = \frac{d_1}{d_2} \text{ and } D = \frac{R_1 d_2}{d_1},$$

Connecting the leading wires from the galvanometer to the brushes will give the resistance of armature, brushes and contacts, and subtracting from this value the armature resistance will give the resistance of brushes, brush holders and contacts; an item sometimes of as much importance as the armature resistance.

This method is suitable for measuring resistances between .1 and .001 ohm, but for resistance lower than these values, other methods must be resorted to, such as that by the Thompson bridge, which will measure as low as .0001 ohm.

Uses of the Testing Set.

The uses of the Queen-Acme testing set are taken from the circular issued by the makers of this instrument, Queen & Co., and which is furnished with the instrument.

To Measure Resistance.—Resistances are measured with the Queen-Acme as follows:

Connect the terminals of the resistance to be measured to the line posts *C* and *D*, see Fig. 370, and place the battery connectors on the two upper tips. This throws one cell of the battery into circuit, which is sufficient until balance is roughly attained. Now unplug the 100-ohm coil in each bridge arm, and place the commutator plugs for either high or low resistances. Remove plugs from the rheostat until the aggregate resistance unplugged is, as nearly as may be guessed, equal in value to that of the unknown resistance. Then press the battery key, and, holding that down, momentarily press the galvanometer key. If the galvanometer needle swings toward +, the resistance unplugged in the rheostat is too high and should be reduced. If the deflection is toward −, the resistance is too low and should be increased. By altering the resistance in this way a value will soon be found wherein a slight change either way will reverse the deflection of the galvanometer needle. The rest of the battery may now be put in circuit by placing the right-hand battery connector on the lower left-hand tip. If the keys be again pressed, first the battery key, then the galvanometer key, a greater deflection will be obtained than before for the same variation in the rheostat, and therefore the adjustment can be made more accurately. With bridge arms of equal value this is the best result that can be obtained, but by selecting more suitable values for the two arms a considerably higher degree of accuracy may be secured. A reference to the following table will show the best values of the bridge arms to determine any desired resistance.

The following table shows the values of A and B respectively, to be chosen when measuring any resistance within the range of the set:

Below	1.5	ohms, make	A = 1, B = 1000	Plug for Low.
Between	1.5 and 11	" "	A = 1, B = 100	
"	11 " 78	" "	A = 10, B = 100	
"	78 " 1100	" "	A = 100, B = 1000	
"	1100 " 6100	" "	A = 100, B = 100	Plug for Low or High.
"	6100 " 110,000	" "	B = 1000, A = 100	Plug for High.
"	110,000 " 1,110,000	" "	B = 1000, A = 10	
"	1,110,000 " 11,110,000	" "	B = 1000, A = 1	

Placing the Plugs.—In placing the plugs in the commutator it is sufficient to remember this:

First. Excepting when the two arms are of equal value, *always* make arm A the *smaller.*

Second. If the resistance being measured is higher than 6100 ohms, place the commutator plugs for high; if lower than 1100 ohms, for low. In the first case, the unknown resistance is found by dividing the larger bridge arm by the smaller, and *multiplying* the total unplugged resistance in the rheostat by the quotient. In the second case, the rheostat resistance is *divided* by the quotient. The arrows on the top of the set facilitate setting the commutator plugs. If measuring high resistance, set the plugs in the direction indicated by arrow H; if measuring low resistance, follow direction indicated by arrow L.

Example.—An example will illustrate the method of using the bridge. It is desired to measure a resistance say of about 1000 ohms. Connect the resistance to posts C and D, arrange the commutator in the direction of arrow L, place battery connectors on upper tips, and remove the 100-ohm coil from each bridge arm. From the rheostat unplug 1000 ohms, and upon pressing the keys the galvanometer needle swings to −. Unplug 100-ohm coil, and galvanometer needle swings to +. Try 1050 ohms, moves to −. Try 1070, still −. Try 1090, moves to +. With 1080, needle reverses again, swinging to −. Try 1085, swings to −. Try 1087, it swings to +. Try 1086, swings to −. The true value is, therefore, between 1086 and 1087. To secure more accurate results, change bridge arm B to 1000, and remove 10,860 ohms from rheostat. This proves too little. Try 10,865 and it is found too large. It is probable that with 10,000 ohms out no change in deflection will be noted smaller than will be produced by a change of 5 ohms in rheostat. We see that 10,860 is small and 10,865 large, the true value, therefore lies between them, or say 10,863.

Very Low Resistances.

In measuring very low resistances, excellent results may be secured by interpolation. Supposing a resistance of about .01 ohm is to be measured. Make the bridge arms 1000 and 1 respectively, and arrange the commutator with the plugs in the direction of arrow *L*. Unplug 10 ohms from rheostat, and needle swings to +. Try 5 ohms, and it reverses, swinging to −. Another trial demonstrates that the correct value lies between 7 and 8. That is .007 and .008 ohm. Now to determine the result accurately note the values of the two reverse deflections when 7 and 8 ohms, respectively, are out. In the former case the deflection is −1.4 divisions; in the latter case, +4.1 divisions. The 8 comes more nearly balancing; or, in other words, the true value is more nearly 8 than 7. Now divide the larger deflection by the sum of the two deflections, and annex the quotient to the smaller value removed from the rheostat. $\frac{14}{25}=.56$ or .00756 ohm for the resistance desired.

Wheatstone Bridge and Standard Resistance.

It often becomes necessary to measure the resistance of a heavy copper bar or a conductor of very low resistance. The ordinary bridge method becomes impracticable for the resistance of the leads and the contact resistances alone may be many times that of the resistance of the sample. One method of making such a measurement is illustrated in Fig. 400. The resistance to be measured, shown in the form of a rod, *X*, is connected in series with a standard resistance whose value is comparable with the resistance of *X*. This circuit is connected in series with a source of power, as a battery, and in order to get the proper sensibility the current should be in the neighborhood of 500 amperes per square inch. In the Standardizing Laboratory at the Naval Academy, the unknown resistance is immersed in an oil bath to keep it at a known temperature.

M and R are the arms of a Wheatstone bridge or a resistance box. One should be the ratio arm or arms, and the other the balance arm. It is usually necessary to have the arm corresponding to the smaller of S or X, the ratio arm, so that the necessary number of significant figures may be obtained with the balance arm. The leads connecting M and R to the standard and unknown resistance should have a resistance that is negligible compared to M and R or else a correction should be made.

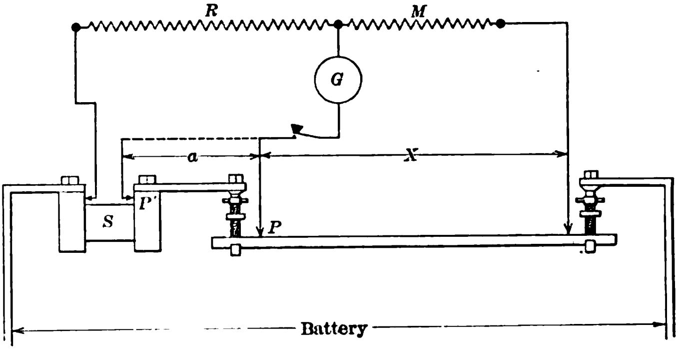


FIG. 400.—Bridge Measurement of Low Resistance.

Suppose that the galvanometer G is first connected to the potential connection P. M is set at some value M_1 and the bridge balanced by adjusting R to a value R_1. Then by the law of the Wheatstone bridge,

$$\frac{X}{M_1} = \frac{a+S}{R_1}, \qquad (1)$$

where a is the contact and lead resistance between X and S.

If the galvanometer lead is now transferred from P to P', a new value of R, as R_2, will be necessary to balance the bridge. To make the case a general one, assume that M_1 has been changed to M_2.

Then

$$\frac{X+a}{M_2} = \frac{S}{R_2}. \qquad (2)$$

Eliminating a between (1) and (2)

$$X = \frac{M_1 S(M_2+R_2)}{R_2(M_1+R_1)}.$$

For the greatest accuracy, a should be made as low as possible, and there should be no possibility of a changing between the two balances.

The Kelvin Double Bridge.

The above method of measuring low resistance is open to the objection that two balances are necessary and the resistance is not determined directly. By means of the Kelvin double bridge, a low resistance can be measured directly, only one balance being necessary.

Fig. 401 shows the simple bridge. It is identical with the Wheatstone bridge, except that the galvanometer connection to the two low resistances divides in two branches, one going to the unknown re-

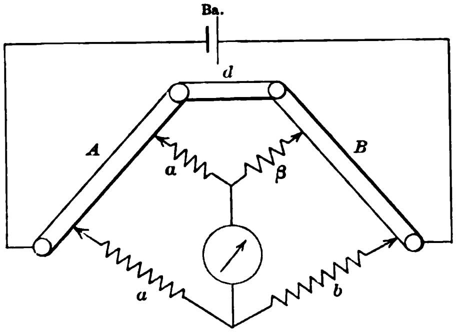


FIG. 401.

sistance and one to the standard resistance. It can be shown by circuit equations that if

$$\frac{\alpha}{\beta} = \frac{a}{b},$$

then $\frac{A}{B} = \frac{a}{b}$ the law of the Wheatstone bridge, and the contact resistance d is eliminated.

The connections of the commercial bridge are shown in Fig. 402. The various parts of the bridge are marked the same as the corresponding parts in Fig. 401. The a, b, α and β resistances are contained in one box. The a-b resistances are in series on one side, and the α-β in series on the other. The galvanometer connections are made to two strips of metal, each arranged so that it may be plugged in at any point of the a-b and the α-β resistances, respectively. This allows a very flexible arrangement. It is only necessary to have the two sides plugged symmetrically and the relation $\frac{a}{b} = \frac{\alpha}{\beta}$ holds true. With the arrangement of plugs shown in Fig. 402, $\frac{a}{b} = \frac{\alpha}{\beta} = \frac{10,000}{100}$.

The adjustable resistance consists of two parts; the first digit is obtained by means of a plug which may be inserted in any of ten resistances as shown at l. The next three digits are obtained by means of a calibrated slide wire, shown at m, which is read with a

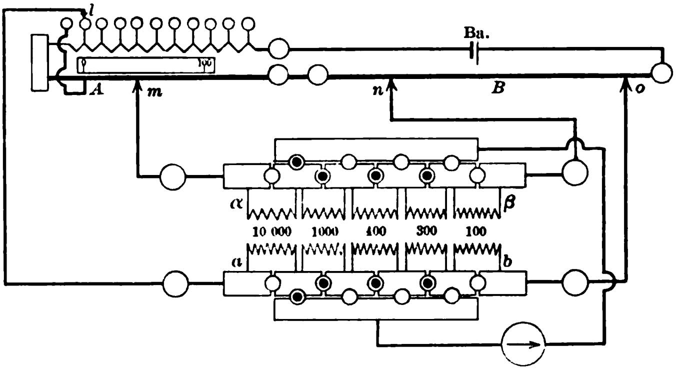


FIG. 402.—Kelvin Double Bridge.

graduated scale and vernier. The most common types have the plug resistances equal to hundredths and thousandths of ohms. The bridge in use in the Standardizing Laboratory at the Naval Academy is an example of the former.

To Compare E. M. F.'s of Cells by Queen-Acme Testing Set.—Connect in all of the cells in the set in the usual way, taking care, however, not to reverse them by crossing the battery cords. Plug the commutator only between *B* and *R*, and remove 1000 ohms from bridge arm *B*. Arm *A* should be all plugged *in*. From the rheostat unplug say 5000 ohms. Now, connect one of the cells, whose electromotive forces are to be compared with its positive terminal, to the + battery post, and its negative terminal to the line post *C*. Upon pressing the keys the needle swings one way or the other. If towards

+ unplug less resistance in rheostat, and if toward − add resistance to rheostat. A value will quickly be found wherein a variation of an ohm either way reverses the deflection. Now, take this value and add to it the resistance unplugged in arm *B*. This divided by the resistance in arm *B* gives the ratio between the potentials of set battery and test cell, respectively. It will be noted that the division is decimal and consists merely in pointing off as many places as there are ciphers in the resistance unplugged from arm *B*.

This operation repeated with any number of cells gives their values in terms of the battery E. M. F. in the set from which their relative values may be obtained. Or, if desired, a standard cell may be used to replace the battery in the set, in which case the first measurement gives at once the value of the E. M. F. of the test cell.

If the E. M. F. of the cell or battery being tested exceeds that of the battery in the set, it is only necessary to reverse the positions of the two batteries, when the results are secured as before.

To Check a Voltmeter.—A voltmeter may be checked up, to determine its accuracy, while in service. Disconnect the battery of the set. Connect the circuit to the battery posts of the Queen-Acme set, positive lead to + post, negative lead to − post. Before doing this, remove say 10,000 from rheostat, plug commutator only between *B* and *R*, and remove 100 ohms from arm *B*. Now, connect a standard cell or one whose E. M. F. is known with positive terminal to + battery post, and negative terminal to line post *C*. Upon pressing both keys a deflection occurs towards + if rheostat resistance is too high; towards − if too low. A few changes will produce a result wherein a slight variation in the rheostat resistance reverses the galvanometer deflection. To find the E. M. F. on the line, add 100 to the rheostat resistance and point off two. Multiply this by the E. M. F., and the result is the desired E. M. F. If the standard is exactly one volt, the total resistance out represents the E. M. F. on the circuit.

The attainable accuracy is greater than could be secured with the best voltmeter, in fact, it is an excellent method of checking the accuracy of all voltmeters.

Battery Resistance.—To measure internal resistance of a cell, first compare its open circuit potential with the potential of battery in set as previously explained. Now, shunt it with a known resistance, say 100 ohms, and again measure its terminal potential. The difference between these values, divided by the shunt resistance, gives the current flowing. To find the internal resistance, multiply the resistance of shunt by ratio between first value measured and second. This method has one important feature; it determines the internal resistance under normal conditions of use, since the shunt may be given any desired value. One is enabled to give a low value to the shunt, and make repeated balances while the cell is discharging, thereby determining the effect of polarization.

As an example of the application of the Queen-Acme to the internal resistance of a battery, take say a silver chloride testing cell and determine its resistance. Measuring its potential in terms of test battery, we find it is .212 of the latter. Shunting it with 1000 ohms, and repeating the measurement we find .179 for the terminal E. M. F. The total resistance, therefore, is to the 1000 ohms shunt as 212 is to 179 or the total resistance $=\frac{212}{179}\times 1000 = 1184$. Deducing the shunt we have 184 ohms as the internal resistance of the cell.

To Check an Ammeter.—To check an ammeter with the Queen-Acme, secure a low resistance and proceed as follows: Connect the low resistance in series with the meter and run leads from it to the Queen-Acme set; one lead from the positive side of the + battery post, the outer from the negative side to the line post *C*. Join a standard cell between the battery posts; positive to + post, negative to − post. Plug commutator between *B* and *R;* remove say 10,000 from rheostat, and 100 from arm *B*. Balance in the usual way by changing rheostat resistance. Now, the difference of potential at the terminals of the shunt has been balanced against the standard cell, and is found by the directions previously given for comparing E. M. F.'s to equal shunt

$$PD = \frac{1.44\times 100}{R+100} = \frac{144}{R+100}.$$

To determine the current flowing, divide this result by the shunt resistance. As the shunt resistance has usually a decimal value, it is necessary merely to point off in the last operation.

Use of the Keys.—The primary use of the keys is very evident, that in the battery circuit to prevent current from flowing all the time, thus running down the battery, and that in the galvanometer to protect that when not in use. It has been stated in making a measurement, the battery key should be first pressed, and at an interval, the galvanometer key. The nature of certain resistances may cause the potential of any two points to be widely different when the current is starting or stopping and yet they may be at the same potential when the current is steady. A current can never rise or fall to its full value instantaneously, and when the unknown resistance is such that the rise or fall takes place at a different rate, the current must be allowed to become steady by first closing the battery key, and then closing the galvanometer key.

In measuring a resistance like that of an electromagnet in which there is great self-induction, or a long line in which there is electrostatic capacity, the proper use of the keys becomes very important. Although there may be an exact balance, yet if the galvanometer key is closed first, the needle may be violently thrown, owing to the momentarily induced current.

In measuring the resistance of an electromagnet, the galvanometer must be placed some distance from it, so it will not be influenced by the magnetic field set up around it. The effect can be tested by opening and closing the battery switch, leaving the galvanometer key opened. If there is any movement at all of the needle, it is proof that some part of the circuit is disturbing it, and this should be corrected before the measurement proceeds any farther.

Earth Test.—If it is not possible to bring both ends of the unknown resistance to the bridge, the test can still be made by connecting one end to the bridge and connecting the far end to a good "earth" connection, and also making connection to earth of one pole of the battery. The earth being at the same potential, will act as though the two were connected to a common terminal. The terminal of the bridge where the far end of the resistance and the pole of the battery would connect is also connected to earth. The measurement is now made as before.

Measurements of Insulation Resistance.

Insulation resistance may be tested either for the ohmic resistance of the insulation or for the ability of the insulation to withstand the potential to which it is ordinarily subjected.

If only the ohmic resistance is required the insulation may well be tested by the Testing Set, but for the ability to stand high potential as well as ohmic resistance the ohmmeter with a small magneto is preferable.

Insulation by Direct Deflection.—Insulation resistance may be measured by the testing set by direct deflection. Connect a known high resistance, say 100,000 ohms, one terminal to the line post *C*, see Fig. 370, one terminal to the + battery post. Remove all plugs from the commutator, and have all plugs in the rheostat, as any resistance unplugged in rheostat is in circuit with galvanometer and battery. Arrange battery tips so as to connect in one cell only. Now upon pressing the keys a deflection of about 8 divisions will be obtained. This deflection is due to the current from one cell through 100,000 ohms. If we multiply the resistance by deflection we have that resistance through which one cell will produce a deflection of one scale division. This is the constant of the galvanometer.

Now, replace the known high resistance by one whose value it is desired to know, and add enough cells to produce as large a deflection as possible. Multiply the constant of the galvanometer, usually expressed in megohms, by the number of cells and divide by the number of scale divisions deflection. The result is the desired resistance expressed in megohms.

If a high resistance is not at hand, one may be readily made for temporary use by marking with a soft pencil on a strip of ground glass. Connect the glass by means of tinfoil ends to the posts of the set, and measure its resistance, adding or removing a small amount of graphite until the desired value is secured.

Method by Testing Set.—The following is the method generally used as a quarterly test required by the regulations. One leading wire is taken from one terminal of the unknown resistance of the bridge to one bus bar on the switchboard. The connections of all voltmeters, ammeters and ground detectors are broken, as well as connections from the generators, this last effected by leaving the main headboard switches open. Another leading wire leads from the other terminal of the unknown resistance to a good earth connection. All lamps in all the different parts of the ship are unscrewed from their sockets, and it is well to test each circuit for continuity by the magneto, as this will tell whether any lamps have inadvertently been left in place. Open all the switches controlling the different circuits at the switchboard. When all ready to go on with the measurement, close a switch connecting one leg of the circuit to be tested to the bridge. As all connections are broken. the circuit can only be completed through grounds or leaks along the one leg of the circuit back to the earth connection and to the bridge. Measure the resistance by the bridge or at least ascertain that it is over some fixed value, say 2 megohms, which it should be in a good circuit. Record the result. Open the switch and close another on the same bus bar, repeat the measurement and record it, and so on until measurements on all circuits have been made on the same bar, say all the + legs. In the case of searchlight circuits, see that the carbons are run apart, and in motor circuits see that disconnections are made at the brushes.

After finishing all the + legs, disconnect the leading wire from the + bus bar and connect it to the − bar, and repeat all the above measurements; record the results in tabular form and number the circuits, distinguishing the legs of a circuit by + and −.

The result of the above measurements will give the insulation resistance of each leg of each circuit to earth, and to obtain the total resistance of each circuit to earth add the reciprocals of the resistances of each leg, and take the reciprocal of this sum.

After the above series of measurements has been made, disconnect the leading wire from the earth connection and take it to the terminal of the bus bar not already connected. Now close both switches of a circuit, leaving all the others open. As all lamps are disconnected, current is only established through leaks from one leg of the circuit to the other. This is a necessary measurement as it may happen that the resistance of each leg to earth is very high, but that from one leg to the other is very low. Repeat this measurement for each circuit on the switchboard.

After this series of measurements is completed, then close all the switches and the resistance will be that of all circuits connected in parallel, which in the poorest installation should not be less than ½ megohm.

Machine Insulation Resistance.—The testing set can be used in a similar manner to test the ohmic insulation resistance of the different circuits of generators and motors. The different windings are disconnected, the brushes raised and connections to the switchboard broken. Ground one terminal of the testing set and connect the other to the different parts and windings, as to the armature, series winding, shunt winding, etc. Take measurements and record the results. By making the proper connections by the leading wires from the bridge such insulation resistances can be made, as armature to series winding, or to shunt winding, or to engine shaft, or to frame, or to earth; or from shunt to series, shunt to armature, shunt to shaft, or such other combinations as will suggest themselves for examining the soundness of insulation.

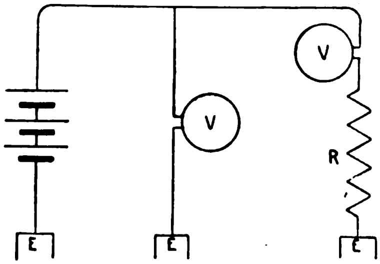


FIG. 403.—Battery Connections for Measuring Insulation Resistance.

Method by Drop of Potential Using Battery and Voltmeter.—The method of using the battery and voltmeter is shown in Fig. 403 which is the same method as that described on page 670.

Let E = E. M. F. of battery,

b = resistance of battery,

X = resistance of voltmeter,

d_1 = deflection of voltmeter connected across battery terminals,

d_2 = deflection of voltmeter in series with insulation resistance,

R = insulation resistance,

I = current through battery, voltmeter and R,

then

$$I = \frac{E}{R+X+b} \text{ and } I = \frac{d_1 - d_2}{R},$$

or

$$\frac{E}{R+X+b} = \frac{d_1-d_2}{R} \text{ and } E=d_1,$$

whence

$$R = \frac{(X+b)(d_1-d_2)}{d_2};$$

b is so small that it may be neglected.

Method by Voltmeter.—The method described of measuring insulation resistance by means of the bridge necessitates stopping the generators, or at least cutting off the current from the switch-

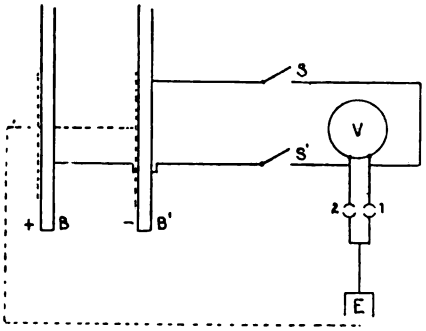


FIG. 404.—Connections for Measuring Insulation Resistance by Voltmeter.

board, but the voltmeter method uses the generator current as the source of supply. The only instrument required in making this measurement is a portable voltmeter of known resistance, and the necessary connections can be made in a few minutes, if they are not already a part of the switchboard installation.

In Fig. 404 B and B' are the bus bars connected to the generator terminals. V is the voltmeter, each terminal having a connection to earth through the plug switches 1 and 2. The bus bars are connected to their respective terminals of the voltmeter through the switches s and s'.

The values of the insulation resistance of B and B' to earth may be deduced by a consideration of the connections shown in Fig. 405.

When the voltmeter is connected between B, the + side, and earth E, there may be leaks from B to E and from B' to E.

Let E = difference of potential between B and B',

E' = deflection shown when B is connected to earth,

E_1' = deflection shown when B' is connected to earth,

X = resistance of voltmeter,

then

$$I_1R_1+IR=E \text{ and } I_2X+IR=E,$$
$$I_1R_1=I_2X=E-IR=E',\ I_1+I_2=I.$$

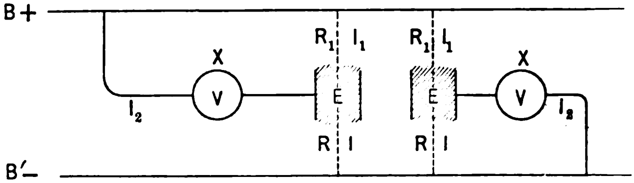


FIG. 405.—Voltmeter Connections to Ground.

The joint resistance of R_1 and X is

$$\frac{R_1X}{R_1+X},$$

and

$$I\left(\frac{R_1X}{R_1+X}\right)=E'.\quad I=\frac{E-E'}{R},$$

or

$$\frac{E-E'}{R}\left(\frac{R_1X}{R_1+X}\right)=E' \text{ and } R=\frac{E-E'}{E'}\left(\frac{R_1X}{R_1+X}\right). \qquad (1)$$

This shows that the value of R, the insulation resistance of B' to earth, depends on the value of the insulation resistance of B to earth. If the voltmeter is connected between B' and earth and gives a deflection E'_1, a similar deduction will give R_1 in terms of R, thus by symmetry

$$R_1=\frac{E-E'_1}{E'_1}\left(\frac{RX}{R+X}\right). \qquad (2)$$

From equations (1) and (2) the values of R and R_1 will be found to be

$$R=\frac{X(E-E'-E'_1)}{E'}, \qquad (3)$$

and

$$R_1 = \frac{X(E - E' - E'_1)}{E'_1}. \tag{4}$$

If the + leg is not grounded, $E'_1 = 0$, and

$$R = \frac{X(E - E')}{E'}, \tag{5}$$

and if the − leg is not grounded, $E_1 = 0$, and

$$R_1 = \frac{X(E - E'_1)}{E'_1}. \tag{6}$$

Example.

A direct reading voltmeter, having 16,000 ohms resistance is connected from the + main to earth. The voltmeter shows 2.6 volts and the difference of potential between mains is 110 volts. Find the insulation resistance between the — main and earth, assuming that the insulation resistance of the + main to earth is (1) infinite; (2) the same as the — main to earth, and (3) one-tenth of the — main to earth.

If the insulation resistance of the + main is infinite, that leg is not grounded, and from equation (5)

$$R = \frac{X(E - E')}{E'} = 16{,}000 \times \frac{110 - 2.6}{2.6} = 660{,}900 \text{ ohms.}$$

Under condition (2) $E' = E'_1$ and from equation (3)

$$R = \frac{X(E - E' - E'_1)}{E'} = 16{,}000 \times \frac{110 - 5.2}{2.6} = 644{,}900 \text{ ohms.}$$

Under condition (3) $E'_1 = 10\,E'$,

$$\text{and } R = \frac{X(E - E' - E'_1)}{E'} = 16{,}000 \times \frac{110 - 28.6}{2.6} = 500{,}900 \text{ ohms.}$$

Suppose it is required to measure the insulation resistance of the − legs to earth. One circuit is taken at a time, the others being cut out; both section switches on the bus bars are closed. The switch s' is closed and plug switch is inserted in 1. The only current then through the voltmeter is from the + bus bar through the voltmeter, through the switch 1 to earth and from earth to earth leaks along the − leg, and thence to the − bus bar. All the − legs can be tested in this way in a few minutes, recording for each circuit the reading of the voltmeter.

To test the + legs, take one circuit, keep both section switches closed; close s, open s' and insert plug in 2. The current is then from + bus bar to leaks along the + leg to earth to the voltmeter through 2, through the voltmeter and switch s to the − bus bar. Record the reading of the voltmeter and do the same for each leg.

The bus bar voltage can be determined by opening both 1 and 2 and closing s and s'. Having this voltage and the drop due to earth leaks, we have the data necessary for calculating the insulation resistances.

Knowing X and E and assuming a value for R beyond which its actual value is not desired, E' can be calculated. If a reading shows above this calculated value, R is less than the assumed value, and vice versa.

Suppose it was not wished to know the actual resistance, provided the resistance to be measured was over 2 megohms, and the voltmeter had a resistance of 13,000 ohms, and we were using an 80-volt circuit, then

$$2{,}000{,}000 = \frac{13{,}000 \times 80}{E'} - 13{,}000,$$

or

$$E' = \frac{1{,}040{,}000}{2{,}013{,}000} = \tfrac{1}{2} \text{ volt practically.}$$

If the voltmeter showed ½ volt or less, the insulation resistance for the particular part measured would be 2 megohms or over.

This is a very rapid and easy method and the insulation of the different legs of the different circuits to ground can be tested at any time while the generator is running, and besides it has the advantage of employing the high potential of the running machine. The only observations are E and E' for each measurement and these can be recorded for each circuit, the calculations can be made after the tests are finished and the whole operation consumes only a few minutes.

Method by Ohmmeter.—To measure insulation resistance by this method requires the use of an ohmmeter and a magneto. The leading wires from the magneto are connected to the proper terminals on the ohmmeter and the circuit to be tested is connected to the other set of terminals. The same preliminary operations as in the other methods are necessary. If one leg is to be tested to earth, one terminal is connected to the leg and the other terminal to earth. The armature of the magneto is rapidly revolved and current is sent through the ohmmeter and circuit, being completed through grounds or leaks. The ohmmeter measures directly the resistance of the circuit being tested, and the result is read off directly from the scale. This is by far the most rapid and convenient method of making this test, and not only is the ohmic resistance of the insulation measured, but the circuit is tested for its ability to stand the high potential developed by the magneto.

The magneto and ohmmeter can be used to test out the different windings and insulation resistance of the various parts of generators and motors in a way similar to that described for the magneto alone, and under the heading "Machine Insulation Resistance."

Galvanometer or Substitution Method.

There are many instances where a resistance to be measured is so high that it is out of range of the methods just described. This often

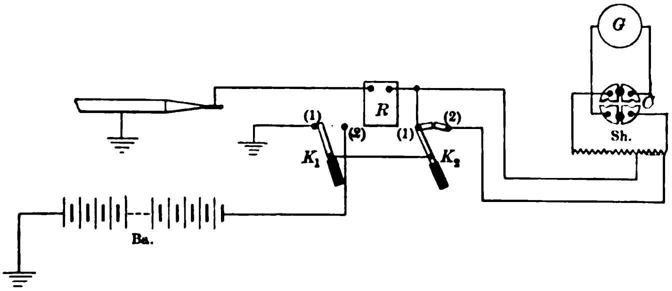


Fig. 406.—Connections for Measurement of Insulation Resistance.

occurs in the case of cable and wire insulation. Resort must then be made to a substitution method involving a galvanometer of high sensitiveness. The galvanometer is first calibrated with a standard resistance ordinarily 100,000 ohms or $\frac{1}{10}$ megohm. The connections are shown in Fig. 406. The battery *Ba* should be at least 100 volts in order to render negligible any electromotive forces in the circuit due to the cable or wire being immersed in water or buried in the ground. A lighting circuit is satisfactory, but where considerable testing is to be done it is well to procure a silver chloride battery for it is light, easily transported and furnishes a very steady voltage. The current required for the test never exceeds 1 milliampere and is usually much less than this.

Two highly insulated keys, K_1 and K_2, are used. When K_1 is in position (1) and K_2 is in position (2) the cable is discharged through the galvanometer. When K_1 and K_2 are in position (2) the current passes from the battery to the cable through the galvanometer.

K_2 is not absolutely necessary but is used as a precautionary measure. When in position (1) any current that is passing does not go through the galvanometer. When in position (2) the current passes through the galvanometer and shunt. K_2 can then be used to protect the galvanometer and the galvanometer need only be in circuit when a reading is being taken. *Sh* is an Ayrton shunt (see pages 709 and 710), although the type of shunt described on page 708 may be used instead. *C* is a commutator for reversing the galvanometer. *G* is the galvanometer and should be much more sensitive than the ordinary galvanometer. The instrument at the Naval Academy has a sensibility of 800 megohms; that is, 1 volt impressed upon the galvanometer in series with 800,000,000 ohms will produce 1 millimeter deflection on a scale at a distance of 1 meter from the galvanometer. Sullivan Bros., England, manufacture a two-point suspension galvanometer in which the coil may be so balanced that any exterior motion does not affect the coil deflection appreciably. Such a galvanometer can be used on board ship. A galvanometer of this type is in use in the Standardizing Laboratory at the Academy though not for insulation tests.

R is a standard resistance, usually $\frac{1}{10}$ megohm. If a cable is to be tested its core should be negative, so that any products of electrolysis will open up any faults.

Let E = battery voltage,
R = resistance of standard in megohms,
R_g = galvanometer resistance including shunt,
r = resistance of leads, contacts, etc.,
m = multiplying power of shunt,
x = unknown resistance in megohms,

D_r = deflection of galvanometer when R alone is in circuit,
D_x = deflection of galvanometer with unknown in circuit,
I_1 = current when R alone is in circuit,
I_2 = current when x is in circuit.

If the cable is short-circuited, then

$$I_1 = \frac{E}{R+R_g+r}, \tag{1}$$

and where the short-circuit is removed

$$I_2 = \frac{E}{R+x+R_g+r}. \tag{2}$$

Since the galvanometer deflection is proportional to the current and inversely proportional to the multiplying power of the shunt,

$$D_r = \frac{I_1}{m_R},$$

$$D_x = \frac{I_2}{m_x}.$$

Also in (1) R_g and r are negligible compared with R, and in (2) R, R_g and r are negligible compared with x. Substituting and dividing (1) by (2)

$$x = R\frac{D_r m_r}{D_x m_x}.$$

If a curve be plotted with deflections as ordinates and times as abscissæ, a curve similar to that shown in Fig. 407 is obtained. When the key is first closed there is a large rush of current which charges the cable electrostatically. This current slowly decreases, due to the absorption in the dielectric, until it becomes constant. This constant value is the current that is leaking through the insulation. From this deflection the true insulation resistance may be determined, but in practice, rather than wait the length of time necessary to obtain a steady deflection, the galvanometer reading at the end of a minute is arbitrarily used in calculating the resistance.

If the cable is discharged by throwing K_1 to the left, a curve similar to that obtained when charging results. This is shown in the figure.

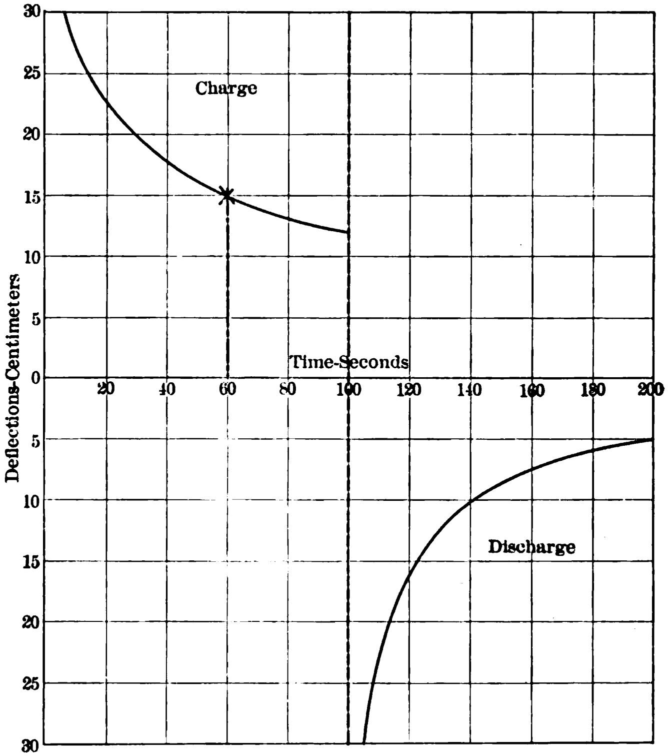


FIG. 407.—Charge and Discharge Curves of a Cable.

When insulation resistance is being measured the temperature should be carefully noted for insulation has a very large resistance temperature coefficient.

The Guard Wire.

If there is any leakage over the end of the cable, more current will pass through the galvanometer than actually leaks through the insulation. This makes the resistance appear much lower than it really is. When the ends of the cable are accessible, a guard wire *AB,* Fig. 408, may be used to prevent this. It consists of a bare wire wound tightly around the insulation at some point where the leakage current passes. It is connected to the further terminal of the galvanometer so that any leakage current will be shunted away from the galvanometer. When a cable is installed and the far end is not accessible the above method cannot be used. In this case the available end should be stripped back some distance, heated with a torch and covered with hot paraffin.

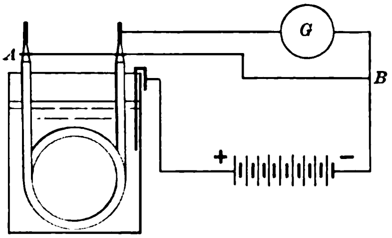


FIG. 408.—The Guard Wire.

Uses of the Magneto.

This instrument finds constant use on board ship. It may be used to locate breaks or faults in circuits, to locate grounds and to a limited extent to measure certain high resistances. It is of particular use when circuits are being wired, also for tracing out breaks in bell circuits, and to a certain extent for testing out the various windings of a generator or motor, as it quickly locates faults or grounds.

To Test for Open Circuit.—On the outside terminals, there are usually connected two short pieces of connecting wires. To test a circuit, these leading wires are secured to the ends of the circuit, and the armature is rapidly revolved. If the circuit is closed, current flows through the armature, around the electromagnet and through the outside circuit thereby causing the bell to ring. If the circuit is broken no current flows and the bell does not ring.

It is always well to short-circuit the terminals and then revolve the armature to see if all the connections in the magneto itself are intact and the circuit continuous.

To Detect a Ground.—Connect one terminal to the circuit to be tested, and the other to a good "ground" or "earth" connection through a steam pipe, or to a bulkhead or the ship's side, seeing that the paint is scraped off to get connection with the bare iron. If there is a ground on the line, current will flow through the ground back through the ground connection and the bell will ring. If there is no bad ground, the bell will not ring.

To Locate a Fault in an Open Circuit.—Suppose that a break showed on one leg of an electric-light circuit. Unscrew all the lamps on that circuit and ground both ends of the conductor. Go to a point about midway along the line, and at some junction box connect one terminal of the magneto to one end of the conductor where disconnected and the other terminal to ground. Ring through. If the bell rings, that part of the circuit is complete. Connect the other end of the conductor where disconnected to the magneto and ring through. If there is no ring, the break is in that part. Connect the circuit again and go to some other point in the direction of the break and ring through again both ways. A few trials like this will soon develop and discover the break.

To Test for Breaks, Leaks or Grounds in Generator Windings.—Treat them exactly as though they were separate circuits, first seeing that all circuits are disconnected from one another and the brushes raised from the commutator. To see if there is a leak from the series winding to the shunt winding, connect one terminal of the magneto to the series winding, the other to the shunt, and ring through. To test an armature for grounds, connect one terminal to the armature through a brush and the other to ground and ring through. The connections to obtain the desired result should readily suggest themselves.

To Measure Resistance by a Magneto.—Each magneto has stamped on it the number of ohms through which current can be sent and consequently the bell rung. The ordinary resistance through which the bell can be rung varies from 15,000 to 100,000 ohms. Knowing the value for a particular magneto, the loudness of the ringing furnishes a rough idea of the resistance being rung through. When the bell rings almost as strongly as when short-circuited, it shows the resistance is very low. When it does not ring at all, it shows that the resistance is above the value for which that particular magneto can ring. If it rings feebly, it shows the resistance is very high.

To Increase the Sensitiveness of a Magneto.—Although the resistance of a circuit may be so high that the bell will not ring through it, in some cases the continuity of the circuit may be shown by putting the hands in circuit. This is done by putting one terminal of the magneto between two fingers and touching the back of the hand to the end of the circuit. Wetting the fingers and back of the hand will add to the sensation of current.

Wrong Indications of a Magneto.—As a magneto gets old, the permanent magnets are apt to lose some of their magnetism, so the voltage for the same speed grows less, and the magneto will not ring through as high a resistance as when new. If the magneto is internally short-circuited, the bell may ring, although the external resistance is infinite. If the magneto is internally open-circuited, the bell will never ring.

A magneto may sometimes ring by simply connecting it up to a circuit in which there is great capacity, even though the circuit is open, thereby giving a wrong indication. There is more or less capacity in all parallel circuits, and a magneto will sometimes ring when connected to the ends of a long coil of double conductor, such as lamp cord, even though the resistance to continuity of circuit may be millions of ohms.

Measurement of the Resistance of Generator Windings.

As an illustration of the general methods of measuring resistances by the use of instruments furnished to ships, a general description will be given of the measurement of the resistances of the different parts of a compound generator; namely, the shunt winding, the series winding and the armature. These values are usually furnished as part of the data when the generators are installed, but it may become necessary to verify them, or to make the measurements in testing for faults or breaks.

The Shunt Winding—By the Bridge.—The resistance of the shunt field is usually sufficiently large to be measured by means of the bridge. The ends of the winding are disconnected from the generator terminals and connected to the terminals of the bridge as the unknown resistance. It requires some skill in making this measurement, for when current is sent around the shunt coils or the circuit is broken at the key, the momentary self-induction reacts on the needle of the galvanometer and gives it a motion which is not its true motion due to the steady current flowing in the circuit. This can be obviated by keeping the battery key pressed down some time before the galvanometer key is pressed, and releasing the galvanometer key before the battery key is released.

By Voltmeter and Ammeter.—A more satisfactory way of measuring this resistance is by means of a voltmeter and ammeter. Connecting the voltmeter to the shunt field terminals, disconnect one end of the field windings and insert an ammeter in series with it.

Then start the generator and let it build up to its full voltage. By altering the shunt field rheostat various simultaneous values of field voltage and field amperes can be obtained, each of which will give a determination of the field resistance by dividing the volts by the amperes.

The data should be obtained rapidly so that the field coils may not warm up appreciably. It is usually necessary to know the hot resistance of the shunt winding, which is calculated by taking the readings of the voltmeter and ammeter after running for two or three hours. If the field has four shunt spools, the total resistance divided by four should give the resistance of each spool, though it is always better to check the measurement by shifting the voltmeter to the terminals of each field spool separately, leaving the ammeter in circuit as before.

The shunt field resistance may also be measured by connecting it directly across the bus bars or the terminals of a running machine. In this case the voltmeter should never be left across the machine terminals when the circuit is being opened. The inductive "kick" will seriously injure the voltmeter.

Series-Winding Resistance.—The resistances of the series windings and armatures of generators and motors are so small, usually less than .01 of an ohm, that measurement by the bridge is not satisfactory. Approximate values of armature resistance can be obtained by assuming a two to five per cent loss in the armature, thus

$$R_a = (0.02 \text{ to } 0.05) \frac{\text{Kilowatts of Output}}{(\text{Armature Current})^2}.$$

Similarly, the series field resistance,

$$R_s = (0.01 \text{ to } 0.02)\frac{\text{Kilowatts of Output}}{(\text{Armature Current})^2}.$$

The method generally practiced and which gives good results, is the fall of potential method. This method of measuring the resistance of an armature has been given under the heading, "To Measure a Resistance with Voltmeter and Standard Resistance," but the following method is a little more practical and with more details:

The connections for making measurement of the series winding of a generator are shown in Fig. 409. For this measurement, current is taken from the switchboard, or some convenient main or

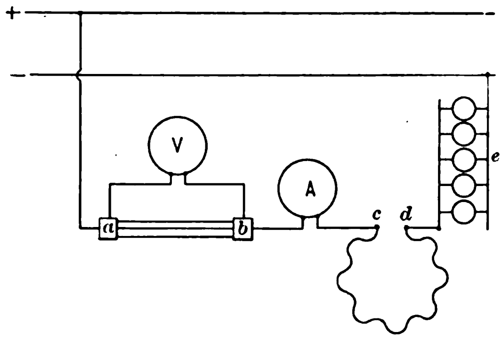


FIG. 409.—Connections for Measuring Resistance of Series Winding.

feeder, being energized by another running machine. The standard resistance *ab* is connected in series with the series winding, and an additional resistance *e* is inserted in series, to steady the current and to prevent short-circuiting the running machine. The standard resistance *ab* should have a resistance somewhat near the supposed resistance of the unknown resistance, say .01 ohm. The resistance *e* can be readily made of lamps, so arranged in series and parallel as to give almost any desired result and heavy enough to withstand the heavy currents.

Only enough current is required from the running generator to give a good readable deflection on the voltmeter, and it is well to insert an ammeter in circuit, as shown at *A*, in order to know just what current is flowing. It is best to start with a low current and gradually work up to the value decided on.

A low-reading portable voltmeter is used and is connected to the terminals *a* and *b*, and the current varied by changes in the lamp bank until a good deflection is obtained. When the current reaches the desired value and becomes steady, read the voltmeter and call this reading E. Then, with this same value of current, transfer the voltmeter to the terminals of the series winding. Call this reading of the voltmeter E'. With three known quantities, the two readings of the voltmeter and the known resistance, the unknown resistance is calculated by the formula previously given,

$$R' = \frac{E'R}{E}.$$

It is seen that the accuracy of the measurement depends on the accuracy of the known resistance.

For very low resistances a current of 10 to 100 amperes and a voltmeter reading to thousandths of volts may be necessary.

Armature Resistance.—The same method may be used to determine the resistance of an armature. The armature circuit is opened and a standard resistance is inserted. The voltage drop is then read across the standard resistance and across the armature terminals. If it is desired to obtain the armature resistance exclusive of the brush resistance the voltmeter leads should be held on the commutator directly under the brushes.

Contact Resistances.—The fall of potential method, with a high resistance, low-reading voltmeter, may be used to determine if good contact is being made by binding screws, by terminal leads to brushes, and by the brushes to the commutator. Good contacts should show very low resistances and these will be indicated by low readings of the voltmeter.

Resistance of Cells.

By the resistance of a cell is meant the resistance to the flow of current between terminals, and it is the sum of the resistances of the separate parts that go to make up the internal circuit. It is a physical characteristic depending on the elements of which the electrodes are made, of the electrolyte, and of the depolarizing substance. The resistance of the electrodes may be reduced by making them in the form of plates, so that a large surface is exposed to the electrolyte. The resistance of the electrolyte may be reduced by shortening the path which the current follows. This is done by bringing the electrodes close together. In some cases, one electrode entirely surrounds the other. The resistance of liquids is high as compared with metals, and that of gases is nearly infinite at ordinary pressure. The resistance of the gases liberated by the chemical action is the chief cause of polarization in a cell. It increases the resistance to such an extent that the current may fall to a very small value. This resistance due to the gases is not properly a part of the

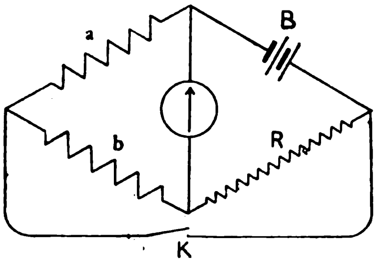


FIG. 410.—Connections for Measuring Resistance of a Cell.

cell resistance, and as it is a variable quantity it should not be included in the internal resistance.

In one method for measuring battery resistance, the battery is inserted as the fourth arm in the Wheatstone bridge, and its ordinary position is taken by leading wires with a key K in circuit. The resistance a should be as low as possible and b high. With the key K open (Fig. 410), current will flow through the galvanometer and a deflection of the needle will occur. If on making and breaking the key K, there is no change in the deflection, the points where the leading wires are connected to the bridge must have the same potential. When this is the case and there is no change in the deflection, the following relation holds:

$$B = \frac{aR}{b}.$$

R should be 1000 ohms if possible, b 10,000 ohms, and then a will usually be less than 20 ohms. b should be adjusted until there is no change in the deflection, but if a change always occurs when the key is opened or closed, determine two values of b, one of which increases, the other decreases the deflection, and take the value which gives the least change.

The galvanometer should be connected between the junction of the two highest and two lowest resistances.

Resistance of a Working Battery.—When a battery is working through an external resistance and a certain current is being drawn from it, the internal resistance is usually different from its resistance on open circuit, and it is frequently of importance to know what the working resistance is. A sufficiently accurate method for determining this is as follows: With a voltmeter measure the difference of potential between the terminals of the battery when on open circuit; call this E_1. Make the same measurement when the current I flows through the external resistance R, calling this reading E_2. This measurement should be made before polarization commences.

When a current is flowing, part of the total E. M. F. is expended in sending current through the external resistance and part through the battery resistance, but only E_2, the fall of potential through the external circuit can be measured. $E_1 - E_2$ is the fall of potential through the battery; therefore, by Ohm's law, where r is the internal resistance of the battery,

$$I = \frac{E_1 - E_2}{r} \text{ and } I = \frac{E_2}{R},$$

or

$$r = \frac{E_1 - E_2}{E_2} R.$$

If an ammeter is connected in the circuit, it is not necessary that the value of R should be known, as

$$r = \frac{E_1 - E_2}{I}.$$

When two known resistances are available, r can be calculated as follows: With the resistance R_1 in circuit, measure E_2 and I_1 and with R_2 measure E_2 and I_2, then

$$I_1 = \frac{E_2}{r+R_1} \text{ and } I_2 = \frac{E_2}{r+R_2}$$

and

$$r = \frac{I_2R_2 - I_1R_1}{I_1 - I_2}.$$

Measurement of Inductance and Capacity.

Below are given four methods of measuring either inductances or capacities. Before describing these methods, a consideration will first be given to the units in which these quantities are measured.

The practical unit of self-inductance is the henry. If 1 ampere produces such a number of C. G. S. flux lines, that when this number is multiplied by the number of turns, the product equals 10^8, *i. e.,* there are 10^8 linkages per ampere, the self-inductance is 1 henry. If the current, changing through the circuit at the rate of 1 ampere per second, produces one induced volt at its terminals, the circuit has an inductance of 1 henry.

The unit of capacity in the practical system is the farad. This unit is so large, however, that for practical purposes the microfarad, or one-millionth of a farad, is used. If 1 coulomb, stored in a condenser, produces a difference of potential of 1 volt across that condenser, then the condenser has a capacity of 1 farad.

Methods of measuring inductance and capacity are:

(a) Bridge methods.
(b) By measuring the voltage, current, power and frequency.
(c) Wave meter.
(d) Ballistic method.

(a) **Bridge Method.**—The connections for the measurement of inductance are shown in Fig. 411, the connections being similar to those of the Wheatstone bridge.

T = telephone receiver,
A, B = variable known resistance, as available in the ordinary bridge or testing set,
R_3 = variable resistance,
L_1 = variable standard of inductance,
L_3 = unknown inductance.

The bridge is first balanced up with direct current, by setting the ratio arms to a 1:1 ratio, and adjusting R_3 for a balance. If the ohmic resistance of L_1 is greater than that of L_3, R_3 should be in the position shown. If the ohmic resistance of L_1 is less than L_3, the E. M. F. terminal should be shifted to (2). When the bridge is thus balanced with direct current, the double-throw switch is thrown to alternating current. Any unbalancing indicated by the telephone receiver must be due to the inductances. Attempt should then be made to balance by means of the variable standard inductance, L_1. Ordinarily, the range of the standard will not be sufficient. If the

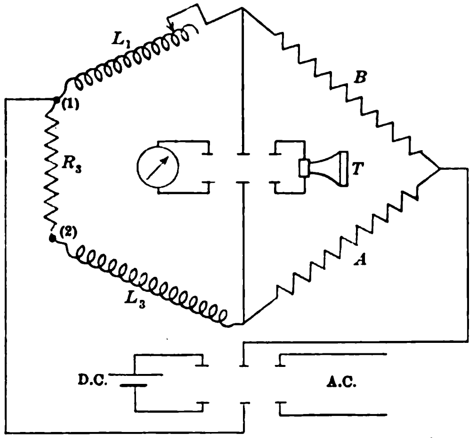


FIG. 411.—Bridge Measurement of Inductance.

minimum sound in the receiver occurs well on the scale, that is the minimum can be passed, the measurement can be made. If the minimum sound occurs at either end of the scale the standard is not of sufficient range. Suppose that the minimum occurs at the upper end of the scale, this means that the standard is too small. The ratio $\frac{A}{B}$ should be made larger, the D. C. balanced again, and another attempt made to balance with A. C. Since the balance may occur with ratios 2:1, 5:1, etc., the resistance A or B should correspond to the C-arm of Fig. 368. Any ordinary frequency or interrupted current may be used but the ear is more sensitive to frequencies from 500 to 1000 cycles per second. In order to have practically no sound in the telephone a sine wave is necessary, but is rarely obtained. If the unknown inductance has an iron core, the A. C. balance will not be sharp due to eddy currents and hysteresis effect. When the bridge is in balance with both D. C. and A. C.

$$\frac{L_1}{L_3} = \frac{B}{A}.$$

This method may be applied without using alternating current, but by making and breaking the direct current battery circuit, as follows:

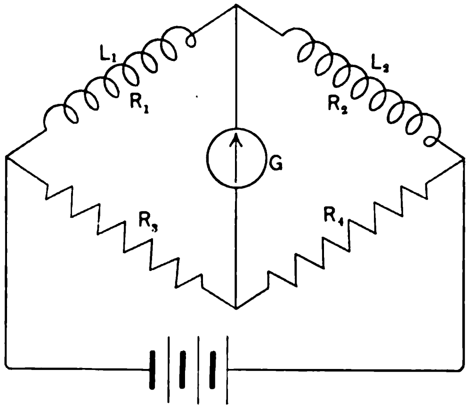


FIG. 412.—Connections for Measuring Inductance.

L_1, L_2 are the two inductances to be compared, whose resistances are R_1 and R_2. They are connected up as a bridge with the non-inductive resistances R_3 and R_4. A balance for steady currents can be obtained if $R_1 : R_2 :: R_3 : R_4$. A balance for varying currents can be obtained if $L_1 : L_2 :: R_3 : R_4$. If a balance of the inductances does not exist, it can be detected by making and breaking the battery circuit. The galvanometer needle will give a deflection one way when the circuit is broken and in the opposite direction when it is made. The deflection is due to momentary current so the method is not sensitive. If, instead of making and breaking the battery circuit, the circuit is reversed, the effect on the needle will be doubled. If the circuit is rapidly reversed and between each reversal the galvanometer circuit is reversed, the effect on this circuit will always be in one direction, and will be greater as the speed of the reversals is increased.

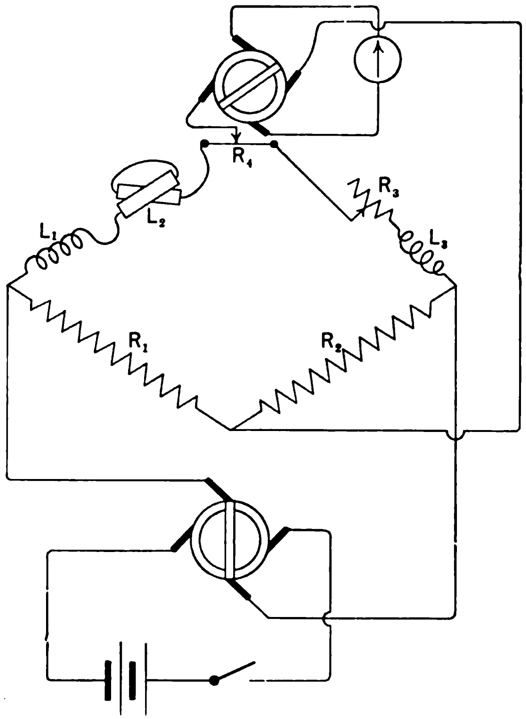


FIG. 413.—Connections for Measuring Inductance. Secohmmeter Method.

The secohmmeter effects the reversal of the battery and galvanometer circuit alternately. Fig. 413 shows the connections, using inductances whose values are known.

R_1, R_2 and R_3 are non-inductive resistances, L_1 and L_2 are known inductances, L_1 being fixed and L_2 being variable. L_3 is the inductance to be measured. R_4 is a stretched wire slightly greater in resistance than the smallest amount by which R_3 can be varied.

The figure shows in the battery-commutator of the secohmmeter at the bottom that the battery circuit is just about to be reversed and will send a current through the galvanometer in one direction due to lack of balance of the inductances. It is assumed that the balance for resistance has been obtained. A turn of 90° of the commutator will again reverse the battery and send a current through the galvanometer, but in the meantime its commutator has turned through 90°, as both commutators are secured to the same shaft, and it is also reversed; consequently the galvanometer is subjected to a pulsating current which is always in the same direction.

L_2 is varied until no deflection is shown when the commutators are rapidly turned. With L_1 and L_2 known, the value of L_3 is readily obtained. L_1 could be dispensed with, if, on turning the standard variable inductance L_2 in its extreme positions, a deflection is shown first in one direction and then in the other, for under those conditions a position of balance could be found.

Whenever the values of the ratio arms R_1 and R_2 are changed and if L_1 is used, the balance for resistance with steady current must be obtained before the balance for inductance.

(b) When a source of alternating current of known frequency is available, the following method is convenient, when alternating current instruments are to be had. Place the inductance or the capacity across the alternating current mains, measure the power absorbed, the current flowing, the voltage across the unknown capacity or inductance and the frequency of the circuit.

$$\text{Then } L = \frac{\text{Reactance}}{2\pi \text{ Frequency}} = \frac{x}{2\pi f} = \frac{\sqrt{\left(\frac{E}{I}\right)^2 - \left(\frac{\text{Power}}{I^2}\right)^2}}{2\pi f},$$

$$\text{or } C = \frac{1}{2\pi \text{ Frequency} \times \text{Reactance}} = \frac{1}{2\pi f\sqrt{\left(\frac{E}{I}\right)^2 - \left(\frac{\text{Power}}{I^2}\right)^2}}.$$

L should be expressed in *henries* and C in *farads*.

This method gives results of fair accuracy, but is not adapted to measurements of low values of inductance.

(c) **Wave Meter Method.**—The expression for the number of oscillations in a closed circuit containing both inductance and capacity is given by the formula

$$n = \frac{1}{2\pi\sqrt{CL}},$$

and the wave length is equal to the velocity of propagation divided by the number of waves, and calling λ the wave length, we have

$$\lambda = V \times 2\pi\sqrt{CL}. \qquad (1)$$

The method consists in discharging the condenser through a spark gap in a circuit containing a known inductance and by means of a wave meter measuring the wave length. In equation (1) everything is known but C, which can be calculated. V is the velocity of light 3×10^8 meters per second.

The Galvanometer Shunt.—It often becomes necessary to shunt a portion of the current passing through a galvanometer. When the first trials are being made in a bridge measurement they may show that the bridge is decidedly out of balance. In this case if a sensitive suspended galvanometer is used, the galvanometer may deflect so vigorously as to injure it, and also considerable time is lost in waiting for it to come to rest again. Further, it may be desirable, as in the case of measuring insulation resistance or electrostatic capacity, to shunt away a definite portion of the total current. To do this the shunt shown in Fig. 414 is often used. Two brass bars are fitted with binding posts to which the line leads and the galvanometer leads are connected. Shunt resistances may be connected between the bars by the insertion of a plug. Each plug position is marked $\frac{1}{999}$, $\frac{1}{99}$, and $\frac{1}{9}$. These portions refer to the ratio of these resistances to that of the galvanometer. When the plug is in the posi-

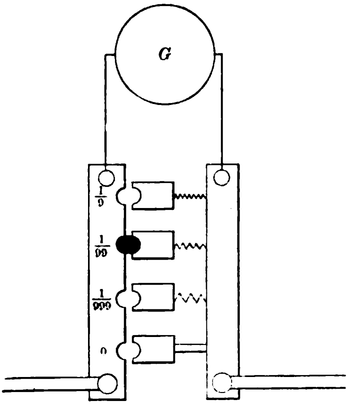


FIG. 414.—Simple Galvanometer Shunt.

tion O the galvanometer is short-circuited and practically no current passes through it. When it is in the position marked $\frac{1}{999}$, $\frac{1}{1000}$ of the current passes through the galvanometer and $\frac{999}{1000}$ passes through the shunt. When the plug is at $\frac{1}{99}$, $\frac{1}{100}$ of the line current passes through the galvanometer when $\frac{1}{9}$ is plugged, $\frac{1}{10}$ of the current passes through the galvanometer and when the plug is not inserted at all the entire current passes through the galvanometer. This can be demonstrated as follows:

Let R_g = the resistance of the galvanometer,
I_g = the galvanometer current,
I = the line current,
n = the ratio $\frac{I_g}{I}$,
R = resistance of the shunt resistance.

Then,

$$\frac{I_g}{I-I_g}=\frac{R}{R_g}.$$

By composition,

$$\frac{I_g}{I-I_g+I_g}=\frac{R}{R+R_g}=\frac{I_g}{I}=n.$$

Thus, if $n=\frac{1}{10}$,

$$R-\frac{1}{10}R=\frac{1}{10}R_g.$$

$$R=\frac{R_g}{9}.$$

The Ayrton Shunt.—The shunt previously described has two very great disadvantages. Each shunt must be adjusted to its respective galvanometer resistance in order to give a true proportionality. In ballistic work the damping is not uniform for the different ratios; that is, the resistance of the local galvanometer circuit would be changed for different positions of the plug so that the current opposing the throw of the coil would be different. The Ayrton shunt shown in Fig. 415 overcomes these difficulties.

A resistance wire AB having a resistance perhaps five or six times the resistance of the galvanometer is connected across the galvanometer terminals. The end B is connected to the external circuit. From this end taps, whose resistances from the end A are some fraction of the resistance AB, are brought out. The ratios are usually multiples of $\frac{1}{10}$. Call the current in the galvanometer I_g, when C is at A. Then when C is at $\frac{1}{10}$ the galvanometer current is $\frac{1}{10}$ I_g, etc. This can be proved as follows: Let I = current, R_g = galvanometer resistance, I_g = current in galvanometer, R_s = resistance of shunt, n = ratio of resistance $\frac{BC}{BA}$. Then by the law of divided circuits,

$$\frac{I_g}{I-I_g}=\frac{nR_s}{(1-n)R_s+R_g}.$$

By composition,

$$\frac{I_g}{I-I_g+I_g}=\frac{nR_s}{R_s-nR_s+R_g+nR_s}.$$

$$I_g=I\frac{nR_s}{R_s+R_g}.$$

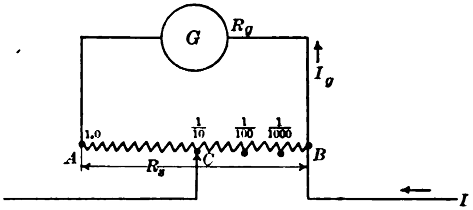


FIG. 415.—Ayrton Shunt.

As R_s and R_g are constants the galvanometer current is then n times a constant quantity. Thus, if $n=\frac{1}{10}$, that is $BC=\frac{1}{10}\,AB$, the deflection will be $\frac{1}{10}$ of the value that would occur if C were at A. A is usually marked 1. $\frac{R_s+R_g}{R_s}$ is the multiplying power of the shunt and is the factor by which the galvanometer deflection must be multiplied when C is at A to obtain the deflection that would occur if the galvanometer were not shunted at all.

Thus if a galvanometer has a resistance of 2000 ohms and the shunt 10,000 ohms the multiplying power of the shunt would be

$$\frac{10{,}000+2000}{10{,}000}=\frac{6}{5}.$$

Then if the galvanometer deflects 25 centimeters when the point C is at 1.0, or A, the galvanometer would deflect $\frac{6}{5}\times 25=30$ centimeters without the shunt. So this type of shunt cuts down the ultimate sensitiveness of the galvanometer somewhat.

Sullivan Bros., of London, have developed an Ayrton shunt whereby suitable slides, any ratio from 1 to 10,000, may be obtained.

(d) **Ballistic Method of Measuring Electrostatic Capacity.**—The absolute measurement of capacity requires the use of laboratory apparatus, one method involving the use of a ballistic galvanometer. This is simply a galvanometer designed with considerable inertia and little damping of the moving part. It swings freely to a maximum throw under the impulse of a quantity of electricity discharged through its coil.

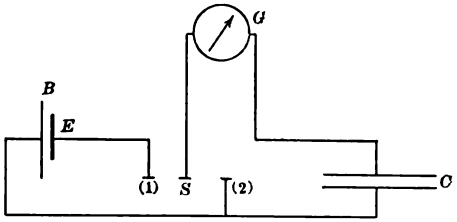


FIG. 416.—Capacity by Ballistic Galvanometer.

The retarding forces acting on the moving coil of the ordinary galvanometer are sensibly proportional to the coil's instantaneous velocity. This being the case, if a quantity of electricity, Q, is discharged through the galvanometer before it starts from rest, the throw of the galvanometer, D, is proportional to the quantity passing through. Thus,

$$Q=KD, \quad (1)$$

where K is the galvanometer constant.

To determine K it is only necessary to discharge a known quantity of electricity through the galvanometer. Therefore, by means of a ballistic galvanometer the capacity of a condenser may be determined.

Referring to Fig. 416, B is a battery of voltage E, G is a galvanometer, C is an unknown condenser, and S is a single-pole, double-throw switch. When S is thrown to the left (position 1) the condenser is charged through the galvanometer, and the galvanometer throw is D_1. Then

$$Q_1 = KD_1. \tag{2}$$

If the switch S be thrown to the right the condenser will *discharge* through the galvanometer and the deflection of the galvanometer will be opposite from what it was before, unless the galvanometer connection has in the meantime been reversed. The two deflections should be equal if the galvanometer constant is the same for deflections to the right or to the left, and the condenser has no absorption or leakage.

To determine K a condenser of known capacity is charged through the galvanometer. Let the resulting deflection be D_2. Then if the battery voltage E remains unchanged,

$$Q_2 = EC_2 = KD_2. \tag{3}$$

Dividing (2) by (3),

$$\frac{EC_1}{EC_2} = \frac{KD_1}{KD_2}, \tag{4}$$

or

$$C_1 = C_2 \frac{D_1}{D_2}. \tag{5}$$

Therefore it is not absolutely necessary to know the constant K, for the capacities are directly proportional to the respective deflections. If the standard and unknown capacities are widely different an Ayrton shunt may be used to make the deflections of the same order.

The above principle is used in practice to determine a break in a cable if the conductor at the break remains insulated from the ground or sheath. The connections are shown in Fig. 417. The Ayrton shunt may not be necessary, but if one is available it is desirable to use it.

Let L be the length of the cable, and P the point where the conductor is broken, a distance X from the end. If possible the return conductor should be looped back to the testing apparatus. Otherwise it would be necessary to carry the testing apparatus to the other end of the cable. The double-throw switch is first thrown to (a) and the resulting galvanometer deflection D_1 is read. When the switch is thrown to (b) the cable is discharged. The cable connection is then transferred from (1) to (2) and the measurement repeated. Call this deflection D_2. Then,

$$\frac{C_1}{C_2} = \frac{X}{2L-X} = \frac{D_1}{D_2},$$

from which X may be determined.

If it is desired to know the actual capacity of the cable, it is only necessary to substitute a standard condenser for the cable and calibrate the galvanometer.

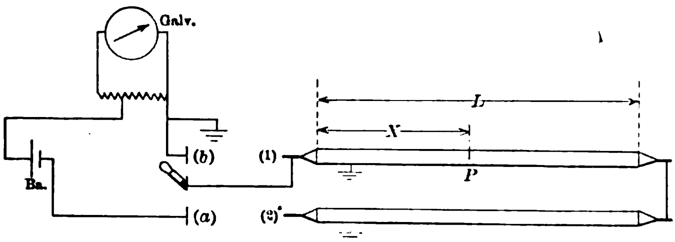


FIG. 417.—Connections for Cable Test.

Bridge Method for Capacity.—A convenient method of comparing one condenser of unknown value with one of a known value is by the *method of balances,* or *zero method,* the arrangement being somewhat similar to that of a Wheatstone bridge. The connections for making this test are shown in Fig. 418.

K_1 and K_2 are the two condensers to be compared; R_1 and R_2 variable resistances, the rheostat arms of two testing sets serving this purpose; G is a galvanometer of one of the testing sets, B a cell, K a double-throw switch for either charging or discharging the condensers.

R_1 and R_2 are so adjusted that the galvanometer shows no deflection either when K is closed up or down, that is, either on discharge or charge. When this condition exists, the following relation holds:

$$\frac{C_1}{C_2} = \frac{R_2}{R_1}. \qquad (1)$$

Knowing three of these quantities, the fourth may be calculated.

Equation (1) is true from a consideration of the following: When no current is flowing through G, the points c and d are at the same potential and therefore the difference of potential between b and c is the same as that between b and d. By Ohm's law this potential difference is equal to the current in each branch times the resistance of the branch, or the currents in R_1 and R_2 are inversely proportional to the resistances. The time during which the condensers are discharging is the same for both, and as the quantities discharged are equal to the products of the currents and the respect-

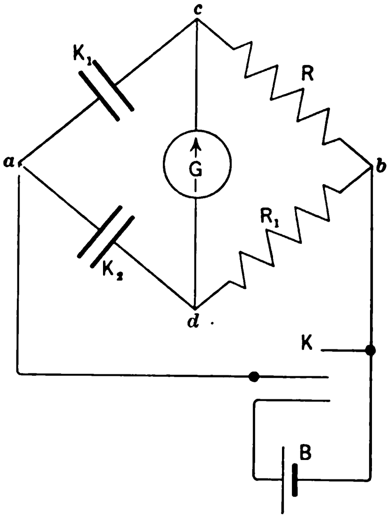


FIG. 418.—Bridge Connections for Comparing Capacities.

ive times, it follows that the quantities are inversely proportional to the resistances, or

$$\frac{Q_1}{Q_2} = \frac{R_2}{R_1}.$$

After a balance is obtained the points c and d are always at the same potential, and therefore the condensers must always be charged to the same potential and the quantity of electricity on each must be proportional to their capacities, or

$$\frac{C_1}{C_2} = \frac{R_2}{R_1}.$$

A source of alternating current may be substituted for the battery and key, and the galvanometer may be replaced by a vibration galvanometer or a telephone receiver.

Induction Coil Method.—A very convenient method in the wireless room is to make use of an induction coil, or the transformer, and replacing the galvanometer by a telephone receiver. The connections are exactly similar to Fig. 418, replacing the galvanometer by the telephone, and inserting the secondary coil of the induction coil between *a* and *b* and connecting one or two cells in series with the primary coil. Some means must be provided for rapidly making and breaking the primary circuit.

The effect of the making and breaking of the current in the primary is to set up increasing and decreasing currents in the secondary. Each *make* charges the condensers and they discharge on *break* and are again charged in the opposite direction and then discharged. When the balance is perfect there is no potential difference between the points *c* and *d* and no sound will be heard in the telephone, but if the balance is not perfect a buzzing sound will be heard owing to the rapidly alternating currents through the receiver.

Magnetic Measurements.

The Determination of *B-H* Curves.—Several laboratory methods of determining the *B-H* curves for iron are in use, among which are the Yoke Method, Double-Bar Method and Ring Method. As the Ring Method is the most accurate of the three and is used in the Standardizing Laboratory at the Naval Academy, it will be described below.

It can be shown that if the flux threading a closed coil of wire be changed, the quantity of electricity displaced, Q, is equal to $\frac{N_2\Phi}{R}$ where N_2 is the number of turns in the coil, Φ the flux change and R the total resistance of the circuit. It has already been shown that the maximum throw of a ballistic galvanometer is proportional to the quantity of electricity which passes through, provided that the quantity passes through before the galvanometer has sensibly started from rest.

. Therefore, the deflection,

$$D = KQ = K\frac{N_2\Phi}{R}.$$

Thus the ballistic galvanometer may then be used to measure magnetic flux.

A sample of the iron to be tested is made in the form of a ring, *I*, as shown in Fig. 419. If sheet iron is used, ring stampings are made

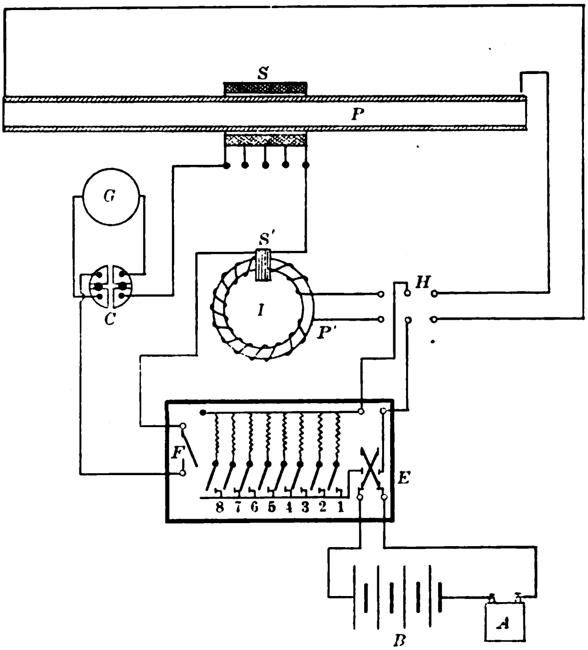


FIG. 419.—Magnetization Apparatus at the U. S. Naval Academy.

and a number of these are taped together. In either case the radial thickness of the sample should be small compared with the diameter of the specimen, so that the flux distribution over the cross-section will be practically constant. A primary winding *P'* of about No. 14 wire is first wound completely around the sample. Then around some convenient portion, a secondary winding, *S'*, is wound with fine wire. The number of turns depends upon the sensitiveness of the galvanometer. The secondary winding may extend completely around the ring, but this is not necessary. At the Academy, a ring having a mean diameter of 16.9 centimeters, cross-section of 1.618 square centimeters, 244 primary turns of No. 14 wire and a secondary of 244 turns has been found to give very good satisfaction.

The galvanometer must first be calibrated. To do this a long air solenoid P (see page 716) having a secondary, S, of N_2 turns of fine wire near its center is used. Knowing the number of primary turns, the area, and the current, the flux may be calculated and from the number of secondary turns, N_2, the galvanometer constant may be determined. Since the deflection $D = K\frac{n_2\Phi}{R}$, R should evidently be kept constant in both cases, first when the galvanometer is used in connection with the solenoid secondary and second when it is used in connection with the sample secondary. A resistance box may be used in place of the secondary that is not in use, but the simplest method is to keep both secondaries in circuit continuously, as shown in Fig. 716. Then R will be the same in each case.

Galvanometer Constant.

Numerical data goes with apparatus at Academy.

Let n_1 = primary turns per centimeter of solenoid = 5.314,

n_2 = total secondary turns of solenoid = 4 coils, 400 each = 1600,

a = area of solenoid 31.66 square centimeters,

Φ_1 = flux in solenoid,

N_1 = primary turns per centimeter length of sample = 4.6 turns,

N_2 = total secondary turns of sample = 244,

A = cross-section of sample 1.618,

Φ = flux in sample,

B = flux density in sample,

D_1 = galvanometer deflection when solenoid is used,

D = galvanometer deflection when sample is used,

R = total resistance of galvanometer circuit.

If a current of I amperes flows in the solenoid primary, then

$$\Phi_1 = \frac{4\pi n_1 I a}{10} \qquad (1)$$

If the circuit is suddenly interrupted the galvanometer will deflect

$$D_1 = \frac{n_2 \Phi_1}{R} = \frac{4\pi n_1 I a n_2}{10R}. \qquad (2)$$

If the solenoid primary is left open and a change of flux $\Delta\Phi$ made in the sample,

$$D = \frac{N_2 \Delta\Phi}{R}. \qquad (3)$$

Dividing (3) by (2)

$$\frac{D}{D_1} = \frac{10 N_2 \Delta\Phi}{4\pi n_1 I n_2 a}.$$

$$\Delta\Phi = D\left(\frac{4\pi n_1 I n_2 a}{10 N_2 D_1}\right).$$

The expression in parenthesis is the galvanometer constant K.

If ΔB is desired it is only necessary to divide by A.

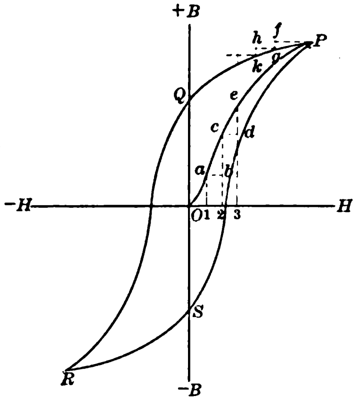


FIG. 420.—Hysteresis Loop.

H, for the sample, may be calculated from the current,

$$H = \frac{4\pi N_1 I}{10}.$$

The ring specimen is tested by an increment method; that is, H is increased by increments and the corresponding increment of flux is determined by the galvanometer. The ring is first demagnetized by reversing the current with a reversing switch or using low frequency alternating current, simultaneously decreasing the current. It is impossible to demagnetize a specimen entirely.

The switch (1), see Fig. 419, is then closed, and the value of H increases from 0 to 1.* The induction or flux at the same time becomes 1a and the galvanometer throw is proportional to this change of flux. When the galvanometer has been brought to rest, switch 2 is closed. H now becomes 2, and can be determined by the ammeter reading. The flux passing through the iron has increased from 1a

* See Fig. 420.

to 2*c*. The galvanometer deflection will correspond to the increment of flux, *bc*. In a similar manner, increment *de* is obtained and similarly the switches are closed until *P* is reached. Here the gal-

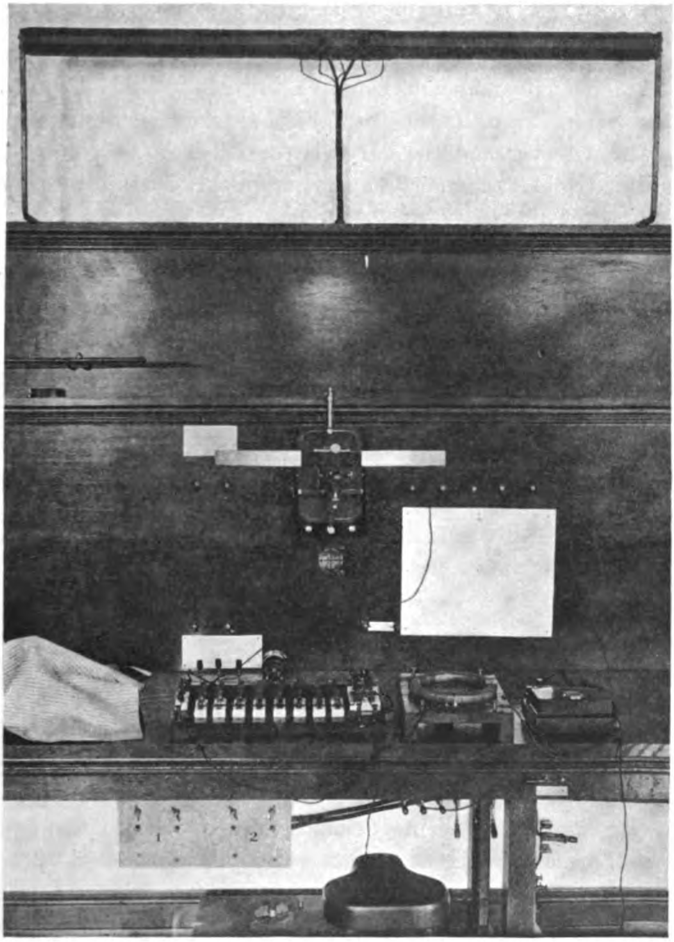


FIG. 421.—Ring Method Apparatus, Standardizing Laboratory, U. S. Naval Academy.

vanometer should be reversed if the deflections are to be in the same direction.

H is now decreased, *P* to *f*, *g* to *h*, etc., by opening switches 8, 7, 6 . . . . until the switches are all out. Simultaneously the galvanometer will register the decrements of flux *fg*, *hk*, etc. When the zero current point, *Q*, is reached, the reversing switch *E* is thrown over and values of $-H$ are obtained by throwing on the switches again, beginning at 1. When *R* is reached the switches are all closed. The galvanometer should be reversed, and the switches withdrawn until zero *H*, or point *S*, is reached. The switch *E* is again thrown over and the curve is carried back to point *P*. In order that the galvanometer may swing quickly back to zero, switch

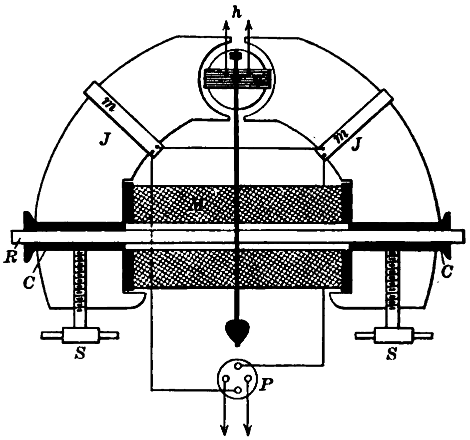


FIG. 422.—Diagram of the Koepsel Permeameter.

F is provided, which is opened until the zero point is nearly attained, and then closed. The galvanometer then sends current through a closed circuit and generator action stops the swing very quickly. When the specimen is being demagnetized or carried through the cycle preliminary to the experiment, the galvanometer is protected by opening *F*.

The ballistic method of determining the *B-H* curve is often too long and tedious for commercial work, so instruments by which *B* may be read directly have been devised. The Koepsel permeameter is perhaps the most satisfactory type on the market. The general scheme is shown in Fig. 422. The instrument is really a millivoltmeter in which the permanent magnet is replaced by an electromagnet and a portion of the magnetic circuit is the sample itself. The instrument consists of two heavy pole pieces, *JJ*, into which the sample, *R*, consisting of a rod, is clamped by means of the clamps *CC* and the screws *SS*. The magnetizing coil *M* surrounds the sample, and is connected in series with the two compensating coils *mm*. These two coils are adjusted so that the instrument reads zero when there is no sample in the apparatus.

Fig. 423 is a half-tone of the instrument and rheostats such as are in use at the Naval Academy.

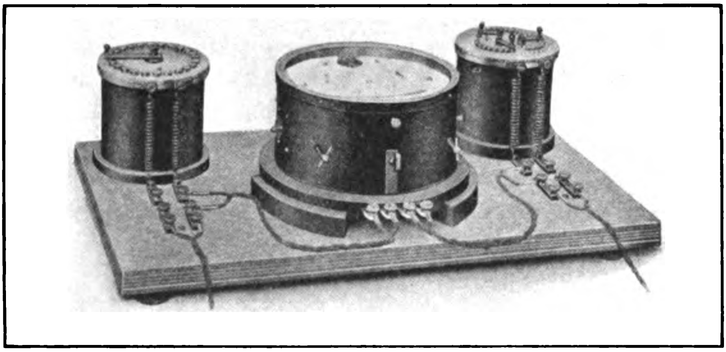


FIG. 423.—The Koepsel Permeameter.

The current to the coil *n* is supplied by a dry battery, and is adjusted by a rheostat until $i = \frac{K}{q}$, where K is the permeameter constant and q is the area of the sample in square centimeters. When this adjustment is made the instrument reads B directly. For the Naval Academy instrument, $K = 0.005$.

There are 79.6 exciting turns per centimeter in coil M so that the ampere turns per centimeter length of the sample are $79.6I$.

Since,

$$H = 79.6I \frac{4\pi}{10} = 100I.$$

H is determined directly by multiplying the ammeter reading by 100. At P is a reversing switch with which this magnetizing current may be reversed. About eight volts are necessary for this circuit.

The instrument comes provided with the adjustable rheostats; an ammeter which, by the transfer of plugs, may be used to read the current in *n* or *M*; and samples of iron and steel with correction curves. Two sets of jaws are provided, one for holding round samples and one for square samples, as a bundle of sheet-iron strips. The sample is clamped in place, the value of the current in *n*, properly adjusted, and a complete hysteresis loop determined by direct reading. The greatest source of error in this instrument, as in others of its kind, lies in the reluctance at the clamps *CC*. Correction curves with which approximate corrections may be made, accompany the instrument. The apparatus yields more accurate results for hysteresis than for permeability.

CHAPTER XXIII.

FAULTS OF GENERATORS AND MOTORS.

The faults in an electric machine all fall under three heads, mechanical, magnetic and electrical. For instance the lubrication of the bearings, the alignment of the shaft in its bearings, the maintenance of a smooth polish on the commutator, and of a perfect fit of the brushes come under the head of mechanical problems. Similarly the maintenance of tight connections, proper setting of the brushes, detection of open circuits in armature or field windings are classed as electrical problems. The magnetic phase is of less importance. The magnetic circuit of a completed machine usually remains intact indefinitely and seldom requires alteration, except perhaps in the case of a motor where the speed may be lowered by inserting an iron shim between the field core and the yoke.

A large percentage of the troubles in operation of commutator machines comes in the commutator itself. Trouble there, once started, is cumulative and goes from bad to worse. Accurate brush setting will do much to prevent commutation difficulties. Accurate brush setting consists (a) in grinding the brushes with coarse and then fine sandpaper to a perfect fit, and (b) in making the distance between brush sets exactly equal. This last should be done, not by making the number of bars between brush sets equal, but by checking up the distances between brush sets by a steel tape. The brush pressure should be determined as a compromise between too weak and too strong, jumping of the brush indicating too little pressure and heating of the commutator indicating too great pressure.

As suggestive of the common faults occurring in direct current machines, the following table is submitted:

FAULTS.	CAUSE.	HOW MOST READILY DETECTED.	REMEDY.
1. Too high voltage.	1. Too high speed of engine.	1. Voltmeter reads greater than standard, and lamps burn with undue brilliancy.	1. Slow the engine.
	2. Too strong magnetic field.	2. Same.	2. Introduce more resistance in shunt field.
2. Too low voltage.	1. Too low speed of engine.	1. Voltmeter shows lower than standard and lamps burn dimly.	1. Increase speed of engine.
	2. Too weak magnetic field.	2. Same.	2. Take out resistance in shunt field.
	3. Brushes not properly set.	3. Same.	3. Rock rushes back and forth till highest voltage consistent with sparkless commutation is shown.
3. Excessive current.	1. In a generator, too many lamps burning or motors running.	1. By too high reading of ammeter for capacity of machine. By excessive sparking of dynamo brushes and too high reading of dynamo ammeter.	1. Cut out necessary numbe of lamps. Reduce load on motor cir cuits. In this case non of the motors may be do ing too much work, bu there may be too many i dynamo circuit.
	2. In a motor, too much mechanical work being done by it.	2. By excessive sparking of motor brushes and too high reading of motor ammeter.	2. Reduce the load on th motor.
	3. Short circuit; leak or ground in external circuit.	3. By excessive sparking of brushes, and heating of *whole* armature.	3. Locate and remove leaks o grounds.
	4. Short circuit in armature coil.	4. By heating of short-circuited coil more than the others.	4. Stop machine. Locate coil If entirely burnt out, mus be renewed.
	5. Grounds in armature. Two grounds to the core amount to a short circuit.	5. Same as 4.	5. Locate the grounds. Reinsulate the coils contain ing them.
	6. Due to excessive friction in bearings or by armature striking pole pieces. In general any cause tending to slow motor.	6. By sparking of brushes. By sound of armature striking while running. By heating of motor bearings.	6. File away pole pieces, o recenter armature. Clean and oil journals, o refit bearings.
4. Excessive sparking at brushes.	1. Excessive current; therefore due to any of the causes given under that head.	1. Same as given under "Excessive current."	1. Same as given under "Ex cessive current."
	2. Brushes improperly set.	2. By taking brushes out of holders and examining rubbing surface. By measuring the peripheral distance between brush sets.	2. Fit and set accurately, the shift the brushes backward or forwards till sparkin is reduced to a minimum
	3. Brushes make poor contact with commutator.	3. By sighting underneath between brushes and commutator.	3. Sandpaper the brushes an adjust the spring tensio until they rest evenly o commutator with light bu even pressure.
	4. Rough, non-concentric commutator.	4. A rough commutator can be detected by lightly touching finger nail to it while running; an eccentric commutator by the regular rise and fall of the brushes.	4. Smooth commutator wit fine sandpaper. If ecce tricity is due to uneve wear of bearings, renew c reline them.
	5. "High" or "flat" bars in commutator.	5. By the jumping or vibrations of the brushes.	5. Same as above, or tur down the commutator i lathe. Slot out the mic to a depth of $\frac{1}{16}$ to $\frac{1}{32}$ inch

FAULTS.	CAUSE.	HOW MOST READILY DETECTED.	REMEDY.
	6. Broken circuit in armature or commutator.	6. Commutator flashes, and nearest the break is cut and burnt. Flashing continues when armature is slowly turned.	6. Locate coil by drop of potential method. If in commutator, bridge over the break. If in armature coil, it must be renewed.
	7. Weak field magnetism, caused by broken circuit in field winding or short circuit in same; two or more grounds in windings; reversal of one or more field coils.	7. Dynamo fails to generate full E. M. F. If very weak, motor runs very slow, taking a current many times full load current.	7. Short circuits or grounds are easily located and remedied if external to the windings. If internal, faulty coil must be rewound or repaired if only grounded. A reversed coil will lower the voltage instead of increasing it, and it is remedied by reversing the connections.
	8. Unequal magnetism.	8. One brush sparks more than the other.	8. Only remedied by reshaping pole pieces.
	9. Dirty commutator, causing brushes to vibrate, particularly if of carbon.	9. Flashing around commutator.	9. Clean commutator (methods given later).
	10. Poor brushes, especially if of high-resistance carbon, hard blisters forming on them.	10. By ragged appearance of brushes around edges and formation of hard spots.	10. Renew brushes. Try different grades of hard and soft brush.
	11. Vibration, especially of brush holders, causing rapid vibration of brushes.	11. By a humming, singing sound of brushes.	11. Reduce cause of vibration or give the brushes a little greater pressure on commutator.
4 (a) Excessive sparking in interpole machines.	12. Wrong interpole polarity.	12. With low field excitation, examine field polarity with a compass, the armature being first removed.	12. In motor, progressing in direction of armature rotation, polarity should be N-n-S-s, etc. In generator, progressing in direction of armature rotation, polarity should be N-s-S-n, etc.
	13. Interpoles not exactly over commutation belt.	13. By inspection.	13. Adjustable when poles are bolted to the frame.
	14. Brushes not set so that coils undergoing commutation are under interpole.	14. Trace out by following up coil ends.	14. Usual setting is in geometric neutral. Set for minimum sparking under average load.
	15. Interpole air gap too long or too short.	15. See if all interpole gaps are equal.	15. Adjustable when poles are bolted to the frame. Weaken interpole strength by shunting the interpole winding.
5. Heating of armature.	1. Excessive current through it and therefore due to any of the causes given under that head.	1. Same as given under "Excessive current."	1. Same as given under "Excessive current."
	2. Eddy currents and hysteresis in core.	2. Core becomes hotter than armature coils after running for a short time.	2. No remedy, except to rebuild armature with thinner laminations and of iron of lower hysteresis loss.
	3. Conduction from other parts as from commutator or bearings, the heat being conveyed to armature.	3. Other parts connected to armature, as commutator, shaft or bearings, hotter than the armature.	3. Locate source of heat by thermometer or feel by the hand, and correct it by cleaning and lubrication.
6. Heating of commutator.	1. Too great pressure of brushes, friction causing heat.	1. By feeling the commutator with the hand.	1. Reduce pressure by adjusting spring.
	2. Excessive sparking.	2. Same.	2. Discover the cause of sparking and correct it, according to the particular cause given under sparking.

FAULTS.	CAUSE.	HOW MOST READILY DETECTED.	REMEDY.
	3. Excessive current.	3. Same.	3. Discover cause of excessive current and correct according to particular cause already given.
	4. Conduction from other parts.	4. Same.	4. If from bearings, lubricate or refit them.
7. Heating of field coils.	1. Excessive current in field circuit, due to short circuits or grounds.	1. Too hot to bear by the hand. If exceedingly hot, by smell of burning shellac or varnish or charring cotton.	1. Locate the particular coil in which fault lies and repair or rewind. Methods given later.
	2. Eddy currents in pole pieces, heat being conducted to the coils.	2. The pole pieces are hotter than the coils after a short run.	2. Only remedied by better design, use of laminated pole shoes.
8. Heating of bearings.	1. Lack of lubrication.	1. By feeling with hand. Oil cups empty or feeding pipes clogged.	1. Fill oil cups; clean feeding pipes.
	2. Dirty or gritty bearings.	2. By feeling with hand.	2. Remove cap and thoroughly clean.
	3. Bearings out of line.	3. Unequal wear of bearings, and shaft will not turn freely by hand.	3. Bearings must be lined up or shells rebabbitted. If very serious, new bearings will have to be made.
	4. Rough or cut shaft.	4. Shaft will show the roughness in the bearings.	4. Turn down shaft in lathe or if not too bad, reduce by filing.
	5. Shaft bent.	5. Unequal wear in bearings and armature will wobble. Very hard to move by hand.	5. Shafts can only be straightened by disconnecting from armature and reheating and reforging.
	6. Oil rings stuck.	6. Inspection.	6. Adjust rings in grooves.
9. Too low speed (referring to motors).	1. Too much load.	1. By speed indicator; heavy sparking, heating of all parts and bearings.	1. Reduce the mechanical load.
	2. Any of the causes given under "Heating of bearings" causing excessive friction.	2. Same, and same as given under "Heating of bearings."	2. Discover particular cause and remedy same as given under "Heating of bearings."
	3. Short circuit or grounds in armature.	3. By motor taking excessive current without load as shown by ammeter or heavy sparking and heating.	3. Same as under 5, "Excessive current."
	4. Too low voltage at terminals.	4. By motor voltmeter or speed indicator. By heavy sparking and heating.	4. By increasing the line voltage.
10. Too high speed (referring to motors).	1. Too light load (in series motors).	1. By noticeable increased speed.	1. Increase load.
	2. Weak field shunt motor.	2. Same.	2. Strengthen field.
	3. Too high voltage at terminals, due to high voltage of dynamo.	3. Same.	3. Correct line voltage by remedies 1 and 2 under "Too high voltage."
11. Dynamo fails to generate E. M. F.	1. Too weak residual magnetism, caused by a jar or reversal of current not sufficient to reverse magnetism.	1. Very little attraction by the pole pieces when tested with a piece of iron.	1. Send a current through field from a few cells or from a running dynamo.
	2. Short circuit within machine, or grounds in field windings.	2. Magnetism very weak.	2. Locate the grounds or short circuits and correct them.

FAULTS.	CAUSE.	HOW MOST READILY DETECTED.	REMEDY.
	3. Reversed field coils.	3. All poles should have alternate magnetism; if a coil is reversed it will show magnetism, but may not be of opposite polarity.	3. Make polarity opposite by reversing the connections of the coil. Each pole should be opposite to the one on each side of it.
	4. Series and shunt windings connected up opposite to each other.	4. Voltage falls as load is increased, the external circuit being closed, showing that they are working against one another.	4. Reverse connections of either field, but not both.
	5. Brushes not properly placed.	5. Magnetism and E. M. F. increased by shifting the brushes.	5. Find central position by experiment or from drawings of connections.
	6. Open circuit in field or armature. Brushes not making good contact with the commutator. Loose connections.	6. Test circuits with magneto.	6. Set up on all connections. Press brushes on commutator to start building up.
	7. Too much resistance in the shunt field circuit, *i. e.*, greater than the "critical" resistance. Shunt field bucks the residual magnetism.	7. Voltage does not exceed that due to residual magnetism. The voltage due to residual magnetism drops when the shunt field circuit is closed.	7. Cut all resistance out of the shunt field circuit. Reverse the shunt field.
Motor fails to start.	1. Too much load.	1. No motion and fuse in circuit melts or circuit-breaker acts. See if motor runs all right when light.	1. If motor does not start at once, turn off current and search for cause. Reduce load on motor.
	2. Excessive friction, due to any causes given under heading "Heating of bearings."	2. Same, and motor hard to turn when not loaded, and with no current.	2. Remedies same as given under "Heating of bearings."
	3. Short circuit of field or armature or among connections.	3. Motor refuses to revolve, though shows signs of strong magnetism. Will turn easily by hand if unloaded and with no current. If current is very great, it is indication of short circuit. If fault is in field, magnetism will be weak.	3. If connections are made wrong, consult maker's diagram and correct them. Test for continuity and short circuits as given later.
	4. Open circuits due to field switch open, fuse melted, loose or broken connections, or some fault at generator.	4. Weak magnetism shows a loose connection in field circuit; no magnetism, that field switch is open. May be heavy current in armature. If there is no armature current there will be no spark at brushes when raised.	4. Turn current from motor, and search for cause of discontinuity; examine all switches, fuses and connections, tightening all. Test for continuity in machine circuits and repair broken or burnt-out coils.
Flickering of lamps.	1. Uneven running of engine, probably due to governor failing to properly function.	1. By flickering of lamps or vibration of voltmeter indicator.	1. Overhaul engine, especially governor.
	2. Loose connections, either on machine, switchboard or external circuit.	2. Same.	2. Examine all connections and see that they are firm and make good contact. Look for arcs.
Noise.	1. See third fault (6), fourth fault (4, 5, 9, [illegible] 11). eighth fault (3, 4, [illegible] and tenth fault.		
	2. Armature running against the brushes.	2. By unusual noise.	2. Correct direction of rotation.

CHAPTER XXIV.

TESTS FOR AND LOCATION OF FAULTS.

Under the heading *Remedy* given in the table of the preceding chapter most of the remedies given are simple and explain themselves, as for instance: Remedy No. 1, under Fault No. 1, "slow the engine," which would of course be done by throttling down the steam; No. 2, "Introduce more resistance in shunt field," which would be done by a proper manipulation of the field rheostat. Some, however, are but indicated, as No. 3, under Fault No. 3, "Locate and remove leaks or grounds," and it is the purpose of this chapter to enter a little more into the detail of the simple tests and the location of the faults.

Short-Circuit in External Circuit.

This would be indicated by the melting of the fuses in that circuit, or possibly by the melting of the main fuses or by the opening of the circuit breakers. After determining the circuit upon which the short occurs, an examination along the circuit, if it is accessible, may lead to the location of the fault. If not, a test may be made by the magneto or ohmmeter, by unscrewing all the lamps and opening the circuit at different points and ringing through both ways. Working from the switchboard, try the feeder first by disconnecting at the feeder junction box. By connecting the ohmmeter to the two ends, resistance between conductors can be roughly measured; it is either very high if the short is not there, or very small if it is. By opening the circuit at various points, the short can be located within limits and further observations will accurately determine it.

The short-circuit indicated by the melting of the circuit fuse would show that it was either on the feeder or mains, for each branch is protected; if it occurred in a branch it would only burn out the branch fuse. Short-circuits in the external circuit usually occur in branches and particularly in portables, but under these conditions they are easily located as the branches are short. Most of them are due to moisture in the wiring accessories, or to the insulation being torn from portable wires or burnt by hauling over hot coals or ashes.

Grounds in External Circuit.

A ground on an external circuit would be indicated by some type of ground detector connected to the mains.

Lamp Detector.—This, with its connection, is shown in Fig. 424. *A* represents a positive bus bar, and *B* a negative bus bar, from which are lead the circuits through the ship. 1 and 2 are two incandescent lamps connected in series across the bus bars. Between the

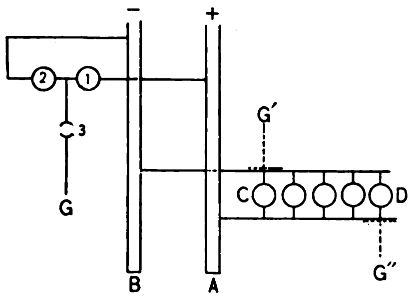


FIG. 424.—Connections of Lamp Ground Detector.

lamps there is a connection to earth marked *G*, with a plug 3 to make the connection to earth complete. *C* and *D* are lamps on a circuit. If there are no grounds on the circuit, the lamps 1 and 2 will burn with equal brilliancy, but reduced candle-power, as with the same E. M. F. there is double the resistance, so only half the current flows through each lamp. If a ground occurs on the negative leg of the lamp circuit, the current will now flow from the + bar through 1, but will avoid the high resistance of 2, so will take a path through ground to the ground on the main as at *G′*, and thence to the − bar. The result of this is that 1 now has full current and will burn with full candle-power, while 2 will be extinguished. If it is only a slight ground, both lamps may burn but with unequal brilliancy. If the ground was on the positive leg, the current would now avoid 1, taking the path through ground *G″* to *G* through 2 to the — bar, and 2 would burn with increased brilliancy while 1 was lowered if not extinguished.

With several circuits closed from the bus bars it becomes necessary to discover on which circuit the ground exists. This is done by cutting out the circuits, one at a time. If upon cutting out a circuit the ground disappears, it must have been on that circuit. Upon locating the faulty circuit, keep that circuit in and cut out all the others. Then pull out the portables on that circuit one at a time, and if the ground disappears when a certain one is pulled out, the ground must have been on that particular portable.

Grounds generally are due to moisture in the junction boxes or wiring accessories, or to the slipping of connections in lamp sockets, by which a bare wire may touch the outside shell which in turn may rest against some grounded conductor. A fruitful source of grounds is in the portable ventilating fans, the support of which frequently touch some exposed part of the leading wires.

Of course, grounds may occur in the mains, due to moisture and rotting of the insulation. This can be tested with the magneto, connecting one end to the main, the other to a ground and ringing through.

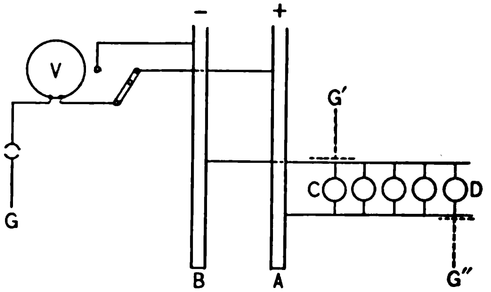


FIG. 425.—Connections of Voltmeter Ground Detector.

Voltmeter Detector.—Fig. 425 represents the typical connections for using a voltmeter to detect grounds. *V* is a double-reading voltmeter with the zero in the middle of the scale. The indicator is deflected to the right or left, depending on the direction of the current through it. One terminal is connected to a contact piece fitted with a switch by which it may be connected to either bus bar of the generator, A or B, and the other terminal is connected to a ground through a plug switch.

If connected as shown to the positive bar and there are no grounds on the negative side of any of the circuits, there will be no current through the voltmeter and no deflection, or the reading will be zero. If there are any grounds on the negative side, as at G', current will then flow from the + bar through the voltmeter to ground G to G' and to − bar. If it is dead ground, the full difference of potential between the bars will be indicated; if only a slight ground, the fall of potential, owing to the high resistance, will be very small.

Connected to the negative bar, any grounds on the positive side of the circuit will be detected, the current then being from the positive bar through the ground, as at G'', through ground G, through voltmeter to negative bar; the indicator now deflecting in an opposite direction to that of the first case.

The method of locating the particular circuit on which the ground exists is exactly the same as with the other ground detector, and also the same procedure is necessary to further locate the ground in the circuit.

The method of calculating the ground resistance is given on page 687.

Short-Circuit in Armature.

A short-circuit in the armature usually attracts attention by the smell of burning varnish or shellac. When this is discovered, the armature should be stopped at once, and felt all over by the hand for the short-circuited coil is much hotter than any of the other parts. A piece of iron held near a revolving armature with a short-circuited coil will be strongly affected once a revolution, as the coil passes the iron. If a large part of the armature is short-circuited, it is not so easy to distinguish the parts by the heat, so some fall of potential method is resorted to.

One way is to pass a strong current through opposite commutator bars and measure the difference of potential between the points where contact is made with the commutator. Then connect one terminal of a portable voltmeter to one connection and the other terminal to the different bars of the commutator. If the armature is sound, there should be the same fall of potential from the leading-in point to bars each side equally distant from it. In this way the fall of potential from bar to bar may be determined, and the fall should be regular. If between any two bars there is a smaller fall of potential than the average it shows the presence of a small resistance, or probably the short-circuited coil.

A short-circuited armature coil can only be remedied by rewinding.

Short-Circuit in Field.

Usually a short-circuit is confined to the windings of one spool; this causes weak magnetism in the short-circuited coil, and a piece of iron held at an equal distance between poles will be more strongly attracted by the sound spools than by the faulty one.

A short-circuited coil will cause the resistance of the total field to be much reduced, and this can be detected by roughly measuring with the bridge. The fall of potential method can be used to detect the spool in which the short-circuit exists.

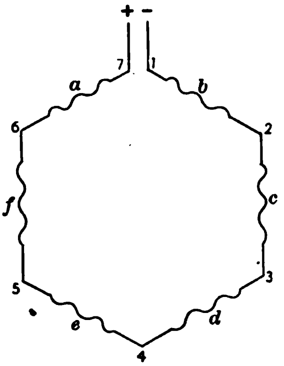


FIG. 426.—Testing for Short Circuit or Open Circuit in Field Winding.

Suppose the coils are represented by *a, b, c, d, e* and *f,* in Fig. 426, and a source of current is connected to 1 and 7.

If the field coils are all sound, then the voltage drop across each coil will be the same. However, if one is short-circuited, the voltage drop across it will be materially less than that across the others, especially if a large portion of the coil is short-circuited. To locate the faulty coil touch the terminals of the voltmeter across 1-2, 2-3, 3-4, etc. If the reading across 2-3 is materially less than it is across the others the short-circuit must be in coil *c*.

Grounds in Armature.

A single ground in an armature is not a source of trouble, but two or more, especially in the same coil, become a short-circuit and so cause trouble. The particular coil in which grounds to the core exist may be determined by connecting all the commutator bars together by wrapping the commutator with a bare conductor and passing a current through this wire, taking the other leading wire to the iron core. Current then flows through the armature coils through the grounds to the iron core, thus magnetizing the coil in the vicinity of the grounds, and these points can be detected by a small compass needle moved around the armature.

Grounds in Field.

One ground in a field magnet may not be noticeable if the rest of the system is insulated. It is nevertheless undesirable, for an accidental ground anywhere else in the system immediately causes current to flow which may injure the field and cause a wide variation in the generator voltage. Two grounds in a field will cause a short-circuit. To locate a ground disconnect each field coil, one at a time, and test to the frame of the machine with a magneto or ohmmeter.

Open Circuit in Armature.

This can usually be detected by violent flashing on the commutator, that commutator bar nearest the break being burnt or cut. A bad case of high or low bars may produce this same flashing, but if produced by this cause, it will disappear when the armature is slowly revolved, and this is not true if a fracture exists.

In the case of armature-coil fracture no particular coil will be heated more than another; the fractured coil may even be cooler than the others, as the current does not flow through it.

To locate the fracture measure the drop between adjacent segments. When the voltmeter bridges the two segments between which the open circuit occurs, it will read a voltage equal to the voltage across the machine terminals. It should read zero across the other segments lying between the same brushes. As there are several paths between brushes the test should only be made on that portion which shows no voltage between adjacent segments. The fault may lie directly under the brushes and being so bridged does not appear when the test is made. In this case the armature should be turned slightly and another test made.

Open Circuit in Field Winding.

If there is a complete open circuit in the shunt winding of a generator it will refuse to excite. The test for fracture can be made with the magneto, and the coil containing the fracture detected by fall of potential.

Suppose in Fig. 426 *a, b, c, d, e* and *f* represented the field coils in a six-pole machine, and that they were connected with a source of current at the terminals marked + and −. If there were a break in a coil, say in *e*, a voltmeter connected to 7 and 6 would not indicate; it would also not indicate if connected to 7 and 5; but, if connected to 7 and 4, it would indicate the terminal voltage as the circuit is now complete. This shows that the voltmeter has bridged over the break in coil *e*. If there were also a break in *d*, connection between 7 and 4 would show no voltage, but it would between 7 and 3. Connection between 3 and 4 would show no indication if there were a break in both *d* and *e*, but would if it were only in *d* alone. If breaks were in both *d* and *e* connection between 3 and 5 would show current, and in this way it can be determined absolutely in which coils breaks occur.

If the open circuit is external, it is comparatively easy to repair, but if internal, the coil will probably have to be rewound. Excessive vibration sometimes carries away the connections between the spools and they may break off under the outside layers.

To Test for Magnetism.

Magnetism can be detected by any magnetic material, such as a piece of iron or steel or iron tool, as screwdriver or knife, being brought up to the supposed magnet. Magnetism will be shown by the iron held in the hand being attracted, requiring at times considerable force to hold it away from the magnet. To detect very weak magnetism a small compass needle is used, as this is deflected by the very faintest trace of magnetism.

The polarity may be determined by the compass needle, if it be remembered that like poles repel and unlike attract.

For this test a very weak excitation should be used. Full excitation so changes the magnetism of the compass needle that no determination of polarity can be made. This test is performed most satisfactorily with the armature removed.

To Test for Speed.

This is done by the use of a tachometer, which by applying its shaft to the shaft of the rotating armature indicates at once the number of revolutions. A speed indicator may also be applied to the end of the armature shaft and the number of revolutions in a given time counted. Mechanical tachometers are not always reliable and should be checked occasionally by means of a speed counter.

To Test for Heat.

Under the table of faults, the greatest number of faults falls under the general head of heating, such as heating of armature, heating of commutator, heating of field coils, heating of bearings, and even the faults due to excessive current and excessive sparking are mostly faults due to the heat produced by them.

Remarks on Heating.

The expression "excessive heating" is somewhat vague. That which appears excessive in one instance might not be excessive in another.

The rise in temperature that is allowed in the armature coils and field windings above the temperature of the surrounding air is limited by specifications, but the degree of heat that is positively injurious is easily determined by feeling the various parts. If the temperature of any part of the winding is greater than the hand can stand for a few seconds, then it is higher than the safe limit. If the hand can stand it for two or three minutes, it is usually not considered excessive. If there are any signs of smoke or smell of varnish, shellac, or rubber, the temperature is far too high. The only way to cool heated parts is to stop the machine, except possibly in the case of bearings, where water may be used.

For accurate temperature measurements the thermometer should be used on the various parts. The bulb should be protected from the outside air by waste and the highest reading taken. To find the temperature of the field windings, calculations should be made from the cold and hot resistances, knowing the per cent increase per degree rise of temperature, see page 538.

It is also very necessary to locate the exact source of the heat. The hot part may not be the source of its own excessive heating, but the heat may have been conducted there from other places. A hot bearing might make a hot commutator or armature and vice versa. In locating heat troubles the hottest parts should be located as they are probably the source of trouble. If a certain part heats under certain conditions, it will undoubtedly do so again under the same conditions. To discover the parts that heat first, it is better to start with the machine absolutely cool in all its parts, and then after a short run to feel all over for the hot parts, for in a short run, there will not be time for the heat formed to be conducted to other parts. After a long run, only average temperatures are obtained, but it is not certain just what the source of heat is, for there is a general distribution of heat all over the machine.

Uses of Electric Fault Finder.

The following tests are given in the instructions furnished with the instrument and refer particularly to armature tests. Reference should be made to Fig. 372, Chapter XXI.

Test No. 1. To Discover Leaks.—Screw down Switch No. 1 and unscrew switches Nos. 2 and 3. Pull up battery switch. Adjust rheostat until sound is as loud as the ear can comfortably endure with the test terminals in contact. With the test terminals separated, there will be no sound in receiver. Place one test terminal on armature shaft, and other test terminal on commutator. If there is a leak, a sound will be heard. With one test terminal held tightly in each hand, the loudness of sound indicates a resistance of 10,000 ohms or more.

Test No. 2. To Locate Grounds.—Screw down switches Nos. 2 and 3 and unscrew switch No. 1. Pull up battery switch. Adjust rheostat until there is no sound in receiver with the test terminals in contact. Place one test terminal on armature shaft and pass other test terminal around the commutator. If there is a grounded coil or bar, the sound will decrease as grounded coil or bar is approached, and will almost or totally disappear when grounded coil or bar is reached. If in test No. 1 sound is so loud that a ground is indicated, and, if in test No. 2, sound on all commutator bars is the same and very faint, it shows that the entire commutator is grounded.

Test No. 3. To Locate Short-Circuits.—Adjust the fault finder as in test No. 2. Place one test terminal on any commutator bar and the other test terminal on the next bar. Follow around the commutator keeping the test terminals on adjacent bars (the handles are flattened so this can be done with one hand after the spacing is adjusted). When the short-circuit is found, sound in the receiver will be gone or be very faint. If the sound is loud, an open circuit exists and should be found as per test No. 5. The other end of the coil may be found as per test No. 4.

Test No. 4. To Locate Coil Ends.—Adjust the fault finder as in test No. 2. Mark a bar on the commutator and place one of the test terminals on it. Then move the other test terminal around the commutator and when the other end of the coil is reached, there will be very little sound in the receiver. Should the coil be open, the sound will be very loud.

Test No. 5. To Locate Open Circuits.—Adjust the fault finder as in test No. 2. Mark a bar on the commutator and place one of the test terminals on it. Next find the other end of the coil as per test No. 4. Then pass both test terminals from bar to bar in the same direction around the commutator, being careful to stay at the ends of each coil. When the open circuit is reached, the sound in the receiver will be the loudest.

The following instructions apply to field coil testing:

Test No. 6. To Locate Grounds.—If in test No. 1 a loud sound is obtained and the armature and field are connected, the ground may be in either armature or field. Disconnect field from armature and test each separately. If field is grounded, test separately each field coil, thus determining which coil or coils are grounded. Remove field coil and repair. When coil is removed, connect one test terminal with each end of coil and determine if coil is open. If coil is open, find open-circuited layer as per test No. 8. While coil is removed, also test for short-circuits as per test No. 7.

Test No. 7. To Locate Short-Circuits.—Adjust fault finder as in test No. 2. Strip insulation about one-half inch wide, on end of coil exposing each layer. Place one test terminal on exposed wire of outside layer and place other test terminal on exposed wire of next layer. Next, advance second test terminal one layer, when the sound will be louder. Continue this way and the sound will increase for each layer tested. When the short-circuited layer is reached, the sound, instead of increasing, will remain the same.

Test No. 8. To Locate Open Circuits.—Adjust fault finder as in test No. 2. Proceed as in test No. 7. When open-circuited layer is reached, sound will be loudest. Tests Nos. 7 and 8, locating the trouble exactly, will give information sufficient to determine whether the coil should be scrapped or repaired.

The above tests on dynamo electric machines will suggest numerous other tests on electric circuits in general, which may be made with the electric fault finder. For instance, by using the fault finder as in test No. 1, all the testing usually done by a magneto may be performed by one man, with much greater accuracy, and over a wider range of resistance, than with a magneto. In general, when using the fault finder for exploration work—which is the kind of testing usually done with a magneto—adjust the fault finder as per test No. 1. When a faulty low resistance circuit is to be located among a number of low resistance circuits, adjust the fault finder as in test No. 2.

CHAPTER XXV.

TELEPHONES.

The underlying principle of the telephone is *the increase or decrease of intensity of an unbroken electric current,* and in order to transmit sounds of the voice over an electric conductor it is necessary that a current be caused to flow in the conductor and that the change in intensity of the current is in accord with the vibrating movements of the sound-producing body.

FIG. 427.—Simple Telephone Connection.

The early invention of the telephone is illustrated in Fig. 427. In its simplest form it consists of a *permanent bar magnet A* with one end surrounded by a coil of fine wire *B,* in series with the line connecting the stations. A soft-iron diaphragm *C,* is mounted close to one end of the magnet. When a sound is made in front of the diaphragm, it vibrates in exact accordance with the sound waves striking against it. The vibrations produced by the voice are transmitted by the air to the diaphragm and this latter vibrates back and forth in front of the magnet. These vibrations of the diaphragm change the permeance of the magnetic circuit shown in Fig. 428. When the diaphragm moves toward the permanent magnet, the number of lines passing through the bar increases, and when the diaphragm moves away from the magnet, the number of lines decreases. This pulsation of magnetic flux takes place through the coil *B,* so an E. M. F. is induced in this coil and this E. M. F.

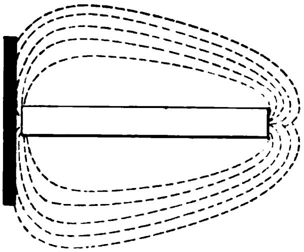


FIG. 428.—Magnetic Field at Telephone Receiver.

is in accordance with the voice acting on the diaphragm. If coil *B* is connected to a similar coil *B'*, having a bar-magnet core and a diaphragm similar to that of *B*, the alternating current passing through *B'* will cause the magnetic flux in *A'* to increase and decrease in accordance with the induced current which flows over the line. Therefore, diaphragm *C'* will vibrate in a manner almost identical to that of the diaphragm at *C*, and the sound made at *C* is reproduced at *C'*.

No battery is needed with this system. The only currents that flow are those which are induced by the vibrating diaphragm. As the only source of energy is the voice, this system can be used for very short distances only, and even then the reproduction of the sound may be too feeble for the ear to detect.

Variable Resistance Transmitters.

The source of energy in the simple telephone circuit described above being very limited it has no practical value except for very short distances. The early experiments to secure a more practical transmitter were in the direction of causing a variation in the strength of some external current, this variation always remaining in accordance with the movements of the diaphragm. A battery was used and the transmitter was designed so that the vibrating diaphragm caused a variation in the current strength by changing the resistance in the battery circuit.

Edison Transmitter.—One of the first practical transmitters was devised by Edison and carbon was the substance by which the resistance of the circuit was varied. Carbon granules in contact have a variable electrical resistance which depends on the pressure which is exerted on them. The first type consisted of a platinum disc secured to the diaphragm bearing against a button of compressed plumbago. The circuit was completed through this contact and the resistance was varied by greater or less pressure on the plumbago button caused by variations in the sound waves striking the diaphragm. This change of resistance caused variations in the current that passed over the line to the receiver.

Hunning's Transmitter.—In Hunning's transmitter the variable resistance medium consists of a quantity of finely divided carbon granules held between two conducting plates, and through which the battery current flows. This form has a large number of imperfect contacts and the change in resistance is caused by the change in the pressure exerted on the granules. The diaphragm is so arranged as to press more or less firmly against these carbon particles and thereby produce changes in resistance which cause currents of varying intensities to flow in the line.

Nearly all successful transmitters are modifications of this type.

Hughes' Microphone.—This type of sound transmitter or sound multiplier depends on the variations in resistance of an electric circuit caused by *loose contact* of electrodes. The elementary principles are illustrated in Fig. 429.

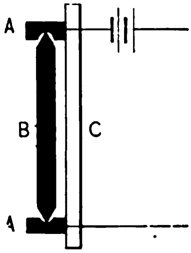


FIG. 429.—Hughes' Microphone.

C is a sounding board holding two cup-shaped contacts *A, A* of carbon, between which lightly rests a carbon strip *B,* which makes imperfect contact at *A, A*. These are connected to a battery in which a receiving instrument is included. The slightest noise, imperceptible to the unaided ear, sets up vibrations which vary the contact of *A* and *B,* and so sets up variable currents in the line which are reproduced in the receiver with great distinctness. The clearness and distinctness of the sounds vary with the pressure, and as this is gradually increased, the sounds become weaker, though always clear, until when the contact is perfect the sound ceases.

This indicates that it is not the resistance of the carbon itself which changes under pressure, but the change of resistance is caused by the imperfect contact at the carbon electrodes.

Of the different theories advanced for the explanation of the change of resistance of carbon under pressure, the most probable one is that the change of resistance is due to the variation of the area of contact, and in the granular form it is the variation in the number of granules in contact. An increase of pressure increases the area of contact, lowers the resistance and allows greater current to flow, while a decrease of pressure produces the opposite effect.

Carbon Transmitters.

Of the variable resistance transmitters mentioned in the preceding section, those made on the principle of the Hunning's transmitter have been the most successful, and no substitute for carbon as the variable resistance medium has been discovered. Carbon has all the properties requisite for telephonic or microphonic work; it produces change of resistance by surface contact; it can be easily made into the desired form; it does not oxidize or corrode; it is abundant and cheap.

The form of transmitter almost universally used in this country in the early days of telephones was the **Blake transmitter.** In this transmitter a platinum pin is pressed by a light spring against a polished plug of *hard* carbon, forming an imperfect, delicate contact through which the current flows. This mechanism is mounted behind the usual disc which takes up the vibration of the voice, and greater or less pressure is brought on the contact of the platinum pin and carbon. This varying resistance produces the requisite varying intensity of the line current.

This transmitter is very delicate and transmits the quality of the voice in an excellent manner, but it lacks power.

Many forms of the carbon granular type have been made, and although all present peculiarities, the general principle of construction is the same, and a description of one will render clear the action of all. The type of transmitter in general use by the American Bell Telephone Company is known as the "*solid back,*" or **White transmitter.** Its general construction is shown in Fig. 430.

The front, *A,* is of metal, forming with the back, *B,* a complete metallic casing for the working parts of the instrument. The diaphragm, *D,* is of aluminum, held by a soft-rubber ring *E,* and against which are held two damping springs, *F,* only one of which is shown. *C* is a metallic block, hollowed out to form an enclosure for the electrodes, and is held rigidly in place by a supporting bridge, which is secured to the metal front piece. The inner circular wall of *C* is lined with paper, and screw-threaded into its inner face is a metallic piece, *I,* against which rests the back electrode of carbon *J.* The front electrode, *K,* also of carbon, is carried on a metallic piece, *L.* On the flange of the piece, *L,* is carried a mica washer, *M,* held in place by the screw nut, *N,* and the washer is of sufficient diameter to cover the cavity in the block, *C,* when the front electrode is in place.

The space between the two electrodes is filled with granular carbon, and as the electrodes are slightly smaller in diameter than the cavity, the space around them is also filled with the granules.

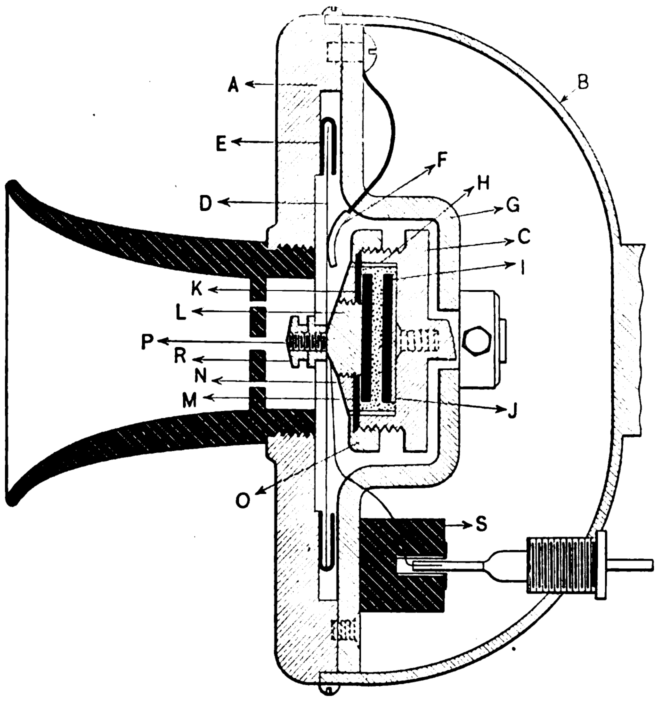


FIG. 430.—White "Solid-Back" Transmitter.

There is sufficient space left to allow for the expansion of the granules due to the heat of the current, and this form allows a large current without undue heating.

When the carbon granules have been put in the cavity and the front electrode is in position, the mica washer is slipped in and the nut, *N,* is screwed in place; after which the cap, *O,* is screwed on, binding the washer firmly against the face of the block, *C*, and confining the granules in the cavity.

The screw-threaded portion, *P*, of the piece, *L*, passes through a hole in the center of the diaphragm and is held in place by the nuts, *R*. The vibration of the diaphragm is conveyed to the front electrode, which can move against the elasticity of the mica washer, while the back electrode is firmly held, and thus more or less pressure is brought to bear on the carbon granules between them.

The back electrode is in metallic connection with the back of the instrument which forms one terminal, while the other terminal is mounted on an insulating block, *S*, and is connected to the front electrode by a flexible connecting wire.

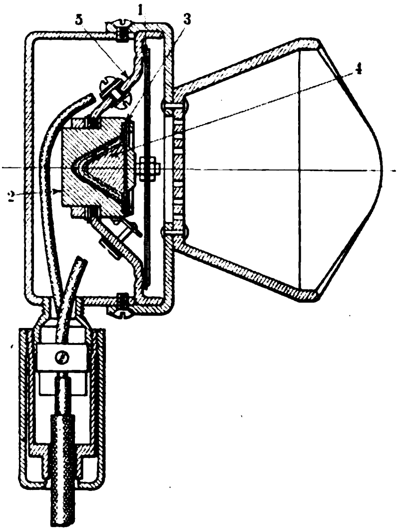


FIG. 431.—Navy Type Transmitter.

The Navy Type Transmitter.—Ordinary telephone transmitters have the disadvantage that if they are held flat, that is, with the carbon electrodes horizontal, the granular carbon all rests on the back electrode, and the transmitter becomes inoperative owing to lack of contact between the front electrode and the carbon granules.

Owing to the nature of the service which fire-control telephones undergo, it is extremely important that the transmitter should operate in all positions. In order that the granules should at all times be in contact with both electrodes, the electrodes of the navy type Holtzer-Cabot transmitter are of conical form; that is, the front electrode is a cone and the back electrode is a hollow cone. Both electrodes are coated with thin sheet platinum which will not become tarnished or oxidized.

A diagram of this transmitter is shown in Fig. 431. The diaphragm, shown at 1, does not differ materially from that of the ordinary transmitter.

The back electrode 2 and the mica diaphragm 3 which supports the front electrode 4 form the container for the carbon, the rim of the cup in which the back electrode is mounted being crimped over the diaphragm so as to form a tight joint. The exterior of the back electrode cup is threaded and the cup is locked to the bridge by a nut. The metal diaphragm 1 is carried by a stud extending through the mica diaphragm from the front electrode cone 4. Its adjustment is secured by varying the pressure with which it is set up against a rim on the bridge 5. To avoid grounding, both metal diaphragm and the cup containing the electrodes are insulated from the bridge.

The terminals of the transmitter are carried by the bridge and are insulated from it.

Receivers.

The typical form of telephone receiver is shown in the elementary sketch in Fig. 427, and it might be said that the receivers used in modern practice are but developments of the single permanent magnet, with one end wound with a coil of fine wire.

In the first days of telephone work, the receivers were of the single-pole type. In general they consisted of a compound bar magnet formed of two pairs of magnetized steel bars, placed with their like poles together. Between the bars at one end is clamped a soft-iron pole piece, and at the other a similarly shaped iron block. The soft-iron pole piece formed the core of a coil of wire which was slipped over it, and near this coil was secured the vibrating diaphragm. The whole was mounted in a conveniently shaped rubber shell, formed of two pieces, one enclosing the magnets, and the other screwing into it and holding the diaphragm in place. Heavy leading-in wires ran from the coil along the inside of the rubber shell to terminal pieces at the bottom which projected through and formed outside terminals to which the line wires were connected.

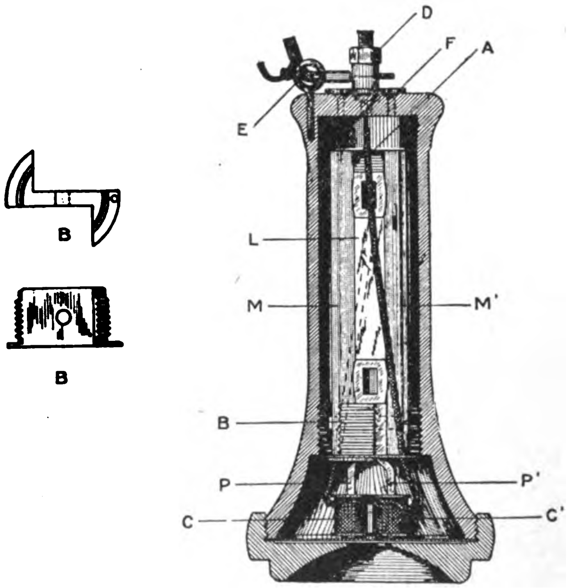


FIG. 432.—Bell Telephone Receiver.

Bipolar Receivers.—The object of bipolar receivers is to strengthen the field in which the diaphragm vibrates by presenting both poles to the diaphragm. By this method the flux path in air is greatly shortened and the lines of force are concentrated near the point where they are most effective. There have been as many different forms of receivers made as transmitters, but the governing principle remains the same, and the construction of one successful receiver will illustrate all the principal points. A receiver used by the Bell Companies is shown in Fig. 432.

In Fig. 432 are shown two magnets, *M* and *M'*, secured at one end by screws through an iron tail block, *A*, and at the other end by a threaded brass block, *B*. The pole pieces, *P*, *P'*, carry the coils, *C*, *C'*, and are clamped between the pole end of the magnets and the block, *B*. This block screws into a threaded portion in the rubber body of the shell and by turning it the magnet poles are moved nearer to or farther from the diaphragm, and after once being adjusted, it is held by a pin through the shell. The binding posts, *D*, are fitted with lock-nuts and there is an eyelet, *E*, fitted to take the strain cord, so no strain will come on the terminals if the receiver should happen to fall. In order to give sufficient weight to properly work the hook switch, a lead weight, *L*, is clamped between the magnets. The diaphragm is secured between the two pieces of rubber shell. More recent types have concealed binding posts.

Watch-Case Receivers.—In some classes of work it is necessary to hold the receiver constantly at the ear, so that the hands may be free, as in radio telegraphy, fire control or switchboard work. For such purposes a special form of receiver that can be held in place over the ears has been devised which, from its shape and small weight, has been called the "watch case" or "head" receiver.

One or two receivers may be used to cover one ear or both as desired. They are provided with straps to go over or around the head to hold them securely in place.

The permanent magnets are usually of the horseshoe type and semicircular in shape. The pole pieces which carry the coils are secured to a ring magnet and mounted within it and their pole faces rest close to the diaphragm as in the ordinary receivers. The working mechanism is mounted in a hard-rubber shell and the diaphragm is secured between this shell and the ear piece.

Use of Induction Coils.

The first practice in connecting telephonic instruments was to connect the transmitter, the receiver and battery at one station directly in the line leading to the other station, considering for the present but two stations. The change in resistance of the whole line, whereby currents of varying intensities were produced to actuate the receivers was caused by the change of resistance in the transmitter. In case of a long line this change of resistance was very small in comparison to the whole resistance and the current variations were consequently very feeble. To remedy this difficulty, Edison proposed to use an induction coil with the primary in the circuit of the transmitter.

The connection of the induction coil is shown in Fig. 433.

T represents the transmitter in series with the battery *B* and the primary *I′* of the induction coil; *I″* the secondary of the induction

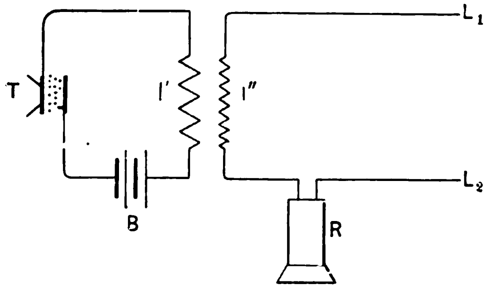


FIG. 433.—Connection of Telephone Induction Coil.

coil is in series with the receiver *R* and the line L_1L_2. The transmitter in this connection is operating in the low resistance of the primary circuit, rather than over the resistance of the whole line, and any change of resistance caused by the transmitter bears a much larger ratio to the resistance of the primary circuit than it does to the resistance of the whole line, consequently, for the same voltage, the changes of current will be proportionately larger in the primary and the induced electromotive forces in the secondary upon which the line currents depend will be proportionately greater. The fluctuations of line current produced by the aid of the induction coil are many times greater than could be produced by the transmitter alone.

Another advantage of the induction coil is that the primary being of few turns while the secondary is of many, the induced electromotive forces in the secondary have a very high value as compared to those in the primary, and transmission can be effected over much greater length of line and over much higher resistance than as if the transmitter was used alone.

Calling Apparatus.

Before conversation can be carried on between points, there must be some means by which a person at one station can attract attention at the other. Ordinary vibrating call bells or buzzers are used, fitted with separate lines and batteries or the talking battery may be used over separate lines, or over the talking lines. For long distances, ordinary batteries will not furnish sufficient current to operate call bells. In some cases, they have been used with induction coils, using the high voltage of the secondary windings to furnish the desired current.

In many systems, especially in that known as the local-battery system, a form of generator is used that is very similar to the magneto shown in Fig. 371, Chapter XXI. This furnishes alternating currents of high voltage and actuates a vibrating bell at the called station.

In central stations using the "local-battery" system attention is called by the ringing of the call bell, and at the same time by the dropping of a shutter which indicates the number of the calling station.

In the "common-battery" system, the attention of the operator is called, by the lighting of an incandescent lamp when the calling party removes the receiver from the hook.

Local-Battery System.

This system, as its name implies, has a local battery at each station to furnish the talking current. The system is classified under two heads, **series** and **bridging**. The series system is used when a number of instruments are used in series on the same circuit, and the bridging system where the instruments are placed in multiple or bridged across the line. This latter is the more common practice.

The calling and talking apparatus operate over the same line, and when the circuit is complete for one operation it must be open for the other and vice versa, so means must be provided for attaining this result. It is now universally accomplished by a switch actuated by the weight of the receiver. When the receiver is hanging in its provided place, the talking circuit is cut out and the calling circuit is closed ready to operate for calling.

At each station in this system there must be provided the transmitter, receiver, induction coil, battery, switch, bell and generator. It is customary to place the generator, the bell, the switch and the induction coil in one box and the battery in a separate box.

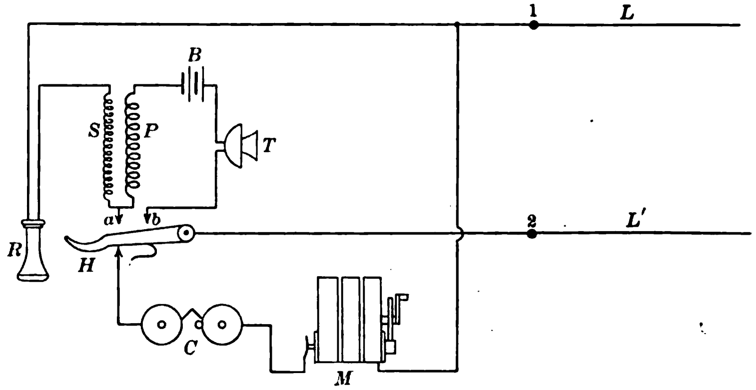


FIG. 434.—Local Battery System, Magneto Call.

The connections for a complete station of the local battery system are shown in Fig. 434.

L and *L'*, the two incoming line wires, are connected to the telephone binding posts 1, 2. *M* is a magneto, *C* the local bell, *T* the transmitter, *B* the local battery, *P* the primary of the induction coil, *S* the secondary of the induction coil, *H* the hook, and *R* the receiver.

To call from this station it is only necessary to turn the magneto handle, when the hook switch is down. The line 1, 2, is then connected directly to the magneto terminals through the local bell *C*. The talking circuit is open under these conditions. When the receiver is taken from the hook the two contacts *a* and *b* are made. The calling party talks into the transmitter *T*, and a variable current from the battery B flows around the local circuit through the transmitter, contacts b and a, the hook and the primary of the induction coil. This primary current induces an alternating E. M. F. in the secondary of the induction coil and current flows out on the line L through the receiver R, and on line L' through the contact a and the hook.

When this station is being called the hook is down and the ringing current coming in on the line LL' finds that the only path is through the magneto M and the calling bell C. Calling bell C is actuated by a polarized armature that is pulled back and forth by the action of the alternating current.

When the receiver R is removed from the hook H, the incoming talking current passes from line L through the receiver R, the secondary S, the contact a, and out on line L', completing this circuit.

Some modifications of this ringing system are commonly found. The magneto and bells may be connected directly across the line, as the high reactance of this circuit prevents the high frequency telephone currents from entering. In the bridge system the magneto and bells are connected in parallel directly across the line. In this latter case the magneto may be provided with a switch which closes the magneto circuit only when the magneto handle is being turned.

These systems are commonly used for the so-called "desk sets" and "wall sets."

Common-Battery System.

In the local-battery system, it is usual to make use of the magneto for calling central, but in the common-battery system signals are made both by simply lifting the receiver from the hook and by replacing it. In some types of signals, lifting the receiver has the effect of lifting a target within sight of the operator and holding the signal displayed until the receiver is again hung on the hook. Then the target drops in place, either by its own weight or under the action of a spring.

The modern method is to use a small incandescent lamp which is illuminated as soon as the hook is released by the removal of the receiver. To signal any station from central requires some type of sound apparatus to attract attention, and current to operate this must come over the same line as the talking current. The signal apparatus must be in circuit so that it may be energized at any time while the receiver is on the hook. At the same time there must be no connection between lines at the subscriber's station through which direct current can flow; otherwise the signal lamp at central will be lighted continuously.

An alternating current is the solution of this problem, for it does not require a continuous metallic circuit, but it will pass through a condenser where direct current will not. A condenser then is connected in series with the bell across the line. This bell is energized by a magneto at the central station. The condenser allows this alternating current to pass through it, and at the same time it prevents the current of the common battery at central from passing.

The illuminating lamp at central may be placed either directly in series with the common battery and the line, or in a relay circuit, which is operative only when the battery circuit is established by the lifting of the receiver. In the former case, the high resistance of the condenser in the signal-bell circuit is sufficient to prevent enough current from flowing to illuminate the lamp, but when the receiver is raised, the battery current flows through the low resistance of the transmitting circuit and produces sufficient current to light it.

As the name of this system implies, there is but one battery and that is installed at the central. This battery furnishes current for talking as well as for the signal apparatus at the central.

The complete connections from a station to central are illustrated in Fig. 435.

The station on the left (Fig. 435) represents one station and that on the right, the central, connected by the two wires L_1 and L_2. A battery of about 24 volts is kept connected at central to all the lines entering it, but no current flows from this battery as long as the receivers, *R*, are on their hooks, *H*. In that condition there is no circuit for the direct current of this battery, as the condenser, *C*, acts as an infinite resistance to it. If central wishes to call the station, it is only necessary to throw upon the line an alternating current which passes in and out, or through the condenser. This is done by operating a ringing key *x*, which connects the wires L_1, L_2 to an alternating current generator *G*. As the alternating current flows through the coils of the bell magnets, the armature which is pivoted, is drawn first towards one magnet and then towards the other, vibrating back and forth between the bells *B*, producing a ringing sound. The sleeve *e* of the ringing jack is connected to the positive terminal of the battery, and when the subscriber is called the battery circuit is opened by the relay *K* opening the contacts.*

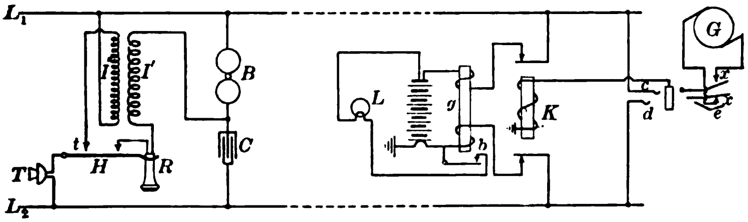


FIG. 435.—Common Battery Telephone Circuit.

If the station wishes to call central, it is only necessary to lift the receiver *R* from the hook *H*. This closes the line circuit at *t* and allows current from the battery to flow in the line through the transmitter. At the same time the current flowing energizes the electromagnet *g*, and its armature is attracted, closing the lamp circuit containing the lamp *L* at *b*. This illuminated lamp attracts attention of the operator who moves a switch to connect the central telephone to the calling station.

As the calling station talks into the transmitter the strength of the battery current through the transmitter is varied according to variation in resistance due to the pressure on the diaphragm. This causes similarly varying current to flow in and out of a circuit made up of the transmitter, receiver, condenser and winding *I'* of the induction coil. These variations, by induction with the winding *I''* of the coil, increase the amount of variation in

* The ringing jack has three contacts which are called the tip, the ring and the sleeve. The tip and ring make the contacts for the alternating currents used for ringing. The sleeve contact completes the circuit through *K* via ground to other side of battery.

the line circuit including one side of the repeating coil in the operator's cord circuit at the central office. (See under Repeating coils.) The winding I'' of the induction coil has a greater number of turns than I' and is usually known as the secondary. It should be noted, however, that this is not exactly true, as on receiving this winding I'' acts as primary, and on talking the primary and secondary currents are combined on one circuit. This, however, does not interfere with the distinctness of speech.

When the operator finds what station is required, it is rung up and connection is made with it by a plug *e* containing a flexible cord, which is pushed into the contacts *c* and *d*. When the conversation is over the receiver is replaced on the hook and this lights a second lamp (not shown) at the switchboard. The operator then disconnects the two stations.

Switchboards.

Telephone switchboards are used for interconnecting telephone lines centering at a common point. The two general systems,

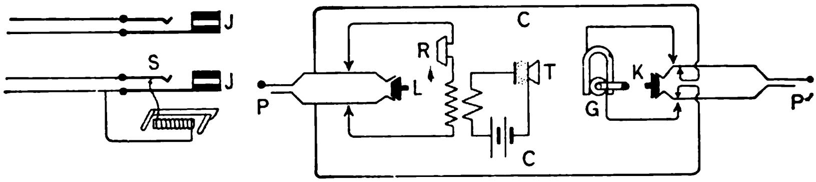


FIG. 436.—Magneto Switchboard.

local-battery or magneto system and central-battery system require each a different arrangement of the talking and calling apparatus, though they contain certain parts that are common to each.

The terminals of all lines entering the exchange at the switchboard are secured to **jacks**, by which the line may be connected to another by the insertion of a plug in the jack. These jacks are small switch sockets, and so arranged that both lines of the metallic circuit are continued in a flexible cord by the insertion of the plug. This is generally accomplished as follows and can be seen in Fig. 436. One terminal of the line is secured to a circular ring which forms the socket for the plug, and the other terminal ends in a spring contact. The plug is so constructed that its tip end makes contact with the spring contact of the line terminal while the body of the plug forms a sleeve and makes contact with the ring socket. The tip and sleeve of the plug are insulated from each other and the terminals of the flexible cord are secured, one to each.

Cord circuits are common to switchboards used with the two principal systems. Ordinarily it is a term which refers to two plugs with the connecting flexible wire and the necessary calling and talking apparatus by which an operator may answer a call or complete a connection with any line. In magneto switchboards a cord circuit consists of two plugs adapted to fit the jacks, with the connecting cord; a listening key by which the operator can connect the central talking apparatus so that conversation may be had with either one or both communicating stations, and a ringing key by which the central magneto is connected to one of the plugs and the station whose jack is plugged may be called.

Magneto Switchboard.—The essential parts of a magneto switchboard are shown in Fig. 436. The lines on the left are those from distant stations and all end in the jacks, *J, J*. In the lower line is shown the calling apparatus or "drop" with which each line is provided. It consists of an electromagnet energized by currents produced by the generator at a calling station, which pass over the line and around the electromagnet. When the core becomes magnetized, it attracts its armature, shown to the left, and which is pivoted at the upper end and connected to the rod above the magnet. This rod ordinarily holds in place the front shutter which is hinged at its lower end. As the armature is attracted, the shutter is released and drops, exposing the number of the calling station.

The cord circuit consists of the two plugs, *P* and *P'*, fitted as above described with tip and sleeve contacts to engage the jacks, *J*, the flexible cord, *C, C*, and the talking and calling apparatus. The general operation of calling and talking would be as follows: Suppose the lower station calls by turning his magneto handle. This throws an alternating current on the line and upon the electromagnet at central becoming magnetized, the armature is attracted and the shutter drops. On seeing the number of the calling station, the operator pushes the plug, *P,* into the jack, *J,* and presses the listening key, *L.* This connects the operators talking circuit in series with the line circuit of the calling station and disconnects the signal circuit, by the tip of the plug raising the spring contact, *S.* On finding the number of the station desired, the operator pushes the plug, *P′*, in the jack of the desired number and presses the calling key, *K.* This connects the central generator, *G,* to the line of the desired station, and on turning the handle of the generator, current is sent over the line and rings the bell at the desired station. While the calling key is depressed, the talking circuit is cut out, by means of the spring contacts shown at *K,* so the alternating current of the generator cannot go over the line of the original calling station.

There is usually fitted, in addition, another electromagnet across the cord circuit, *C, C,* which is actuated by current from either station while the jacks are still plugged to indicate that the conversation is finished.

Common-Battery Switchboard.—The circuits of a modern common-battery switchboard as developed by the Western Electric Company are shown in Fig. 437. The leads L_1 and L_2 (heavy lines) are connected to a station, and another station, which could be shown on the right would be exactly similar. The **cord circuit** for the switchboard embraces all the portion between the plugs *P* and *P′*, and in addition the switchboard also embraces the circuit shown on the left under the heavy lines L_1L_2 of the calling station. A station on the right, or called station, would have an exactly similar equipment at the switchboard.

To signal the operator, the calling station takes the receiver from the hook. Circuit is then completed from the battery *B′* through the **line relay,** *LR,* through the primary of the induction coil at the calling station and the two armatures of the **cut-off relay,** *CO.* As soon as the line relay magnet is energized, it attracts its armature and closes the circuit of the **line lamp,** *LL.* This circuit is completed by the armature and one side of the battery being grounded, as shown at *E.* The operation of removing the receiver at the calling station thus results in lighting the line lamp, *LL.*

When the operator sees this, plug *P* is inserted in the jack, *J,* and battery *B* is thrown on the line. The plug has a third strand connected to the sleeve of the plug with connections as shown through **a supervisory lamp,** *SL,* and resistances. When the plug is inserted, current from battery *B* flows around an electromagnet, *SR,* called the **supervisory relay** and the effect is to attract its armature and

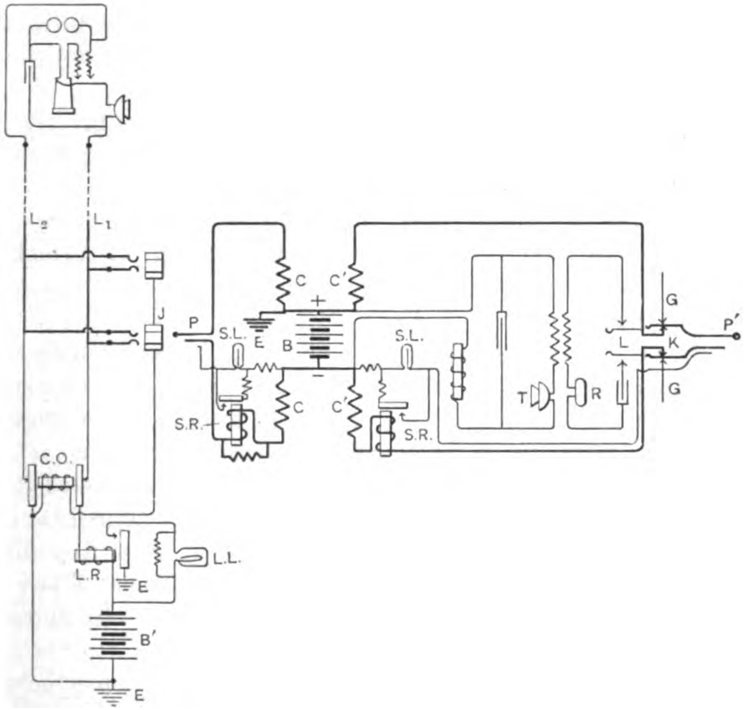


FIG. 437.—Elements of Common-Battery Switchboard. Western Elec. Co.

shunt the lamp *SL,* through the resistance shown. Thus the supervisory lamp is not lit as long as the receiver is off the hook at the calling station.

Another effect of entering the plug *P* in the jack, *J,* is to cause the line lamp to be extinguished. This is accomplished as follows:

Current from the ungrounded side of battery *B* flows through the coil of *SR,* which is then energized and attracts its armature which completes the circuit to the sleeve of the plug through the resistances in line and around the lamp. From the ring of the jack current flows around the electromagnet, *CO,* known as the cut-off relay, to ground. This energizes the electromagnet, *CO,* and its armatures are attracted, breaking the circuit to the line relay. The electromagnet *LR* being no longer magnetized, its armature falls by the action of gravity and consequently the circuit through the line lamp is broken.

When the plug *P* is in the jack and the receiver is off the hook at the calling station, current from the battery *B* is flowing through the two strands of the cord through the plug and jack over the line and through the transmitter of the calling station, thus energizing it and putting it in a condition to vary the intensity of current by the changes in its resistance caused by the sound waves striking the diaphragm.

After the operator inserts the plug in the jack, the **listening key,** *L,* is closed, which throws the central's transmitter and receiver in line with those of the calling station and conversation may be effected. When the desired number is obtained, the plug, *P′*, is inserted in the proper jack, and the **calling key,** *K,* is closed for a moment. This connects the generator circuit to the desired station, and at the same time cuts out the cord circuit to *P,* so the calling current cannot produce any signal at the calling station. When the called station answers, the two stations are now connected through the cord circuit and conversation can take place.

When the conversation is over, the receivers are hung on the hooks at each station, with the result that the supervisory lamps *SL,* one for each station, are lighted, which allows the operator to know that the call is finished. On withdrawing the plug, *P,* the lamp, *SL,* on that side is extinguished and in withdrawing *P′*, the one on the right is extinguished. The above operations are accomplished as follows: When the receiver is hung on the hook, the circuit of battery *B* is broken at that point, and consequently the magnet *SR* ceases to be magnetized and its armature is drawn away, breaking the shunt circuit around the lamp. Current now flows from the ungrounded pole of the battery through the lamp *SL* to the sleeve contact on the plug and through the cut-off relay to ground and to the grounded pole of the battery. Finally, on withdrawing the plug from the jack, the circuit on that side is broken and the lamp is extinguished. The same operation holds good for the station on the other end of the cord circuit.

Repeating Coils.*—The coils *CC* and *C'C'* shown in Fig. 437 are called repeating coils. Though they are shown as four separate windings, they are in reality wound on one core. The object of this winding and of inserting the battery in parallel with the talking stations is as follows: By this arrangement current from the battery divides at the junction of the coils *C* and *C'* and part goes to the instruments at each station and for a given difference of potential at the battery a greater current will flow in each portion of the cord circuit than if the battery was connected in series. The circuit in which change of resistance is caused by the transmitter is only that from a station to the switchboard, consequently it bears a greater ratio to the resistance of the line than if the change in resistance took place in the whole line connecting the two stations and the fluctuations of current are correspondingly greater.

A change in the current of either circuit produced by a transmitter acts inductively through the repeating coil of the other circuit and causes corresponding changes of current to act on the receiver of the other line. Thus, when the left-hand station is transmitting, coils *C* and *C* act as primary coils and coils *C'* and *C'* as secondary coils, and the opposite is the case when the right-hand station is transmitting.

Interior Telephones.

Interior telephone circuits are used where a number of people located close together desire a complete intercommunication with one another. There are several systems that have been devised to

* The repeating coil is similar in principle to the induction coil, see page 747.

meet different requirements and they are generally classified under the following heads:

1. Intercommunicating system.
   a. Selective talking, or
   b. Common talking.
   c. Selective ringing, or
   d. Common or code ringing.
2. Central switchboard system (private branch exchange).

In the intercommunicating system each station can make its own connections without a central operator. The selective talking system requires that at least one wire for each telephone be connected for every telephone on the system, and besides these, other wires are necessary, depending upon the plan of wiring adopted. In the selective talking circuit system as many conversations can take place at the same time as there are pairs of instruments; the common talking circuit only allows one conversation at a time. With common ringing all bells ring when one button is pressed and code ringing is therefore necessary.

In the central switchboard system the services of an operator are necessary and this system does not differ materially from regular city exchanges except in the number of telephones.

Intercommunicating Systems.—As an example of a successful means of interior communication, a common ringing, common talking system manufactured by the Holtzer-Cabot Co. is shown in Fig. 438.

This system requires only four common wires. Across the different pairs of these wires the corresponding terminals of each set are connected. Two batteries are required, one for ringing and one for talking. In series with the talking battery an impedance coil is connected to prevent the high frequency talking currents from entering the battery. Each battery consists of three dry cells which give about four volts. Six telephones may be connected and operate satisfactorily. If more than six telephones are connected or if the lines are unusually long, the bells must be wound to a higher resistance.

To explain briefly the operation of the system, assume that station No. 1 desires to call No. 3. The key, k_1, is depressed. This makes a connection between the line wire *C* which is connected directly to one terminal of the ringing battery, and wire *X*, to which one terminal of every bell is connected through the contact made by the other keys resting against their upper contacts. The other terminal of each bell is connected directly to the other battery terminal through line *A* and the receiver hooks pressing on their lower contacts. Therefore, all three bells will ring, so some code or designated ring as one long and one short ring is necessary to call the party at (3). When the receivers at (1) and (3) are taken

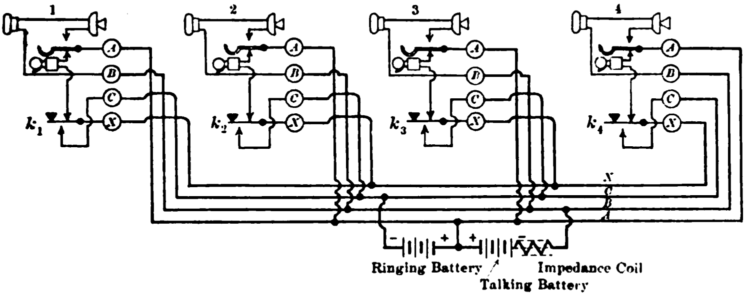


FIG. 438.—Common Ringing, Common Talking System.

from their hooks, the talking instruments are in series with one another, and the talking current is being supplied by the battery.

Fig. 439 shows a selective ringing, common talking system. This system is similar to the system shown in Fig. 438 with the addition of the wires necessary for selective ringing. Three common wires, *ABD,* plus one for each telephone installed to all telephones are required. The talking system is the same as that described in the common talking system in Fig. 438. The selective ringing feature may be traced out quite easily.

In wiring intercommunicating systems it is customary to make all the wires connecting the stations and such extra wires as may be needed, in one cable, each wire being insulated from the other, and the whole completed cable insulated. The wiring from the instruments and connection terminals is made in one cable and lead to connection boxes fitted with properly marked terminals. The connecting cable between stations is then led to these terminal boxes, and connecting pieces are soldered to the wires of the cable and

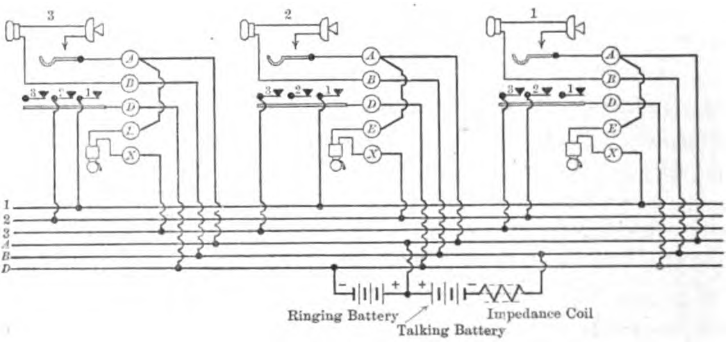


FIG. 439.—Selective Ringing, Common Talking System.

secured to the terminal contacts. Fig. 440 shows the cabling connections of a typical intercommunicating system and is recommended by the Western Electric Company.

FIG. 441.—Typical Wall set.

FIG. 442.—Typical Desk Set.

Fig. 441 shows a typical wall set and Fig. 442 a typical desk set for selective ringing. Both are manufactured by the Western

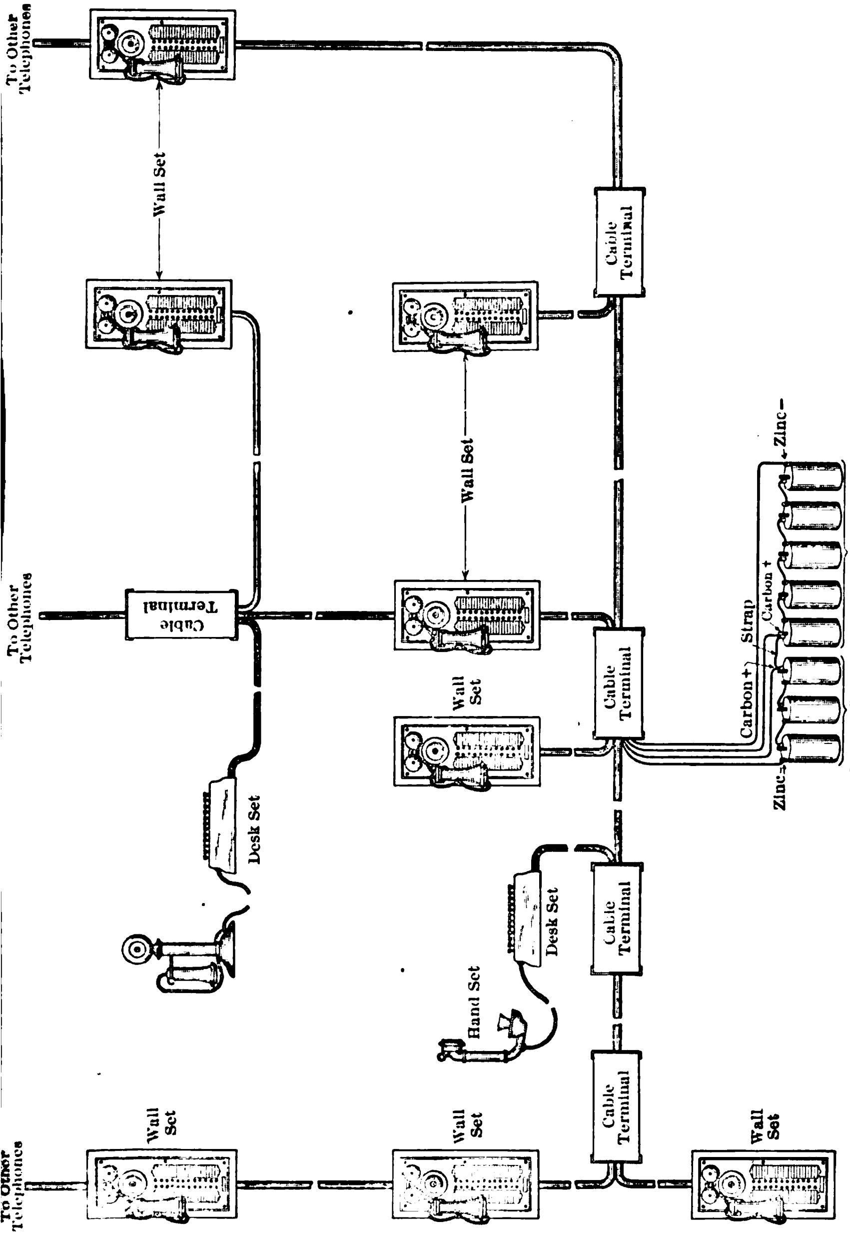


FIG. 440.—Diagram Showing Cabling of a Typical Inter-phone System.

Electric Company. A typical Holtzer-Cabot hand set is shown in Fig. 443.

FIG. 443.—Typical Hand Set.

Navy Standard Telephones.

Telephone instruments, switchboards and typical circuits as used on board our ships of war are dealt with in Chapter X, Vol. II, Electrical Interior Communications.

CHAPTER XXVI.

THE PRINCIPLES OF RADIO TELEGRAPHY.

DEFINITIONS.

An **alternating current** is one that periodically reverses its direction in its circuit, flowing first in one direction and then in the other. This alternating current is due to an alternating E. M. F., that gradually increases from zero to a positive maximum then decreases to zero, and then reverses its sign, increases to a negative maximum and then decreases to zero.

The greatest positive or negative values of the alternating current is called the **amplitude** of the alternations.

Each complete set of operations is called **a cycle.**

The time that elapses between the commencement of the current in one direction and its beginning again in the same direction is called a **period.**

The number of periods per second is called the **frequency** of the alternations.

A **high frequency alternating current** is one in which the frequency is reckoned in thousands, and, for convenience, if the frequency is above 1000, such an alternating current is said to be of high frequency and below that number it is said to be of low frequency.

An **electric oscillation** is defined to be an alternating current whose frequency is reckoned in the hundreds of thousands.

Sustained or undamped oscillations are those in which the alternations do not lessen in their amplitude.

Damped oscillations are those consisting of a limited number of alternations, the amplitudes of which are continually decreasing.

Under damped oscillations, if the lessening of the amplitude is very rapid, they are called **strongly damped** oscillations, and if it is slow, they are called **feebly damped** oscillations.

Electric Waves.*

It is by means of so-called electric waves that radio signals are transmitted. The propagation of these waves and their detection constitute radio telegraphy.

To James Clerk Maxwell, whose brilliant mind first conceived the true nature of electric waves, rightly belongs the honor of outlining the fundamental principles upon which all developments in radio telegraphy have been based.

In 1865 Maxwell promulgated his famous paper upon the electromagnetic theory of light. This paper was the result of a careful mathematical analysis of the experimental work of Faraday.

The theory of Maxwell was that electric oscillations produce electric waves in the surrounding ether and that these waves travel with the velocity of light, and that light itself is simply electric waves of very short wave lengths.

The experiments of Faraday in reference to electromagnetic and electrostatic fields have been referred to in previous chapters of this book. The experimental facts upon which Maxwell based his paper may be summarized as follows:

I. When current is flowing through a conductor a magnetic field is established in the surrounding space.

II. When the magnetic field surrounding a conductor varies in strength an E. M. F. is induced in the conductor.

III. That the space between two charged bodies is filled with so-called lines of electric force and that energy is stored in the separating medium.

About 1880, Sir Oliver Lodge conducted some experiments using two circuits each of which contained a condenser and a spark gap. The inductance of one circuit was made variable. Oscillations were set up in the circuit of constant inductance by connecting the terminals of its condenser to the knobs of an electric machine and producing condenser discharges across the spark gap. By varying the inductance gradually in the other circuit it was noted that at a certain point sparking was produced, though no direct energy had

* Also called electromagnetic waves or ether waves. The lines of electrostatic stress are assumed to be surrounded by lines of magnetic stress at right angles to their direction and to the direction of propagation of the waves.

been applied to this circuit. According to Maxwell's theory this energy was due to the electric waves propagated by the other circuit.

In 1888, Professor Hertz carried out a series of experiments demonstrating clearly the existence of the electric waves propagated by electric oscillations and showed that these waves could be reflected, refracted and polarized and had the properties of light waves. He also measured the wave length of electric waves. A description of these experiments will be found in any standard text book in physics. In view of the inestimable value of this work as outlined above, electric waves are sometimes called Hertzian waves.

Electric Oscillations.

The production of oscillations is necessary in radio telegraphy. Electric oscillations may be produced in the following ways:

I. Condenser discharge.
II. Arc.
III. High frequency alternator.

In 1842, Professor Joseph Henry, of Princeton University, while conducting a system of experiments became convinced that the discharge of a condenser under certain conditions was oscillatory in character. Prior to this time it had been assumed that the discharge consisted merely of the neutralization of the opposite charges of the two plates. These conclusions of Henry were verified by later experiments; and in 1853 Lord Kelvin deduced a beautiful mathematical proof which gave the theoretical relation that must exist between the resistance, inductance and capacity of the condenser circuit in order that the discharge should be oscillatory. If current is flowing in the circuit by Ohm's law the sum of the instantaneous values of the E. M. F.'s will equal to zero. That is:

$$Ri + L\frac{di}{dt} + \frac{q}{C} = 0. \quad \text{But } i = \frac{dq}{dt}, \text{ and } \frac{di}{dt} = \frac{d^2q}{dt^2}.$$

The equation now becomes

$$\frac{d^2q}{dt^2} + \frac{R}{L} \cdot \frac{dq}{dt} + \frac{q}{LC} = 0.$$

The solution of this differential equation gives a value for q, therefore i; and by mathematical deduction it can be shown that when $R > \sqrt{\frac{4L}{C}}$ the current is unidirectional, rises to a maximum and dies away; but when $R<\sqrt{\frac{4L}{C}}$ the current is oscillatory. In the mathematical deduction of the relation existing between R, L and C in a condenser circuit, the fact that the value of a resistance in an oscillatory circuit is not the same as its value in a continuous or low frequency alternating circuit was not considered, but it is sufficient to remember that when the resistance of a condenser circuit is small compared with its inductance, the discharge will be oscillatory. In this case i, the instantaneous value of the current is given by the equation

$$i=\frac{2E}{\sqrt{\frac{4L}{C}-R^2}}\cdot\epsilon^{-\frac{Rt}{2L}}\sin\left\{\left(\sqrt{\frac{1}{LC}-\frac{R^2}{4L^2}}\right)t\right\}.$$

in which E = initial value of the E. M. F. in volts,

L = the inductance in henries,

C = capacity in farads,

R = resistance in ohms.

This is in the general form of an equation for an alternating current of decreasing amplitude, $i=p\sin\omega t$ where

$$\omega=2\pi f=\sqrt{\frac{1}{LC}-\frac{R^2}{4L^2}}\qquad\therefore f=\frac{1}{2\pi}\sqrt{\frac{1}{LC}-\frac{R^2}{4L^2}},$$

and when the value of R is small compared with L the equation becomes $f=\frac{1}{2\pi\sqrt{LC}}$. This equation is called the fundamental equation of radio telegraphy. It is of great importance as it demonstrates the fact that every body has an electrical as well as a mechanical period of vibration and that the frequency of the electrical vibration may be considered as depending solely upon the inductance and capacity.

In Fig. 444 a typical spark circuit is represented with a capacity at C, an inductance at L and a spark gap at S. If an alternating E. M. F. is applied at the terminals of C, energy will be stored in the condenser which is equal to $\frac{1}{2}CE^2$ where E is the instantaneous value of the applied E. M. F. and C the capacity of the condenser. The energy is stored in the electrostatic field located in the dielectric of the condenser. When the value of E becomes sufficiently large the air dielectric at S is ruptured, and a spark jumps across and oscillatory currents flow in the circuit which have a period depending upon the capacity and inductance of the spark circuit.

It has been stated in the previous chapters that every conductor possesses a certain amount of resistance, inductance and capacity. In the case of a long, straight wire these properties are said to be distributed. In the circuit shown in the figure the inductance and capacity are said to be concentrated. There is a certain amount of inductance and capacity distributed throughout the circuit, but it is so small compared with the concentrated effects that it may be

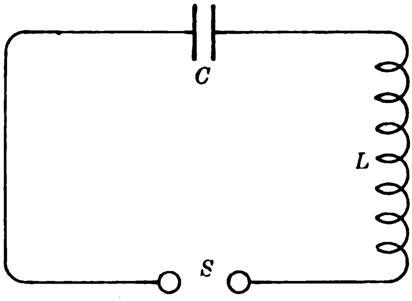


FIG. 444.—A Typical Spark Circuit.

ignored. Such a circuit as described above constitutes an important part of every apparatus used to produce damped electric waves. In radio telegraphy this circuit is called the oscillating circuit. In the discussion of this circuit it is interesting to assume in the first place that there are no losses and that all energy that is stored up in the condenser when the spark gap was ruptured remains in the circuit.

At the instant then that the sparking begins all the energy is electrostatic and, as noted above, is equal to $\frac{1}{2}CE^2$ where E represents the difference of potential of the condenser plates. Due to this difference of potential a current flows through the circuit, and since the resistance of the circuit is neglected the instantaneous value of the terminal E. M. F. will be equal to $L\frac{di}{dt}$. As a harmonic current flows, its instantaneous value is given by the equation $i=I \sin \omega t$

where I equals the maximum value of the current and ω equals the angular velocity. Therefore,

$$e = L\frac{di}{dt} = LI\omega \cos \omega t.$$

At the end of one-quarter of a period this E. M. F. becomes equal to zero and no difference of potential exists between the condenser plates and hence there is no electrostatic field. The energy of the circuit is now all electromagnetic and is equal to $\frac{1}{2}LI^2$ where I is the maximum value of the current, and at the end of the half period the condenser is charged again at the same potential, but the polarity of the plates is reversed. The condenser immediately begins to dis-

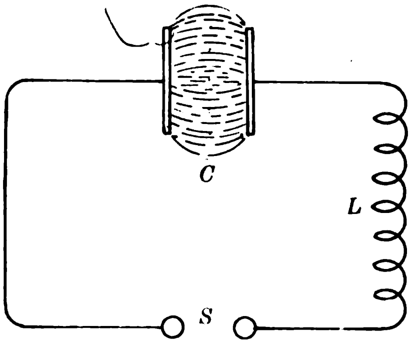


FIG. 445.—Electrostatic Field.

charge again and at the end of the three-quarter period the E. M. F. is again zero and there is again no difference of potential between the plates of the condenser. At the end of the full period the circuit is again restored to its original electrical condition. If there were no losses these oscillations would continue forever.

In the actual oscillating circuit, energy is expended in heat at the arc and in the resistance; and some energy is radiated and, therefore, comparatively few oscillations take place before the potential difference becomes too small to rupture the spark gap. The oscillation then ceases until the condenser is again charged to the required potential from an outside source.

In Fig. 445 an attempt is made to represent the electrostatic field of the condenser. Due to the rapid reversal of polarity of the plates some of the stress lines of the electrostatic field are supposed to become detached and propagated through space as electric waves. This is called radiation. As the electrostatic field is concentrated in the arrangement of this circuit there is very little radiation and therefore this circuit is called the oscillating circuit to distinguish it from the antenna circuit which is called the radiating circuit.

In Fig. 446 the concentrated capacity of the condenser is replaced by two capacities C and C' in the shape of metal plates. If the plates are at a difference of potential an electrostatic field will be established between them which may be represented by lines of electric force terminating on the plates. When oscillating currents are established in this circuit there will be rapid reversal of polarity in the plates and electric waves will be radiated. This was the principle of the Hertz oscillator. The period of the oscillations and radiated waves depended upon the inductance and capacity of the circuit In this circuit the plates C, C', are subjected to maximum changes of potential while the maximum changes of current take place at the spark gap. As the spark gap is supposed to be a perfect conductor when sparking there will be no difference of potential at that point. Hence the ends of the circuit will represent potential loops and current nodes and the spark gap will be a potential node and current loop.

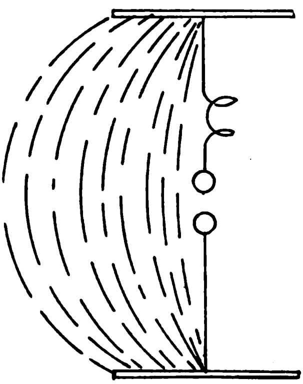


FIG. 446.—Principle of Hertz Oscillator.

To Marconi falls the honor of first demonstrating the practical uses of electric waves for sending distant signals. In his experiments, he used an antenna with the lower end grounded to radiate the electric waves.

The principle of this apparatus is shown in Fig. 447. This method of grounding the antenna is used exclusively, as it has been shown that the waves are guided by the earth and thus act more efficiently than waves propagated into space. The principles of the earthed waves is explained by a knowledge of the so-called theory of images.

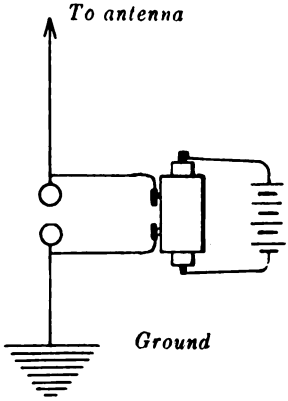


FIG. 447.—Simple Marconi Circuit.

If A is a body charged to a potential of $+V$ units near the earth, the electrostatic field is as represented in Fig. 448 showing the lines of electric force linking the charge to the earth.

If two isolated balls are charged, one to a potential of $+V$ units and the other to a potential of $-V$ units assuming the earth at zero potential, the electrostatic field would be as represented in Fig. 449. The plane DC midway between the charges would be a plane of zero potential. Thus, the electrostatic field of a charged body near the earth may be studied by assuming a similar charge of opposite potential at the same distance below the surface of the earth. Therefore, an earthed circuit acts in the same manner as a Hertz circuit on the assumption that one-half of the Hertz circuit is below the surface of the earth. In the case of the earthed antenna the upper end represents a potential loop and a current node, while the grounded end is a current loop and a potential node.

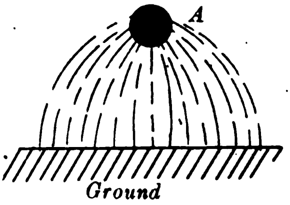


FIG. 448.

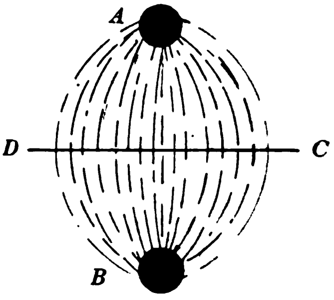


FIG. 449.

Illustrating the Theory of Images.

In the simple Marconi circuit a source of oscillating E. M. F. of high potential was applied directly to a spark gap located in the antenna. An induction coil was used to produce the high E. M. F. required.

Resonant Circuits.—In all the later systems of producing damped oscillations resonant circuits are employed. The experiments of Sir Oliver Lodge with his resonant Leyden jars has been described. It has been shown that the frequency of electrical oscillations of any circuit is given by the equation $f=\frac{1}{2\pi\sqrt{LC}}$. From this equation it will be seen that the frequency depends upon LC, the product of the inductance and the capacity. Two circuits will be in resonance if this product LC is the same for each circuit. If two resonant circuits have their inductances near together or if they are connected in any way it can be shown that if energy is imparted to one circuit and it begins to oscillate, that after a small interval of time the energy

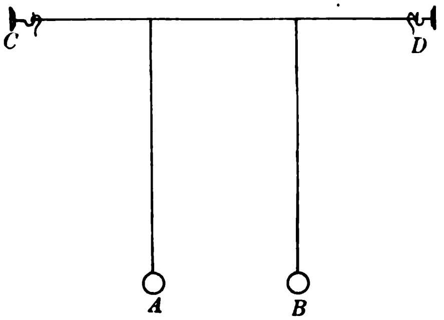


FIG. 450.—Transfer of Energy Between Resonant Circuits.

will be transferred to the other circuit and a short time later returned to the original circuit. The energy is thus transferred back and forth between the two circuits until it is radiated or expended in heat.

A good idea of this transfer of energy between resonant circuits can be obtained from the behavior of two similar pendulums attached to a flexible support. (Fig. 450.)

Two equal pendulums consisting of two bobs attached to strings of equal length are attached to the flexible supporting line CD. If A be made to vibrate it will be noticed that B will soon be affected, and in a short time the amplitude of B's vibration will become almost equal to the original amplitude of A's vibration while A will cease to vibrate. B then begins to transfer energy to A which takes up the vibrations while *B* loses energy and comes to rest again. This transfer of energy continues until the energy of the system is expended, due to the resistance of the air, etc.

If the two pendulums are near together, the transfer of energy is rapid and illustrates close coupling. If the pendulums are separated the energy is transferred slowly, representing loose coupling. If the lengths of the pendulums are not nearly the same no transfer of energy will take place as they are not in resonance.

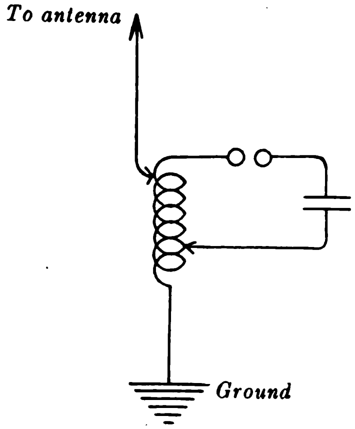


FIG. 451.—Direct Coupling.

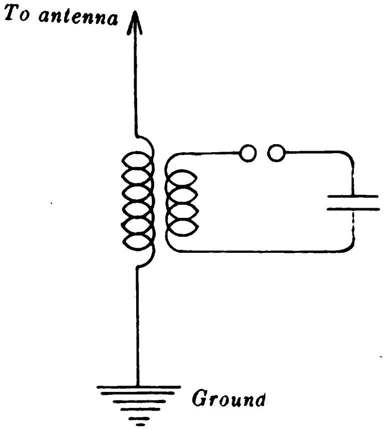


FIG. 452.—Inductive Coupling.

Due to this property of resonant circuits it is usual to have a closed or oscillating circuit and an open or radiating circuit in transmitting sets.

It is thus seen that to send out radio signals the following apparatus is desired:

I. A source of alternating current.

II. A transformer designed to give an E. M. F. of 10,000 to 30,000 volts at the terminals of the secondary.

III. A spark circuit containing a condenser connected across the terminals of the secondary.

IV. An antenna or radiating circuit in resonance with spark circuit and directly or inductively connected to it.

In the first sets supplied to the navy, induction coils were used to supply a high alternating E. M. F. A source of continuous current was connected to the primary and some form of interrupter was used to induce the high alternating E. M. F. in the secondary. This system has been replaced by motor generators generating alternating current and a transformer, the secondary of which consists of many turns in order that the high E. M. F. necessary to charge the condenser may be provided. The spark gap is so adjusted that it breaks down at the potential desired and produces oscillations in the closed circuit.

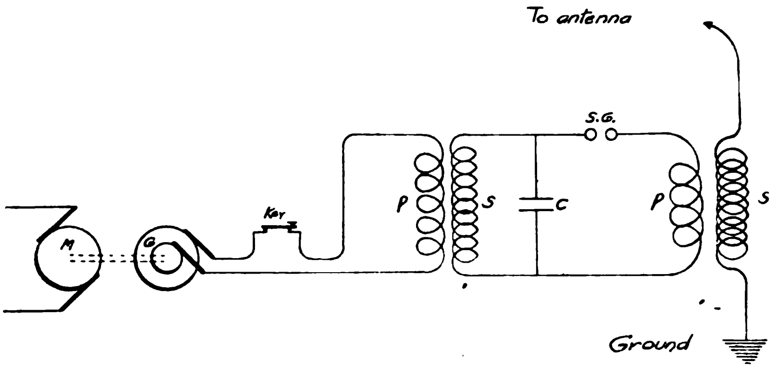


FIG. 453.—Elementary Radio Transmitting Set.

There are two methods of connecting the oscillating and radiating circuits. These are illustrated in Figs. 451 and 452.

In Fig. 451 the antenna is directly connected to the closed circuit and the two circuits are said to be directly connected. In Fig. 452, the inductances of the two circuits are near each other and the circuits are said to be inductively connected. If the mutual inductance of the two circuits is great they are said to be tightly coupled or closely coupled. If the mutual inductance of the two circuits is small they are said to be loosely coupled.

Fig. 453 is an elementary diagram of a radio transmitting set. The circuits to be considered are as follows:

1. The primary circuit consisting of the armature winding of the alternators, the leads to transformer and the primary winding of the transformer.

2. The secondary circuit consisting of the secondary winding of transformer, the leads to the condenser and the condenser.

3. The closed or oscillating circuit consisting of the condenser inductance and spark gap in series.

4. The open or radiating circuit consisting of the antenna with its inductance and ground.

5. A circuit consisting of the secondary of the transformer, the inductance and spark gap. This circuit is not effective unless the spark gap remains conducting which would be the case if an arc were formed and in this case the condenser is short circuited and there is practically no energy transferred to and radiated by the open circuit.

The frequency of the primary and secondary circuits is determined by the frequency of the alternator supplying the energy. In the first radio sets used in the navy 60-cycle alternators were used. This was the frequency used for commercial purposes. The frequency was later changed to 120 and at the present time 500-cycle alternators are used almost exclusively on board naval vessels.

It has been determined by experiments that a radio transmitting set works more efficiently when the natural frequency of the secondary circuit as determined by its capacity and inductance is the same as the generator frequency. This fact is taken into consideration in the design of the transformer.

Reactance regulators or choke coils consist of variable inductances in series with the primary whereby the impedance of the circuit can be changed and current regulated.

In all the later radio sets the spark gap is set so that it breaks down only once each alternation. That is when the terminal E. M. F. of the secondary circuit reaches its maximum value.

Due to the great number of turns in the secondary and the iron core of the transformer that circuit has a very large inductance and hence a very much larger natural period than the oscillating circuit. When the condenser discharges take place the closed circuit oscillates as if it were entirely disconnected and independent of the secondary circuit. When using a 2000-meter wave these oscillations have a frequency of 150,000 per second. In a very minute fraction of time the secondary E. M. F. falls below the value required to break down the spark gap, and the resistance of the closed circuit becomes enormously great and the oscillations cease. Owing to the high frequency, however, a certain number of oscillations have taken place. This energy is transferred to the open circuit, which is in resonance, and radiated as electric waves. The energy radiated at each alternation of the charging current is called a wave train.

If the alternator has a frequency of 500 the number of alternations will be 1000 and the distance between wave trains will be $300{,}000{,}000 \div 1000 = 300{,}000$ meters. In all wave motion $V = f\lambda$ where V equals the velocity of propagation and f the frequency and λ the wave length. The velocity of propagation of electric waves is assumed to be $3(10)^8$ meters per second.

If we assume that 10 oscillations take place and that 10 waves are radiated at each condenser discharge and that the wave length is 2000 meters, the thickness of a wave train would be 2000×10 or 20,000 meters.

The Sending Circuit.—An elementary diagram of a typical sending circuit is given in Fig. 453. The considerations governing the design of the various parts of this circuit will now be discussed.

It has been noted that the frequency of the alternator is usually 500. The reason for the adoption of this frequency is that telephone receivers are used in the detector circuits for receiving signals, and the frequency of the vibrations imparted to the diaphragm of the telephone receiver depends upon the number of wave trains. If the spark gap is set to break down once each alternation the number of wave trains will equal the number of alternations of the alternator. The human ear is more sensitive to vibrations of some frequency than of others. By increasing the frequency from 120 to 500 the distinctness of signals was greatly intensified. Dr. Austin, of the Bureau of Standards, conducted a most interesting series of experiments in this connection which are given in the Bureau of Standards' pamphlet. In designing the transformer the natural frequency of the secondary circuit is made the same as the generator frequency since experiments have shown that this produces greater efficiency.

The amount of energy stored in the condenser of the oscillating circuit at discharge depends upon the capacity of the condenser and the maximum E. M. F. of the secondary. It is equal to $\frac{1}{2}CE^2$ where

C = capacity of condenser.

E = maximum value of applied E. M. F.

By making the capacity of the condenser large a great amount of energy can be stored in the closed circuit and a very large momentary current can be made to flow. This will be illustrated by a numerical example:

Example.—The maximum value of the E. M. F. applied to the terminals of the condenser of a closed circuit is 20,000 volts. If the condenser discharges at this potential, what will be the energy stored in the circuit and what will be the maximum value of the current? Neglect losses. The capacity of the condenser is .01 microfarad and the inductance of the circuit is equal to 0.1 millihenry.

$$\text{Energy } W = \tfrac{1}{2}CE^2 = \frac{1 \times .01 \times 4(10)^8}{2(10)^6} = 2 \text{ joules.}$$

If the losses are neglected the energy of the circuit is also equal to $\frac{1}{2}LI^2$ where I is the maximum value of the current. Hence,

$$\tfrac{1}{2}LI^2 = 2.$$

$$I^2 = \frac{4}{L} = 4(10)^4.$$

$$I = 200 \text{ amperes.}$$

In order to vary the period of the closed circuit the capacity or inductance must be varied. It is usual to keep the capacity fixed and use a variable inductance.

The reason for using an oscillating circuit coupled to a radiating circuit, instead of inserting the spark gap directly in the antenna circuit, is that on account of the small natural capacity of the antenna it would be necessary to use a very high applied E. M. F. and a long spark gap to store sufficient energy in the circuit. This has practical disadvantages. By calibrating a closed or open circuit is meant to vary its capacity or inductance, generally the latter, in order to give it a prescribed wave length. This calibration is done by means of a wave meter which consists of a closed circuit whose inductance or capacity can be varied at will, and the resultant wave length can be read off on a small scale provided. A description of a standard type of wave meter will be given in the next chapter. By tuning a circuit is meant to vary its inductance or capacity or both so that it will have the same period as another circuit. Leyden jars were usually used for the capacity of the closed circuit. A standard .002 microfarad jar is manufactured. Any desired capacity can be obtained by arranging these jars in parallel or series parallel. A description of a plate condenser used with a later type of radio transmitting set is given in the next chapter.

The Antenna.—The capacity of the antenna is the capacity of the aerial wires. This capacity is increased by using several parallel wires. In the early experiments, efforts were made to have the aerial as high as possible as it was thought that the waves were projected in straight lines and that the curvature of the earth would interfere

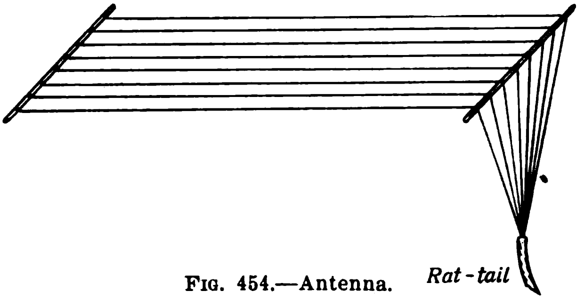


FIG. 454.—Antenna.

with the reception of a signal at a distant station. This has been found to be an error as the waves are guided by the surface of the earth. The natural length of the wave radiated by a grounded vertical wire is about four or five times the length of the wire.

The general type of antenna used for vessels of the navy is illustrated in Fig. 454. The most of the capacity is concentrated in the parallel horizontal wires. This is called an L-shaped antenna.* If the rat tail were connected at the center of the horizontal wires, the antenna would be called a T-shaped antenna. Recent experiments have demonstrated that the T-shaped antenna is the more efficient radiating circuit. The antenna must be well insulated from the mast and supporting rigging.

The fundamental wave length of the radiating circuit depends upon its inductance and capacity, the latter depending primarily

* Also called an inverted L antenna.

upon the number, length and spacing of the horizontal wires and the height of the center of capacity above the earth. When the antenna is coupled for sending, the wave length is increased depending upon the amount of inductance used in coupling. When very long waves are sent out with an antenna having a short fundamental wave length, it becomes necessary to use an extra inductance or loading coils in the antenna connection to ground. In sending waves shorter than the fundamental, a capacity is used in series with the antenna inductance to reduce its effective value. In some receiving sets, a variable condenser is used in series with the antenna inductance to adapt it for short waves and in parallel when long waves are being received.

For large shore stations like Key West and Arlington three towers are used occupying the vertices of a triangle, and systems of parallel wires are supported by these towers thus giving a larger capacity at a greater resultant vertical distance above the earth.

The quality of the ground has an important effect on the efficiency of the radiating circuit. In the theoretical discussion of grounding the lower end of the antenna it was assumed that the earth was a perfect conductor. This is not always true, and it is important that the ground used at the sending station should be a good one. The ground connection is generally made by burying large metal plates or sheets of wire netting to which the lower end of the antenna is connected. At Arlington the station is located on a small hill where the soil is generally dry and that probably explains the reason why the efficiency is not greater than it is. The new station at Darien on the Isthmus of Panama will be located differently and being almost entirely surrounded by water with a powerful installation and well-designed antenna it is hoped that new records will be established in long distance communication. The importance of having additional natural capacity in aerials will be understood by reference to the equation $W=\frac{1}{2}CE^2$ which represents the energy delivered to the closed circuit at each alternation. If all the energy could be transferred to the open circuit and its capacity was only one-ninth that of the closed circuit the maximum E. M. F. would be three times as great. This rapid rise of E. M. F. in the antenna limits to a great extent the power used.

Spark Gap.—To be efficient a spark gap should be a perfect insulator before it breaks down or oscillations begin and a perfect conductor during the short period in which the oscillations continue. One trouble experienced with the earlier forms of spark gaps was that it remained conducting after the E. M. F. had fallen below that for which the gap was designed to break down. This was supposed to be due to the volatile gases between the electrodes. One of the means used to prevent this was to use an electric fan to cool the arc and cause the gap to resume its non-conducting properties.

Coupling Circuits.—Reference has already been made to the method of coupling the closed and open circuits. The oscillation transformer is the name given to the air-core transformer which includes the mutual inductances of the closed and open circuits.

These two circuits are disconnected and tuned to the same wave length and are then either inductively or directly connected in order that the transfer of energy should take place. The rapidity with which the transfer takes place depends upon the degree of coupling. It has been found that under ordinary conditions the coupled circuits radiate two waves, one longer and one shorter than the natural wave of either circuit. The variation between the wave lengths of the two waves is dependent upon the degree of coupling. With a tight coupling there existed quite a difference between the waves and with a very loose coupling there was very little difference and practically the natural waves were radiated.

This phenomenon was caused by the mutual induction of the circuits. This mutual inductance virtually changed the self-inductance of each circuit upon which the period depended and the result was the propagation of a wave with two humps. This resulted not only in a loss of efficiency, but also affected adversely the sharp tuning of the receiving circuit. The difference between the lengths of the two waves sent out divided by the natural wave length is called the percentage of coupling. If the natural wave length of each circuit is 1000 meters and waves of 1100 and 900 meters are produced, the percentage of coupling equals

$$\frac{1100-900}{1000}=20 \text{ per cent.}$$

When very close coupling is employed the difference between the humps becomes very great. A wave sent out under these conditions is called a broad wave, as it may be detected by receiving stations, tuned to a wide variation in wave lengths. When very loose coupling is used a select wave is radiated which will not be heard by a receiving station selectively tuned to a wave length materially different. Therefore, in sending out distress calls a very tight coupling is used so as to be detected by all stations within radius, although they may be tuned to a wide variation in wave lengths. By increasing the coupling the energy transferred to the antenna is increased, but a broad wave is sent out which is more strongly damped. By decreasing the coupling the energy transferred is less, but the waves are more select and the damping less. Excessive damping renders sharp tuning difficult. It has been found that very sharp tuning is impossible when a wave train consists of less than 15 oscillations. To prevent interference, therefore, stations are forbidden by law to use a greater log decrement than two-tenths. This decrement corresponds to about 15 oscillations per wave train.

Log Decrement.

The logarithmic decrement is the Napierian logarithm of the ratio of the two successive maximum currents in the same direction. It is designated by the symbol δ. The equation for the instantaneous current in a set of damped oscillations is as follows:

$$i = I\epsilon^{\frac{-Rt}{2L}} \sin pt$$

where I represents any maximum value of the current and ϵ the base of the Napierian system of logarithms, R the high frequency resistance and L the inductance. Let $I_1 I_2 I_3$ represent successive maximum values and if T equals the period and sin pt equals unity, we have

$$I_1 = I\epsilon^{\frac{-RT}{2L}} \qquad I_2 = I\epsilon^{\frac{-RT}{L}},$$

$$I_3 = I\epsilon^{\frac{-3RT}{2L}}$$

$$\therefore \frac{I_1}{I_2} = \frac{I_2}{I_3} = \epsilon^{\frac{RT}{2L}}$$

$$\text{Log decrement} = \log \frac{I_1}{I_2} = \frac{RT}{2L} = \frac{R}{2fL}.$$

This formula cannot be used for finding the log decrement of a transmitting circuit on account of the difficulty of determining the value of R and L. The practical method of finding the log decrement is by using a wave meter whose log decrement is known or can be obtained from the equation $\delta = \frac{R}{2fL}$. It has been proved mathematically that when two circuits are loosely coupled the combined decrements are given by the following equation:

$$\delta_1 + \delta_2 = 2\pi \left(1 - \frac{\lambda}{\lambda_m}\right) \sqrt{\frac{I^2}{I^2_m - I^2}},$$

where λ_m represents the wave length corresponding to resonance, and I_m the corresponding value of the maximum current; and where λ is another value of the wave, less but nearly equal in value to λ_m, and I the corresponding value of the current.

If in the above equation I^2 be taken equal to $\frac{1}{2} I_m^2$, $\sqrt{\frac{I^2}{I^2_m - I^2}}$ reduces to unity and the equation becomes

$$\delta_1 + \delta_2 = 2\pi \left(1 - \frac{\lambda}{\lambda_m}\right).$$

This affords a simple method of finding the value of the log decrement which is sufficiently accurate for practical purposes. It is customary with radio operators to use a modified form of the above equation which permits the use of wave-meter condenser readings in degrees instead of wave lengths. Since frequencies are inversely proportional to wave lengths, the last equation may be written

$$\delta_1 + \delta_2 = 2\pi \left(1 - \frac{f_m}{f}\right),$$

where f_m and f represent the frequencies corresponding to λ_m and λ, respectively. Substituting in this equation $\frac{1}{2\pi\sqrt{LC_m}}$ for f_m and $\frac{1}{2\pi\sqrt{LC}}$ for f, it becomes

$$\delta_1 + \delta_2 = 2\pi \left(1 - \frac{\sqrt{C}}{\sqrt{C_m}}\right),$$

where C and C_m represent capacities of the wave meter corresponding to the two conditions.

The capacity depends upon the area of the plates used in the variable condenser. In the usual semicircular plate type, the area is proportional to the square of the circular measure of the arc common to the two sets of plates. This equation may then be written

$$\delta_1 + \delta_2 = 2\pi\left(1 - \frac{C'}{C'_m}\right),$$

where C' and C'_m indicate the condenser reading in degrees for the two conditions chosen.

Given below are instructions for finding the log decrement based upon these principles:

1. Loosen the coupling of the oscillation transformer. Place the fixed inductance or pick-off coil of the wave meter close enough to the transmitter to get a good deflection of the watt meter, but not close enough to throw the needle off the scale.

2. Determine the position of resonance on the condenser by moving the pointer over the condenser scale. When this position is found the watt meter will give a maximum reading. Make note of the condenser reading in degrees at the position of resonance and call this C'_m.

3. Run the pointer over maximum until the watt-meter reading falls to one-half of that at maximum. Call this condenser reading C'_1.

4. Run the pointer under the maximum position until the watt-meter reading again falls to one-half its maximum reading. Call this condenser reading C'_2.

Then, by formula $\delta_1 + \delta_2 = \pi\left(\frac{C'_1 - C'_2}{C'_m}\right)$.

This gives the decrement of the transmitter plus the decrement of the wave meter. The decrement of the wave meter used must be known and subtracted from the total decrement which leaves the decrement of the transmitter.

The above formula gives the log decrement for a complete period. The readings being taken on each side of the position of resonance insures greater accuracy.

Sometimes the formula, $\delta_1 + \delta_2 = \frac{\pi}{2}\left(\frac{C'_1 - C'_2}{C_m}\right)$, is used which gives the log decrement for half a period. If this formula is used, the result obtained for $(\delta_1+\delta_2)$ must be multiplied by 2 and the log decrement of the wave meter subtracted to give the correct log decrement.

When this method is employed, it is necessary to use a wave meter whose decrement is known, and which is fitted with a wattmeter or device indicating effective values of the current.

The Receiving Circuit.—The receiving circuit like the sending circuit generally consists of an open and a closed circuit. It is customary to use the same antenna for sending and receiving. By means of a convenient switch, the operator can connect the antenna for sending or receiving as desired.

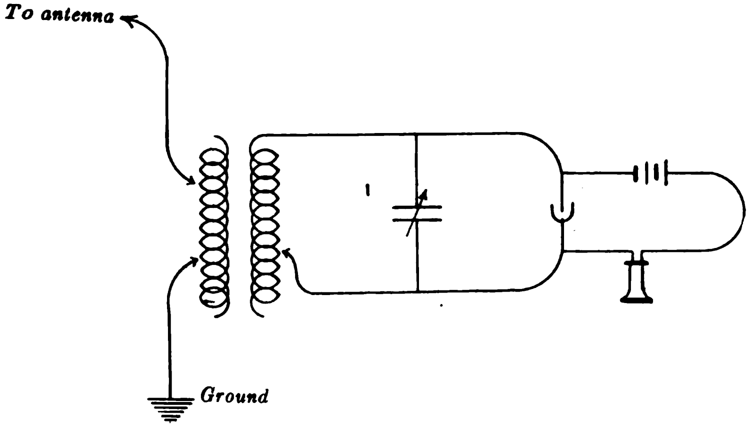


FIG. 455.—Elementary Receiving Circuit.

A typical receiving circuit is shown in Fig. 455. The closed circuit is similar to the closed circuit of the sending circuit except that the detector takes the place of the spark gap. The efficency of the receiving circuit depends upon its ability to receive the energy of the electric wave trains and utilize it to make definite signals on an indicating instrument. The indicating instrument generally used is a sensitive high resistance telephone receiver, although the energy of the wave train may be employed to operate a sensitive relay in connection with an ordinary telegraph receiving instrument.

Detectors.

The detector is the appliance used to utilize this energy to operate the indicating instrument. The necessity of an appliance of this kind will be apparent when it is realized that the oscillations have a frequency of 100,000 or more, and no instrument could be designed with so little inertia that these rapidly reversing oscillations could be indicated. The number of wave trains, however, is of the order of 1000 per second and by employing a suitable detector the combined energy of each train may be used to operate the indicating instrument causing definite signals to be made. The detectors now used for damped oscillations may be divided into three classes:

1. Electrolytic detectors.
2. Crystal or rectifying detectors.
3. Vacuum detectors.

The Electrolytic Detector.

The electrolytic detector consists of a small electrolytic cell with platinum electrodes. The electrolyte is a solution of nitric or sulphuric acid and is contained in the small cup *D*, Fig. 456. The positive electrode consists of a small platinum wire which is sometimes covered with glass so that only the point is left exposed. When a current from battery *B* flows through the electrolyte, electrolytic action begins and oxygen is left at the anode and hydrogen deposited on the cathode and the cell becomes polarized. The variable resistance *R* is used to regulate the current in the battery circuit. When a train of waves passes the energy is sufficient to overcome the polarized condition of the cell and allow current to flow and thus actuates the diaphragm of the telephone receiver *T*. This type of detector is now rarely used except for the purpose of comparing the sensitiveness of other forms of detectors.

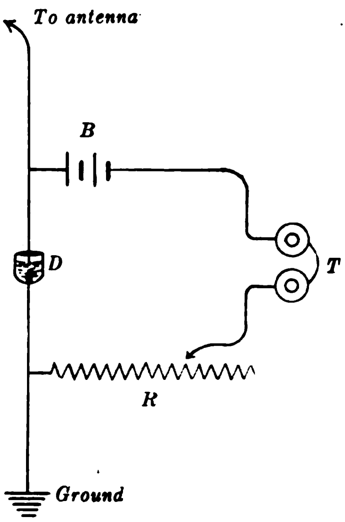


FIG. 456.—The Electrolytic Detector.

The Crystal Detector.

Crystal or rectifying detectors are at present very much more generally used than any other type. There are many varieties of this type. They are all based upon the discovery that where certain substances are brought together in more or less loose contact they form a combination which has the property of rectifying an alternating current.

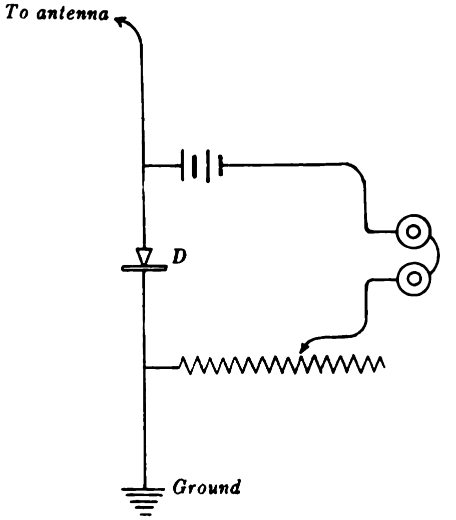


FIG. 457.—The Crystal Detector.

If a train of waves strikes an antenna as shown in Fig. 451 the detector *D* allows current to flow in one direction, but prevents its flow in the other; and, hence as the train passes, the upper part of the antenna will be charged to a different potential from the earth due to the sum of the successive impulses of the waves in the same direction. This E. M. F. acts with or against the battery E. M. F. and causes a change of current in the telephone circuit which actuates the diaphragm of the receiver. In some type of crystal detectors no battery is used and the indications of telephone receivers are made directly by the energy of the wave trains. In most forms of these detectors, however, a battery in circuit increases the distinctness of the signals. Some of the substances which, when used in combination, have this rectifying property are carbon and steel, silicon and any ordinary metal, bornite and molybdenite, etc.

Different crystals of the same substances vary greatly in sensitiveness. The sensitive spots in the crystal are found by trial, a testing buzzer being used to produce the oscillations. This operation is called "getting a point on a detector."

In the figures, for the sake of clearness, the detectors were shown connected directly in the antenna. In all practical receivers the detector is placed in a secondary circuit which, while receiving signals, is in resonance with the primary containing the antenna.

The Vacuum Detector.

This type of detector is very sensitive and has many advantages. It indicates by a rectifying process similar in principle to that described for the crystal detector. When a filament and a plate are placed in an exhausted bulb and not in metallic connection, the plate connected to the positive pole of a battery and the filament to the negative no current will flow as the circuit is not completed. If, however, the filament be heated to incandescence, thereby heating the enclosed gas and the battery is of relative high E. M. F., a current will flow. If connections of battery to filament and plate are reversed no current will flow. This shows that this device will allow current to flow under certain conditions in one direction, but not in the other. This peculiar effect is due to the cathode rays emitted from the cathode under the conditions given. This cathode stream flowing from the filament to the plate really consists of electrons of negative electricity which are propagated by the filament and bombard the positive plates. This is equivalent to a flow of positive electricity from plate to filament. This has the effect of making the gaseous medium a conductor for electricity flowing in one direction, but a non-conductor when the E. M. F. is applied in the opposite direction. If now a source of high frequency E. M. F. is applied to the terminals of this device a resultant minute positive charge will be deposited on the positive plate at every oscillation as the current can flow in one direction only. Due to this cumulative effect the resulting potential difference between plate and filament will be increased by the passage of each wave train. This will result in a momentary increase of current through the battery circuit. If a telephone receiver be placed in the circuit this change of current, due to the passage of wave trains, will be indicated by the sounds caused by the vibratory diaphragm. One of the great advantages of this type of detector is due to the fact that the conducting gaseous medium does not follow Ohm's law and when a critical potential difference between the plate and filament exists any small additional E. M. F. will cause a current to flow, which is out of all proportion to the increased E. M. F. It is this property which renders the detector

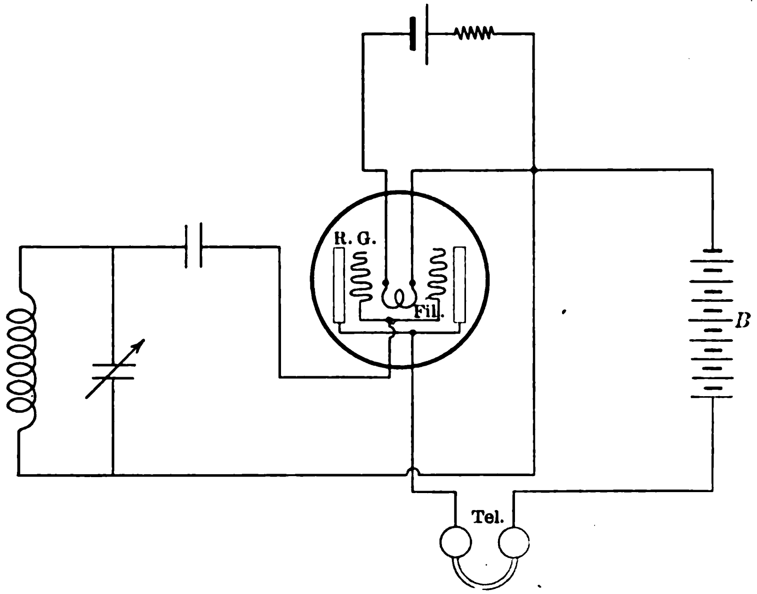


Fig. 458.—Elementary Diagram of Audion Detector Circuit.

so sensitive. Another advantage is that when the vacuum detector is once adjusted it remains so, and it is therefore unnecessary to be continually changing it as in the case of some other types.

The best known detector constructed on this principle is the "Audion," manufactured by the De Forest Radio Telephone and Telegraph Co. An elementary diagram is given above. (Fig. 458.) In addition to the plate and filament described above there is a "grid" or wire as shown. By connecting the source of high frequency to "grid" and filament, instead of plate and filament, a higher resultant E. M. F. is added at the passage of each wave train, due probably to the fact that the "grid" would be charged to a higher potential than the plate by the minute charges on account of its small capacity, or that owing to the uneven distribution of resistance in the conducting medium, the location of the grid makes the additional applied E. M. F. more effective.

One of the important developments of the "Audion" is the Audion amplifier which consists of a combination of two or three Audion bulbs and microphone attachments, which has the power of amplifying the signals as much as 50 to 75 times. Many of these amplifiers have been supplied to vessels of the navy.

Methods of Producing Undamped Oscillations.

The Arc Method.—The spark method of producing electric oscillations results in a series of damped waves. For many reasons it would be advantageous to use undamped waves. The elementary principle of the arc method of producing undamped waves is described in the chapter on Radio Telephony and a description of the Poulsen arc system, which has been used successfully, is described in the next chapter.

The High Frequency Generator Method.—The principle of this method is the same as the principle involved in the construction of an ordinary low frequency alternator. The mechanical difficulties to overcome have been very great as it is desired to have a frequency of 100,000 as well as a high power. Several alternators have been built with the high frequency required, but they have been usually of small power. The high frequency alternator invented by Dr. Rudolph Goldschmidt has been installed at New Hanover, Germany, and at Tuckerton, New Jersey. These stations have a normal output of 100 kilowatts and effective communication is carried out between them. The frequency employed is 50,000, which corresponds to a wave length of 6000 meters.

Receiving Devices for Undamped Oscillations.

In receiving damped oscillations as in the case of the usual spark method, attention has been called to the fact in using the telephone receiver as an indicator the frequency of vibration of the telephone diaphragm corresponded to the number of wave trains, and that it would be impracticable in this way to indicate the wave frequency as this would be about 100,000 and would be beyond the limit of audibility. In receiving persistent oscillations, therefore, some method must be devised to transform the frequency to the order of 1000 in order that it may be within the limits of audibility. This may be done by means of a "ticker" which makes and breaks the circuit at the required frequency. This results in a loss of energy and therefore a loss of intensity in the receiving signals. In the Goldschmidt system, a receiving device called the tone wheel is employed. This instrument is a frequency changer and it is claimed to be much more effective than the method outlined above.

The Heterodyne Receiver.—This receiver, invented by Professor Fessenden, is designed to receive and amplify signals made by persistent oscillations. It depends upon the production of "beats" caused by the interaction of two waves of different frequency. This action is analogous to the production of beats in music by the interaction of two sound waves of different frequency. It will be remembered that the resultant of two such waves, provided that the periods were constant, resulted in a wave which regularly waxed and waned in amplitude. The number of "beats" thus produced was equal to the difference in the frequencies of the two waves. This same action takes place when two ether waves of different frequency are impressed upon the same circuit. In the earlier forms of this device a static telephone was used as an indicator for the reason that the ordinary polarized telephone receiver could not be used directly in this circuit. It being necessary to use some indicating device of non-polarized type in which an effect is given which is proportional to integrated applied energy regardless of the polarity. It has been shown in the chapter on the Principles of Alternating Currents that indicating instruments for alternating currents must be based upon certain principles. The same principles hold here, and hence if an indicating device is to be used directly in the circuit to indicate the increase and decrease of current as shown by the beats it should be constructed on the dynamometer principle or that of the electrostatic attraction. Both of these methods were employed and, although signals were heard at a distance of 3000 miles, using a static telephone receiver both types were most inefficient indicators. The method of using the heterodyne is as follows: In receiving sustained oscillations of frequency of 100,000 a source of alternating current of a frequency of 99,000 was used at the receiving station. This current was under the control of the operator who could vary the frequency as desired to produce the proper number of beats when the local current interacted with the antenna current. A small high frequency alternator or an arc was used to produce the local current. In the example given above 1000 beats per second would be produced and a vibration frequency of 1000 would be imparted to

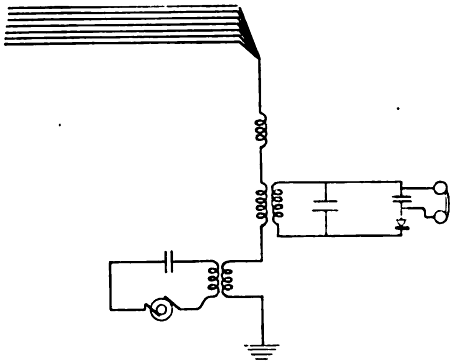


FIG. 459.—The Heterodyne Receiving Circuit.

the indicating device. In the latest forms of this receiver an arrangement has been designed which permits the use of the ordinary telephone receiver as an indicator. By this arrangement the efficiency has been greatly increased. This arrangement is shown in Fig. 459. It will be seen that the combined wave due to the antenna current and the local current is impressed upon the receiving circuit containing a rectifying detector. The current is thus rectified and the "beat" frequency is reproduced in the diaphragm of the telephone. The amplifying quality is due to the fact that the energy supplied by the local current, which is relatively large compared with the antenna current, causes the indicating force to be much greater than that due to the antenna current alone and this results in intensifying the signals.

CHAPTER XXVII.

RADIO TELEGRAPHY APPARATUS.

The object of this chapter is to acquaint the reader with some of the details regarding the construction, arrangement and operation of the practical apparatus used in a modern radio transmitting set. In this connection a description will be given of a 500-watt equipment manufactured by the Wireless Improvement Company of New York. This low-powered set has been chosen for the reason that while it embraces most of the principles employed in modern radio construction, it is simpler and more easily understood than a high-powered set would be.

The reference letters, used in the description, refer to Plates 1, 2 and 3 at the end of the chapter. These figures and the wiring diagram should be studied carefully in connection with the description given.

THE 500-WATT RADIO TRANSMITTER.*

The apparatus comprising the transmitting equipment is divided into three groups. The first group is the motor generator set. The second and third groups, which may be designated in a general way as the *power apparatus,* and the *radio apparatus,* are mounted on slate (lower) and Micarta (upper) panels, respectively.

The Construction of the Panel.

(Plates 1, 2 and 3.)

The angle iron frame on which these two panels are mounted consists of two supporting members, each bent in the form of the letter L. To the vertical portion are fastened both the power and high-tension panels. The horizontal portions are braced by iron

* For high-powered sets, the motor generator is usually installed in a different compartment from that in which the operating panels are installed, and the panels for the radio apparatus and operating apparatus are mounted in separate iron frames.

straps, fastening to the vertical portion at an angle of 60°. The horizontal extensions of the angle iron frame are connected by two iron straps, and to these straps is fastened the motor generator set. To install the set it is only necessary to mount it upon a suitable support and fasten it rigidly by means of anchor bolts (or leg screws) through the horizontal extensions of the angle iron frame. When the equipment is in place, the weight of the motor generator set balances the weight of the panels, so that there is no tendency for the anchor bolts to loosen.

All power and radio apparatus is securely bolted to the panel, but always in such a way that it is readily accessible and may be easily removed and replaced. In general, any unit may be removed from the panels without disturbing its internal construction or connections and without disturbing the neighboring units and wiring.

The protection appliances on the control panel are supported on iron brackets which are bolted directly to the angle iron frame.

In order to effectively shield them from the high-frequency fields which surround the oscillation transformer and antenna inductance, all wires are carried in iron conduit. These wires terminate in studs on porcelain covers on condulets. Connections are made from these studs to the various instruments, by means of rigid copper bus of suitable size. The condulets are so located that these bus connections may be as short as possible. Wherever possible, splicing of the wire in conduit or condulets is avoided. Connections are made by copper bus on the outside of the porcelain cover. Stranged wire with National Electric Code insulation is used in the conduit system. This conduit system supplies complete mechanical protection for the insulated wires. It also makes it possible to remove any unit from the panel without disturbing the wiring.

The Motor Generator.

(Plate 2, *W.*)

The motor generator consists of a 110-volt direct-current motor, driving a 110-volt 500-cycle single-phase alternator. Each of these machines has its own cast-iron field yoke. The two armatures are pinned on a common steel shaft and between them is mounted a fan to keep the windings cool. The two field-yoke castings are connected by a cast-iron frame, and on the outside are bolted castings which carry the bearings. Thus, the machine is a two-bearing equipment. These bearings are equipped with a single oil ring in an oil well with an overflow cup attached on the side which serves to indicate when the oil level in the oil well is at the proper point.

The motor is of 1-horse-power size, shunt wound, and has four poles. The generator has 24 poles and delivers 500 watts on continuous duty at not less than 80 per cent power factor. The speed of the equipment is 2500 R. P. M.

Care should always be taken to see that the oil wells are full. If the equipment is so installed that the motor generator shaft is not truly horizontal, it will be found that the bearing on the low end will use more oil. The gage cocks should be inspected at least once every two days to see that the oil wells are full.

The Control of Generator Voltage.

In tuning the equipment and adjusting for a pure musical tone, it is generally necessary to vary the voltage of the generator. This is accomplished by means of a field rheostat (Plate 3, *E*) mounted on the lower panel and controlled from the front of the panel by a handwheel (Plate 1, *U*). The dial plate behind this handwheel reads *to raise voltage* and when the handwheel is rotated in the direction of the arrow on the dial plate, the resistance in series with the generator field, is decreased, increasing the voltage of the generator.

The Automatic Starter.

(Plate 1, *J*.)

In order to simplify the starting of the motor generator set, a single step automatic starter is used. This automatic starter has three essential parts; first, a solenoid; second, a plunger carrying a contact arm; and third, a resistance unit divided into three sections. When the D. C. service switch is closed, the solenoid and one section of the resistance are connected in series across armature of the motor. One side of the line is connected directly to the armature of the motor, and the other side of the line is connected through the second section of the starter resistance to the armature of the motor. When the counter E. M. F. of the motor armature has risen to a predetermined value, the solenoid lifts its plunger, short circuiting the second section of the resistance, and inserting in series with the solenoid the third section of the resistance.

The Resonance Transformer.

(Plate 3, *O*; Plate 2, *O*.)

The resonance transformer is of the open core dry type. It is mounted horizontally on the rear side of the control panel, and is supported in position by wooden end supports which are bolted to the slate. These end supports have recesses into which the core and primary slip. The secondary sections are slipped over the core and primary winding and are thus supported between the end pieces. The recesses in the end pieces are provided with removable caps so that the complete core and primary may be removed and the sections of the secondary replaced, when necessary, without removing the entire transformer from the panel.

The core consists of a bundle No. 18 B. & S. soft Norwegian iron wire. This wire has a slight deposit of oxide on its surface which serves to insulate the wires from each other and thus decrease the eddy-current loss in the core. The wire has a minimum hysteresis loss, and is particularly adapted for use in this type of transformer. It has the further advantageous property of high specific resistance and excellent thermal conductivity. The space factor is also improved by the use of this wire in preference to sheet-iron laminations. The core is covered with an asbestos insulating tube on which the primary is wound.

The primary consists of a single layer of No. 14 silk-enamel copper wire. This primary winding is arranged with leads at each end which are connected to lugs passing through fiber bushings in the end-piece caps. The primary is covered with a second heavy insulating tube of Micarta and thus the primary and core together form a unit which may be slipped into the recesses in the end pieces.

The secondary sections are wound by a special process. The wire used in these coils is No. 33 silk enamel. The leads from these coils are brought out, one at the bottom of the coil at one side and one at the top of the coil at the other side. The sections at the ends are provided with a piece of heavily insulated cable by which connection is made to the secondary terminals. The sections are mounted between insulating discs of Micarta and between each pair of sections an air duct is left.

The Quenched Spark Gap.

(Plate 1, *F*.)

The quenched spark gap is mounted on the front of the upper panel. The frame consists of two cast-iron brackets bolted to the panel, and carrying a clamping or pressure screw by means of which the proper pressure upon the gaskets between the gap plates is secured. Between these castings run two insulating rods of Micarta, upon which the plates rest. The plates are held in position in the rack by means of the pressure screws, which are tightened by means of a wrench. Connection to the gap is made directly through the end castings, but flexible leads are provided at each end of the gap frame so that the gaps at the end of the group may be short circuited, thus decreasing the number of gaps in circuit. The leads to the gap terminate in special clips which slip over the edge of the gap plates to make connection at any desired point. In adjusting the pressure screws, care should be taken to see that the group of plates is spaced equally between the two end pieces. Sufficient pressure should be applied to make the sparking chambers absolutely air tight and to give them the proper length. The gaskets which are supplied have been carefully selected with reference to their thickness so that when the gasket is compressed sufficiently to give air tightness, the sparking chambers will have the proper length. The gap plates have electrolytic-copper sparking surfaces at their centers, and are machined accurately to within five ten-thousandths of an inch. The gaskets are of a special heat-resisting composition rubber packing. Each gap plate has two sparking surfaces, one on each side.

The gap should be frequently tested, to ascertain if any of the gaps are inactive, by short circuiting each gap successively by means of the test rods supplied. In making this test the generated E. M. F.

should be as high as possible without impairing the tone. If this process of short circuiting the gaps does not produce a noticeable change in the note for each gap short circuited, that gap is inactive and should be permanently short circuited by means of one of the clips. When several of the gaps have become inactive, all of the plates should be removed from the frame. It will be found that a vacuum has been created in the sparking chambers and that the plates will have to be pried apart by the use of a screwdriver. This should be done with great care in order that the flanges of the plates may not be bent. If the plates are heated up by allowing a continuous discharge for several minutes, with large power in the closed circuit, it will be found that they may be separated much more easily. The sparking surfaces of the plates may be polished with very fine emery or crocus paper, provided care is taken not to destroy the true plane or flat character of the surface. The corrugations upon which the gaskets rest, should be cleaned with alcohol and the gap carefully reassembled with new gaskets. Care must be taken to see that the gaskets are assembled concentric with the plates.

The Condenser Battery.

(Plate 3, *L.*)

The capacity for the closed oscillating circuit consists of a battery of eight Murdock condenser units of approximately .0017 microfarad each. These condensers are divided into two groups of four units each in series across the secondary of the transformer, the units in each series group being in parallel. The resultant capacity is .0034 microfarad.

The condenser rack consists of a skeleton wood frame fastened directly to the Micarta panel. To hold the condenser units in place, two Micarta straps are provided. On the rear face of the rack, three bus bars are mounted. The condenser units are connected to the bus bars by means of short braided copper pigtails.

The Murdock condenser units are rugged high-tension condensers. They consist of a group of thin sheet copper plates moulded under high pressure into a composition insulating material. The copper leads are brought out to form two connection points on the top of the unit. The overall dimensions of the unit are approximately 6 × 6 × 1 inch, which indicates their space efficiency. The insulating material is very hard, giving mechanical strength and insurance against breakage.

Choke Coils.

(Plate 3, *K* and *C*.)

In order to prevent possible surges of radio frequency energy from passing through the end sections of the secondary of the transformer, two choke coils are provided. These are connected between the secondary terminals of the transformer and the condenser battery, one on each side. The choke coil consists of a hard wood spool upon which are wound many turns of No. 33 silk-enamel wire. This winding is protected by a Micarta case which completely encloses it, the ends of the winding being brought through to studs on the top and bottom of the coil. The choke coils are mounted, one at each side of the condenser rack, by means of Micarta supports.

Protection Appliances.

(Plate 3, *F, P*.)

Surges of radio frequency energy are prevented from getting back to the A. C. generator or the D. C. line by means of protection appliances. These consist of two paper condensers in series connected across the A. C. and D. C. lines, respectively. The point between the two condensers is grounded, and the condensers themselves are protected by small spark gaps about 0.01 inch long, across their terminals. The condensers and protective spark gaps are mounted on a slate base.

Antenna Inductance.

(Plate 2, *M*; Plate 3, *A*.)

The inductances for the radio circuits are constructed of round-edged copper strip ($\frac{1}{4} \times \frac{1}{16}$ inch). These helixes are supported on skeleton frames of Micarta. The frames are supported on wooden legs with brass feet, which are bolted to the Micarta panel.

The **antenna inductance**, 9¾ inches in outside diameter, has 50 turns with $\frac{3}{16}$-inch pitch. The wave-length switch is mounted on the Micarta panel on electrose insulators, the studs being carried through the panel to the rear, where they are arranged to be connected to the antenna inductance by means of solid copper bus. Six pieces of this bus bent to the proper dimension and provided with a clip for connecting without solder to the winding of the antenna inductance, are supplied. These buses are all long enough to reach to the far end of the coil. When the equipment is installed the proper points for the various radiating circuit wave lengths are determined, the buses are cut to the proper length and connected to the points on the wave-length switch (Plate 1, *M*) by means of the hand clamps supplied.

Oscillation Transformer.

(Plate 2, *B, C;* Plate 3, *I*.)

The **oscillation transformer** consists of two concentric coils. The outer coil or secondary, 9¾ inches in outside diameter, has 19 turns at a $\frac{3}{16}$-inch pitch. This secondary is arranged to slide in an axial direction, along suitable guides over the primary. The mechanism by which this motion of the secondary is secured and coupling varied, consists of a cord and a series of pulleys, actuated from the front of the panel by means of the outer handwheel. Behind this handwheel is mounted a dial which revolves with it. The calibration of the dial is arbitrary and merely indicates the position of the secondary with respect to the primary. On the secondary frame is mounted a connector-clip rod along which clips for making connection to the winding slide. One of these clips is for connection to the antenna inductance, the other for connection to the antenna circuit ammeter. These clips may be connected to any desired turn of the secondary, but care must be taken not to put the two clips so close together that the shortest distance between them is less than 1½ inches.

The primary of the **oscillation transformer** (Plate 2, *B;* Plate 3, *I*), 7 inches in outside diameter, has 33 turns at a pitch of $\frac{3}{16}$-inch. This inductance is continuously variable by means of a contact arm

(Plate 3, *H*) which revolves inside the coil and travels along a twisted shaft, actuated from the front of the board by means of the inner handwheel (Plate 1, *B;* Plate 2, *B*). Behind this handwheel is mounted a dial which makes one revolution for every 33 revolutions of the handwheel. The dial is calibrated to read the closed circuit wave length directly and is reasonably accurate. The tension on the cord which actuates the secondary may be adjusted by means of the tension adjusting pulley at the rear end of the upper track.

Ventilating Equipment.

(Plate 1, *P, Q*.)

To prevent excessive heating of the quenched spark gap (Plate 1, *F*), a small fan (Plate 1, *P*) is mounted directly beneath it at the top of the lower panel. This fan is operated by a 110-volt direct-current motor (Plate 1, *Q*) and is thrown in circuit as soon as the D. C. service switch (Plates 1 and 2, *I*) is closed.

The Antenna Relay and the Break System.

(Plate 1, *O*.)

The **panel radio transmitter** is equipped with a break system by which the receiver is retained in circuit with the antenna except when the transmitter is active. That is, the receiver is short circuited only when the key is depressed, and between each dot and dash, or during the interval between letters or words, the operator may receive signals from the distant station. This end is accomplished by means of an antenna relay whose magnet windings are connected in series with a fixed resistance across the 110-volt D. C. line. The rear contacts on the Morse key (Figs. 1 and 2, *L*) short circuit the magnet windings of the relay, so that when the key is open, these magnets are deenergized and the relay remains open. The heavy contacts of the relay form a break in the grounded end of the antenna circuit, and across these contacts (which are connected to two binding posts immediately below the relay) is connected the receiver. Thus, when the relay contacts close, the receiver is effectively short circuited, and this occurs the instant that the rear contacts of the key are opened.

The Morse Key.

(Plates 1 and 2, *L*.)

Supplied with this equipment is a modified standard Morse legless type key. Its contacts are of silver and are of sufficient size to break the transformer primary current. Its rear contacts, as mentioned above, are arranged to short circuit the magnet windings of the antenna relay. The usual cutting-in switch of the Morse key has been modified on this key to form a second opening in the circuit of the antenna relay magnets in series with the rear contacts of the key. When this switch is thrown open, the antenna relay magnets remain in circuit independent of the position of the key and the receiver is thus continuously short circuited. This key is furnished with a length of flexible cord so that it may be installed remote from the panel. The cord passes through a bushing on the lower board and is connected to studs on a condulet cover.

If it is desired to transmit and receive without using the break system, it is only necessary to put the wave-length switch (Plate 1, *M*) in the lowest point (which connects the antenna directly to the receiver), throw the break-system switch (Plate 1, *N*) from the *in* to the *out* position and open the switch on the key. The antenna circuit is then connected directly to the receiver and no energy from the transmitter can enter it. When it is desired to transmit, it is only necessary to replace the antenna switch in the point corresponding to the wave length desired.

Indicating Instruments.

Switchboard type meters are provided for the indication of the voltage of the D. C. supply circuit and of the 500-cycle generator, the power in the primary of the transformer and the current in the antenna circuit. The A. C. and D. C. voltages are indicated by a three-stud voltmeter (Plate 1, *H*). This meter has two calibrations, one reading to 250 volts for the alternating current voltage, the other reading to 125 volts for the direct current voltage. The common point of this voltmeter is connected to one side of both the A. C. and D. C. lines. A voltmeter switch located at the lower right-hand corner of the lower panel serves to connect the other voltmeter points to either the A. C. or D. C. lines on the other side.

The **watt meter** (Plate 1, *R*) is so connected as to read the power input to the primary of the transformer. Its scale reads to 750 watts. The watt meter is connected permanently in circuit.

The **hot-strip ammeter** (Plate 1, *D*) is connected in series in the grounded end of the antenna circuit. Its scale reads from 0 to 10 amperes. All meters may be adjusted for correct zero reading by means of the small screwdriver supplied.

Control Devices.

The **panel radio transmitter** of the 500-watt size is arranged for manipulation by a single operator. He has control of the apparatus through the following devices:

1. The **wave-length changing switch** (Plate 1, *M*), with which is also combined the sending-receiving switch. This switch has seven points, six of these points correspond respectively to the six wave lengths to which the antenna circuit is tuned. The seventh point connects the antenna, through the break-system switch (Plate 1, *N*), directly to the receiver.

2. **Oscillation Transformer Primary Handwheel** (Plate 1, *B*).—This handwheel varies the wave length of the closed oscillating circuit directly and continuously from 300 to 1200 meters.

3. **Oscillation Transformer Coupling Handwheel** (Plate 1, *C*).—This handwheel moves the secondary of the oscillation transformer in an axial direction over the primary, thereby varying the coupling or mutual inductance.

4. **Quenched Spark-Gap Leads.**—By means of these leads the operator is enabled to vary the number of sparking chambers in circuit. This is accomplished by slipping the clips on these leads over the flange on the spark-gap plate.

5. **Generator Field Rheostat Handwheel** (Plate 1, *U*).—By means of this handwheel the generator field current and, therefore, the voltage are varied, to produce proper tone quality.

6. **D. C. Service Switch** (Plate 1, *I*).—This switch controls the supply of direct current power to the equipment. When the switch is closed the automatic starter operates to start the motor generator set, the fan starts, and the antenna relay is connected in circuit and will be energized the moment the key is depressed.

7. 500-Cycle Circuit-Breaker (Plate 1, *S*).—This circuit-breaker is in one leg of the A. C. circuit and is adjusted to open at the safe maximum current. It may be tripped and closed by hand if it is necessary to open up the A. C. circuit for adjusting purposes, and it is not desired to shut down the set.

8. The Break-System Switch (Plate 1, *N*).—When this switch is thrown in the *in* position, the contacts of the antenna relay are connected respectively to the antenna ammeter and to ground. The midpoint of this switch connects to the antenna ammeter. When this switch is in the *out* position and the sending-receiving switch is in the *receiving* position, the relay contacts can no longer short circuit the receiver, and no energy from the closed oscillating circuit can possibly reach the antenna circuit or the receiver.

Operation of the Transmitter.

Assuming the set to be shut down, and assuming no particular position for any of the adjustments, but assuming that all parts of the equipments are in proper working order, we may set down the following series of steps to be taken in tuning the transmitter for sending on any definite wave length:

1. Place the wave-length switch in the position corresponding to the desired wave length, close the break-system switch in either the *in* or *out* position as desired.

2. Rotate the inner handwheel which controls the primary of the oscillation transformer, until the desired wave length appears on the dial. Close the 500-cycle circuit-breaker.

3. Close the voltmeter switch downward and notice on the voltmeter whether the direct current voltage is at its rated value; namely, 110 volts. If the voltage is correct, close the D. C. line switch which starts the motor generator.

4. Watching the antenna ammeter, vary the inductance of the primary of the oscillation transformer and the coupling until a maximum current in the antenna circuit is obtained.

5. Vary the voltage of the generator, by means of the generator field rheostat until the note is high pitched and musically clear.

6. Note the reading on the watt meter, and if it is less than 500 watts, increase the number of gaps in circuit by one, and readjust

the generator field rheostat for proper tone. If the power has not increased sufficiently, add another gap and readjust the tone, until the power as read on the watt meter is 500 watts and the note is high and musical.

7. The equipment is now completely adjusted for transmitting at the wave length chosen. It may be desirable to now test the various gaps to see if any of them are inactive. This is done by means of the gap test rod which is inserted between the flanges of the plates so as to short circuit one gap at a time. If this process does not produce a noticeable change in the tone for each gap so short circuited, those gaps which produce no change are inactive and should be permanently short circuited by means of one of the clips provided for that purpose.

To shut down the set it is only necessary to open the D. C. service switch. If the circuit-breaker opens, there is an overload or possibly a short circuit on the generator and the circuit-breaker should not be again closed until the trouble has been located and removed.

Receivers.

The Telefunken Receiver.—Fig. 460 shows the Telefunken receiver which has been used to some extent on board naval vessels. The secondary inductance is varied by means of plug connectors. Two variable condensers are used. One in series with the antenna when receiving short waves, and in parallel with it when receiving long waves. The other condenser is in the secondary circuit. By varying the capacity of this condenser in connection with the variable inductance referred to above the wave length can be varied at will.

The 1-P-76 Receiver.—The 1-P-76 receiver shown in Fig. 461 has been supplied to nearly all the vessels of the navy and has given very satisfactory service. A detailed description of this set will be instructive and will illustrate the principles of construction of receivers in general.

The 1-P-76 receiving set consists of an inductively coupled transformer, two solid rectifier detectors, and the necessary accessory apparatus, compactly mounted in an oak box, with hard rubber top. The receiving circuit of this set is shown in Fig. 462.

The aerial, or receiving antenna, is connected to *A*, and the circuit is completed through the primary *P* of the transformer to the ground connection *G*. This circuit, which is called the primary circuit, is tuned or made resonant to any desired wave length by varying its inductance, *i. e.*, the number of turns of wire included in the primary circuit. The greater the number of turns of wire in the primary circuit, the greater is the inductance, and hence the longer the wave length with which the circuit is in tune.

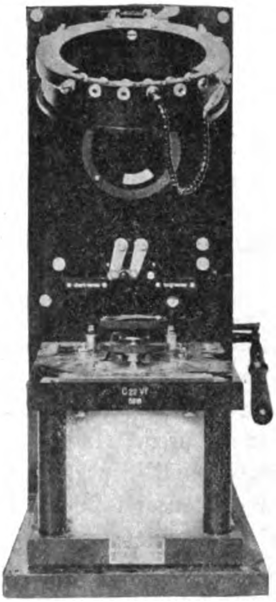


FIG. 460.—Wireless Telegraph Receiver.

Inductively coupled to the primary circuit is the secondary winding *S*, including the variable air condenser *F*. This secondary circuit is tuned to the primary either by variation in the length of its winding, or by variation of the condenser *F*. While it is possible to adjust the inductance of the primary circuit by single turns, the secondary is made adjustable only by relatively large steps, so that for accurate tuning the condenser *F* must be used.

In parallel or shunt with the secondary circuit is placed the detector *D,* and a small fixed, or storage condenser *U*. This shunt or detector circuit is of very high resistance, or impedance, so that at each oscillation in the secondary circuit, only a small amount of energy overflows into the detector circuit, thereby leaving the secondary free to oscillate, or, as it is termed, feebly damped.

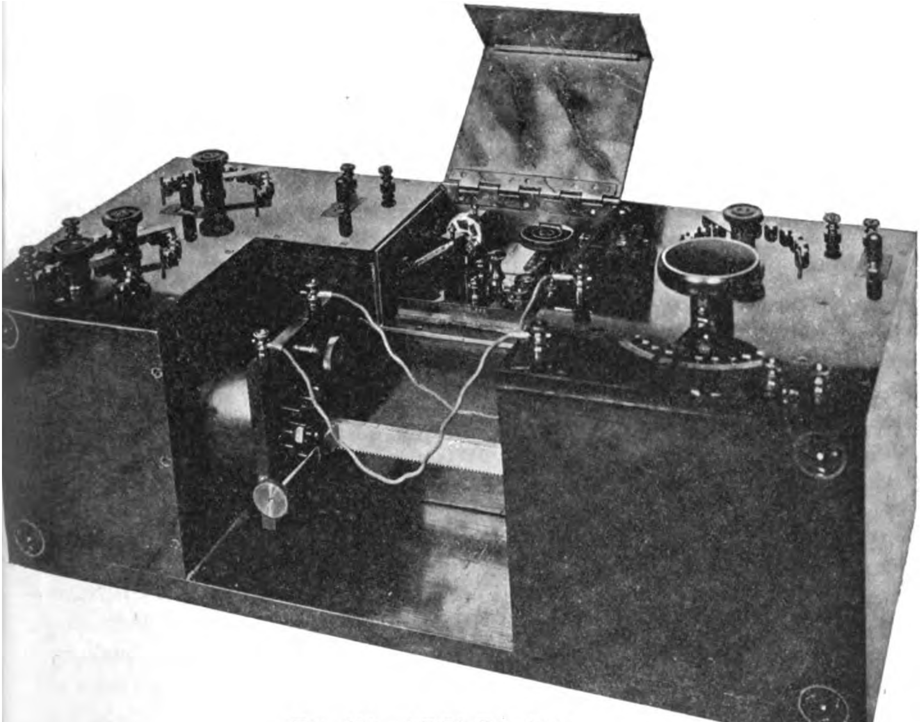


FIG. 461.—1-P-76 Receiver.

The complete detector circuit comprises a solid rectifier detector and a fixed value mica condenser, across which condenser the potentiometer and telephone receivers are connected. The detector used in this set is of the solid rectifier type, still popularly and incorrectly known as the "crystal" or "thermo-electric" detector. Its action is, however, that of a rectifier, or electric valve, which permits current to flow only in one direction, and the materials used therein are not crystals, but fragments of either massive zinc oxide, or the element silicon.

As the currents set up in the secondary circuit by the received signals are in the form of high-frequency oscillations, first in one direction, then in the other, it will readily be seen that as the detector forms an electric valve, only every other half oscillation will overflow into the detector circuit, and charge the storage condenser *U*. After a series of alternate half oscillations have in this manner overflowed through the detector, the greater part of the energy originally present in the secondary circuit will be found stored as a charge in the condenser *U*, and already beginning to discharge through the telephone receivers.

The telephone circuit consists of a pair of special adjustable telephone receivers, and a potentiometer *E*, adapted to give small values of E. M. F. The discharge of the condenser *U* through the telephone receivers gives the sound of each signal from the distant station, and the potentiometer is employed to introduce a small E. M. F. into the circuit, causing a small current to flow through the detector in the direction of its rectification, such a current rendering the action of the detector more regular and efficient.

Inductively linked with the secondary is a testing or buzzer circuit *NVR*, whose function is to excite very feeble electrical oscillations in the secondary, in order that the detector, potentiometer, and telephones may be adjusted to their maximum efficiency, in the absence of test signals from a distant station. This buzzer circuit consists of a condenser *V*, and a single-turn coil *N*, shunted across the contacts of a buzzer *R*. At each make and break of the buzzer contacts the condenser *V* is charged and discharged, and at each discharge a highly damped oscillation surges through the coil *N*. By induction, this highly damped oscillation causes a sustained oscillation in the secondary circuit, corresponding exactly with the oscillations set up by signals received from distant stations.

Taking up now the connection of the set in the antenna circuit, its adjustment and operation, it is first necessary to connect the primary circuit with the antenna and ground leads. The lead from the antenna (or from the antenna switch) is connected to post *A* (Fig.

462), while post *G* is connected to the station ground. If the receiving antenna is very large, and it is desired to receive short wave lengths, it is advisable to connect a variable air condenser of about .005 M. F. maximum capacity in series with the post *A* and the antenna.

To adjust the set for use move knob at *J* to connect detector circuit and then move switch throwing in buzzer circuit and vary position of secondary *S* so as to obtain the necessary mutual inductance between it and the buzzer inductance. Then throw the switch (*O*) between the detectors to the left, and adjust the left hand, or perikon detector, by grasping its hard rubber head between the thumb and forefinger, slightly drawing it back, and rotating it so as to bring new points into contact between the bornite fragment in the small front cup, and the zinc oxide fragments in the larger cup at the rear. When a sensitive contact is established, the sound of the testing buzzer will be heard at its loudest in the telephone receivers. Then turn the switch (*O*) to the right, and adjust the silicon detector in a precisely similar manner, moving the arsenic alloy contact over the silicon fragments in the large rear cup until the best response is obtained.

To obtain the best results, both detectors should be finally adjusted on a very weak signal, which may be obtained by decreasing the mutual induction.

When both detectors are in the best adjustment, throw in the local battery by moving potentiometer switch (*E*) until a further improvement in the response is obtained. It will be found that the silicon detector requires about twice as much battery as the perikon, or, say, about 7 or 8 steps of the potentiometer switch.

After the detectors have been adjusted, and the potentiometer set at its best value, the telephone receivers should be adjusted. The receivers supplied with this set have adjustable pole pieces, controlled by a milled head screw at the rear of the case. To adjust the receivers, first turn the screws to the *left* until the diaphragms are clear, which may be determined by gently tapping on the diaphragm through the hole in the ear piece. Then, with the phones on the head, gradually turn the screws to the *right* until the signals are loudest.

After the detectors and accessory apparatus have been adjusted, the next step is to tune the primary and secondary circuits to the desired wave length. Leaving long wave-length tuning out of consideration for the present, set the left-hand upper dial switches, marked *X*, on zero, and vary the two lower switches. That portion of the primary winding controlled by the two lower switches has 100 turns of wire, divided into two sections, one of 10 single turn coils controlled by the lowest, or units switch, and the other of nine 10-turn coils controlled by the switch marked in tens. As these switches are connected together at a common zero point, with the switches working on opposite sides of this point, the total number of turns included is always the sum of the readings of the two switches.

It is difficult to even approximately state the wave length corresponding to a given number of turns in the primary circuit, for the reason that this varies with the size of the antenna.

After the set has been installed, it is a simple matter for the operator to construct a table by calibrating a number of points on the primary winding from stations or sources of known wave length. By plotting these points as ordinates against a scale of wave lengths, a curve will be obtained which will enable the operator to use his antenna and primary as a wave meter for distant stations.

To bring the primary circuit into resonance with longer waves than is possible with the first section of 100 turns, an extra primary has been provided, controlled by the two upper dial switches marked *X*. This second portion of the primary has an inductance of 5000 microhenries, and by means of the two dial switches any portion, from 50 to 5000 microhenries, may be included in the primary circuit.

After the primary circuit has been tuned, the secondary circuit should be brought into resonance. This is accomplished by varying the number of turns in the secondary winding and the capacity of the variable air condenser *F*. Referring to Fig. 462, it will be noted that the dial switch *H* plays over six contact studs, marked 10, 20, 40, 80, 160 and 320, corresponding to the number of turns cut in at each of these steps. As it is often disadvantageous to have the entire secondary winding of 320 turns tied to the secondary circuit, when only a few turns are in use, an automatic switch (*M*) is provided, which disconnects the last 160 turns entirely from the circuit, save when the entire winding of 320 turns is used.

In shunt with the secondary winding is placed the variable air condenser *F*, with an arbitrary scale of 180°. As the circuit formed by the secondary winding and this condenser is entirely self-contained, and is not in any way affected by the size of the antenna employed, it is capable of quite exact calibration to different wave lengths.

Condenser	Secondary Turns					
	10	20	40	80	160	320
0°	120	190	340	550	920	1420
10°	130	205	370	600	1000	1550
20°	140	230	435	745	1200	1815
30°	160	270	505	870	1365	2065
40°	180	315	560	960	1530	2300
50°	205	355	615	1045	1685	2510
60°	230	390	670	1120	1830	2710
70°	255	420	715	1190	1970	2910
80°	280	440	755	1260	2100	3100
90°	300	460	795	1325	2200	3270
100°	315	480	830	1385	2300	3425
110°	325	500	865	1445	2390	3560
120°	335	520	900	1505	2475	3695
130°	340	540	930	1565	2560	3820
140°	345	560	960	1620	2645	3940
150°	350	575	990	1670	2730	4060
160°	355	590	1020	1720	2810	4175
170°	360	600	1050	1770	2890	4290
180°	365	620	1080	1815	2965	4400

It is apparent that most wave lengths can be tuned in by several different combinations of secondary winding and condenser capacity.

In general, the loudest signals are obtained with the longest possible secondary winding and the smallest condenser giving the desired wave length. The sharpest tuning, on the contrary, is usually obtained by using a shorter secondary, and a larger capacity, for the reason that the detector circuit, which is practically the only source of damping for the secondary circuit, is connected in shunt therewith. The potential across the detector is at a maximum with the maximum number of turns in the secondary winding, and, consequently, the response is the loudest, but at the same time the drain of energy from the secondary circuit is at its maximum for each oscillation, and the sharpness of tune is at its minimum, owing to the rapid damping out of the oscillations. With the shorter secondary and the larger condenser capacity, the potential is lower, and the amount of energy drained from the secondary to the detector circuit at each oscillation is less, making the damping smaller and the tuning sharper.

For listening in, or receiving in the absence of interference, it is advisable to use the longest secondary and the smallest capacity that will give the desired tune, together with a fairly tight coupling, that is to say, the secondary should be well to the left, and partly inside of the primary winding. To cut out interference, these conditions should be reversed, and a short secondary and a large capacity should be used, together with as loose a coupling as possible, the secondary being well outside the primary, to the right.

When sending, always set the "detector" knob, *J*, in the "send" position. This will preserve the adjustment of the detectors, as they are thus isolated from the circuit and enclosed in a wave-proof metal box.

When not in use, the set should be covered, either with its own wooden cover, or with a cloth. This will keep dust from the switch contacts, and prevent deterioration of the hard rubber top.

A trace of oil on the contact studs of all the dial switches will make them work easier, and also insure better electrical contact. Likewise, a drop of oil on the mineral contacts will sometimes be found advantageous, particularly in damp, hot climates.

The zinc oxide fragments in the large cup of the perikon detector should be occasionally cleaned, preferably with a stiff, bristle brush, wet with carbon bisulfide. Such cleaning will often double their effective life. In a like manner, occasionally clean the silicon fragments of the other detector.

Although the perikon detector supplied with this set is slightly the more sensitive, the silicon is by far the more stable. If severe interference from a nearby station is encountered, or if "static" is very heavy, difficulty may be experienced with the perikon from loss of adjustment. In such cases, switch over to the silicon detector, which is but little affected by the most severe electrical disturbances.

It will be found an excellent practice to make a note of the various dial switch settings; the best point on the coupling scale; and the setting of the condenser, for stations frequently read. It will then be possible to quickly adjust the set to receive from such stations, without loss of time in "hunting" over the scales for them.

The set is protected from severe inductional and other discharges, by means of the safety spark gap (Y) between the posts A and G. It is well to occasionally make sure that this is clear, by running a thin piece of paper through the gap.

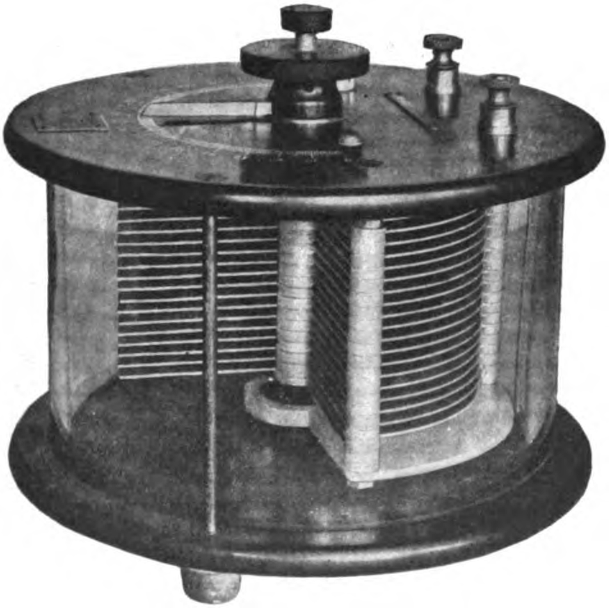


FIG. 463.—Variable Condenser.

Variable Condensers.

In Fig. 463 is shown the type of variable condenser used in radio receiving circuits and wave meters. It consists essentially of two sets of semi-circular plates one fixed and the other capable of being rotated so that its plates may occupy positions between the plates of the fixed set. The capacity is varied by the relative position of the semi-circular plates. The condenser shown is manufactured by the De Forest Radio Telephone and Telegraph Co. for general radio work.

Variable Inductance.

The inductance of a receiver or wave meter is generally varied by the step-by-step method, that is, by plugging in more turns or using different coils. In Fig. 464 is shown a variometer manufactured by

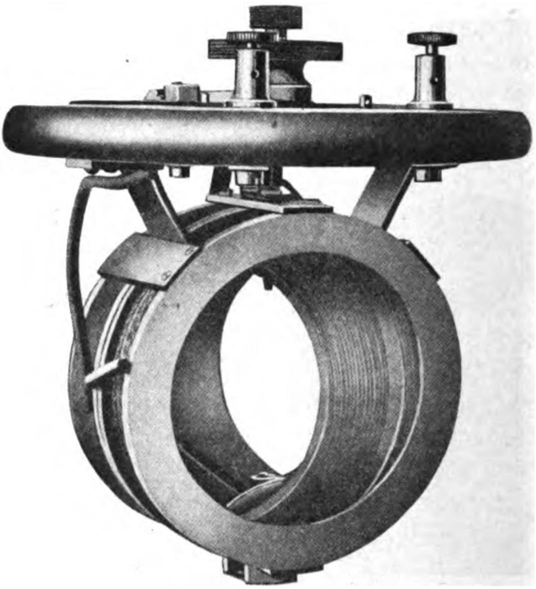


FIG. 464.—Variable Inductance or Variometer.

De Forest Company, which permits of a continuously varying inductance.

Fixed Condensers.

Fixed condensers of the Leyden jar type were used almost exclusively at first, but plate condensers, similar to the one described in the typical set, are now used extensively. This type of condenser can be made very rugged and is more compact, thereby resulting in the saving of space.

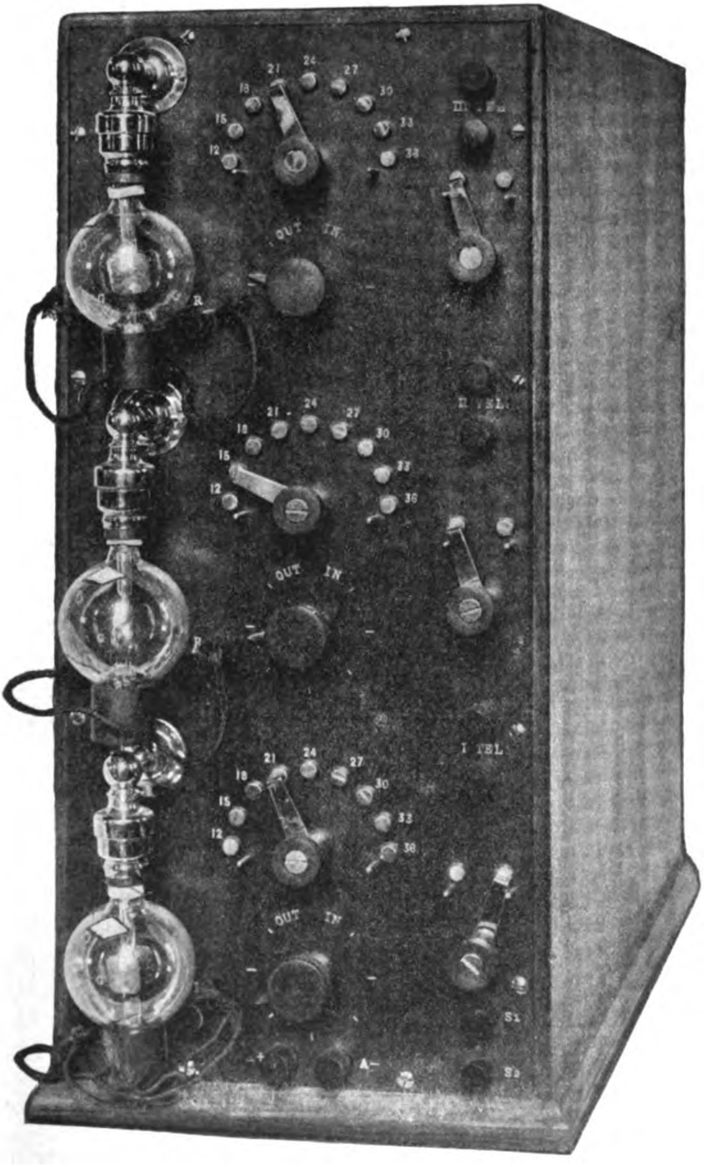


Fig. 465.—De Forest Three-Step Amplifier.

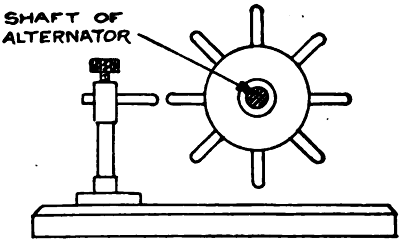
Amplifiers.

The "Audion" three-step amplifiers manufactured by the De Forest Telephone and Telegraph Co. is illustrated in Fig. 465. The elementary principle involved has been explained in the preceding chapter. Many of these amplifiers are in use on board ship. Excellent results have been obtained in using this instrument to amplify weak signals which otherwise would have been unintelligible. A book of instructions is supplied with this instrument giving necessary information in regard to care and operation.

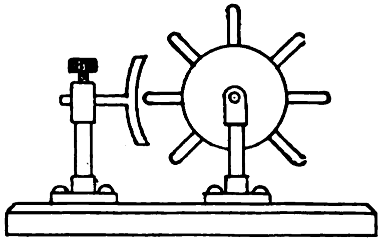
Spark Gaps.

As mentioned before a spark gap should be a perfect insulator except during the infinitessimal time that the oscillations take place

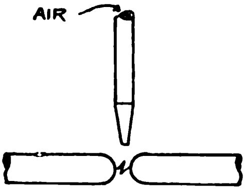
SPARK GAPS.*



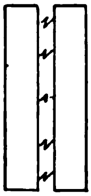
SYNCHRONOUS ROTATING SPARK GAP
FIG. 466.



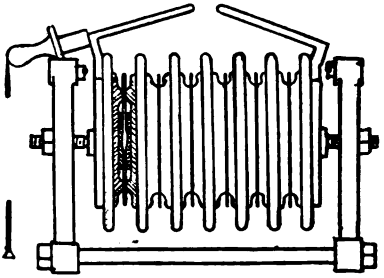
NON-SYNCHRONOUS ROTATING SPARK GAP
FIG. 467.



AIR BLAST GAP
FIG. 468.



PARALLEL GAP
FIG. 469.



QUENCHED SPARK GAP
FIG. 470.

* Several of the cuts used to illustrate this chapter were reproduced from The Manual of Wireless Telegraphy (Radio) by Captain S. S. Robinson, U. S. Navy, published by the U. S. Naval Institute.

when the condenser discharges and during this short period of time should be a perfect conductor. The earlier types of gaps possessed the great objection of arcing over after sparking and thus remain conducting. The mutual transfer of energy between coupled circuits has been explained in the preceding chapter. To increase the radiation the gap should become non-conducting as soon as the energy is transferred to the radiating circuit and thus prevent any transfer back to the oscillating circuit which would necessarily result in loss of efficiency. Various modifications of the original spark gap have been employed. In some forms an air blast between the electrodes was used to clear the gap. Rotating gaps were used whereby the sparking took place between different points preventing the great heat due to incessant sparking between the same electrodes. The quenched spark gap explained in connection with the transmitting set seems to be the most efficient type now in use. The sparking takes place between plane surfaces enclosed in air-tight compartments. This seems to quench the gap very quickly and therefore increase the efficiency of transmission. Illustrations of the various forms of gaps are given in Figs. 466-470.

Direction Finders.

The principle of the direction finder is, that the strength of the signals received by any station is greatest when the plane of its antenna corresponds with the direction of propagation of the electric waves.

This subject has not been thoroughly developed, but experiments are being carried out with an installation on shore which consists essentially of an antenna composed of thirty-two symmetrical aerial wires, one corresponding to each point of the compass. A distinguishing signal is sent out over the different antennæ in succession, and an approaching vessel by listening in and knowing the code employed can determine the bearing of the station by the relative intensity of signals.

Antenna Accessories.

The plates used in connection with the description of the transmitting set show a form of inductance used in the antenna circuit. In Fig. 471 is shown another form of variable inductance which is frequently used. A lightning switch as shown in Fig. 472 is generally placed outside of the station and affords a means of connecting the

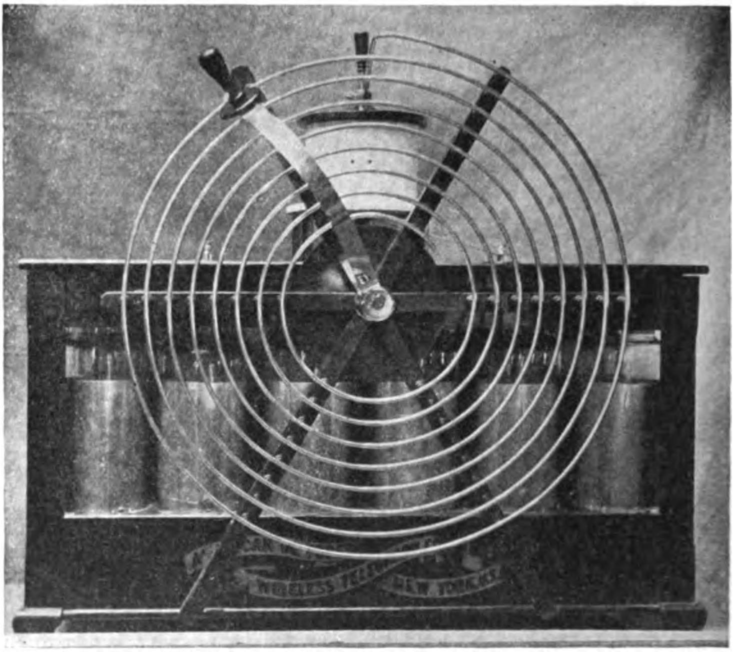


FIG. 471.—Spiral Inductance.

antenna directly to ground to avoid a chance of accident during electrical storms. In Fig. 473 is shown a hot-wire ammeter which is very useful. It is connected in series with inductance and ground, and by indicating the effective value of antenna current measures the radiation. In the later sets an instrument of this kind is used in the closed sending circuit and affords an easy means of telling when the closed and open circuits are in resonance.

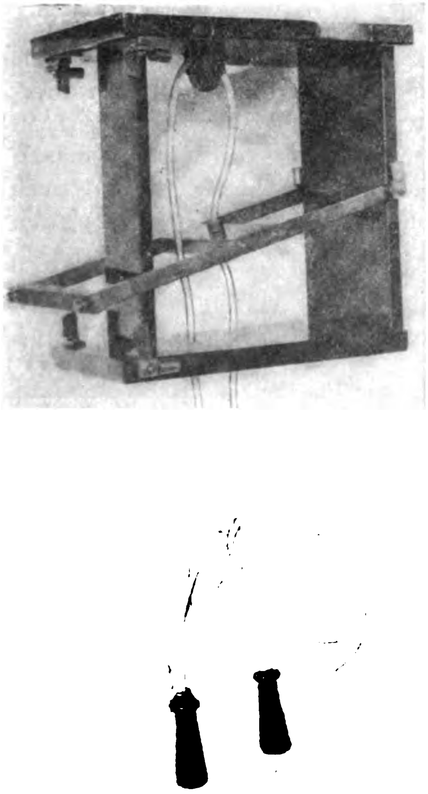


FIG. 472.—Lightning Switch.

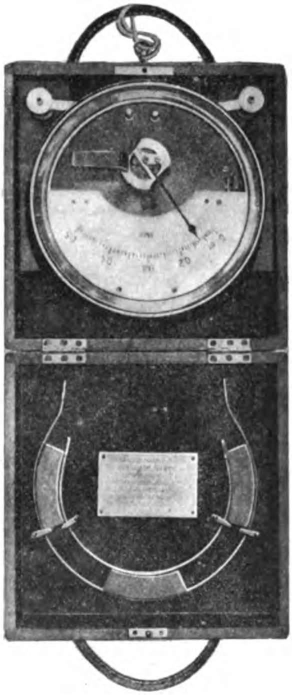


FIG. 473.—Hot-Wire Ammeter.

The Federal-Poulsen System of Radio Telegraphy.

This system uses, for radio transmission, an undamped or continuous electromagnetic wave, as distinguished from the damped oscillations produced by the discharge of a condenser across a spark gap.

One great advantage obtained by the use of undamped waves lies in the fact that when transmitting over long distances, where the daylight absorption is great and a long wave length is desirable, the daylight absorption, if the wave length be over 3000 meters, is much less with an undamped wave than with a damped wave.*

The method of producing the undamped wave is by utilizing the well-known discovery of Valdemar Poulsen; namely, that a direct current arc, maintained in an atmosphere containing hydrogen, will generate an undamped oscillating current in a circuit having inductance and capacity, shunted around the arc (see Fig. 474). If such an arc be placed in a strong magnetic field the intensity of the oscillation will be greatly increased.

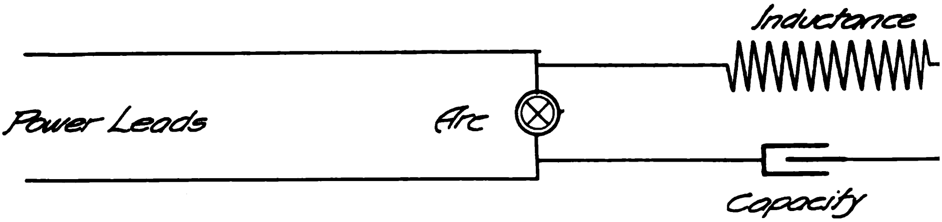


FIG. 474.

The frequency of these oscillations is controlled mainly by the electrical characteristics (capacity and inductance) of the shunted circuit. When this latter consists of an antenna and ground, or

* Austin, Bul. Bur. Stds., Vol. 7, p. 341, the formula for daylight transmission of *Damped Waves* is

$$I_r = 4.25 \frac{I_s h_1 h_2}{d\lambda} e^{-\frac{ad}{\sqrt{\lambda}}},$$

where

I_s = Sending antenna current in amperes,
I_r = Received antenna current in amperes,
h_1 = Effective height of antenna in kilometers, transmitting,
h_2 = Effective height of antenna in kilometers, receiving,
λ = Wave length in kilometers,
d = Distance in kilometers,
a = Daylight absorption coefficient $= 15 \times 10^{-4}$.

Fuller, "The Effect of Wave Length on the Absorption of Undamped Waves" gives

$$I_r = 4.25 \frac{I_s h_1 h_2}{d\lambda} e^{-\frac{\beta d}{\lambda^{1.5}}},$$

where all characters retain the same meaning, except that $\beta = 45 \times 10^{-4}$. This formula is derived from actual daylight tests made between San Francisco and Honolulu over a period of six months.

counterpoise (see Fig. 475), continuous or undamped waves are radiated.

The Federal Telegraph Company has developed this method of radio transmission and has in commercial operation, day and night,

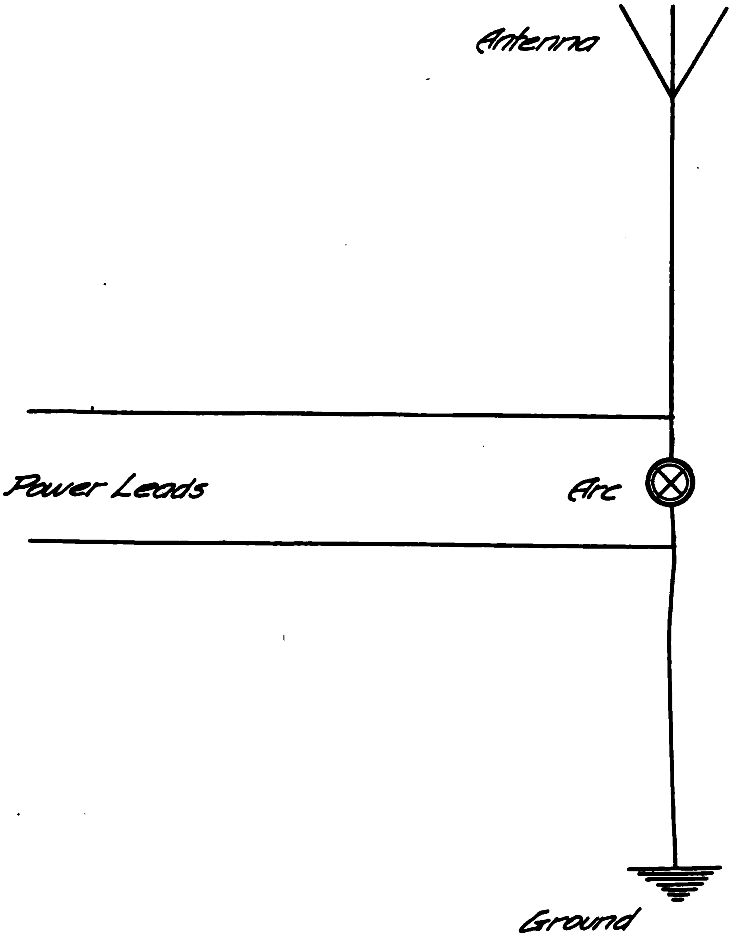


FIG. 475.

stations at Honolulu, San Francisco and other points. The distance from Honolulu to San Francisco is 2100 nautical miles and the 100-kilowatt equipment of these stations is similar to that being installed by this company at Darien in the Panama Canal Zone, for the Navy Department.

Other stations use 30-kilowatt sets, such as the Navy Department is placing at Boston, Mass.; Point Isabel, Texas; New Orleans, La.; Guantanamo, Cuba, and the Great Lakes, while 12-kilowatt and 5-kilowatt sets are made for ships and smaller land stations.

A typical 100-kilowatt set will be described.

The Antenna.

The antenna at south San Francisco is supported by three guyed wooden towers, placed in a triangle, one of 608 feet and two of 440 feet in height, and is of the flat-top type. Its capacity is 0.010 microfarad, with a natural period of 2300 meters, and an effective height of approximately 425 feet.

The insulation of the antenna from the towers, and also that of the guys (which are insulated every 100 feet of length) is composed either of long wooden breaks or, in the case of the 608-foot tower, of stone blocks, 10 inches × 10 inches × 10 inches in size.

The Ground.

This is a radial network of wire extending beyond the projected area of the antenna on the earth.

The Helix, Wave-Changing Switches, etc.

The antenna lead is brought with suitable insulation to a switch for transferring the antenna from the sending to the receiving circuits. The sending inductance is a helix of 1-inch copper tubing, 52 inches in diameter, and, in the case of the Darien installation, 16 feet 6 inches long.

The cathode terminal of the arc being grounded, the anode is connected through a hot-wire ammeter to a number of wave-changing switches. Any one of these may be made to engage clips connected to points on the helix, giving, according to the number of turns utilized, a great range of wave lengths.

No condensers are used.

Signals and Keys.

In this system the oscillations in the antenna are continuously produced by the arc, therefore the signals are not made by completely breaking this oscillatory circuit, but by making a small change in wave length.

This change is made by short circuiting part of the transmitting inductance by means of a multiple contact, solenoid operated relay key of rugged construction, capable of handling the heavy currents necessary to be broken. The contacts are cooled by an air blast.

The current in the key solenoid is made and broken by a "key controller." This consists of two copper contacts in a sound-proof chamber, operated in a magnetic field in order to reduce arcing between them. One contact is moved by a second, exterior, solenoid, and this in turn, by a small current and an ordinary Morse telegraph key. The speed obtainable with this relay key is greater than that of the fastest hand sending.

If it be desired to render signals audible on ordinary "spark" receiving apparatus using crystal detectors, and the like, a "chopper" is inserted in the key-antenna circuit, this being merely a rotary means of changing the continuous oscillations into wave trains of audible frequency.

The Arc.

The arc itself is maintained in a water-cooled, air-tight chamber, within a strong magnetic field and in an atmosphere of hydrogen vapor.

Means are provided, either by a spring lid or a poppet valve in the chamber, for releasing any undue pressure caused by striking the arc in an explosive mixture of air and hydrocarbons.

The cathode electrode is of carbon, readily replaceable, and is rotated constantly while the arc is in operation, in order to keep its erosion even and the arc steady. The distance between it and the anode is regulated either by hand or motor control.

The anode is copper, water cooled; both it and the cathode being suitably insulated from the arc chamber.

The necessary atmosphere of hydrogen is supplied by introducing into the chamber ordinary illuminating gas, alcohol, ether, water, steam or other compounds containing hydrogen.

Projecting through the sides of the chamber are the poles of two powerful electromagnets, in the field of which the arc is maintained. These are connected, either in series or parallel, to the power supply to the arc, usually 600 volts direct current.

Choke coils are inserted in the power leads to protect the latter from high-frequency current.

A starting resistance is provided to take care of the momentary short circuiting of the power line caused by striking the arc. This resistance is rapidly cut out when the arc is established. The same result may be accomplished by striking the arc at a low voltage and raising the same subsequently to full power.

In practice, in the case of the 100-kilowatt arc, the operations of turning on or off of cooling water, gas or alcohol; of starting and stopping the carbon drive, blower, tikker motors, etc., are all done automatically upon starting and stopping the arc, the latter being struck and its length adjusted by remote control also. The operating room is usually entirely separate from that containing the arc and accessories.

Receiving.

In receiving, owing to the accurate tuning obtainable with undamped waves, a very loose coupled (and therefore highly selective) circuit is used.

An elementary diagram of the connections for the receiving circuit is shown in Fig. 476. The variometer being used to vary the wave length when long waves are being received, and the condenser is used to adapt the antenna for the reception of short waves.

The Federal-Poulsen tikker, the device rendering audible in the telephone undamped oscillations received by the antenna, consists of a revolving brass disc upon which lightly impinges a fine steel wire and is very sensitive, the received watts in the antenna necessary for unit audibility (or where the dots and dashes of signals can just be differentiated) being 3.2 10^{-10} watts. Metals other than brass and steel may be used. The elementary diagram Fig. 476 shows the location of tikker in the receiving circuit.

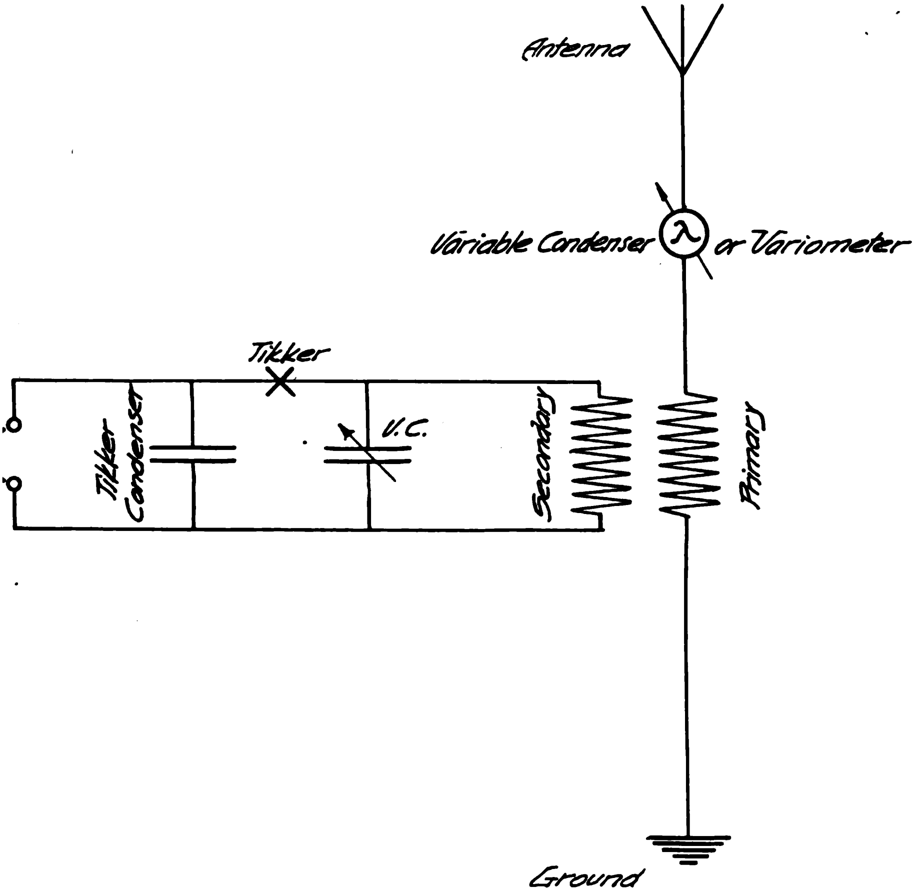


FIG. 476.—Elementary Poulsen Receiving Circuit.

Wave Meter.

The wave meter is a necessary adjunct to every radio station. It is a closed oscillating circuit of which the capacity or inductance, or both, may be varied. It is very carefully calibrated so that the wave length corresponding to any capacity and inductance used may be read directly from an attached scale. When two circuits are in resonance any oscillations set up in one will have the maximum effect in the other. Thus, by placing a wave meter near any oscillatory circuit and varying the capacity and inductance of wave meter and thus gradually changing the period of the wave meter circuit, the current-indicating device will give its maximum indication when the two circuits are in resonance. At this time the scale of wave meter will show the wave length of the resonant circuits. This is one of the principal uses of the wave meter. In this way the various circuits may be calibrated so as to permit the use of any wave length desired.

The wave meter may be used as a receiver when any form of detector is included in its circuit. It may be used also as a miniature sending set with proper means of exciting it. When used in this way, it may set up, in a near by oscillatory circuit, waves of any desired length within the limits of the meter. This method is always used in calibrating the receiving circuit. The Telefunken wave meter, large E. G. W. type, is extensively used in the naval service.

Type E. G. W. Wave Meter.

This wave meter is manufactured by the Telefunken Wireless Telegraph Co. from whom the following description was obtained. A general view of it is shown in Fig. 477.

Uses.

The wave meter may be used for the following operations:

1. Tuning and measuring wave lengths of all the circuits of a radio telegraphic installation, *i. e.*:
    a. The closed sending circuit.
    b. The open sending circuit (aerial).
    c. The closed receiving circuit.
    d. The open receiving circuit.
2. Testing of transmitter tone.
3. Testing of detectors for sensitiveness.
4. Determination of capacity, self-induction, coupling coefficients, long-distance wave lengths, etc.

Description.

The wave meter is a closed oscillating circuit, consisting of a six-step self-induction and a variable capacity. The principle involved is that of electric resonance. For the purpose of indicating when the closed circuit is oscillating with maximum energy in resonance with another circuit, a hot-wire ammeter, helium-tube detector or telephone in series with a detector may be used. When

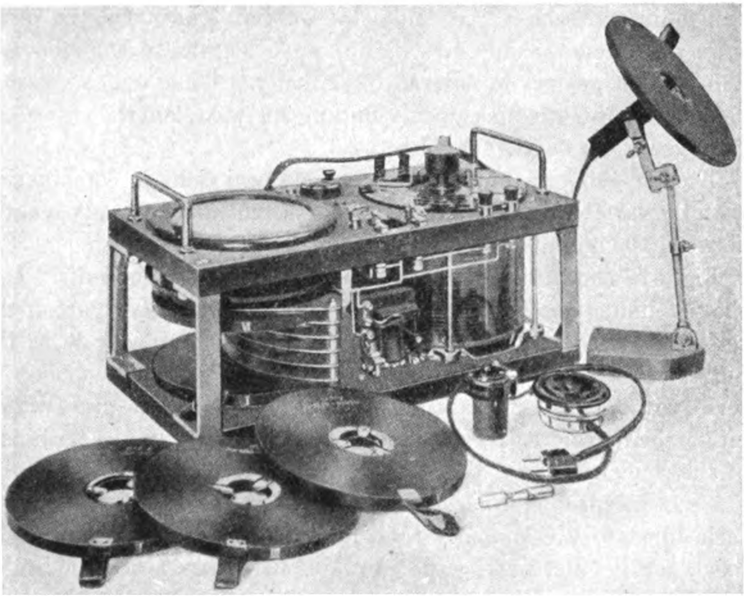


FIG. 477.—General View of E. G. W. Wave Meter.

a closed oscillating circuit is acted upon inductively by another circuit, it oscillates with maximum energy when tuned to the circuit furnishing the energy; or, in other words, when two oscillating circuits undergo mutual induction, the receiving circuit takes up the greater part of the energy when they are tuned alike, that is, when their frequencies of oscillation are equal. Observations for maximum effects on any of the three detectors afford means of bringing the wave meter in resonance with any circuit by means of the variable capacity and six-step inductance. Two scales are provided on the variable capacity which are read by means of pointers attached to the spindle of the movable plate of the condenser. From one scale the amount of capacity in circuit can be obtained from the indicated degrees in arc by reference to accompanying blue prints, which show the absolute value of the capacity for each degree of the scale. Curves are also furnished for each of the six inductance coils which show the wave lengths for the capacity corresponding to each degree indicated on this scale. On the other scale three semicircular arcs permit wave lengths in common use, 400 to 3400 meters to be read off directly. These scales are convenient for roughly and quickly finding the wave lengths; for accurate results the curves should be used.

The steps of self-induction are so arranged that, in combination with the variable capacity, accurate measurements of all wave lengths between 100 and 6000 meters can be made.

Fig. 478 shows the elementary connections of the circuits. *L* is the self-induction coil, *C* the variable condenser, *M* that part of the self-induction that is connected to the hot-wire ammeter *W*, *S* the buzzer with a primary cell, *H* the helium tube, *T* a telephone in series with a detector *D*, and *B* a revolving switch by means of which either the detectors or buzzer can be connected across the terminals of the condenser.

The **condenser** is a variable plate condenser secured in a recep tacle filled with a specially prepared paraffin oil. It has a set of fixed, parallel and equally spaced plates of semicircular form, all of which are connected to one terminal. A second set of plates connected to the other terminal may be moved into the spaces between the plates of the fixed set by means of a hard rubber handle which serves to protect the operator from accidental shocks. The effective surface and hence the capacity of the oscillating circuit depends upon the angle through which the movable plates are turned. *F* is a spark gap which short circuits the terminals of the condenser when too great voltages are set up across the plates.

The **self-induction** is built up of helically wound coils mounted in flat discs. On changing discs, the three-coil terminals fit into spring clamp contacts, all six discs having like connections. Care must be taken that the white lines on discs and disc holder corre-

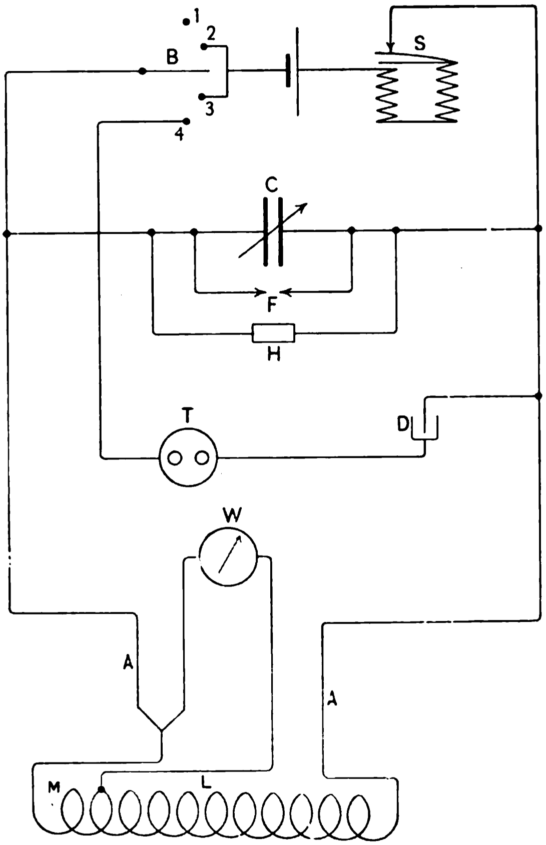


FIG. 478.—Diagram of Connections. Wave Meter, Type E. G. W.

spond when connections are made. The range of wave length for each disc is marked on the back of the disc.

In combination with condenser values from 20° to 170° the inductance coils measure approximately the following wave lengths:

Disc.	Wave length.
I	90- 260 meters
II	180- 500 meters
III	400-1050 meters
IV	650-1800 meters
V	1200-3400 meters
VI	2100-5700 meters

The **hot-wire ammeter W** shows the energy load of the wave meter. It is directly connected across a part of the self-induction in such a way that the power taken by the wave meter from the inductance coils is negligibly small, and on the other hand the damping effect in all discs is small and nearly constant. The screw on the side is for adjusting the zero point of the scale. When the hot-wire instrument is used, the switch must be on contact 1.

The **helium tube** and **telephone** with detector serve as a substitute for the hot-wire instrument when only general results (average of maximum value of energy) are required. The helium tube connects directly across the terminals of the condenser and is clamped under spring contacts which are mounted on the wave meter. When the tube is in use the switch must be on contact 1.

The **telephone T** and **detector** are connected in series across the terminals of the condenser. The telephone can be plugged into the holes *T* and the detector connected at *D*. During their use the switch must be on contact 4.

The **buzzer** and **battery** also connect across the terminals of the condenser, and when they are used, the switch should be on contact 3. Contact 2 is a key contact for making test letters.

As an accessory to the wave meter proper, there is a stand to facilitate changing the connection (relative position of the inductance) with any circuit undergoing test.

Employment.

I. Tuning of All Circuits of a Station.

Two circuits are tuned to each other, that is are brought into resonance, when they are of the same wave length or have the same oscillation period. Tuning then is a matter of wave length.

A. Transmission Circuits.

1. Wave Measurement with Hot-Wire Ammeter.—This method is specially adapted for the very accurate tuning of wave lengths. Place the movable switch on contact 1. The disc which is connected in circuit with the condenser by means of the flexible circuit *A* is brought close to the oscillation circuit which is to be measured.

The pointer of the instrument gives the greatest deflection when resonance is accomplished. The wave length may then be taken from the proper curve, using as an argument the condenser reading in degrees. In beginning do not couple in too fast, lest the hot-wire ammeter be burned.

NOTE.—**The hot instrument is protected by means of a horse-shoe holding magnet and short circuiting terminals when the needle has been thrown to its limit of deflection.**

2. **Wave Measurement with Helium Tube.**—The helium tube is clamped under its holding contacts and the switch set on contact 1. The tube is now brought to incandescence by varying the capacity *C*. If the tube remains lighted through a great range of the capacity, the wave meter has been *coupled too closely*. The disc should be removed from the coil undergoing test, until, by means of changes in the condenser, the tube is illuminated within a small range.

3. **Wave Measurement with Telephone and Detector.**—The detector is connected at *D,* the telephone plugged to *T* with switch on contact 4. The condenser is turned until the maximum sound is received in the telephone. The wave length is then read off from the proper curve. The wave meter should be coupled very loosely with the source of oscillations.

B. Antenna.

The antenna should be placed in direct circuit with the usual spark gap, Fig. 479, or with the buzzer, Fig. 480. Otherwise the measurement is made exactly as described under A.

C. Closed Receiving Circuit.

The wave meter is arranged as a transmitter by setting switch to contacts 2 or 3, and the condenser at the desired wave length for the disc used. The inductance coil is so arranged that the energy given off by it affects the circuit to be tuned. The capacity or inductance of the closed receiving circuit is then varied until a maximum sound is received. In this case also the meter should be removed from the circuit under test until the detector indicates only within a small range.

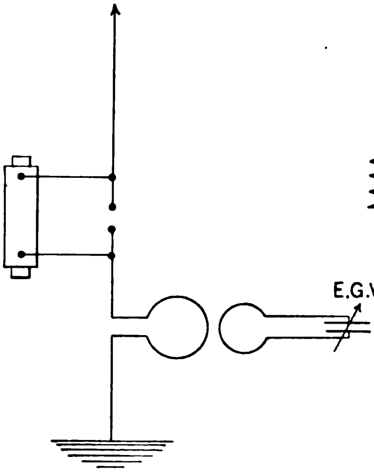


FIG. 479.

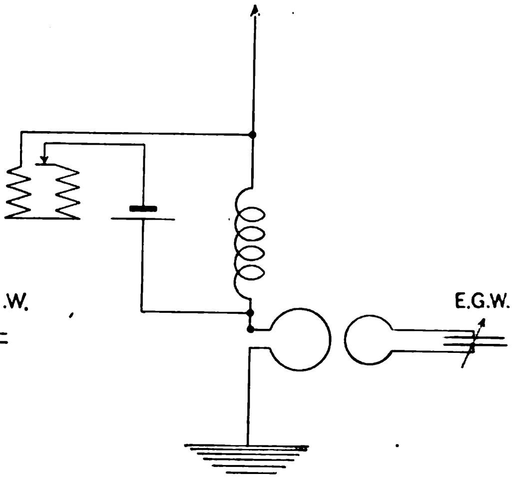


FIG. 480.

FIG. 479.—Connections for Tuning Antenna Using Spark Gap.
FIG. 480.—Connections for Tuning Antenna Using Buzzer.

D. Receiving Antenna.

The wave meter, set for the desired wave length, is connected as a transmitter, as described under B, and is so placed that it affects the receiving antenna. If the antenna wave is now varied (generally by varying the inductance) the maximum effect on an aperiodic coil coupled with the antenna will give the desired tune.

II. Testing Transmitter Tone.

The wave meter should be loosely coupled with the transmitting circuit, and the detector and telephone switched in. The switch should be set on contact 4 and the wave meter brought to resonance. The tone emitted by the transmitter is then heard in the telephone, and any irregularities of sound due to ragged discharge or the hissing sounds of arcing current can be corrected by changes in the spark gap.

III. Measurement of Sensitiveness of Detectors.

1. Connect detectors in the receiving circuit as usual.
2. Connect wave meter arranged and tuned as a transmitter.
3. The coupling between wave-meter inductance and detector should be kept loose until detector approaches limit of receptive ability.
4. Detectors should be exchanged without making any other changes.
5. Tighten or loosen coupling so as to bring the second detector to approximate limit of reception.
6. The looser the limit of coupling, the more sensitive is the corresponding detector, or, the range of the receptive limits will be a measure of the relative sensitiveness of the detectors.

IV. Determination of Electromagnetic Capacity.

1. Arrange a closed oscillating circuit containing a chosen known self-induction L and the unknown capacity C_x.
2. Couple loosely an aperiodic receiving coil with the closed oscillation circuit.
3. Tune the wave meter as transmitter with the closed oscillation circuit.
4. A known capacity C is then substituted for the unknown capacity C_x. C is then varied until the receiving coil is again tuned. The known variable capacity is the equal to the first unknown capacity.

Measurement of Coefficient of Self-Induction.

1. Form a closed oscillating circuit consisting of an unknown self-induction L and a known capacity C.
2. Couple loosely an aperiodic receiving coil with the oscillation circuit.
3. Tune the wave meter to the closed oscillation circuit.
4. Take the value of the wave length from the scale or curve. The self-induction L in henries is then obtained from the formula

$$L = \frac{\lambda^2}{4\pi^2 K V^2},$$

in which λ represents the wave length in centimeters, K the known capacity in farads and V the velocity of light in centimeters.

Measurement of Degree of Coupling of a Transmitter.

If a coupled transmitter is allowed to influence the wave meter, two wave lengths are found, λ_1 and λ_2, as opposed to a wave length λ_c when each circuit oscillates alone. The coupling coefficient is found from the formula

$$K = \frac{\lambda_1 - \lambda_2}{\lambda_c}.$$

Measurement of Wave Length of Incoming Waves.

1. Tune the receiving antenna to the unknown wave.
2. Arrange the wave meter as a transmitter and couple with antenna.
3. Vary tuning of wave meter and loosen coupling until the detector responds only to a certain wave length.
4. The incoming wave length is then equal to the wave length shown on the wave meter.

NOTE.—The above examples show the many uses to which the wave meter can be put. It follows naturally that there are many other uses which will be understood without further explanation, such as measurement of capacity of antenna, etc.

CHAPTER XXVIII.

PRINCIPLES OF RADIO TELEPHONY.

Radio telephony differs from radio telegraphy in that it transmits articulate sounds while telegraphy limits itself to the transmission of inarticulate sounds, which are made the basis of a code by which words may be sent or received in the form of messages. In telegraphy the sound produced in the telephonic receiver is that due to vibrations whose frequency falls within the range necessary for the production of sound and the frequency or period of the vibrations is not important; but for the reproduction of articulate sounds, there must be a very wide range of frequencies to correspond to the large variations in the number of vibrations required for the reproduction of speech.

The range of frequencies for the production of sound varies between 16 double vibrations per second and 40,000 double vibrations, the former giving the lowest audible sound and the latter the highest musical note. For men's voices, the average number of double vibrations per second is about 128 and for women's voices it is from 256 to 512.

The efforts of the earlier experiments in wireless telephony were directed to the idea of using the connection afforded by the earth. In general, the scheme consisted in stretching two parallel wires, one at each station, the extremities being taken to earth. In one of these wires was inserted a microphone with a battery of dry cells; and in the other a telephone which reproduced words pronounced at the microphone.

Although such schemes did not require a connecting wire between stations, yet the total length of the parallel wires at the two stations was required to be about the same length as the distance between the stations. Such a telephonic circuit has been in operation for some years in England, where communication is held between the lighthouse on the Isle of Skerry and the coast-guard station of Cemlin, a distance of about three miles.

Theoretical Principles.

In 1878, two American physicists, Graham Bell and Summer-Tainter discovered that a beam of light that had been made intermittent, falling upon a thin sheet held against the ear, gave a sound, the number of whose vibrations is equal to the number of interruptions in the source of light. By making the duration of the intermissions longer or shorter, the duration of the sound produced was longer or shorter. Any source of light whose intensity can be varied can be used in this experiment, but the distance to which the phenomenon can be manifested is increased by using a receiving circuit composed of a selenium resistance in series with a telephone and battery.

Crystalline Selenium.—Nearly every specimen of this substance has the remarkable property of being a much better conductor of electric currents when illuminated by a beam of light, and of increasing its conductivity with the intensity of the beam. If such a resistance is exposed to a luminous radiation of variable intensity, the variations of intensity will cause variations in the resistance of the selenium and consequently in the battery circuit. This will vary the current flowing through the telephone which will in turn emit sounds corresponding to the changes in the quantity of light.

If the electric arc is used as the source of light, variations in intensity may be produced by certain properties it possesses when arranged as discovered by Duddel, and known as Duddel's singing arc.

Duddel's Singing Arc.—If an alternating current of small intensity be superposed in certain ways upon a continuous current which is feeding an electric arc, the arc itself will emit a sound. At the same time equal oscillations are produced in the light of the arc. If the alternating current is set up in the circuit of a microphone by speaking in it, the oscillations produced in the arc can be received by a selenium receiver placed at a distance, and the luminous oscillations will cause the spoken words to be reproduced in the telephone in the receiving circuit.

The alternating current may act on the circuit which feeds the lamp in a shunt circuit from the feeding circuit, or it may be in another circuit which acts inductively on the feeding circuit.

Fig. 481 shows the connections for the first condition.

R is a resistance wound on a soft-iron core, around which passes the whole of the current feeding the arc. From the ends of the coil is connected a microphone *M*. *R* can be so adjusted that a battery in connection with *M* will be unnecessary. As the microphone is spoken into, the variations in resistance caused by the sound waves changes the current feeding the arc and the light of the arc will vibrate in rhythm with the diaphragm of the microphone and similar vibrations will be set up in the selenium receiver and the words will be reproduced in the telephone of the receiving circuit.

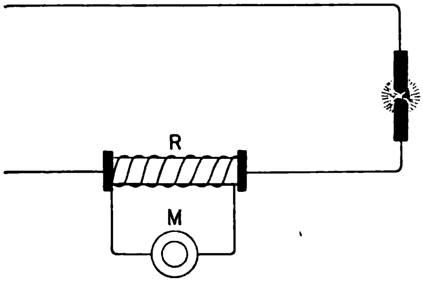


FIG. 481.—Duddel's Singing Arc.

Explanation of the Singing Arc.—In the phenomenon of the singing arc, the variation of the feeding current caused by the superposition of the current due to the microphone develops greater heat in the arc, as the heat is proportional to the square of the current. Similar variations in the volume of the incandescent gases forming the arc are caused by this variation in heat, and these variations in volume are those which generate sound vibrations in the air, reproducing the vibrations in the microphone, and causing the arc itself to sing.

Duddel's Circuit.—In this circuit, the extremities of the arc are joined with a circuit comprising a capacity and inductance as shown in Fig. 482.

D is a generator supplying continuous current to the arc *L*, joined to the extremities of which is a circuit composed of a capacity *C* and inductance *I″*. Such a circuit has a natural period of electrical vibration depending on the values of the capacity and inductance.

If certain conditions are satisfied at the instant when the circuit of the arc is made, the condenser becomes charged and discharged with a frequency depending on the oscillation period of the circuit, thereby producing alternating currents which overlap the continuous current feeding the arc and cause it to vibrate with a period equal to that of the alternating current. If this frequency lies within the range of perceptible sounds, the arc emits a musical note.

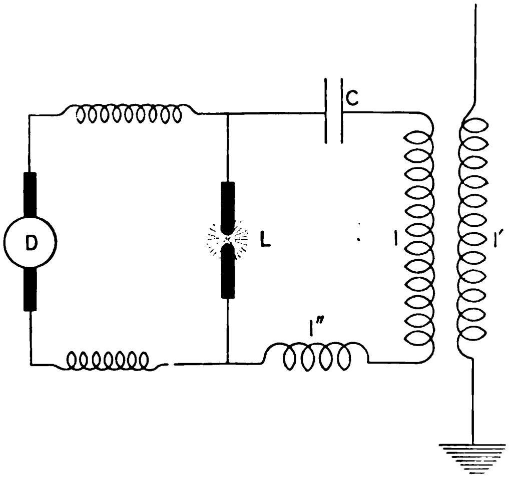


FIG. 482.—Duddel's Circuit.

If the arc is made between the poles of a powerful magnet, either permanent or an electromagnet, both the frequencies and intensities of the alternations are much increased.

This oscillating circuit does not radiate its energy. To produce radiation, the circuit may be inductively connected through an air transformer to an open circuit which may be made an **aerial** similar to that of radio telegraphy, one end being grounded. This transformer is shown at *I, I'*, where *I* is the primary of the transformer inductively connected to the secondary *I'* which forms part of the aerial, the lower end of which is grounded.

The portion of the circuit *LCII''* is known as **Duddel's circuit.** As this circuit possesses a natural period due to its inductance and capacity, oscillations are set up which differ, however, from those set up in a spark circuit in having very little damping; and if this circuit is coupled with a resultant antenna circuit undamped waves will be radiated.

In such an arrangement, therefore, as shown in Fig. 482 under certain conditions there would be a continuous radiation from the aerial of a definite period and amplitude. If the amplitude of these waves could be varied by the vibrations due to the voice, the train of radiated waves would consist of all the elements necessary to the transmission of speech.

Such a condition is effected by introducing a microphone in the aerial between the secondary and the ground. If this is now spoken into, the constant radiated energy of the aerial will have superimposed on it the varying energy caused by the changes in the microphone resistance and consequently the radiated waves will have all the varying amplitudes caused by the sounds of the voice speaking against the diaphragm of the microphone.

Electromagnetic Waves.

From the preceding explanation it will be seen that the waves radiated from the aerial of a radio-telephone sender differ from those of a radio-telegraph sender in that the amplitude of each wave in a wave train from the former varies according to the impulses that have been given to it by the voice and consist of all the various irregularities of amplitude that are characteristic of sound waves, while those from the latter are probably of nearly equal amplitudes. Aside from this difference the two series of waves are practically the same.

Receivers.

The receiver necessary to respond to every fluctuation of the energy of the transmitter may be any of the various forms of automatically restoring detectors using a telephone receiver, such as the electrolytic detector, the crystal or rectifying detector or vacuum detector. The type last mentioned seems to be the most sensitive and to give the clearest quality to the reproduced tones. A detector of this type is the "Audion," or hot-gas responder, devised and patented by De Forest, and which has been described in a previous chapter..

After the practicability of using the electromagnetic waves for transmitting telegraph signals was demonstrated by Marconi, many experiments were carried out to develop a radio telephone using the spark discharge similar to that used in sending out the damped electromagnetic waves used in radio telegraphy. All these attempts were unsuccessful as it was impossible to obtain a sufficiently high spark frequency to represent the wider range of vibrations necessary for the reproduction of speech. It now seems to be the opinion of those who have made a study of the matter that a successful practical radio telephone can be devised by using a source of undamped electromagnetic waves of high frequency with a device for changing the amplitudes of these waves in accordance with the modulations of the voice. By suitable arrangement at the receiving end, this varying intensity of the electromagnetic waves may be made to actuate a telephone receiver and reproduce the sounds of the voice.

The two methods used for producing undamped waves are the arc method and the high-frequency generator. These methods have been described in the chapter on Radio Telegraphy. The fact that many practical difficulties appear in using either method is apparent when it is realized that no radio telephone has been perfected to such an extent as to cause it to be adopted for use on board vessels of the navy.

De Forest Radio Telephone.

This system is manufactured by the De Forest Radio Telephone and Telegraph Company of New York. The system is based upon the modulation by a telephone transmitter of trains of undamped electromagnetic waves of relatively high frequencies. Originally these waves were generated in a way, following the methods shown by Thomson and Duddel, the frequency of the oscillations becoming so great as to enter the range of Hertzian waves.

The direct-current arc was used in connection with an alcohol flame, special arrangements being made to render the arc quiet and free from hissing or popping sounds which would render the reception of speech more or less obscure. To adapt an arrangement of the low-potential arc to wireless transmission of speech it is necessary to secure a spark frequency exceeding the tones used in speech.

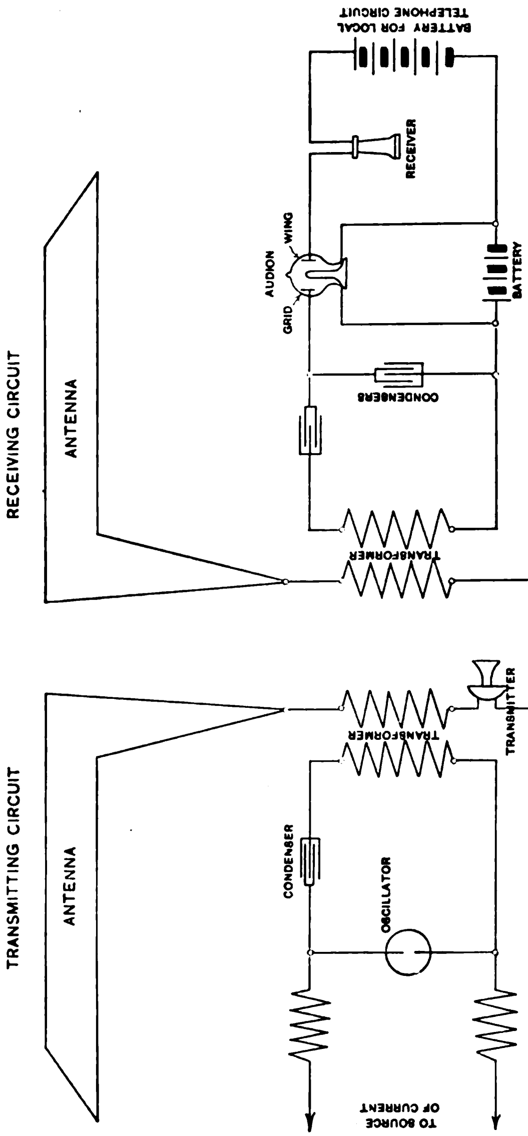


FIG. 483.—Elementary Connections of De Forest Radio Telephone Set.

If this frequency be higher than that, having for example, over 40,000 vibrations per second, the pitch of the aerial vibrations produced by the spark becomes so high as to make them inaudible to the human ear, and the articulation and clearness become perfect.

The 40,000 double vibrations correspond to a wave length of

$$\frac{300,000,000}{40,000}=7500 \text{ meters.}$$

The variation of the amplitude of the radiated waves is accomplished by placing a microphone transmitter in the earth lead of the aerial between an inductance and the ground; this inductance being inductively coupled with the closed oscillating circuit. The microphone is placed near the ground where the high-frequency currents are maximum and the potentials are the least.

The general elementary diagram of this system is shown in Fig. 483, and the sending circuit can be studied in connection with the Duddel circuit shown in Fig. 482. The receiving circuit can be readily understood from the description of the Audion previously given.

This type of De Forest telephone was not very successful and although some were installed on board naval vessels, with which partially successful experiments were carried out, they were finally removed. The principal difficulty was in the arc control. This company has recently developed a radio telephone using an alternator instead of an arc and experiments with this type have apparently been successful, and these new radio telephones have been put on the market. The same method of using a microphone to modulate the intensity of waves is employed as before.

INDEX.*

NOTE.—Titles of articles are given in bold-face type when principal references, and in italics when cross references, other cross references are given in plain Roman type.

* The general arrangement of this index is the same as used in The American Handbook for Electrical Engineers.