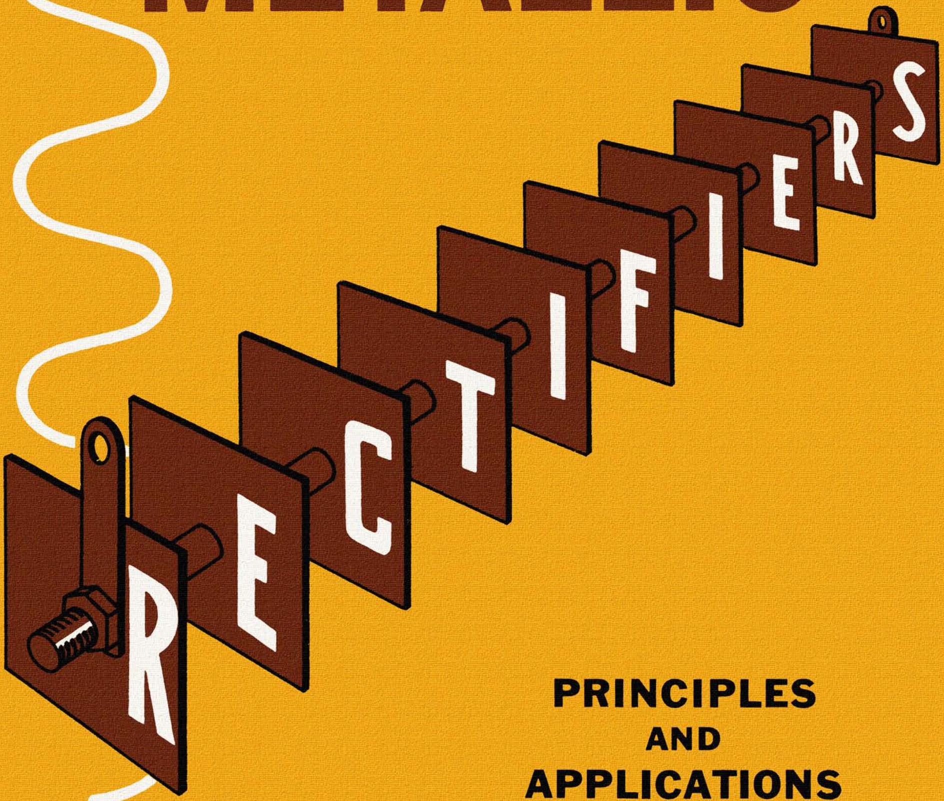
METALLIC RECTIFIERS



PRINCIPLES AND APPLICATIONS

by

Leonard R. Crow

A Howard W. Sams PHOTOFACT PUBLICATION • MRC-1

$3.00

METALLIC RECTIFIERS
PRINCIPLES AND APPLICATIONS

by

LEONARD R. CROW

FIRST EDITION—FIRST PRINTING

JANUARY 1957

MRC-1

Published by

HOWARD W. SAMS & CO., INC., INDIANAPOLIS 5, INDIANA

A Howard W. Sams PHOTOFACT PUBLICATION

Library of Congress Catalog Card Number: 56 – 12941

PREFACE

Without too much fanfare the metallic or semiconductor rectifier has become an important circuit component for use by the electrical or electronic designer, the engineer, and the technician because it facilitates rectification, instrumentation, and control. Although metallic rectifiers have been known since 1920 and have been used for more than 25 years in the laboratory and for railway signaling, their availability from commercial sources in standard stock sizes, their improved stability, and their competitive pricing have been notably apparent since World War II.

The improved metallic rectifiers are not only useful for the conversion of alternating electrical energy into direct current energy, but, also, because of their simply attained one-way valve characteristic, they provide unique elements for control circuits.

There is scattered through the technical literature a host of valuable articles on metallic rectifiers covering both theory and application, but, as far as the writer is aware, there is no compilation of this material in a somewhat simple and practical form for the vocational or technical student or for the not too recently graduated electrical engineer.

Hence, for this type of reader and for the man who is more interested in the principles and applications rather than the actual manufacture or design of the metallic rectifier, this book has been prepared to present the principles, types, and versatile uses.

For the more advanced reader, a fairly complete and classified bibliography on the subject is included in Appendix III at the rear of the book to permit more detailed study.

Leonard R. Crow

ACKNOWLEDGEMENTS

The writer gratefully acknowledges aid, photographs, and permission to use material previously published. Credit for photographs have been indicated in the titles; in particular the following organizations have given photographs of metallic rectifiers and applications which are used in this book:

W. Green Electric Co.

General Electric Co.

Vickers, Inc.

Radio Receptor Co.

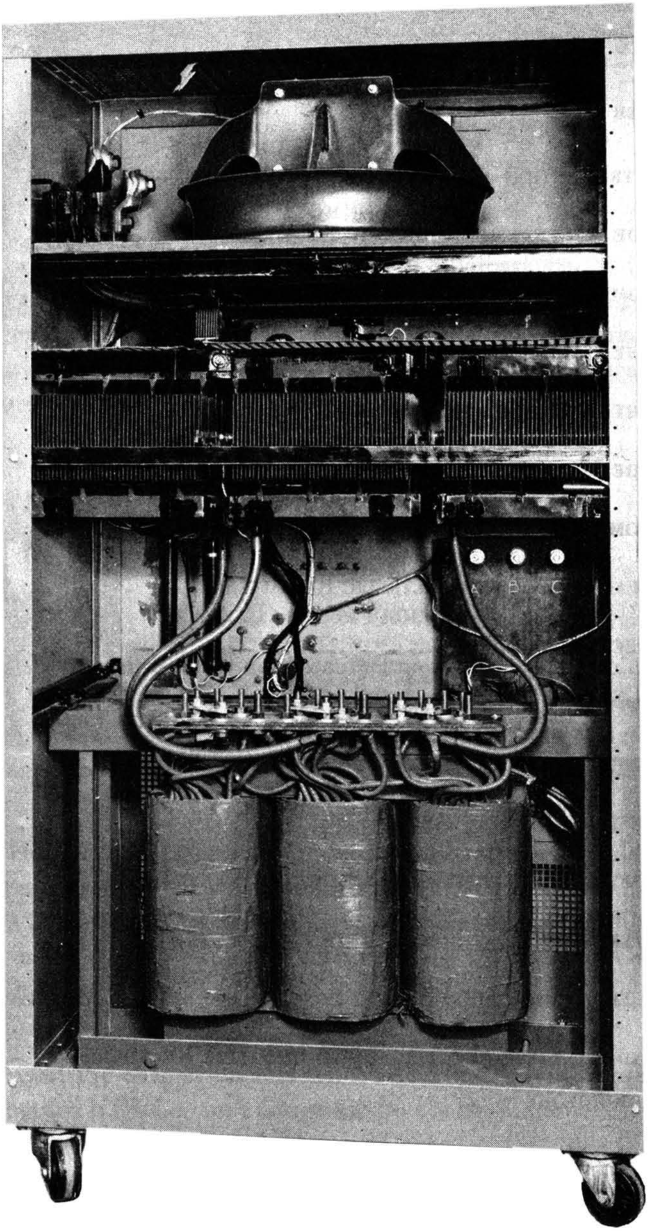
Sylvania Electric Products

Helpful material was obtained from technical literature supplied by General Electric and Westinghouse on copper-oxide and selenium rectifiers. Federal Telephone and Radio Corp., International Rectifier Corp., and Radio Receptor Co. supplied like material on selenium rectifiers.

The chapter on Magnesium-Copper Sulfide rectifiers would not have been present but for the kind permission of P. R. Mallory Co. and The Electrochemical Society, both of whom granted permission to use material from Samuel Ruben's article "Magnesium-Copper Sulfide Rectifier" published in the Society's Transactions, Vol. 87, pages 275-287 (1945).

Moreover, the chapter on Instrument Rectifiers would have been absent but for H. B. Conant's permission to use the material from his booklet "Instrument Rectifiers."

TABLE OF CONTENTS



Frontispiece

Rear View of Rectifier Cabinet for Elevator Control. (Courtesy of W. Green Electric Company, Inc., New York.)

CHAPTER 1

Introduction

The Problem

The bulk of electrical energy, more than ninety per cent, is generated and transmitted as alternating current and is used to operate household appliances, alternating current motors, electric furnaces, and electrical lighting systems. The chief reasons for generating the electrical energy with an alternating waveform are:

A. Alternating electrical energy can be easily generated at high voltage. By employing high voltage, economical transmission of electrical energy over long distances is accomplished. If this high voltage is alternating in waveform, it is readily reduced in voltage at the application end of the transmission by means of efficient, non-rotating electrical step-down devices called transformers.

B. It is desirable to have electrical energy available in alternating waveform so as to be able to employ alternating current motors of the induction type which are cheaper, more efficient, and trouble free than direct current motors. These induction motors are used in great numbers in industry and in domestic appliances and systems, for example, fans, heating and ventilating systems, phonographs, and magnetic tape recorders.

C. It is more economical to generate electrical energy in large units at a central powerplant than to generate it in small units near the point of utilization. Only alternating electrical energy lends itself to the remote generation and the economical transmission in large units.

Despite these good reasons for the almost universal presence of electrical energy in the alternating waveform, there are many electrical products and techniques which require direct current for efficient operation and control. Common applications where direct current is necessary are:

AC-DC radio power supply
Acoustic shunt
Aircraft engine starting
Aircraft power supply
Arc suppressors
Arc welders
Automotive rectifiers
Battery chargers
Battery eliminators
Burglar alarms
Business machines
Computers
Carbon arc lamps
Carrier control
Cathodic protection
Chemical testing
Circuit breakers
Coin machines
DC solenoids
DC magnets
Electro cleaning
Electro etching
Electro painting
Electro plating
Electro precipitation
Electric hammers
Elevator controls and brakes
Engine starters
Exciter lamps
Fence controls
Field excitation
Filament supply
Fire alarms
Inductive surge absorber
Lifting magnets
Magnetic amplifiers
Magnetic brakes
Magnetic separators
Magnetic valves
Magnetic clutches
Model trains
Oscillograph power supply
Plate voltage power supply
Polarized relays
Proximity fuses
Railway signaling
Rectifier instruments
Relays
Telegraph power supply
Telephone power supply
Television power supply
Time clocks
Traffic control
Trickle charger
Truck chargers
Voltage multipliers
Vibrator feeders

When direct current is needed, it must generally be obtained from the universally present alternating current system. The alternating current must be converted in some manner into direct current. This conversion of alternating current into direct current is called rectification and may be accomplished in the manners to be described.

The Mechanical Approach

Mechanical rectifiers have been used to convert alternating current into direct current. Fig. 1-1 shows one method of accomplishing this mechanically. A synchronous motor M drives a shaft S upon which are mounted two slip rings A and B and a two segment commutator C having segments x and y.

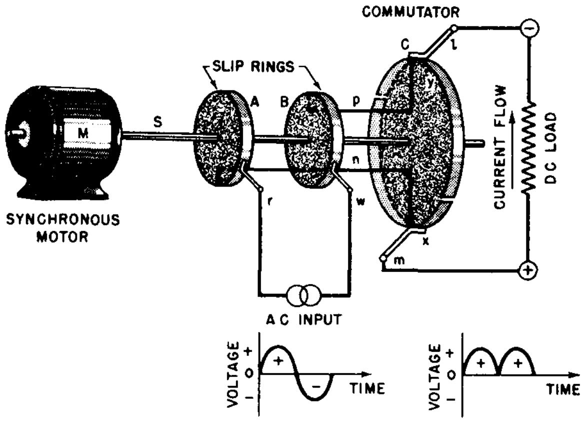


Fig. 1-1. A Mechanical Rectifier (Full Wave).

The slip rings and the commutator segments are insulated from the shaft. A conductor n connects slip ring A with commutator segment x while a conductor p connects slip ring B with commutator segment y. Brushes r and w engaging the slip rings A and B apply the alternating current to the rotating system. Brushes l and m, engaging the commutator segments as they rotate, provide the commutated direct current to the load. The reader can follow that the synchronously driven system provides direct current flow through the load circuit; for, at that instant when the alternating input polarizes brush r positive and brush w negative, the output brush m is positive while the output brush l is negative. One half cycle later (one half revolution of the commutator and slip rings because the mechanical system is synchronous with the alternating voltage which is driving the synchronous motor) brush r is negative while brush w is positive. Because the commutator has rotated one half of a revolutation by this time too, brush r now energizes brush l, whereas brush w now energizes output brush m. Thus the output brush polarities remain unchanged and a direct current flows through the load with the polarity as shown. That is, the commutator segments are connected as shown so that, when the alternating input reverses, the connections to the direct current or output circuit are simultaneously reversed resulting in a direct current output. The voltage-time curve shown below the AC input in Fig. 1-1 illustrates the sinusoidal input voltage or current; the curve below the DC load illustrates the fully commutated AC input resulting in a direct current flow of varying amplitude.

The disadvantages of the mechanical rectifier are that the moving parts require frequent maintenance, and practical considerations of applied voltage and sparking at the brushes limit the device to small current and voltage outputs.

The Vibrating Reed Rectifier

The vibrating reed rectifier is also mechanical in nature and operates on the same basic principles as the mechanical or rotating rectifier just described. In the vibrating rectifier, however, a pair of contacts are reciprocated between two sets of stationary contacts by means of a tuned reed or armature, which is synchronously driven by the alternating current to be rectified. To drive the reed at synchronous speed it is

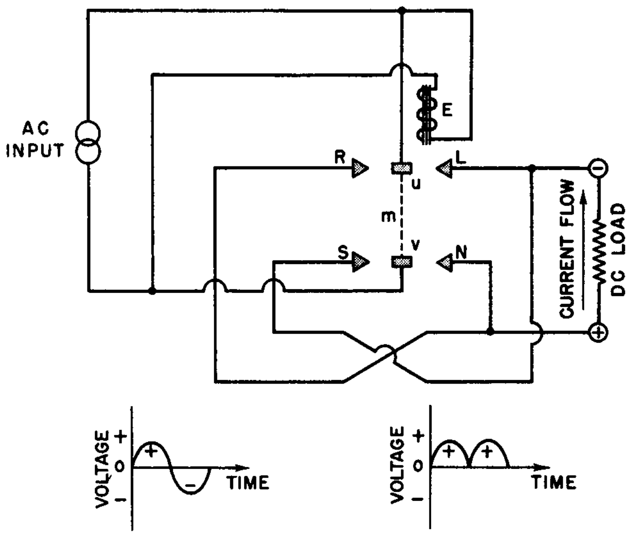


Fig. 1-2. A Vibrating Reed Rectifier (Full Wave).

necessary for it to be magnetically polarized. This is accomplished by means of a permanent magnet slug mounted in a favorable position in the magnetic circuit of the vibrating rectifier. The schematic diagram of the vibrating reed rectifier is given in Fig. 1-2. The tuned reed m carries a pair of contacts, u and v, which are insulated from each other and from the reed. The electromagnet E which is part of the magnetic circuit (not shown) vibrates the moving contacts u and v between the pairs of stationary contacts R S and L N. The vibration is synchronous because the magnetic circuit is energized by the same alternating current which is to be rectified. The moving contacts are connected each to a respective terminal of the AC input. The stationary contacts are cross-connected, that is, R to N and S to L with the common connection between each becoming the positive and negative terminals of the DC output.

Thus, during that part of the alternating cycle when the AC input polarizes contact u negative and contact v positive, the electromagnet E may be so connected as to attract the magnetized reed to the right causing contact u to engage fixed contact L while contact v engages fixed contact N. The upper output terminal is then negative while the lower output terminal is positive. During the next half cycle when the movable contact u is positive and movable contact v is negative, the electromagnet E also has its magnetic polarity reversed because of the change in the polarity of the applied alternating input, thus causing it to repel the reed m and permitting the movable contacts u and v to engage the fixed contacts R and S respectively. Because of the cross-connections between the fixed contacts, that is, R strapped to N and S strapped to L, the alternating input is mechanically commutated so that the upper output terminal is maintained negative while the lower terminal is maintained positive. Hence, the output of the vibrating reed is direct current of varying amplitude. Again the graphs near the input and output show the waveform of the current flow or voltage present at those terminals respectively.

Moving parts and small output have limited the use of this rectifier which was formerly used to charge small storage batteries. At the present time a modified form of this vibrating-reed rectifier operated synchronously with a vibrator chopper permits the operation of automobile radios from the car storage batteries.

The Chemical Approach

Another type of rectifier formerly used to change alternating current to direct current is of the chemical or electrolytic type. See Fig. 1-3. This rectifier consists primarily of a lead plate electrode and an aluminum plate electrode immersed in a solution of sodium bicarbonate or ammonium phosphate contained in a glass jar. When the electrolytic cell is energized so that the lead plate is positive and the aluminum plate is negative, electrical current flows readily. When the applied potential to the electrodes of the electrolytic cell is reversed, that is, the lead plate is made negative and the aluminum plate

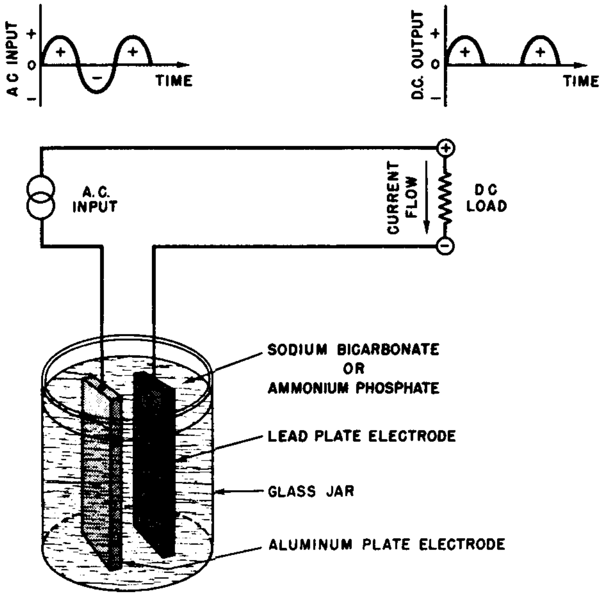
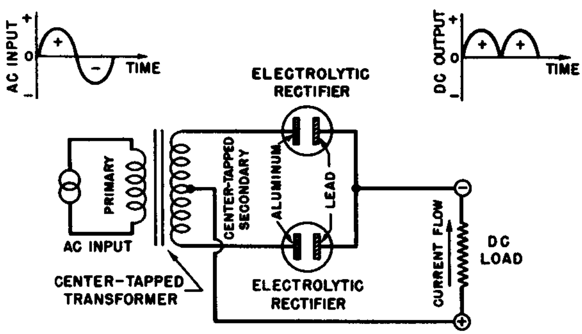


Fig. 1-3. An Electrolytic Rectifier (Half Wave).

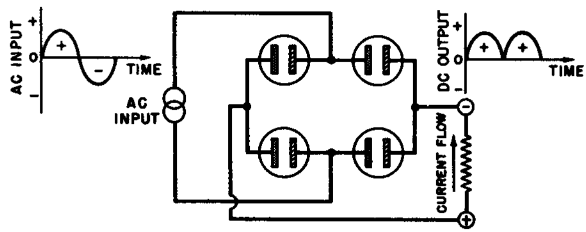
positive, a thin insulating film of aluminum oxide forms instantly over the aluminum electrode and acts as an insulator up to a breakdown voltage of approximately 150 volts. This oxide film prevents the flow of electrical current when the aluminum plate is positive and the lead plate is negative, provided the breakdown voltage is not exceeded. The resulting unidirectional conduction of the electrolytic cell makes it behave as a rectifier.

In the arrangement shown in Fig. 1-3 wherein a single electrolytic cell is used, half-wave rectification occurs, that is, every other half cycle of the alternating current is permitted to flow through the DC load. It is necessary to employ two such cells with a center-tapped transformer as in Fig. 1-4A, or four such cells in a bridge circuit as in Fig. 1-4B, before full-wave rectification (unidirectional current flow from both negative and positive alternations of the alternating current waveform) can be accomplished. Circuit details in connection with any type of rectifier cell used in half-wave and full-wave will be throughly discussed in the chapter dealing with "Rectifier Circuits."

Small current capacity, low efficiency, as well as the generally messy nature of the electrolytic cell rectifier have limited the use of this means of rectification.



(A) Using Two Cells and a Center-Tapped Transformer.



(B) Using Four Cells in a Bridge Circuit.

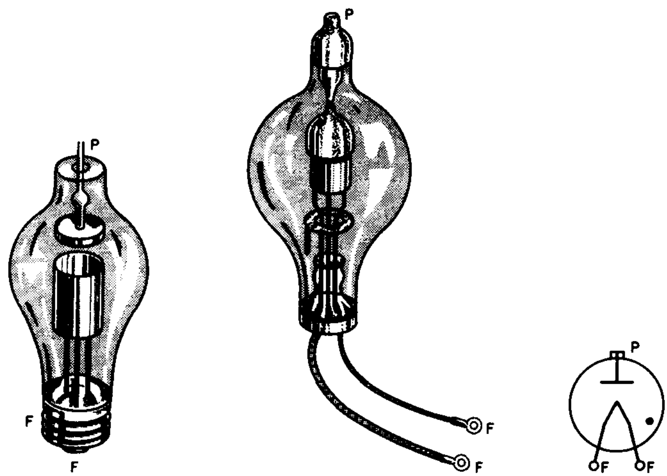
Fig. 1-4. Full Wave Rectification with Electrolytic Cells.

The Motor-Generator Approach

Alternating current motor-driven DC generators have also been used to indirectly change AC to DC by means of an electromechanical transfer. These arrangements have been and are still being used in some electroplating organizations. Electroplating service is a low-voltage, high-current application and the efficiency of motor-generator combinations is low at low output voltages — of the order of 25 to 30 per cent. For full output voltage the efficiency of the motor-generator combination may approach 60 to 80 per cent. Moreover, the motor-generator combination requires frequent overhauling and attention to the brushes and commutator, for it is difficult to protect it from the corrosive electroplating fumes as the machine must be mounted near the point of application to secure short copper bus bars to the job. Short bus bars are essential so as to minimize the electrical losses which would be excessive as a result of the heavy current employed for plating.

Mercury Arc Rectifiers

For the abundant rectification of alternating electrical energy, especially in the metal manufacturing industries, very large mercury-arc rectifiers of the glass enclosure or steel tank construction have been used. Small mercury-vapor rectifiers have been used for battery charging for 40 years. Some examples of small mercury-vapor rectifiers available for general purpose rectification at high voltages and moderate current of the order of 10 to 15 amperes are shown by the



(A) Screw-Base Mercury-Vapor Rectifier. (B) Flexible-Lead Mercury-Vapor Rectifier. (C) Symbol for Mercury-Vapor Rectifier.

Fig. 1-5. Small Mercury-Vapor Rectifiers Rated at 10 to 15 Amperes.

sketches of Fig. 1-5. Large mercury-arc rectifiers have been constructed with capacities up to several thousand kilowatts. The large glass type mercury-arc rectifiers are obsolete today and the steel tank type mercury-arc rectifiers are being superseded by the ignitron, fundamentally, a mercury-arc tube containing in addition an igniting electrode and the necessary associated actuating circuits.

The Metallic or Dry Disc Rectifier

Another type of rectifier, the subject of this book, is the metallic or dry disc rectifier. This type of rectifier has become widely accepted because of its simplicity, absence of moving parts (hence, negligible maintenance), silent and instantaneous operation, practically unlimited life, and low cost.

The metallic rectifier is identified by a variety of names still in common usage. The original rectifier cells were fabricated from discs, hence, the title "dry disc rectifier". Still later some manufacturers started using square or rectangular plates for the rectifier cells, originating the noun "dry plate rectifiers". In recent years, as the mechanism of the metallic rectifier is becoming better understood, some people have emphasized one of its important elements by calling the device a "semiconductor rectifier". The communication engineers call the metallic rectifier "varistors", more specifically "non-symmetrical varistors" defining a varistor as "a two-terminal circuit element composed of an electronic semiconductor and suitable contacts which has a markedly nonlinear volt-ampere characteristic".

The National Electrical Manufacturers' Association has identified the rectifier under discussion as metallic rectifier and this term is the name which was selected to identify it in this book.

The basic principle of the metallic rectifier for converting alternating current into direct current is that the resistance to the passage of electrical current in one direction is exceedingly great, whereas the resistance to the flow of electrical current in the opposite direction is almost negligible. The result is that, when an alternating potential is applied across a series circuit comprising a metallic rectifier and a load, the current flow is substantially unidirectional — the metallic rectifier performs as a one-way valve for the alternating current.

Certain combinations, such as iron or aluminum and selenium, magensium and copper-sulphide, or copper and copper-oxide have this valuable property of passing an electric current unidirectionally; because of this property, these combinations are used as rectifiers or converters of alternating into direct current.

In so far as the writer is aware the original discovery of the metallic rectifier was made in November, 1920, by L. O. Grondahl and P. H. Geiger of Union Switch and Signal Company.

The first type of rectifier involved copper and copper-oxide elements.

The discovery that a copper-copper oxide junction had rectifying characteristics was the by-product of another research problem under study at that time. This problem was to produce an electrical relay without moving parts or contacts. The experimental procedure for this research was to study all forms of electrical impedance which could be easily and non-mechanically changed through a large resistance range to simulate the opening and closing of electrical contacts as by relay contacts.

One of the experiments towards achieving non-mechanical relays involved photoelectric cells using selenium or copper oxide. The copper oxide was selected for the tests since its properties had been more stable during previous laboratory experiments.

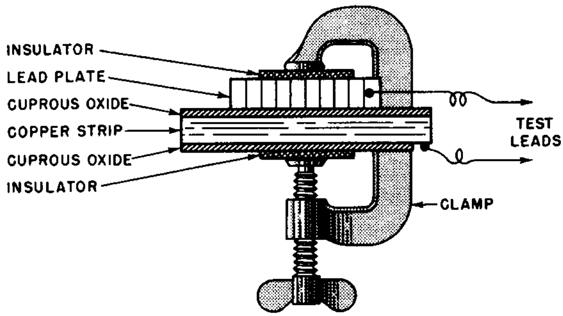


Fig. 1-6. Exaggerated Cross-Sectional View of Original Copper-Oxide Type, Half-Wave, Metallic Rectifier.

The first experimental model of the relay comprised a strip of copper which had been heated in an electric furnace at about 1000 degrees centigrade for one hour. A connection to the copper plate was made by breaking off the cuprous oxide at one end. The cupric oxide on the surface of the copper strip which had formed during the cooling was ground off by an emery wheel. Contact to the surface of the cuprous oxide was obtained by means of a piece of lead sheet compressed against the cuprous-oxide surface by means of a clamp. Sheets of insulator material at either side of the assembly prevented short circuit of the test junction due to the metal clamping means used. See Fig. 1-6.

This assembly was tested by means of a Wheatstone bridge energized by direct current so as to determine its resistance with and without light falling upon the active cuprous oxide surface. It was hoped that light falling upon the active surface would greatly reduce the normally high resistance — simulating the non-mechanical actuation of a circuit switch.

Wheatstone bridges are commonly used in the laboratory for resistance measurements and the circuit diagram with the essential operating equation is shown in Fig. 1-7. Ra and Rb are predetermined fixed resistances and are called the ratio arms of the bridge. The unknown resistance, Rx, is connected to the test terminals of the Wheatstone bridge. The fourth arm of the bridge consists of a variable, but known resistance Rs, in the nature of decade resistance boxes or a calibrated resistance slide wire. Across one diagonal of the resistance bridge is connected the electrical energizing means, a low voltage battery. Across the other diagonal of the bridge is connected in series a galvanometer switch and a galvanometer. The adjustable known resistance, Rs, is varied until there is no difference of potential across the diagonal containing the galvanometer. This condition is detected when closure of the galvanometer switch does not result in a deflection of the galvanometer pointer from its null position. When Rs is adjusted to achieve null balance the potential drop across Ra and Rx is equal to the potential drop across Rb and Rs. This condition is necessarily so if there is to be no difference of potential across the galvanometer.

Hence,

$$\frac{Rx}{Rs} = \frac{Ra}{Rb}$$

or

$$Rx = \frac{Ra}{Rb} \; Rs.$$

When measurements on the experimental copper-copper oxide assembly were made by means of the DC Wheatstone bridge, it was found that the photoelectric effect was nil, but a peculiar effect was discovered. At times the experimental assembly measured a resistance of 400 ohms and at other times the assembly measured 1200 ohms. It was soon determined that the resistance value of the assembly depended upon the polarity of the battery powering the Wheatstone bridge or upon the way in which the assembly was connected to the bridge, that is, whether the assembly was connected to the bridge so that the copper electrode was connected to terminal A and the copper oxide electrode to terminal B or vice-versa. Refer to Fig. 1-7.

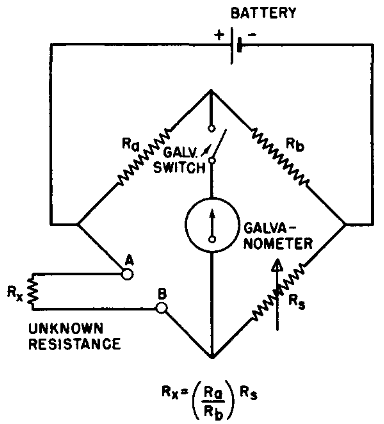


Fig. 1-7. A DC Wheatstone Bridge for Measuring Unknown Resistances.

The two values of resistance measurement indicated a non-symmetrical conduction of electrical current through the experimental assembly and this copper copper-oxide combination was recognized as a potential rectifier of alternating current. Because the available rectifiers of the early 1920's were bulky, unstable, or difficult to use and consisted of rotating or vibrating mechanisms or chemical cells already described, and because there was a need for a simple and reliable rectifier for the operation of a DC relay from an AC source, the copper-oxide combination was further improved. By 1924 a practical installation was made in a train control equipment which actuated a DC relay from an AC supply. As late as December, 1947, this rectifier was still operating in the same application.

Another pressing problem of those days accelerated the development of this accidental finding. In the early 1920's the filaments of vacuum tubes used in radios were energized by means of 6-volt storage batteries which were called "A" batteries. These "A" batteries required chargers to maintain them as sources of electrical energy. During the latter part of 1926 the Westinghouse Electric Corporation was producing 6000 "A" battery chargers a day employing copper oxide assemblies.

In the succeeding years the magnesium-copper sulphide and the selenium rectifiers were developed by others and commercially applied. Currently the design and application engineer has a choice of the three types of metallic rectifiers. Certain advantages or properties of one of the types may help in the decision of which of the three to use for a specific application. These properties will be described in later chapters of this book.

CHAPTER 2

The Generalized Metallic Rectifier

Introduction

The need for conversion of alternating current into direct current was discussed in Chapter 1. Various methods for this conversion were described involving mechanical, chemical, and gaseous vapor and arc tubes. A short history of the discovery of the metallic rectifier was given and it was stated that this type rectifier was to be the subject matter of this book. By means of this device efficient and inexpensive rectification of alternating current into direct current is obtained for all but huge amounts of electrical energy as used in the metal industries.

In this chapter,some of the general properties of the metallic rectifier will be described before presenting the three specific types of these rectifiers commerically available; these three types are the copper-oxide, the magnesium-copper sulphide, and the selenium.

Some Conventions and Nomenclature

Although there is presented at the end of the book an abbreviated section on nomenclature and standards on metallic rectifiers, it is thought best to define here some of the more pertinent conventions and rectifier terminology.

Electric Current Flow. The conventional direction of electric current flow in the circuit external to the applied potential is from the positive to the negative ternimal.

Electron Flow. In a circuit the electron flow is from the negative terminal of the applied potential to its positive terminal.

Conductor. Substances in which the electrons are able to pass readily from atom to atom under the influence of a small applied potential are called conductors; examples of conductors are silver, copper, aluminum, etc.

Insulator. Substances in which the electrons are so tightly bound that it takes enormous electric potential to cause current flow are called insulators; examples are ceramics, glass, and mica.

Semiconductor. Substances which are not good conductors and yet are not insulators are called semiconductors; examples are carbon, metal oxides, and certain alloys.

Rectifier. A rectifier is an electrical device for converting alternating current into direct current; it possesses this property because it conducts current effectively in only one direction.

Metallic Rectifier. A rectifier utilizing the non-symmetrical conduction of the junction between dissimilar solid conducting substances to obtain unidirectional flow of electric current is called a metallic rectifier. It is also frequently called a "dry-disc rectifier", a "dry plate rectifier", or a "semiconductor rectifier".

Cell. The elementary metallic rectifier having one positive electrode and one negative electrode between which is located a single rectifying junction is called a cell. It may also be called a rectifier plate, rectifier element, or a rectifier couple.

Rectifying Junction. The region in a metallic rectifier cell which possesses the unidirectional conductivity is called the rectifying junction. It is also called the barrier or blocking layer.

Forward Direction. The forward direction of a metallic rectifier is the direction of least resistance to current flow through the cell. With conventional current flow the forward direction is from positive to negative.

Reverse Direction. The reverse direction of a metallic rectifier cell is the direction of greatest resistance to current flow through the cell; with conventional current flow the reverse direction is from negative to positive.

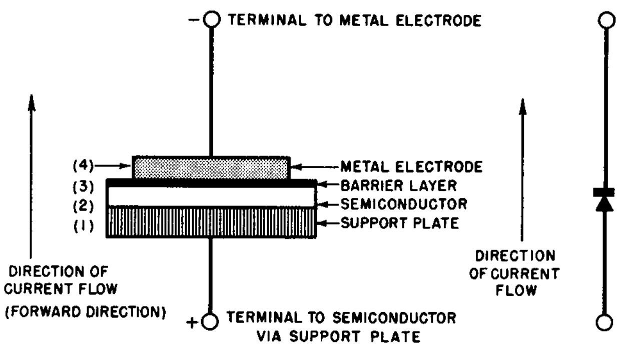
Rectifier Stack. A rectifier stack comprises a single columnar assembly of one or more metallic rectifier cells.

Half-Wave Rectification. Half-wave rectification is rectification wherein only one half of the alternating cycle is transmitted as unidirectional current.

Full-Wave Rectification. Full-wave rectification is rectification wherein both halves of the alternating cycle are transmitted as unidirectional current.

The Generalized Metallic Rectifier

It will be seen later in the book that the three commonly used metallic rectifier cells can be simply represented by a generalized rectifier element comprising four essential components. In the generalized rectifier element the specific identification of these components will not be necessary (specific examples will be given in subsequent chapters); hence, simplified discussion of theory and structural nature of the various rectifier stacks can be given without a confusing recitation of the different metals, alloys, and semiconductors employed.



(A) Exaggerated Cross-Sectional View. (B) Symbol for Metallic Rectifier.

Fig. 2-1. The Generalized Metallic Rectifier Element.

This generalized metallic rectifier element is shown in Fig. 2-1. Fig. 2-1A represents an exaggerated cross-sectional view of the rectifier cell and Fig. 2-1B represents the electrical symbol for the rectifier cell. The generalized metallic rectifier cell is made up of the following four essential components:

1. A metal support plate which does not enter into the rectification process but provides a mechanically strong and stable plate for the rest of the rectifier and serves as one of its terminals.

2. A semiconductor layer the nature of which depends upon the specific rectifier type.

3. A barrier, blocking, or insulating layer which is formed electrically or by heat treatment.

4. A metal electrode making intimate contact with the barrier layer by either plating, metallic spraying, or by mechanical pressure.

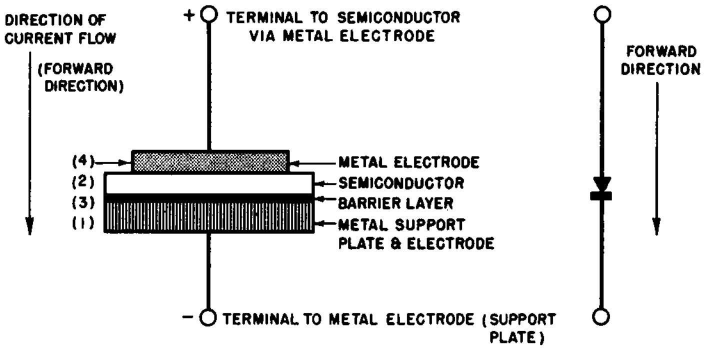
In a typical rectifier cell the whole cross-sectional thickness need not be more than 1/16th inch or less. This will give the reader some measure of the amount of exaggeration in Fig. 2-1A which is not drawn to scale, especially the barrier layer, which in reality is extremely thin.

The pertinent structure of the metallic rectifier cell then is a semiconductor layer separated from a metal electrode by an extremely thin insulating layer, called the barrier or blocking layer. The opposite surface of the semiconductor is in contact with a low resistance metal plate which does not function in the rectification act, except as an electrode and stable supporting means for the semiconductor.

This assembly, as described, has the unique property of readily permitting the flow of electric current in one direction through the rectifier cell, but substantially blocking the flow of electric current in the reverse direction through the rectifier cell. With conventional current flow, defined as from the positive polarized terminal to the negative polarized terminal, the rectifier element described possesses low resistance to electric current flow in the direction from the semiconductor to the metal electrode (defined as the forward direction) and offers high resistance to the flow of electric current flow in the direction from the metal electrode to the semiconductor (defined as the reverse or bucking direction). The arrow to the left of Fig. 2-1A indicates the forward direction when the terminals of the rectifier cell are polarized as shown. Likewise, in the symbol for the rectifier cell shown in Fig. 2-1B as a bar and an arrowhead, the arrowhead indicates the forward direction.

In a practical rectifier cell the ratio of forward resistance to the reverse resistance under rated operating conditions may be as high as 1 is to 2000. That is, for a given voltage it is 2000 times easier for the electric current to flow from the semiconductor to the metal electrode than in the reverse direction—from the metal electrode to the semiconductor. Hence, the device described performs substantially as a oneway valve to electric current flow. This is the property required of the device to make it function as a rectifier—convert alternating current into direct current. The higher the resistance ratio between the reverse and forward direction, the more efficient the rectifier cell.

Some people think of metallic rectifiers as comprising three essential parts in place of the four listed previously, that is, the semiconductor and two suitable electrodes. The barrier layer is not mentioned since it is not tangible nor added physicially during the manufacturing process but is derived by electroforming or by heat treatment. However, the presence of the barrier layer is absolutely essential to the successful operation of the metallic rectifier and in this book will be included as a necessary member of the rectifier cell.



(A) Exaggerated Cross-Sectional View.

(B) Symbol for Metallic Rectifier.

Fig. 2-2. The Modified Generalized Metallic Rectifier Cell.

Moreover, the exact position of the barrier layer is not always self-evident. It may be positioned as shown in Fig. 2-1 or as in Fig. 2-2. Both types of rectifier cells are commercially available and both generalized rectifier cells, as shown in Figs. 2-1 and 2-2, are electrically equivalent. The only difference between the two cells is in the location of the barrier layer. In Fig. 2-1, previously described, the barrier layer is located between the metal electrode and the semiconductor layer. A good example of this cell is the selenium rectifier cell. In Fig. 2-2 the barrier layer is located between the support plate and the semiconductor; an example of this type cell is the copper-oxide rectifier.

The position of the barrier layer determines the forward direction of current through the metallic rectifier cell. To avoid confusion, as each type of rectifier is presented in subsequent chapters, there will be given an exaggerated cross-sectional view of its rectifying components together with the correct forward direction.

The reader may remember the following general rule regarding present-day commercially available metallic rectifiers irrespective of the arrangement of the rectifying junction components. The forward direction or direction of substantial current flow in a metallic rectifier occurs when the applied polarizing potential is directed from the semiconductor to the adjacent metal across the barrier layer.

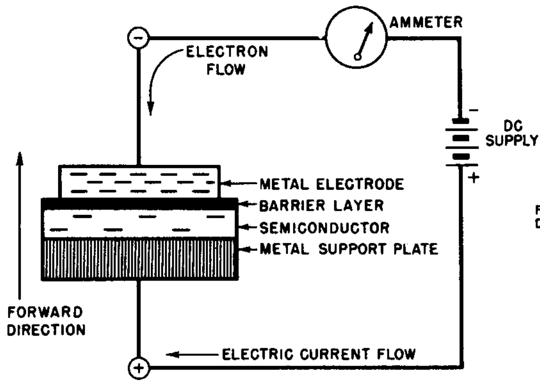
Rectification in a metallic rectifier occurs at the rectifying junction called the barrier or blocking layer. This layer is at the interface of two dissimilar conducting materials, the metal electrode and the semiconductor—in fact, it is sandwiched between the two. This rectifying couple formed by the metal plate and the semiconductor layer presents a high resistance to an applied voltage of one polarity and a considerably lowered resistance when the applied voltage is of the opposite polarity.

Theory of the Rectifier Junction

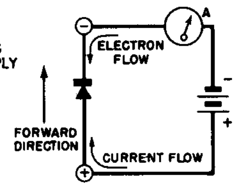
The rectifier cell described in the preceding discussion may be considered as a resistive device having a low resistance in one direction and a very high resistance in the opposite direction. Electric current flows freely in the forward direction (the low-resistance direction) while in the reverse direction (the high-resistance direction) very little current flows.

To learn in detail the latest opinions of the experts as to the explanation for the non-symmetrical conduction properties of the rectifying junction requires studying reference books much more complex than the present book. For our purpose, however, an explanation given by E. A. Richards ten years ago will suffice as a brief and simplified account for the rectifier junction behavior.

It was stated that the rectifying junction consists primarily of a semiconductor and a good conductor, the two dissimilar conductors being separated by a barrier layer. This barrier layer, which is extremely thin and in itself an insulator, will permit electrons to pass in either direction through it provided the potential gradient across it is of sufficient magnitude. Of the two dissimilar conductors, the metal electrode is an abundunt source of free electrons, while the semiconductor, which is the poor conductor, is a sparse source of free electrons. In Fig. 2-3A the free electrons are represented by short dashed lines, a greater number of free electrons being placed in the metal or front electrode than in the semiconductors. The rectifying junction is shown as part of a series circuit comprising a current indicating instrument (ammeter) and a source of direct current power. Fig. 2-3B gives the equivalent schematic diagram of Fig. 2-3A.



(A) Exaggerated Cross-Sectional View.



(B) Schematic Diagram.

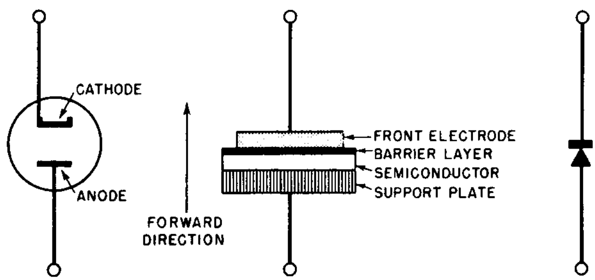
Fig. 2-3. The Rectifier Junction Showing Proportion of Free Electrons in Metal Electrode and in the Semiconductor.

When the two dissimilar conductors are connected to a source of direct current electricity, as shown in Fig. 2-3, the opposite polarities set up an electric field across the barrier layer; as this barrier layer is so very thin, a nominally small potential difference across it will result in a steep potential gradient. If the metal electrode is connected to the negative terminal of the direct current source and the semiconductor is connected by way ot the support plate to the positive terminal as in Fig. 2-3A, the free negative electrons in the metal electrode are accelerated to a sufficient velocity to pass through the barrier layer and the inter-crystalline space of the semiconductor to the metal support plate with the result that this flow of electrons constitutes an electric current flow in the forward direction.

The characteristic curves of the rectifier cell to be discussed later support this theory in that the rectifier junction has high resistance in the forward direction for very low applied voltage; as the applied potential is increased, more free electrons from the metal electrode are accelerated and reach the support plate resulting in greater current flow through the rectifier.

When the applied polarity to the rectifying junction is reversed, that is, the metal electrode is polarized positive and the semiconductor polarized negative, the same action takes place but a new condition exists. Now the semiconductor has to supply the free electrons and, as it is a sparse source of free electrons because it is a poor conductor, few electrons will be able to penetrate the barrier layer and make contact with the metal or front electrode; hence, the resulting current flow is much smaller. This current flow in the reverse direction is called reverse current or leakage current.

The function of the metal support plate is to afford a conducting support for the semiconductor layer and provide one terminal of the rectifying junction. It is essential that no barrier layer be formed between the semiconductor and its support plate for the type of rectifying junction shown in Fig. 2-3A; should this occur, counter rectification would take place and the rectifying properties of the cell would be reduced or nullified. For equal voltages in both directions across the rectifying junction, the forward current is several thousand times greater than the reverse current.



(A) Cold-Cathode Diode Rectifier.

(B) Exaggerated Cross-Sectional View of Metallic Rectifier.

(C) Symbol for Metallic Rectifier.

Fig. 2-4. Comparison of Metallic Rectifier Cell to Cold-Cathode Rectifier.

The rectifier junction may be compared to a cold cathode electronic tube as shown in Fig. 2-4, in which the front metal electrode forms the cathode; the metal support plate, the anode; and the semiconductor and barrier layer, the insulator between the two electrodes. The function of the semiconductor is chiefly that of a medium between the anode and the barrier layer to enable the accelerating positive potential to be in extremely close proximity to the cathode without simultaneously resulting in a high reverse current.

From this assumption the thickness of the semiconductor and its crystalline structure should have considerable influence on the performance of the rectifying junction; this is verified in practice. The forward resistance of the rectifier cell is a function of the semiconductor, the barrier layer and the front electrode; the reverse resistance is the function of the barrier layer.

It can be inferred from the above theoretical explanation, and this is borne out in practice, that the barrier layer is the most important part of the rectifying junction as to its performance and stability.

Volt-Ampere Relationship of the Junction

The unidirectional conducting property of the metallic rectifier is best shown graphically by its volt-ampere curve — the graph which shows the relationship between the applied voltage to the junction and the resultant current flow. This type of curve may be obtained experimentally by the circuit given in Fig. 2-5.

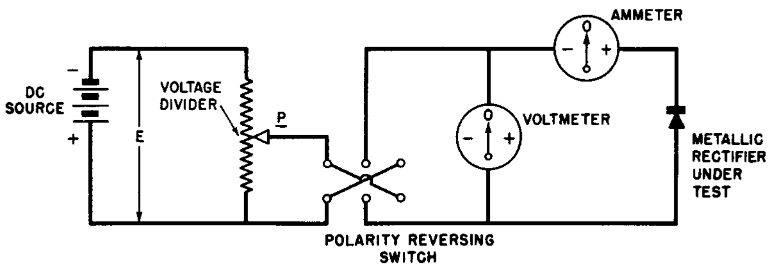


Fig. 2-5. Test Circuit for Rectifier Junction.

Here a source of direct current power energizes a voltage divider; any desired value of DC voltage from zero to E may be obtained by adjusting the position of the slider, P. This adjustable voltage is then applied to a polarity reversing switch the output of which is applied to the metallic rectifier junction under test. An ammeter in series measures the current flow and a voltmeter across the circuit indicates the magnitude and the polarity of the applied voltage.

The characteristic of the rectifier for one polarity is determined by maintaining the polarity of the applied voltage fixed and increasing the applied voltage by successive adjustments of the slider P and noting the current flow at each value of applied voltage. Reversing the polarity switch and repeating the process gives the opposite polarity performance. The experimental data thus obtained can be plotted in the form of a curve.

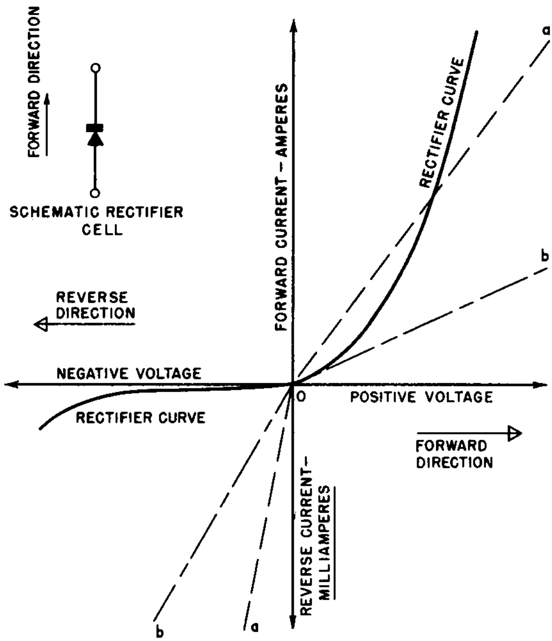


Fig. 2-6. Volt-Ampere Curve for Generalized Metallic Rectifier Junction.

This curve depicts the voltage-current characteristic of the metallic rectifier cell. Such a characteristic curve is shown in Fig. 2-6; from this type of information it becomes possible to more quickly determine the operating properties of the rectifier for circuit applications.

Since the reverse current is so much smaller than the forward current, the current scale of the graph is plotted as amperes per unit area above and in milliamperes per same unit area below the voltage axis. This is common practice in metal rectifier graphics. Moreover, for reference and comparison two other volt-ampere curves A and B are also drawn in Fig. 2-6. These are characteristic curves for pure resistors, curve A for a moderate value of resistance; curve B for a higher ohmic resistance. The break in the linear resistor curves as they pass through O is due to the non-symmetrical current axis described in the foregoing.

The non-linear properties of the rectifier junction is clearly seen when its curve is compared with that of the pure resistors. As the applied voltage is increased in the forward direction, the current through the rectifier junction increases quite slowly at first; then, the current rate becomes quite rapid with applied voltage approaching a linear characteristic for its larger values.

In the reverse direction the applied voltage must be increased to large values before even small amounts of current flow are detected.

In the forward direction the maximum applied voltage (voltage drop across the cell) is limited by the maximum rated current for the particular rectifier. This rated current is based mainly upon the effective rectifier cell area and the permissible temperature at which the rectifying junction operates. Typical forward direction voltages for commercial cells of the types to be described are of the order of a fraction of a volt to a few volts.

In the reverse direction the maximum applied voltage across the rectifying junction is limited by the breakdown across the barrier layer when the potential gradient becomes too great. When a breakdown occurs the cell junction no longer has the rectifying properties and symmetrical current flow results. Some of the commercial rectifying junctions to be described possess self-healing rectifying junctions against voltage breakdown troubles provided the junction is not unduly and prolongly abused. For power rectifier type junctions the maximum reverse direction voltage varies from 5 to 32 volts rms per cell, depending upon the type of junction. Small current rectifiers have been made to withstand 50 or more volts per cell in the reverse direction.

The forward or positive polarity values correspond to the low resistance direction of the rectifier, while the reverse or negative polarity values represent the high resistance direction. The curve described previously clearly shows that the metallic rectifier performs substantially as a unidirectional valve readily permitting current flow in the one direction while resisting current flow in the opposite direction. This is the function of a rectifier cell. The ideal rectifier would have zero resistance in the forward direction and infinite resistance in the opposite direction. The volt-ampere curve of Fig. 2-6 illustrates that the commercial rectifier nearly approaches this ideal rectifier. This type of graph is also called the static characteristic of the rectifying junction because the applied voltages and the resulting current flows are direct, not alternating.

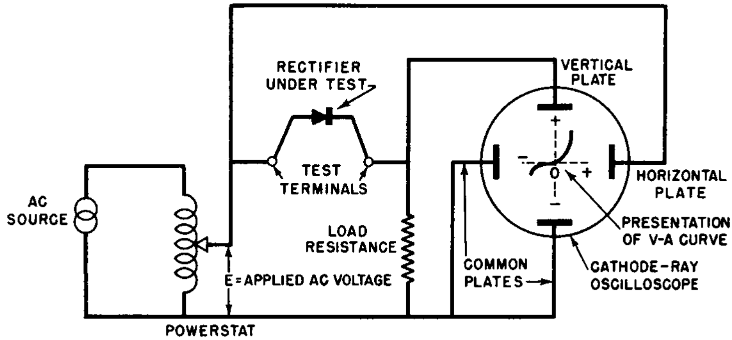


Fig. 2-7. Circuit for Testing Dynamic Volt-Ampere Properties of Metallic Rectifier Cells.

Often it is desirable to obtain the voltage-current curve simultaneously with changes in circuit conditions; of course, this would be impossible with laborious data seeking and plotting technique described before. By using a direct-coupled cathode-ray oscilloscope with suitable amplification in both the vertical and horizontal axes, an automatic and instantaneous presentation of the voltage-current characteristic of any rectifier junction may be had for any desired circuit condition. This type of presentation is called the dynamic characteristic of the rectifying junction. The simplified circuit for obtaining this information is given in Fig. 2-7. This arrangement is very useful for production or receiving inspection. The nominal curve of a rectifier with desired performance can be traced upon a transparent sheet and placed before the oscilloscope screen. The characteristics of the unknown rectifier cells can be quickly compared with the desired standard — making out of the arrangement a "go", "no-go" inspection device for testing newly produced rectifier cells from the assembly line or newly received rectifiers from a vender. Moreover, it may be desirable to see the changes in performance of a given rectifier for varying ambient conditions such as temperature, humidity, or varying applied frequency. All this is readily possible with the dynamic type of characteristic presentation.

Voltage-Resistance Properties of the Junction

The voltage-resistance properties of a generalized metallic rectifier junction of unit area is shown in Fig. 2-8. The graph shows the resistance of the junction or rectifier cell in the forward and reverse direction as a function of applied voltage of positive and negative polarity.

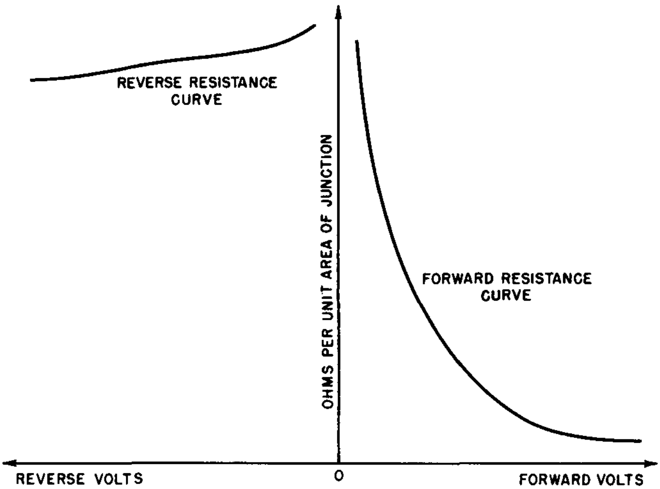


Fig. 2-8. Static Voltage-Resistance Properties of a Generalized Rectifier Junction of Unit Area Operated Within its Voltage Limits.

This curve may be obtained for any junction by using the experimental arrangement of Fig. 1-7 where a Wheatstone bridge method of resistance measurement is shown. The voltage applied to the bridge is varied in discrete steps and the corresponding resistance measurements made. The actual applied voltage to the junction may be obtained by computation or by means of a DC vacuum-tube voltmeter.

The actual voltage-resistance curve for any specific rectifier junction may differ from the one shown in Fig. 2-8 but in general the following comments will apply. As the applied voltage is increased in the forward direction the resistance decreases very quickly at first and then gradually approaches a constant value. In the reverse direction the resistance also decreases with applied voltage of opposite polarity but the rate is very small within the limits of the rated cell voltage.

It can be inferred from Fig. 2-7 and 2-8 that the resistance of a metallic rectifier junction is not constant with respect to current flow and in the forward direction decreases as the current increases. See Fig. 2-9.

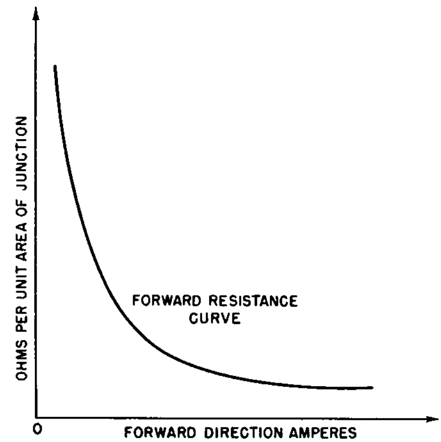


Fig. 2-9. Forward Resistance Versus Forward Current for Generalized Rectifier.

The non-linear resistance properties of the rectifying junction in the forward direction may be employed in a number of interesting applications, an example is voltage regulators in direct current circuits.

Other Properties of the Metallic Rectifier Cell

Other properties of the metallic rectifier cell such as temperature effects, current and voltage rating, efficiency, forming, speed of operation, and the like are too difficult to generalize since they differ so radically for the three types of rectifiers to be discussed. Hence, these and other effects will be reserved for later discussion under the specific types.

CHAPTER 3

Some Commercial Practices in Metallic Rectifiers

Physical Outline and Sizes of Rectifier Cells

The metallic rectifier cell has a current rating which is limited by its effective area and by the allowable temperature rise. To facilitate the manufacture of rectifier assemblies of various current capacities, the producers of these rectifiers usually standardize on a number of basic rectifier cell sizes. These basic cell sizes are arbitrary, and one manufacturer's standard need not have any relationship to another producer's basic sizes. The basic rectifier cells may be round, square, or rectangular in outline. The round cells may be available in diameters from tiny disks of 1/32 inch to large cells of 4 3/8 inches in diameter. In the square and rectangular cells the dimensions may start from a square of about one inch to plates 5 x 6 inches or larger. Current ratings depend upon the rectifier type, that is, whether the junction is copper oxide, copper sulphide, or selenium.

Grading of Rectifier Cells

After the rectifier cells are carefully manufactured they are graded according to their forward and reverse resistance and according to the intended circuit application. The grading by forward resistance is the most important, for rectifier cells to be used in parallel must be matched to avoid unequal current flow burdens. This matching is not critical for most applications, especially power rectification, as cells with the lower forward resistance will ultimately match with the other cells as the rectifier assembly ages.

Although it is important to keep the reverse resistance high (the ideal rectifier cell should have infinite resistance), in most applications, low reverse resistance can only produce electrical losses by heating. In half-wave rectifier circuits, of course, the output voltage across the load is a function of the reverse resistance because of the subtracting effect of the reverse current through the load.

In special applications of the rectifier junction, for example, direct current valves, the lowered reverse resistance decreases the efficiency or range of the device.

Only cells of the same size can be connected in series or parallel. Assembly of heterogeneous cells would not be practical in production and would result in unequal current through the cells causing the smaller cells to carry more than their normal load.

Means to Obtain Voltage and Current Ratings Higher Than Cell Rating

To increase the voltage rating of a metallic rectifier the proper number of cells are connected in series; if the assembly is for full-wave or multi-phase operation, then the same number of cells are used in each leg.

To increase the current rating of a rectifier assembly, additional cells are placed in parallel with the identical series-parallel arrangement maintained in each leg of a bridge or multi-phase rectifier.

Rectifier cells, then, are assembled in series or parallel in the same manner as dry cells. As an example; five cells, each rated at 26 volts when assembled in series, give the stack a 5 x 26 volts rating or 130 volts. In a like manner, 5 cells each rated at 5 amperes, give the assembly using five of these cells in parallel a 25 ampere rating. In the series example the current rating of the stack remains the same as the original rectifier cell rating, only the voltage rating is increased. In the parallel example the voltage rating of the stack remains the same as the original rectifier cell rating, only the current rating is increased. When it is desired that both voltage and current ratings of the assembly be increased, it is necessary to use series-parallel arrangements of the rectifier cells.

The Stack Assembly

Rectifier stacks are fabricated of the required number of rectifier cells assembled upon a threaded stud covered with an insulating sleeve. Metal washers space the cells to allow convection or forced-air cooling in one type of the metallic rectifier. In another type, cooling fins are required in the assembly; these cooling fins are simultaneously used as terminals to engage the front and back electrodes of the rectifier cells. Electrical connections to the front and back of the other type of rectifier cells are made by means of terminals extending from the center to beyond the periphery of the cells. The terminals or the terminal cooling fins are located centrally between the cells and at the end of the stack assembly as required. See Figs. 3-1 and 3-2.

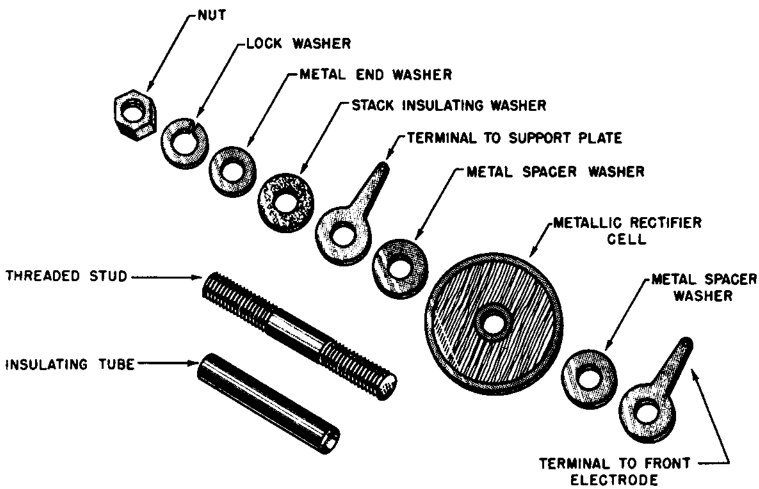


Fig. 3-1. Elements of a Selenium Rectifier Stack Assembly.

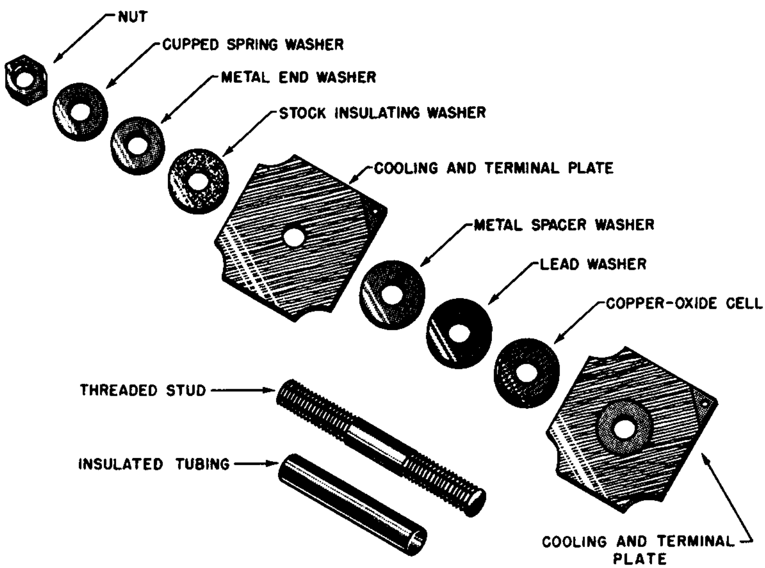


Fig. 3-2. Elements of a Copper-Oxide Rectifier Stack Assembly.

Spring washers at either end of the assembly keep the stack tightly together and minimize the possibility of damage

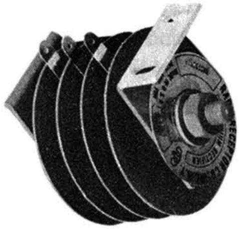


Fig. 3-3. A Full-Wave Bridge Rectifier. 24 volts AC Input, .6 Ampere DC Output. (Courtesy of Seletron Division of Radio Receptor Co., Inc.)

to the stack due to twisting in handling. In some types of rectifier assemblies (copper-oxide, for example), the spring washers are also required to keep the stack assembly under pressure for electrical reasons to be subsequently discussed.

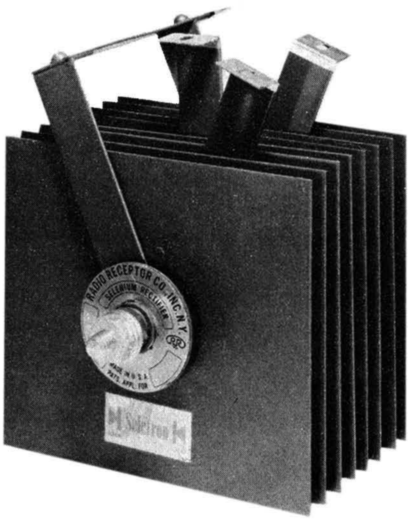


Fig. 3-4. A Single-Phase Full-Wave Bridge Rectifier. Maximum Input 52 Volts rms. Output 37.8 Volts, 7.5 Amperes, DC. (Courtesy of Seletron Division of Radio Receptor Co., Inc.)

Figs. 3-3, 3-4, and 3-5 illustrate some examples of rectifier stacks manufactured by the Seletron Division of the Radio Receptor Company of New York. These rectifier stacks use selenium rectifier cells. The full-wave bridge of Fig. 3-3 can be seen to comprise four round cells, one rectifier cell to each leg of the full-wave bridge. This stack arrangement will be described in the section dealing with full-wave rectification.

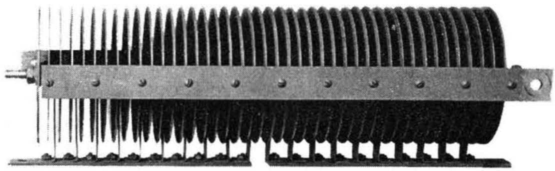


Fig. 3-5. A Center-Tap Type, Full-Wave Rectifier. 24 Volts AC Input, 80 Amperes DC Output. (Courtesy of Seletron Division of Radio Receptor Co., Inc.)

Fig. 3-4 comprises a full-wave bridge having two cells in each leg of the bridge, totaling eight cells for the whole assembly. The cell plates used are 4 1/2 x 5 inches and the complete rectifier weighs one pound and ten ounces.

Fig. 3-5 is a heavy duty, center-tap type full-wave rectifier. The circuit arrangement and details for this type stack will also be described later.

Protective Coatings

Metallic rectifier assemblies require the same care and protection from high humidity, corrosive dust, acid and alkali atmospheres, and fungus conditions as do other types of electrical equipment. To render this protection some kind of finish coating is necessary to cover the rectifier assembly. This coating should be applied at the factory as the finish is no better than the manner in which it is applied and handled after the rectifier assembly is completed.

In general, the finish may consist of a coating of special varnish or paint; this is adequate for stacks not exposed to outside atmospheres. A series of varnish or paint coats will produce a finish able to withstand 50 hours of salt spray test. This type of coating is recommended for rectifier stacks exposed to high humidity or adverse climatic conditions. Fungicidal ingredients are necessary in these finishes, if the stacks are to be used in tropical climates.

One manufacturer of metallic rectifiers uses multiple coats of a synthetic varnish which is especially adapted for protection against moisture. As an added feature the varnish is colored black to improve the cooling of the rectifier assembly by radiation.

Care must be exercised in handling rectifiers so as not to damage the finish as a bad scratch or crack in it will make the rectifier vulnerable to an attack by the surrounding atmospheric conditions.

One manufacturer suggests that the users of rectifiers refrain from applying ordinary paints or lacquers to the unfinished rectifiers or to abused rectifiers, until they have consulted the supplier. It is possible that the finish to be applied by the user may be destructive if applied directly to the rectifier cells or applied in combination with such finish as is already on the plates.

For extreme or special applications it has even been possible to enclose the rectifier assembly in an oil-sealed arrangement.

The above comments apply principally to power rectifier assemblies. Small control or instrument rectifiers may be adequately protected by being hermetically sealed in plastic or electron tube-like structures since the heat dissipation requirements are nil.

Half-Wave Rectifier Circuit

In order to discuss such commercial practices as terminal markings and coding of the rectifier stacks, it is necessary to give a preliminary description of several simple power-circuit applications of metallic rectifiers. A more complete discussion of the curcuitry involved will be reserved for the chapter dealing with rectifier circuits.

The chief use of metallic rectifiers is to convert alternating current into direct current; in this conversion when an alternating potential is applied to a circuit containing a rectifier cell in series with a load, current flows when the alternations are of one polarity; negligible current flows when the alternations are of the opposite polarity. The nomenclature and forward conducting polarity of the rectifier cell is shown in Fig. 3-6.

This rectifier cell employed in a simple circuit with the alternating current source and a resistive load is diagrammed in Fig. 3-7A. The small graphs near the voltage source and adjacent to the load resistor display the waveform of the applied voltage and the resulting unidirectional current flow in

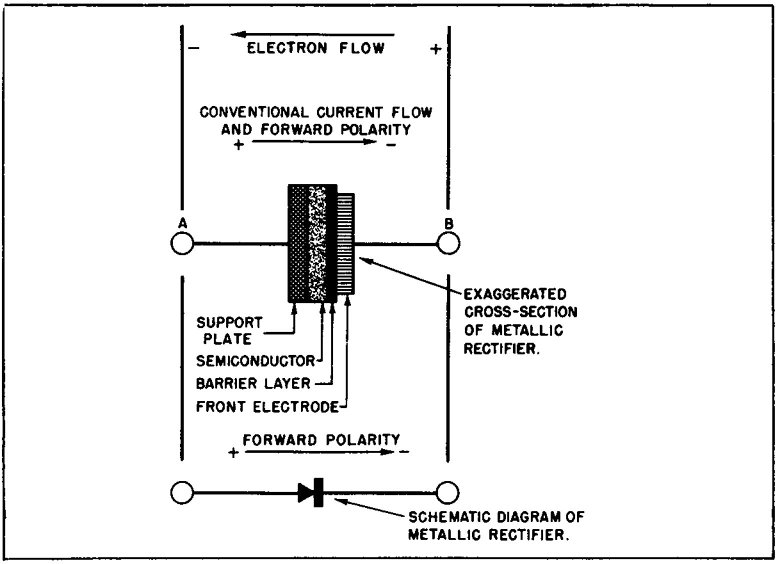


Fig. 3-6. Nomenclature and Forward Polarity of a Half-Wave Rectifier.

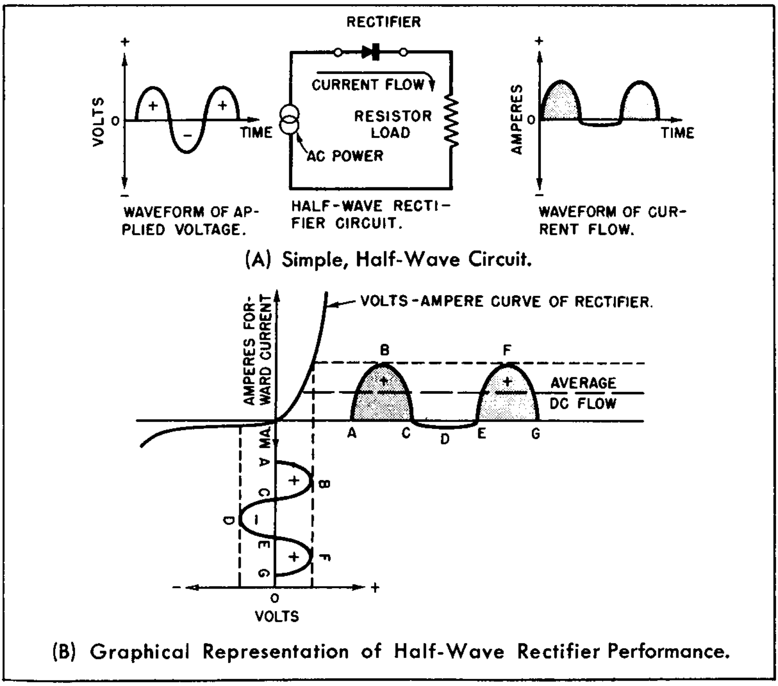


Fig. 3-7. A Half-Wave Rectifier.

the circuit. This simple type of rectifier circuit wherein but half of the input alternation is used is identified as a half-wave rectifier circuit.

The mode of operation of a half-wave rectifier circuit is shown graphically in Fig. 3-7B, where the metallic rectifier cell characteristic has applied to its "input" or vertical axis an alternating potential represented by the sinusoidal waveform A-B-C-D-E-F-G. The projection of this potential curve upon the volt-ampere curve of the rectifier "reflects" on to the horizontal axis the waveform of the resultant current flow. The current flow for the positive alternations is great; the current flow for the negative alternations is almost negligible. The dashed horizontal line through the output current waveform shows the average value of the current flow through the load resistor; that is, it represents the value of direct current flow that a well-damped DC ammeter will indicate.

Output Terminal Markings

The reader will note that the applied polarity required for forward-direction current conduction is shown in Fig. 3-6. He then would assume that the terminals of a commercial rectifier would be likewise marked, that is, terminal A marked positive and terminal B marked negative.

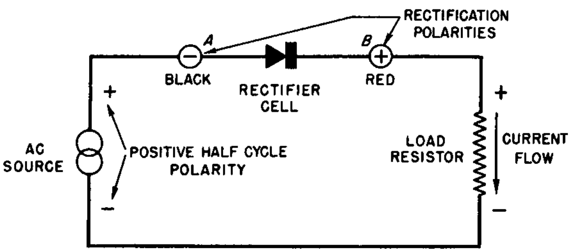


Fig. 3-8. Current Flow and Rectification Polarity Markings.

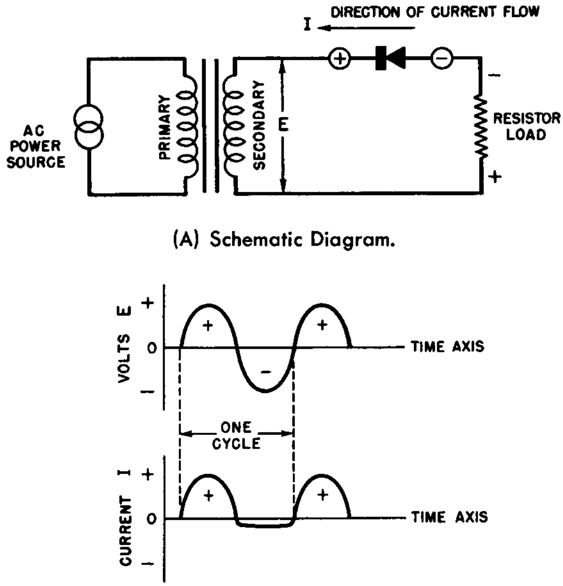
In commercial practice, however, the opposite is true; terminal A of the rectifier cell is marked negative or painted black, while terminal B is marked positive or painted red. The reason for this contradiction is that most users of metallic rectifiers are chiefly interested in the device as a power rectifier and desire to know which terminal of the rectifier represents the positive or negative terminal of the rectified output. For example, in Fig. 3-8 the current flow of the half-wave rectifier is in the direction of the arrowhead when the applied alternating potential is of the polarity shown. On the opposite alternation of the power source, practically no current flows because of the unidirectional conduction property of the rectifier cell. With such applied input polarity that will cause current flow, the voltage drop across the load is as shown in Fig. 3-8 and is defined by the interpretation of conventional current flow. It can be seen that terminal B is connected to the end of the load resistor which is the positive terminal of the rectified voltage drop, while terminal A (through the alternating power source) is connected to the negative terminal of the rectified voltage drop across the load resistor. Hence, in commercial practice where greater interest is in the sign of the rectified output, terminal B of Fig. 3-6 is marked + or painted red, while terminal A is marked − or painted black. These polarity markings may be called rectification polarities of the metallic rectifier cell and are opposite to the forward conduction polarity signs.

In this book, the commercial polarity markings of the rectifier cell or rectifier assembly will be honored and this system will be identified as the rectification polarity markings. In more complex rectifier stack assemblies where AC terminals are separate from the DC output terminals, the AC input terminals are marked AC or marked with a strip of yellow paint.

Full-Wave Rectifier Circuits (Single-Phase)

Several full-wave, single-phase rectifier circuits will be discussed so that the reader may be better prepared to understand the interpretation of the coding system used by manufacturers which will be described later. To introduce the full-wave circuits more simply we will start with the half-wave rectifier circuit discussed previously, only this time we will isolate the rectifier circuit from the source of alternating power by means of a transformer. This circuit is shown in Fig. 3-9; here a transformer is used to couple the primary source of power to the DC load through the half-wave rectifier. The electrical symbol for the metallic rectifier is used and is represented by the arrowhead and bar combination. By commercial convention in rectifier circuits the bar represents the positive electrode whereas the arrowhead represents the negative electrode.

Fig. 3-9 clearly shows that due to the unilateral valve action of the half-wave metallic rectifier, direct current power is available only for the positive alternations of the AC power source; very little current flows during the negative alternations.



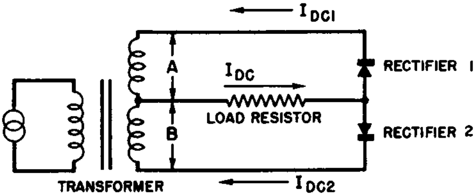
(A) Schematic Diagram.

(B) Voltage and Current Waveforms.

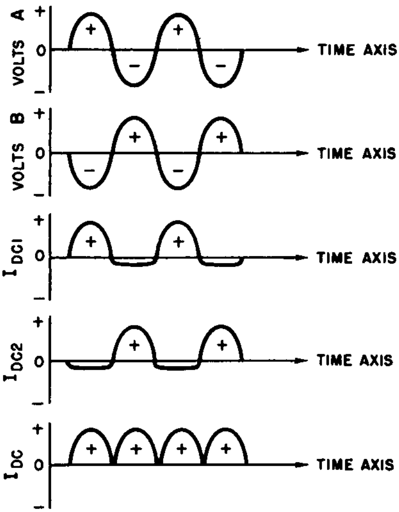
Fig. 3-9. A Half-Wave, Single-Phase Rectifier Circuit.

Frequently, this uneven delivery of DC power is not satisfactory for an application; in this case the circuit of Fig. 3-10 may be used. This circuit is a single-phase, full-wave rectifier circuit using a center-tapped power coupling transformer. By virtue of the center-tapped construction of the power transformer, two equal and opposite voltages are available with the center tap conductor as a reference; these voltages are A and B. Their time and magnitude relationship are shown graphically in Fig. 3-10B. Two rectifiers and the common resistive load connected as shown in Fig. 3-10A produce a full-wave direct current delivery to the load. Rectifier 1 delivers a half cycle of direct current on one alternation while rectifier 2 covers the following alternation. Study the curves I_{DC1} and I_{DC2}. The summation of these two currents graphically yeilds I_{DC} which is the current flowing through the load resistor.

Frequently, the power conversion application does not justify the cost of the special center-tapped power transformer, yet it is necessary to obtain full-wave operation. This requirement may be met by an arrangement known as the single-



(A) Schematic Diagram.

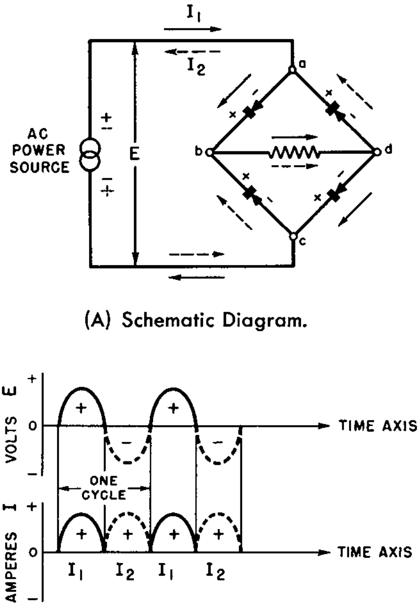


(B) Voltage and Current Waveforms.

Fig. 3-10. A Single-Phase, Center-Tapped, Full-Wave Rectifier Circuit.

phase, full-wave bridge. In this arrangement four half-wave rectifier cells are connected in a manner so as to yield full-wave rectification. The circuit is shown in Fig. 3-11A. When the alternation of the AC power is such that terminal A of the bridge is positive and terminal C is negative, the direction of current flow from the power source is given by the solid arrows.

When the alternation is such that junction C is positive and junction A is negative, the current flow direction is indicated by the dashed arrow lines. It is important to note that although two sets of rectifier cells are used, resulting in two paths of current flow through the legs of the bridge for positive and negative alternations of the power source, the direction of the current flow through the load is unidirectional giving full-wave power to the load. It can be seen that the full-wave bridge rectifier behaves as a synchronous commutator or switching device, electronically converting AC power into DC power.



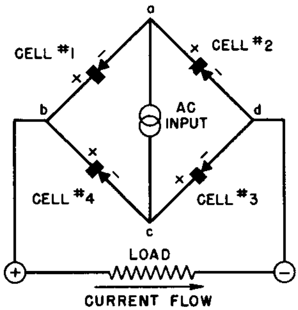
(A) Schematic Diagram.

(B) Voltage and Current Waveforms.

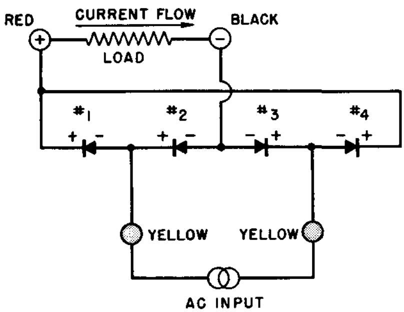
Fig. 3-11. A Single-Phase, Full-Wave, Bridge Rectifier Circuit.

The single-phase, full-wave bridge rectifier circuit of Fig. 3-11 has been redrawn in Fig. 3-12A to show the correct method of wiring the four rectifier cells. As an aid towards this wiring the rectification polarities of each cell are shown as well as the polarity of the rectified power output across the load.

In a commercial stack for a single-phase, full-wave bridge rectifier, the rectifier cells are stacked upon an insulated stud in a columnar manner (see Fig. 3-5); in Fig. 3-12B the schematic diagram of Fig. 3-12A has been rearranged physically to show the stack layout. The schematic diagrams in Figs. 3-12A and 3-12B are electrically equivalent; the cells are identically numbered in each diagram for ease in comparison. Fig. 3-12B also shows the color coding of the AC input and the DC output terminals.



(A) Correct Method of Wiring Four Rectifier Cells for Single-Phase, Full-Wave, Bridge Rectification.

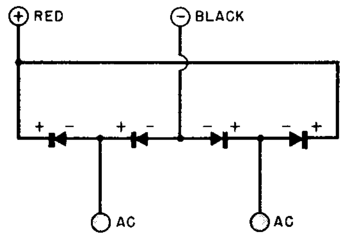


(B) Schematic of the Same Full-Wave Bridge Rectifier as Arranged in a Commercial Stack.

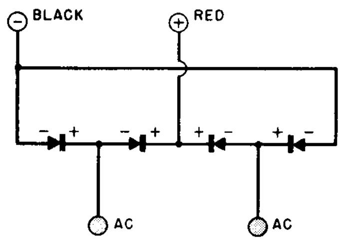
Fig. 3-12. A Single-Phase, Full-Wave, Bridge Rectifier Circuit.

There are two possible arrangements of the rectifier cells upon the insulated stack to make up the single-phase, full-wave rectifier bridge; both arrangements are electrically equivalent and one or the other scheme is used by different manufacturers of rectifiers. To minimize the confusion which might arise over this practice, Fig. 3-13 shows both arrangements with the cell rectification polarities marked. In Fig. 3-13A there is shown the arrangement for the stack assembly in which the outer terminals are positive and strapped together to complete the wiring of the bridge rectifier. In Fig. 3-13B there is shown the arrangement for the stack assembly in which the outer terminals are negative and strapped together to complete the wiring of the bridge rectifier.

Thus far, all of the schematic diagrams have shown one cell per leg for the various rectifier arrangements. It was



(A) A Single-Phase, Full-Wave, Rectifier Bridge Using Four Cells in a Stack Assembly With the Outer Cells Positive and Strapped Together.



(B) A Single-Phase, Full-Wave, Rectifier Bridge Using Four Cells in a Stack Assembly With the Outer Cells Negative and Strapped Together.

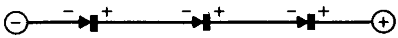
Fig. 3-13. Schematic Diagrams of Commercial Rectifier Stacks.

mentioned previously that the rating of a rectifier assembly could be increased by connecting rectifier cells together much as dry cells are connected (in series, parallel, and series-parallel) until the desired rating is obtained. The only other condition is that the individual cells have similar voltage and current ratings so as to distribute the load — again identical to dry cell wiring practice.

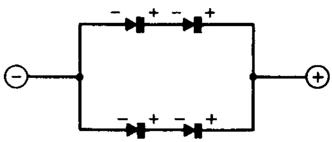
Fig. 3-14 illustrates three rectifier assemblies having more than one cell per leg. In Fig. 3-14A is illustrated a single-phase, half-wave rectifier consisting of three cells in series; the voltage rating of this assembly is three times the voltage rating of its individual rectifier cells.

In Fig. 3-14B is illustrated a series-parallel arrangement of four rectifier cells wired for half-wave, single-phase rectification. Here the voltage and current rating is double that of the individual cells making up the assembly.

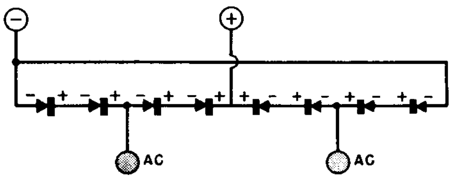
In Fig. 3-14C is illustrated a single-phase, full-wave rectifier bridge having two cells per leg. The voltage rating



(A) Half-Wave Rectifier—Three Cells in Series.



(B) Half-Wave Rectifier—Four Cells in Series Parallel.



(C) Full-Wave Rectifier—Single Phase Bridge With Two Cells in Each Leg.

Fig. 3-14. Series Parallel Arrangements of Rectifier Cells.

of this assembly is double that of the bridge shown in Fig. 3-13 which consists of one rectifier cell per leg. Fig. 3-14C is the

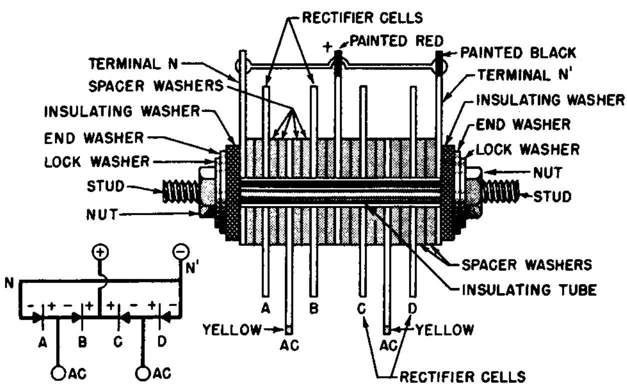


Fig. 3-15. Cross Section of a Commercial, Single-Phase, Full-Wave, Rectifier Bridge Stack Assembly.

schematic diagram of the rectifier stack shown in the photograph of Fig. 3-4.

The reader having, by this time, been introduced to rectifier cells, stacking arrangements, and stacking components is prepared to more easily understand commercial practice in these matters. In Fig. 3-15 is sketched a cross-section of a commercial, single-phase full-wave rectifier bridge stack assembly. For ease in comparison the equivalent schematic diagram of the same arrangement is also shown in this figure and this reveals that the stack has one cell per leg. Commercial practice in polarity and color marking or coding is also indicated.

Coding of Rectifier Stacks

It has been stated previously in this chapter that when it is necessary to increase the voltage and/or current rating of a rectifier, rectifier cells may be assembled in series, parallel, or series-parallel in the same manner as dry cells until the desired rating is achieved. Moreover, rectifier cells may be assembled in half-wave, center-tapped full-wave, full-wave bridge, or in multi-phase arrangements as necessary to meet the requirements.

Furthermore, these rectifier stacks may be assembled from cells whose current carrying capacity may be economically selected; for example, a stack intended for 1/2 ampere capacity may use rectifier cells whose area is two square inches, whereas a stack intended for higher current service may use plates 5 x 6 inches in dimension.

The rectifier stack is marked by its manufacturer's coding system to identify the nature of these variations in the structure. Examples of markings on rectifier stacks from different venders may be listed as follows:

105B7HX1	(Federal)
B1C1SDAG	(International)
1B12C1J	(Mallory)
WH1B1S1B	(Seletron)

These code markings are arbitrary; there is no standardization in this phase of rectifier business as yet (1956) and each manufacturer has his own code system; hence, the key to the code must be obtained from each specific supplier's catalog if interpretation is desired.

Two examples of keys to codes of rectifier stacks from commercial suppliers are given; Fig. 3-16 is the key to the code used by the Seletron Division of Radio Receptor Co., N. Y.

EXAMPLE W H 1 B 3 S 1 C (Wide spacing; 5″ x 6″ Cell; Bridge circuit; 1 Cell in series; 3 Cells in parallel per element; Stud mounting; standard finish; 26 volt Cells)

COOLING
- No letter designation for normal spacing—convection cooling
- W: Wide spacing—convection cooling
- F: Fan cooling

CELL SIZE
- M: 1″ sq.
- P: 1 3/16″ sq.
- Q: 1 1/2″ sq.
- S: 2″ sq.
- U: 3″ sq.
- V: 3 3/8″ sq.
- W: 4″ sq.
- T: 4 1/4″ x 6″
- H: 5″ x 6″
- D: 2 1/2″ diam.
- E: 3 3/8″ diam.
- F: 4 3/8″ diam.
- G: 4 1/2″ x 5″

NUMBER OF SERIES CELLS PER ARM

STACK CONNECTION
- H: Half Wave
- B: Bridge
- C: Center Tap
- D: Doubler
- HA: 3 Phase wye (Half Wave) (+)
- HB: 3 Phase wye Half Wave (—)
- BA: 3 Phase Bridge
- CA: 3 Phase Center Tap (6 Phase Star)

NUMBER OF PARALLEL CELLS PER ARM

TYPE OF MOUNTING
- M: Bracket (One end)
- G*: Bracket (One end)
- N: Bracket (Both ends)
- H*: Bracket (Both Ends)
- S: Stud
- E: Eyelet

*NEMA standard

TYPE OF FINISH
- 1: Standard
- 2: Extra
- 3: Marine
- 4: #2 plus Fungicide
- 5: #3 plus Fungicide
- 6: #1 plus Fungicide

REVERSE VOLTAGE PER CELL (R.M.S.)
- A: 18 volts
- B: 24 volts
- C: 26 volts
- D: Special

NOTE: When the stack assembly deviates from the standard a special number is assigned. Miniature stacks for radio and television are assigned arbitrary identifying numbers.

STACK CONNECTION	ELEMENTS (ARMS) PER RECTIFIER
H: Half Wave	1
C: Center Tap	2
D: Doubler	2
B: Bridge	4
HA: 3 Phase wye (Half Wave) (+)	3
H: 3 Phase wye (Half Wave) (—)	3
BA: 3 Phase Bridge	6
CA: 3 Phase Center Tap (6 Phase Star)	6

TYPE CELL	MAXIMUM NO. OF CELLS
M, P, Q, S, U, V, W (D, E, F, G)	42
WM, WP, WG, WS, WU, WW, T, H (WD, WE, WF, G)	28
WT, WH (WG)	20
All sizes when subjected to vibration	16

TOTAL NUMBER OF CELLS PER RECTIFIER CONNECTION = NUMBER OF ARMS x CELLS IN SERIES x CELLS IN PARALLEL.

Fig. 3-16. Rectifier Stack Coding System Used by Seletron (Courtesy of Seletron Division of Radio Receptor Co., Inc.).

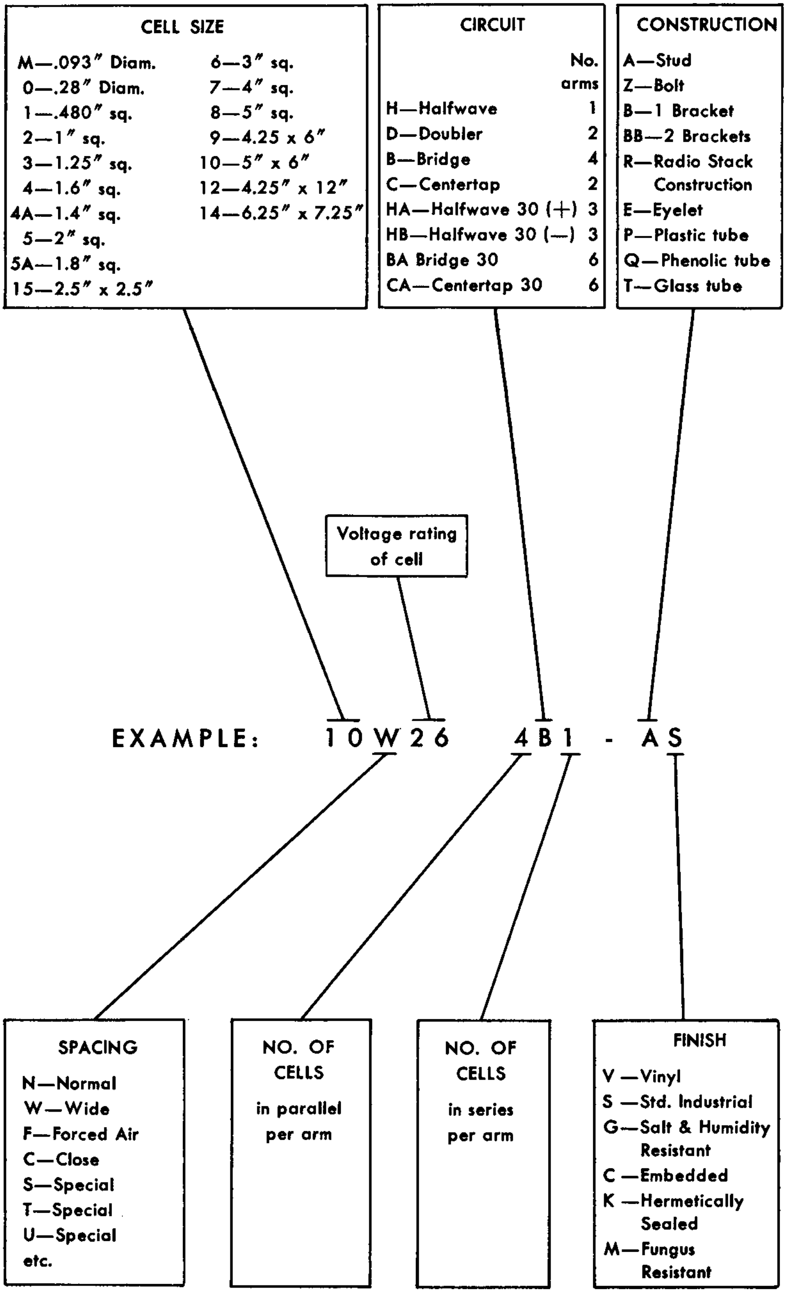


Fig. 3-17. Rectifier Stack Coding System Used by Sarkes Tarzian (Courtesy of Sarkes Tarzian, Inc.).

Fig. 3-17 shows the key to the code used by Sarkes Tarzian Inc., Bloomington, Ind.

With the aid of its respective key, the code to any rectifier reveals quite completely the stack's electrical and mechanical specifications.

Stock and Custom Rectifier Stacks

Because of the great number of combinations possible, it is very difficult to stock rectifier stacks. The factors involved are voltage ratings, current ratings, whether single-phase half-wave or full-wave, or multi-phase half-wave or full-wave, protective coatings, mounting means and others. Several organizations are stocking and having distributed through the industry rectifier stacks of the more popular type — generally single-phase arrangements. Wherever standard stock rectifiers can be used, some time and expense can be saved in an application. However, most applications require some feature not provided in the standard stack necessitating then a custom assembly from the supplier. This requirement is especially true in connection with the design and development of new products.

Close work with the vender's field or sales engineer is necessary for the custom assembly of rectifier stacks to the customer's requirement. As a preliminary effort towards obtaining the required rectifier stack most manufacturers require the following information:

Required DC output voltage.
Required DC output current.
Phase of power source.
Voltage variations in power source.
Ambient temperature limits.
Duty cycle.
Nature of load.
Atmospheric conditions.

This information is usually obtained by a questionnaire form supplied by the vender.

Temperature Range of Operation

Selenium and copper oxide rectifiers are usually rated on a basis of 35 degrees Centigrade. Magnesium-copper sulphide rectifiers may be operated at ambient temperatures of 100 degrees Centigrade or higher. If higher than rated temperatures are required, then the rectifier output must be de-rated or forced cooling of the rectifier must be employed. Specific data on each type will be given in its respective sections.

On the low temperature range, rectifiers have been successfully operated at minus 40 degrees Centigrade and lower.

CHAPTER 4

The Copper-Oxide Rectifier

Introduction

In Chapter 1 the development of the first dry disc or metallic rectifier was described. This discovery of the rectifying property of the junction between the cuprous oxide and the copper base upon which it was formed, was made in November, 1920, by L. O. Grondahl and P. H. Geiger of Union Switch and Signal Company. The discovery was a by-product of an effort to produce an electrical relay without moving parts or contacts, that is, a device whose impedance or resistance could be easily changed through a large range to simulate the opening and closing of electrical circuits as by relay contacts. During this study it was found that the resistance of the copper-copper oxide combination was greater in one direction than in the other, and that a high ratio of resistance existed between the forward and reverse directions of current flow. This, as was previously explained, is the property required of a rectifier cell.

While a description for producing the copper-oxide rectifier cell as used in the original experiment was given in Chapter 1, the past 31 years have seen a great many improvements in the technique of production and in the electrical characteristics of this type of cell. The amazing thing, however, is that after all of these years of development and manufacture there still remains many problems, the solutions of which have not been completely determined because there are so many possible combinations of the variables. Some of these problems have to do with the results of varying the amounts and kinds of impurities in the copper base plate, the proper quenching technique, and the exact reason why import copper is superior to domestic copper.

Though a great many refinements for the production of copper-oxide rectifiers have been evolved during the past years, the exact process for manufacturing these rectifier cells differs with the different manufacturers and also depends to some extent upon the ultimate use.

In this book manufacturing methods for the production of metallic rectifier cells will not be stressed, for certain details are considered trade secrets and besides an itemized account on this subject is beyond the scope of this book. However, a brief description of the production techniques involved will be described more as an illustration than as an exact, complete, or recommended method.

Production

The basic component of a rectifier assembly is the rectifier cell; this copper-oxide rectifier cell is manufactured from copper imported from Chile. Copper from this source produces more consistent cells — perhaps because of lower impurities and also for other reasons not known. This imported copper undergoes a special rolling process and a surface suitable for polishing is provided. The resulting copper sheet is approximately 0.05 inch thick for the average cell. The copper sheet is then punched in the form of washers or plates with centrally located holes used for mounting purposes.

The next step is to provide a thin film of cuprous-oxide with its attendant outer layer of cupric-oxide on the surface of the copper washer or plate. This is done by heating the copper disc or plate to 1000 degrees Centigrade or to the highest temperature which can be used without deforming the copper pieces because of softening action. The duration of this heating or oxidation period is about ten minutes.

After the surface of the copper piece has been oxidized, it must be brought back to room temperature from the high oxidation temperature. In one practice for producing these cells, another furnace called an annealing furnace is provided into which the rectifier cells are placed from the oxidation process so as to bring them to some predetermined temperature from which to cool or quench them. Since the temperature from which it is cooled and the rate at which it is cooled has a profound effect upon the electrical properties of the rectifier cell. The annealing time as well as the rate of cooling between the oxidizing and the annealing furnace is important. From the annealing furnace the cells are quickly quenched or cooled in a water bath.

The cupric-oxide layer formed during the cooling of the rectifier cell from the oxidizing temperature has a very high electrical resistance and is not useful in the rectifying property of the copper-oxide cell. This layer is the outer high resistance layer over the cuprous-oxide layer formed upon the copper piece and must be removed. Originally, this black oxide was removed by grinding; later this surface removal was accomplished by sand blasting or by abrasion with emery cloth. Currently, the same task is done chemically through the use of mineral acids which remove this high resistance layer.

The junction between the copper and the cuprous-oxide has the valuable property of permitting the flow of electrons readily from the copper to the oxide and obstructing the flow of electrons in the reverse direction. With the electrical current flow normally defined as from the positive to the negative, this junction will exhibit a high electrical resistance to the flow of current from the copper to the cuprous-oxide and a reasonably low electrical resistance of current flow in the direction of cuprous-oxide to the copper base plate — this constitutes an electrical valve with oneway characteristics.

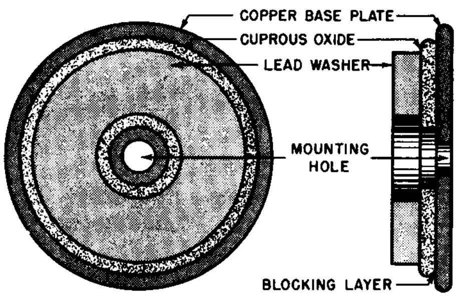


Fig. 4-1. Plan and Exaggerated Cross-Sectional View of Copper-Oxide Rectifier Cell.

To complete the copper-oxide rectifier cell, it is necessary to make electrical contact with the cuprous-oxide surface. This electrical contact with the cuprous-oxide can be made in a number of suitable ways. One method uses a lead washer or disc which is pressed against the oxide surface with a predetermined pressure. See Fig. 4-1. To prevent the lead disc from reacting with the cuprous-oxide surface and cause an increase in the forward resistance of the rectifier cell, a thin coat of tin may be applied to the lead washer surface, or colloidal carbon in the form of Aquadag can be applied to the cuprous-oxide surface of the cell before assembling the lead washer electrode. In another method a portion of the outer surface of the cuprous-oxide is reduced to copper and a coating of a metallic film, such as nickel, is electrolytically deposited on the oxide surface. Then, this plated film is used as the collector of the electric current over the whole of the oxide surface. See Fig. 4-2 for a plan and cross-sectional sketch of this type of copper-oxide rectifier cell. In another arrangement, especially useful for instrument rectifier applications, electrical contact to the cuprous-oxide surface is provided by an evaporated gold film which has been condensed on this surface.

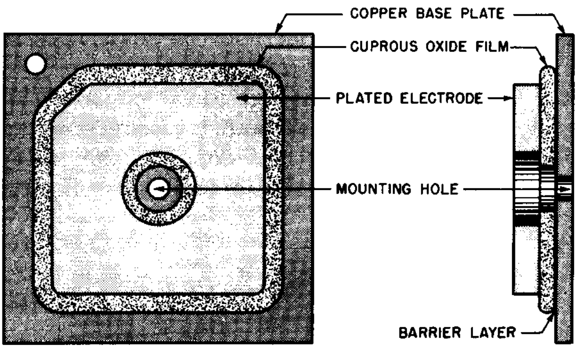


Fig. 4-2. Plan and Exaggerated Cross-Sectional View of Plate Type Copper-Oxide Rectifier Cell.

It is now apparent that the copper-oxide rectifier cell consists primarily of a cuprous-oxide disc and a metallic disc in good electrical contact. To insure this good, electrical contact, the cuprous-oxide is formed directly upon the copper washer, disc, or plate as described previously, resulting in a metallic electrode and an oxide member in molecular contact. When this cell is used in a rectifier assembly, electrical connection to the copper plate is obtained by a connector tab. Electrical connection with the oxide surface is obtained through the medium of a disc of soft metal, metal foil placed in contact with the oxide surface, or by means of electroplating or condensation of a metallic film.

In any of the arrangements described the blocking or barrier layer is in the junction between the copper-oxide and the base plate of mother copper. How this barrier layer is obtained is explained in a later section.

Construction

The copper-oxide rectifier cells described in the preceding constitute half-wave rectifiers. Combinations of these rectifier cells may be assembled as required to obtain rectifier stacks suitable for single and multiphase rectification.

Physically, the elemental rectifier cells may be in the form of discs or plates similar to that shown in Figs. 4-1 and 4-2. (The cross-sectional views in these figures are grossly exaggerated so that the proper layers of the cell can be seen.) In the form of discs, these cells have been produced with diameters from 3/16th inch or less up to 1 1/2 inches. In the form of plates, copper-oxide cells have been produced in sizes approximately 4 inches wide and ranging from 4 to 12 inches in length.

In the plate type, moreover, the copper-oxide cell may be processed with cuprous-oxide on one or both sides. An example of the latter is shown in an exaggerated cross-sectional sketch in Fig. 4-3.

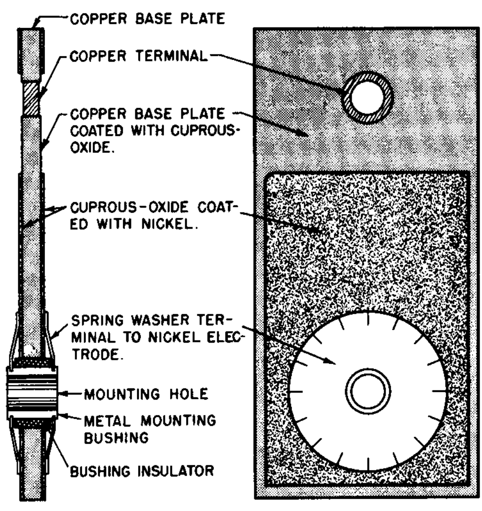


Fig. 4-3. Plan and Exaggerated Cross-Sectional View of Plate Type Copper-Oxide Rectifier Cell With the Oxide Coating on Both Sides.

In the disc-type cell stack, the assembly consists of an insulated stud upon which is placed a nut, a spring washer, a pressure washer, an insulating washer, a terminal or cooling fin, a lead washer, a copper-oxide cell, a lead washer, a steel separator (as an optional spacer), a lead washer, a copper-oxide cell, ect. The circular spring washers maintain a predetermined pressure upon the stack for normal changes in temperature, while the lead washers are placed between the adjacent current carrying elements to secure uniform electrical contact over the entire surface. In the larger disc type assemblies, cooling fins are used for heat dissipation, for the cell column itself is solid. To obtain greater electrical rating (greater electrical output per cell) spacers are used in the column of the stack to derive optimum cooling-fin spacing.

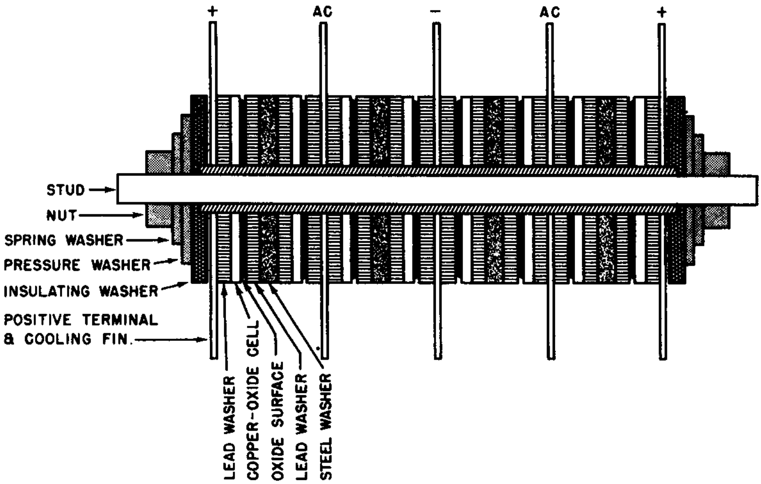


Fig. 4-4. Cutaway View of a Full-Wave, Copper-Oxide Rectifier Stack Assembly.

Electrical connections to the stack are obtained by solder or screw type terminals. Fig. 4-4 shows in cross-sectional detail a copper-oxide stack.

This copper-oxide stack is an assembly of rectifier cells arranged as a full-wave bridge for use in a single-phase circuit. Each leg of the bridge comprises two cells and each group of two cells is mechanically separated by means of cooling fins which simultaneously act as terminals. Moreover, the cooling fins are suitably spaced by means of spacer washers in the assembly so as to obtain the maximum heat dissipation from the stack.

It will be beneficial for the reader to verify these comments by studying the cutaway view of Fig. 4-4. It will be noted that the cutaway rectifier stack of Fig. 4-4 is similar schematically to the single-phase, full-wave rectifier bridge using four cells in a stack assembly with the outer terminals positive and strapped together as shown in Fig. 3-13A. (In Fig. 4-4 the outer positive terminals are not shown strapped together so as to minimize confusion. Usually the customer does this operation while wiring the rectifier into his circuit.) The chief difference between the two stacks is that in Fig. 4-4 there are two cells in series for each leg of the full-wave bridge.

In the assembly of the plate cell rectifiers, the stacks comprise an insulated stud upon which are mounted an end plate, a spring or lock washer, an insulating washer, a terminal, a rectifier cell, a brass or micarta spacer, a rectifier cell, etc. The plate cells are used in rectifier assemblies with the larger electrical ratings. The space between the plates lends the arrangement ease towards forced-draft cooling (fan cooled assemblies). Of course, plate rows are also supplied as self-cooled units.

In either the disc or plate type of rectifier stack, the copper-oxide assembly is protected from humidity and corrosive dust and atmospheric conditions by several coats of insulating varnishes.

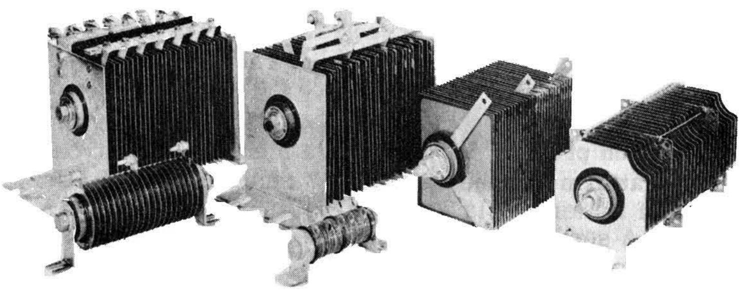
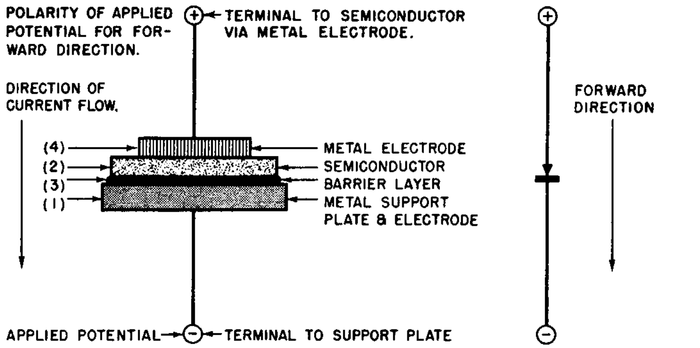


Fig. 4-5. Examples of Disc and Plate Type Copper-Oxide Rectifier Stacks Made by the General Electric Co. (Courtesy of General Electric Co.)

Commercial examples of both the disc and plate type of copper-oxide rectifiers are shown in Fig. 4-5.

Elements of the Copper-Oxide Rectifier Cell

At the begining of this chapter it was briefly described how a copper-oxide rectifier cell may be produced. To better understand this cell and to be able to clearly visualize its elements, it is necessary to review the material in Chapter 2. Here a metallic rectifier cell was represented by the generalized rectifier cell and shown to comprise four essential components. This generalized metallic rectifier cell is repeated



(A) Exaggerated Cross-Sectional View of Generalized Metallic Rectifier Cell.

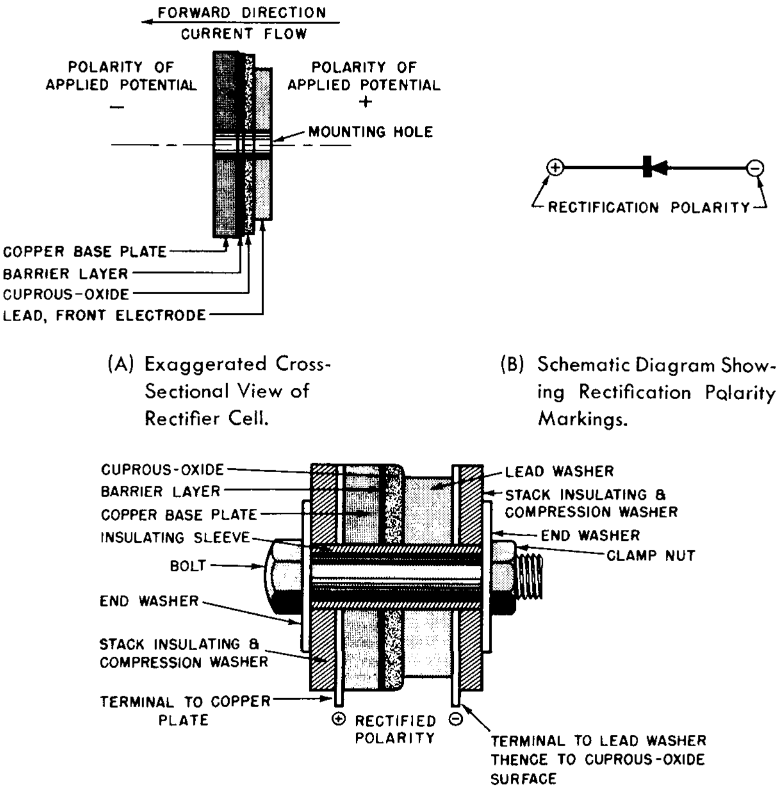
(B) Symbol for Metallic Rectifier Cell.

Fig. 4-6. Generalized Metallic Rectifier Cell

in Fig. 4-6 where Fig. 4-6A represents an exaggerated cross-sectional view of the rectifier cell and Fig. 4-6B represents the electrical symbol for the rectifier cell. The four essential elements of this generalized metallic rectifier cell are:

1. A metal support plate which does not enter into the rectification process but provides a mechanically strong and stable platform for the rest of the rectifier cell and serves as one of its terminals.
2. A semiconductor layer the nature of which depends upon the specific rectifier type.
3. A barrier, blocking, or insulating layer which is formed electrically or by heat treatment.
4. A metal electrode which makes intimate electrical contact with the barrier layer (if of the selenium type) or with the semiconductor (if of the copper-oxide type) by plating, metallic spraying, carbon film, or mechanical pressure.

It will be recalled from the comments in Chapter 2, that the pertinent structure of the metallic rectifier cell is a semiconductor layer separated from a metal electrode by an extremely thin insulating or barrier layer. The opposite surface of the semiconductor is in electrical contact with a low resistance metal plate which does not function in the rectification act except as an electrode. Moreover, the position of the barrier layer determines the forward direction of the rectifier cell — the direction in which substantial current flow occurs when the applied polarizing potential is directed from the semiconductor to the adjacent metal electrode across the barrier layer.



(A) Exaggerated Cross-Sectional View of Rectifier Cell.

(B) Schematic Diagram Showing Rectification Polarity Markings.

(C) Exaggerated Cross-Sectional View of Stack Assembly of Half-Wave Rectifier.

Fig. 4-7. The Copper-Oxide Rectifier Cell.

How then does this description of the generalized rectifier cell apply to the copper-oxide cell discussed previously? It was shown that the copper-oxide rectifier cell consists of a "pure" copper disc or plate upon which a layer of cuprous-oxide is formed by oxidation at a high temperature. The subsequent quench from the annealing temperature causes the oxide to freeze with occasional copper ions missing from the oxide crystals leaving an oxide with an excess of oxygen. At the junction between the copper base plate and the oxide, however, where the copper is rich, a very thin layer of cuprous-oxide remains practically perfect in its crystal structure. Thus is obtained a pure copper metal separated from cuprous-oxide containing an excess of oxygen by a very thin layer of perfect cuprous-oxide. The perfect oxide is inherently an insulator, while the oxide with the excess of oxygen is a semiconductor. Hence, the essential structure of the copper-oxide cell conforms with the generalized metallic rectifier cell as comprising a semiconductor separated from a metal electrode by a thin insulating layer. The rectifier cell is completed by means of an auxiliary metal electrode contacting the free surface of the semiconductor. Current flows readily when the base plate is made negative with respect to the oxide, while practically no current flows when the applied potential is reversed.

In Fig. 4-7A the generalized metallic rectifier cell as exemplified by the copper-oxide type is specified. The forward direction as previously defined is also shown. In Fig. 4-7B the electrical symbol for this rectifier cell is shown. The arrow head points towards the forward direction; however, when the cell is used as a rectifier the rectification polarities are as shown here (see Chapter 3). Fig. 4-7C illustrates how the copper-oxide cell may be assembled to make a practical half-wave rectifier. Of course, having available copper-oxide rectifier cells, one is not limited to half-wave rectifiers but may assemble any suitable combination to meet the requirements. A few such assemblies were described in Chapter 3.

For purposes of comparing the various types of rectifier cells and to achieve simplification of presentation of their characteristics, it is desirable to describe these properties in terms of the basic rectifier cells. This is the approach used in this and the following three chapters.

Volt-Ampere Characteristic

The volt-ampere graph shows the relationship between the applied voltage and the resultant current flow. The experimental method for obtaining this information was described in Chapter 2. The resulting graph for a copper-oxide rectifier cell is given in Fig. 4-8. This is the characteristic curve which will be obtained for a typical copper-oxide rectifier cell having an effective area of one square inch. The electrical symbol for the rectifier cell is given with the polarity of the applied potential shown for the forward and reverse direction characteristics. It will be recalled that the applied potential for the forward direction (the direction in which the current flows readily through the cell) is that potential applied from the semiconductor to the adjacent metal electrode across the barrier layer with the semiconductor polarized positive and the metal electrode polarized negative.

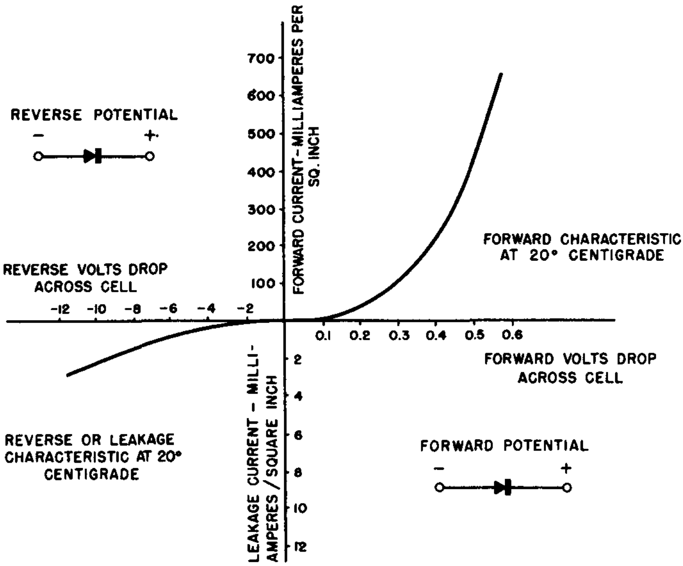


Fig. 4-8. Volt-Ampere Characteristics of Copper-Oxide Cell at 20° C.

Since but a fraction of a volt is required to pass full rated current in the forward direction, the horizontal axis of the graph of Fig. 4-8 is plotted in tenths of volts in the forward direction. The resultant current is plotted in units of 100 milliamperes per square inch.

In the reverse direction a rather large applied voltage is required even for a small flow of current — the leakage current. Hence, the horizontal axis to the left of the vertical current axis of the graph is plotted in volts. Note that the resultant leakage current as measured by the vertical axis below the horizontal voltage axis is plotted in milliamperes, that is, this scale has been expanded 50 times so that the shape of the leakage characteristic can be clearly shown. If this scale had not been expanded, the leakage current curve would have appeared as a horizontal line, practically coinciding with the horizontal axis.

The voltage applied in the conducting or forward direction is plotted against the resultant current in tenths of volts against units of 100 milliamperes per square inch to facilitate comparison with other type rectifier cells in later chapters.

The volt-ampere curve of the copper-oxide rectifier cell demonstrates that the current flow in the forward direction is at least 1000 to 2000 times greater than the current flow in the reverse or leakage direction. For example, a forward or conducting voltage drop across the rectifier cell of about 0.5 volt at 20 degrees Centigrade results in approximately 0.4 ampere per square inch current flow as seen in Fig. 4-8. For the same applied voltage in the reverse or blocking direction, only a fraction of a milliampere per square inch flows through the same copper-oxide rectifier cell at the same temperature.

The non-linear property of the copper-oxide rectifier is also clearly seen from a study of Fig. 4-8. For as the applied voltage is increased from zero in the forward or conducting direction, the current through the rectifier cell increases quite slowly at first. (As an example, for the first 0.1 volt increase the resultant current change is but a few milliamperes.) Then, the rate of current increase becomes quite rapid with the increasing applied voltage and approaches a linear characteristic for the larger increments of applied forward voltage.

In the reverse direction the applied voltage must be increased to large values before even milliampere values of current flow.

In the forward direction the maximum applied voltage (voltage drop across the cell) is limited by the maximum rated current flow which is based mainly upon the effective rectifier cell area and the permissible temperature at which the rectifying junction is to operate.

In the reverse direction the maximum applied voltage across the rectifier junction is limited by the breakdown across the barrier layer when the potential gradient becomes too great. When such a breakdown occurs, the cell junction is no longer effective as a rectifier and symmetrical current flow results.

The forward and reverse characteristics of the copper-oxide rectifier cell are a function of the ambient temperature which will be described later. For this discussion the ambient temperature is taken as 20 degrees Centigrade or 68 degrees Fahrenheit. In the graph of Fig. 4-8 the electrical symbols in the forward and reverse portions of the characteristic show the polarity of the applied voltage to the rectifier cell for the respective characteristic displayed.

It can be seen from Fig. 4-8 that approximately 1 ampere of current flows through the copper-oxide rectifier cell having an effective area of one square inch for an applied voltage of about 0.6 volt.

When the applied voltage is reversed it is an important property of the rectifier cell to block or hold to a minimum value the reverse current flow. Again from the graph of Fig. 4-8 it can be seen that, for the given ambient temperature, an applied reverse voltage of 10 volts causes a current flow of but 2 milliamperes.

Temperature Characteristic

The temperature of a copper-oxide rectifier cell has a profound effect upon its electrical properties. A quick means of discerning the overall effect of the cell temperature is to study cell volt-ampere characteristics at various temperatures. Such a set of curves is given in Fig. 4-9.

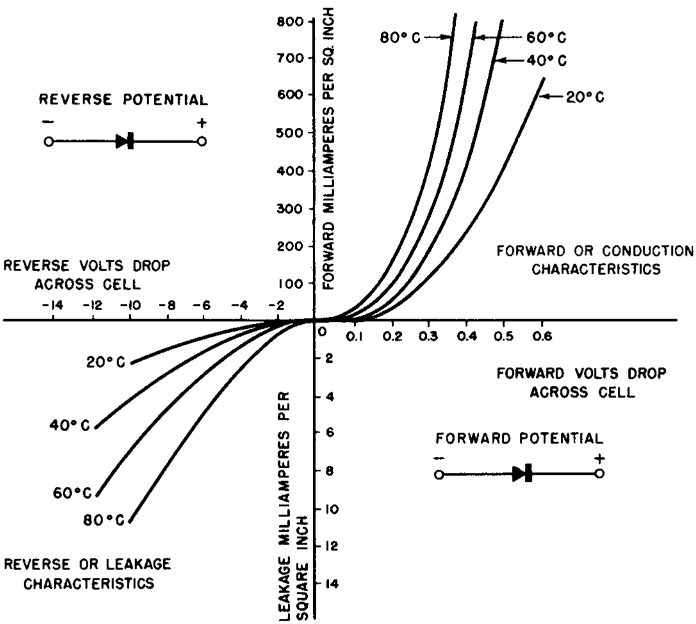


Fig. 4-9. Volt-Ampere Characteristics of Copper-Oxide Cell Versus Temperature.

It will be observed from the family of volt-ampere curves for the copper-oxide rectifier cell that the forward and blocking or reverse resistance decrease with increasing cell temperature; that is, the copper-oxide rectifier cell can be considered as a resistive device having a negative temperature coefficient of resistance. As a resistive device the copper-oxide rectifier cell will have a voltage drop across it when it is a part of an electrical circuit. This forward resistance results in a certain amount of heating, the dissipation of which determines the electrical capacity of the rectifier. This heating is the result of I^2R losses in the conducting direction as well as the losses resulting from leakage during the blocking cycle. Most copper-oxide rectifiers are designed to operate at rated electrical capacity for an ambient temperature of 35 degrees Centigrade (98 degrees Fahrenheit). This allows for a temperature rise for the rectifier of 10 to 15 degrees Centigrade above the ambient or a maximum rectifier temperature of about 60 degrees Centigrade. The 80 degree Centigrade curve in Fig. 4-9 is beyond the rating for copper-oxide rectifiers and is given to illustrate the effects of temperature in an exaggerated manner.

It will be noted from the curves of Fig. 4-9 that the forward characteristics of the rectifier improve with temperature, for, since the forward resistance decreases, less voltage drop is required across the cell to maintain a given current flow. However, the net gain due to the temperature rise is not to the good, for, by examining the negative characteristics versus the cell temperature, the reader finds that the leakage current increases rapidly with temperature. This leakage current, being in the opposite direction to that of the forward current in a rectifier application, reduces the rectification ratio or efficiency of the rectifier. Since operating the rectifier cell beyond its given rating also causes temperature rise in the cell, the curves of Fig. 4-9 graphically show why it is desirable to operate the cells within the ratings assigned by the manufacturer.

Another graphical method to illustrate the volt-ampere characteristic change for different temperatures of the rectifier cell is given in Fig. 4-10. Here the DC volts drop across the cell versus the cell temperature is plotted for three values of constant direct current in the forward direction only. This again shows the large variation in forward resistance of the copper-oxide cell with temperature. In many rectifier applications this variation of forward resistance with temperature is not important. However, in applications of the copper-oxide rectifier where a wide variation in temperature is anticipated, the forward resistance change may have to be considered and compensated. One way to accomplish this is to have the external resistance of the circuit about 10 times greater than the forward resistance of the copper-oxide rectifier at 35 degrees Centigrade. Of course, this larger external resistance swamps out the smaller variation of circuit resistance due to temperature effects upon the copper-oxide rectifier.

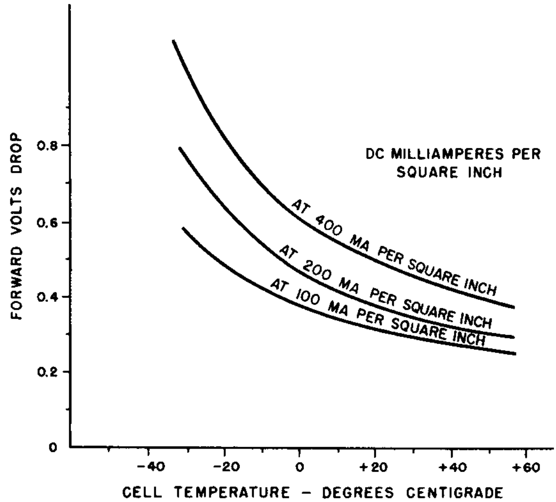


Fig. 4-10. Temperature Characteristics of Copper-Oxide in Forward Direction.

Another approach towards compensation of the temperature effect of the copper-oxide rectifier takes advantage of the

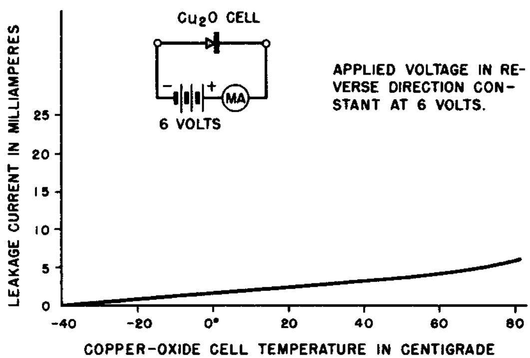


Fig. 4-11. Temperature Characteristics of Copper-Oxide Cell in Blocking Direction.

fact that the temperature characteristic of this rectifier is negative (that is, its resistance decreases with increasing temperature), while the temperature characteristic of copper wire is positive. Thus, where the electrical load of the copper-oxide rectifier is copper — electromagnets, solenoids, motor fields, etc. — the rectifier and load resistance changes are in opposite directions and tend to cancel.

The leakage current resulting during the blocking or reverse applied voltage also varies with temperature and a typical graph, obtained experimentally, is shown in Fig. 4-11.

Voltage-Resistance Characteristic

The general shape of the resistance-voltage curve of a copper-oxide rectifier cell is given in Fig. 4-12. This graph shows that, as the applied voltages approach zero, the forward and reverse direction resistance approach each other in ohmic value. In the forward or low resistance direction and at low values of voltages, the resistance decreases approximately exponentially as the applied voltage increases; at higher forward voltages, the forward resistance becomes nearly constant and low in ohmic value.

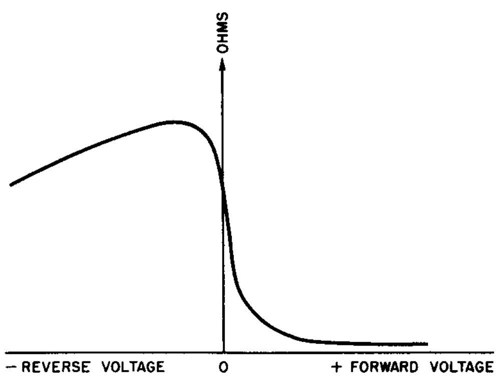


Fig. 4-12. Voltage-Resistance Graph for Copper-Oxide Rectifier Cell.

In the reverse direction the resistance increases with the increasing applied voltage up to a very high ohmic value at about 1 1/2 volts; beyond this voltage, the resistance decreases with the increasing voltage at a rate which is nearly linear. If this reverse voltage is increased too far, a breakdown of the rectification junction takes place.

Voltage Rating of the Cell

Voltage rating of a rectifier cell is defined as the root-mean-square value of the AC voltage applied to the cell. Copper-oxide rectifier cells are generally operated at voltages ranging from 2 to 10 volts rms with 8 volts being the average. Beyond 8 volts the leakage current tends to increase rather rapidly, thus, in effect, a metallic rectifier cell is generally rated by the voltage it will practically withstand in the reverse or high resistance direction.

Current Rating of the Cell

The current rating of a rectifier cell is the maximum current that may be passed through it in the forward or low resistance direction within its thermal rating. It is expressed as average DC amperes as read on a D'Arsonval type ammeter. For the copper-oxide type rectifier the current rating is approximately 1/10 ampere DC per square inch at 35 degrees Centigrade for a self cooled stack (no cooling fins). Current rating is dependent upon stack design and the cooling methods employed.

Voltage Regulation

Copper-oxide rectifier cells are resistive devises and as such have appreciable voltage regulation. Voltage regulation is defined as the ratio of the difference between the output voltage at full load and at no load to the full load voltage in percent, thus:

$$\text{Voltage Regulation} = \frac{\text{No load Voltage} - \text{Full load voltage}}{\text{Full load Voltage}} \times 100\%$$

This difference between the no-load and the full-load voltage is the potential drop across the rectifier cell in the forward direction.

As an example, if the no-load voltage is 9 volts and the full-load voltage is 6 volts, there is a 3-volt drop across this fictitious rectifier cell and its voltage regulation is 50%, for:

$$\text{Voltage Regulation} = \frac{9-6}{6} \times 100\% = 50\%.$$

For the general purpose copper-oxide rectifier cell the voltage regulation is of the order of 15 to 25%. A typical voltage regulation curve for a copper-oxide rectifier cell is shown in Fig. 4-13. In Fig. 4-14 is displayed a family of voltage regulation curves for a single-phase, full-wave bridge, copper-oxide rectifier supplying a resistive load.

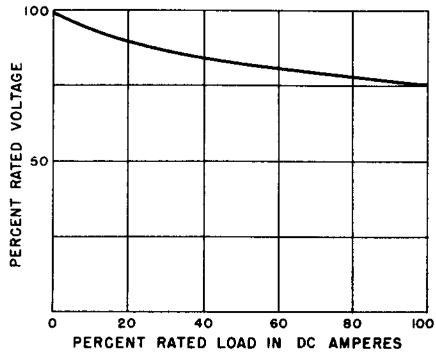


Fig. 4-13. Voltage Regulation Curve of a Typical Copper-Oxide Rectifier Cell.

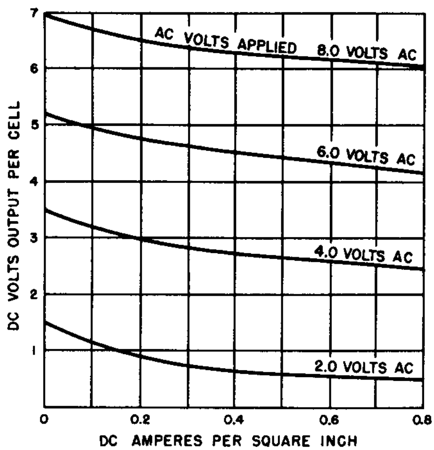


Fig. 4-14. Voltage Regulation for a Single-Phase, Full-Wave Bridge, Copper-Oxide Rectifier Supplying a Resistive Load.

When a single, fixed load is connected to a rectifier, the voltage regulation of the rectifier may not be important. When more than one load is connected to the rectifier, the application should be checked to verify that under minimum load conditions the resultant higher voltage will not destroy or damage the load device. Also in applications which involve short-time current output in excess of the rectifier rating, the application should be checked to insure that under maximum load conditions the voltage is not too low for successful operation of the load device.

Efficiency

Efficiency or the conversion ratio of a metallic rectifier is defined as:

$$\frac{\text{Average DC volts output x average DC amperes output}}{\text{AC watts input}} \times 100\%$$

This may be expressed as the ratio, in percent, of the DC volt-amperes output (average values) to the AC watts input. The efficiency of copper-oxide rectifier cells average somewhere between 60 and 85% depending upon the type of circuit and the rating and operating conditions of the particular rectifier. In a single-phase, full-wave circuit connected to a resistive load, the rectifier stack efficiency at rated load will be from 60 to 65 percent. In a similar circuit with a battery charging load, the efficiency may be from 70 to 75 percent. In three-phase operations 85 percent efficiency is achieved at full-rated output. At low temperatures the efficiency will be slightly less than normal, while at higher operating temperatures the efficiency will be increased somewhat due to the lowering of the internal resistance of the rectifier.

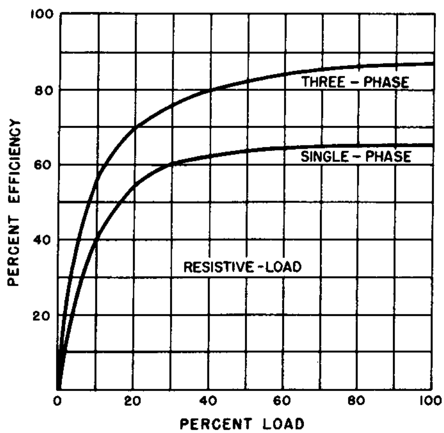


Fig. 4-15. Efficiency of Single-and Three-Phase, Full-Wave Bridge, Copper-Oxide Rectifier Supplying a Resistive Load.

Typical efficiency graphs are shown in Fig. 4-15 for single-and three-phase rectifier stacks supplying resistive loads.

Power Factor

Power factor, the ratio in percent of the AC watts output to the AC volt-ampere input is practically unity for a copper-oxide rectifier at power frequencies because this type of rectifier is a resistive device. The overall power factor is determined by the associated equipment in the rectifier circuit such as the transformer, ventilating fans if used, and the nature of the load. When the rectifier is used in a circuit with a transformer and connected to a normal load such as a resistance device or batteries, the power factor is usually 95 percent or better.

Frequency Characteristics

The majority of past and present applications of copper-oxide rectifier cells and stack assemblies have been for rectification or control of power frequencies ranging from 25 to 60 cycles per second. For this reason the frequency characteristics of the rectifier have not been too important because of the low frequencies involved. It is believed that most copper-oxide rectifier stacks will operate satisfactorily up to about 1000 cycles per second. Beyond this frequency inherent capacitance effects seriously reduce the performance of this type of rectifier. Since the copper-oxide rectifier cell consists primarily of two electrodes separated by an insulating layer, it can be seen that there exists a capacitance effect which becomes active at the higher frequencies. This inherent capacitance of the copper-oxide rectifier cells is similar in its behavior to a small capacitor in parallel to an ideal rectifier cell. The adverse performance caused by this shunting capacitor is to reduce the impedance of the rectifier cell in the reverse direction and, hence, to cause a marked reduction in the efficiency or conversion ratio of the cell as the frequency of the applied voltage is increased beyond, say, 1000 cycles per second.

The value of this "shunting" capacitance is a function of the effective area of the rectifier cell and also depends to some extent upon the strength of the polarizing voltage applied across the cell.

For instrument and control applications it is often necessary to operate small current copper-oxide rectifiers at frequencies almost up to the megacycle range. In this case it is necessary to employ special techniques in the processing of these rectifier cells and, more important, to severely reduce the area of the working surface so as to minimize the shunting capacitance.

Speed of Operation

The copper-oxide rectifier does not deteriorate when not in operation; no electroforming period is required though the rectifier may have been out of circuit and operation for years. Thus, this type of rectifier is always ready to function with rated characteristics as soon as the power is applied.

Effect of Idleness

When a copper-oxide rectifier is idle its reverse resistance tends to increase. The forward resistance will also increase by an amount that is a function of temperature at which the cell or stack is maintained.

At 10 degrees Centigrade for example there will be no change in the forward resistance. (Note: increases in the reverse direction are beneficial while increases in the forward resistance reduce efficiency.) At 25 degrees Centigrade the forward resistance will increase about 10% in a year's time.

Aging and Life

Another copper-oxide rectifier characteristic is referred to as aging. Aging is defined as an increase in the resistance of a copper-oxide cell or stack with time. This change in the rectifier resistance with time is reflected in the output of the cell or stack and can be illustrated by Fig. 4-16. This shows that, in order to maintain a constant DC output, the AC input must be gradually increased during the first 6 to 12 months. There is no run-away tendency of this aging condition and the characteristic becomes stabilized after the initial aging period.

Because of this aging characteristic of copper-oxide rectifier cells and stacks, designs using these rectifiers are customarily provided with tapped transformers having adequate aging taps to permit adjustment of the input AC so as to maintain the DC output voltage constant. Thus, it is possible to increase the AC voltage input to overcome the increased rectifier resistance over the first 6 or more months of operation time. After this initial readjustment is completed there is no further need for additional input changes as the output has stabilized — provided that the rectifier temperature and electrical ratings are not exceeded.

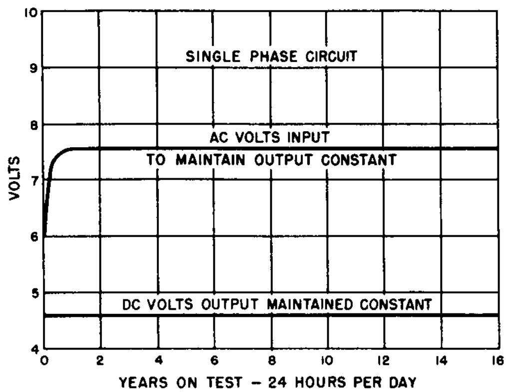


Fig. 4-16. Aging of Copper-Oxide Rectifiers—Continuous Life Test.

The forward aging shows up as an increase in the forward resistance, the amount of increase being a function only of time and stack temperature. Forward aging has no effect on stack ratings as all ratings are based on aged characteristics.

A good average allowance for forward aging is 15 percent, so the transformer range for full load in the aged condition should provide a voltage tap 15 percent greater than the initial tap.

Copper-oxide rectifiers have been used for many years for the charging of fire alarm and railway signal batteries, switchgear control batteries, for DC supply to passenger elevator control circuits, and many other applications where reliability is of great importance; copper-oxide rectifiers installed more than twenty years ago continue to give dependable service. Long experience has demonstrated that when this type of rectifier is properly applied it has an indefinite life.

Threshold Voltage

In some types of metallic rectifiers it is necessary to apply a certain minimum voltage before conduction in the forward direction takes place. If the applied voltage is alternating, then a certain minimum value must be applied before rectification takes place; that is, in either the direct or alternating voltage application, conduction does not initiate for values of voltage below a critical voltage identified as the threshold voltage.

The copper-oxide rectifier cell or stack does not exhibit threshold voltage effects, thus making it particularly useful for instrument and control applications.

Operating Temperature and Derating

Copper-oxide rectifier cells and stacks are thermally rated so that the voltage and current ratings specified will not cause I^2R losses resulting in excessive operating temperatures. These electrical losses causing the heating of the cell or stack are due to two effects — forward resistance producing an IR drop, and reverse resistance producing leakage current under the influence of the reverse voltage. In the ordinary operating temperature ranges, all metallic rectifiers exhibit a negative temperature coefficient of forward resistance. Hence, at any given output current, forward loss drops with rising operating temperature. Leakage current follows a pattren dependent upon temperature and back voltage. The final operating temperature is governed by the choice of voltage and current rating and the heat dissipation design of the stack structure.

The standard electrical rating for the rectifier cell or stack is based on a maximum ambient temperature of 35 degrees Centigrade (98 degrees Fahrenheit). This ambient temperature is the temperature of the air surrounding or moving past the rectifier and need not be the same as the room temperature.

When this ambient temperature of operation exceeds 35 degrees Centigrade, the rectifier losses must be reduced so that the operating temperature does not exceed the safe maximum. To accomplish this reduction of rectifier losses, it is necessary to derate the output voltage rating and, hence, the AC input voltage in proportion to the increase in the temperature over 35 degrees Centigrade. When thus derated the applied reverse voltage is now less than the maximum permitted so the current rating or the forward current can remain the same as at 35 degrees Centigrade or be somewhat higher.

Fig. 4-17 shows a curve for derating the output voltage rating of the copper-oxide rectifier to the proper values for higher ambient temperatures. For example, for service at 50 degrees Centigrade ambient temperature, the DC output voltage rating of the copper-oxide cell or stack must be derated to 70% of normal voltage. Thus, a 50 volt, 1 ampere normal rating must be reduced to 35 volts, 1 ampere for the new operating temperature of 50 degrees Centigrade. No derating of the current is required.

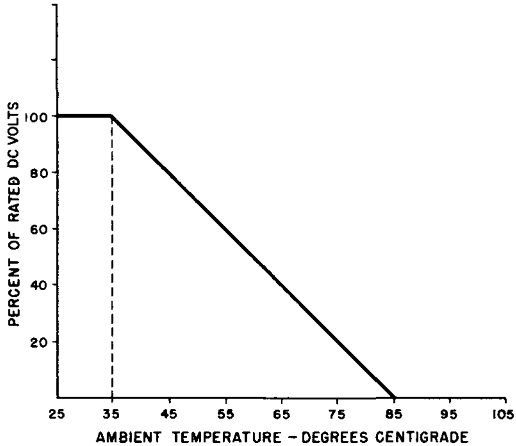


Fig. 4-17. Voltage Derating for High Ambient Temperatures. No Derating of Output Current.

It is interesting to note from Fig. 4-17 that for an ambient temperature of about 85 degrees Centigrade the copper-oxide rectifier has been derated to an output voltage of zero. Safe operation at that temperature is not possible.

Ambient Conditions Other Than Temperature

Though copper-oxide rectifier cells and stacks are fairly robust and immune to normal ambient conditions, they may be adversely affected when exposed to excessive humidity, corrosive vapors, fumes, or dust. For average applications the stacks are treated with special varnishes or similar protective coatings. In especially severe applications the rectifier stacks may be immersed in oil or even hermetically sealed.

Future Outlook

Of the three types of metallic rectifiers the copper-oxide type has had the longest history of useful application and development. Electrical capacities range from milliwatts up to 100 kilowatts output.

Because of the present military requirements of low weight, compactness, and operation at high voltage per cell and high operating temperatures, none of which is well filled by the copper-oxide rectifier, there is no anticipation of startling improvements or development work in this type of rectifier.

CHAPTER 5

The Selenium Rectifier

Introduction

Although the photelectric and rectifying properties of selenium were discovered before 1900, the first commercial rectifier using this material was promoted in Germany around 1928. Its subsequent development and application in Europe proceeded along similar channels with those of the copper-oxide rectifier in the United States. As the manufacturing techniques were improved and new ideas incorporated, the resulting selenium rectifier displayed important and inherently superior characteristics over the copper-oxide rectifier for certain applications.

The selenium rectifier was introduced in the United States in 1938 by the Federal Telephone and Radio Corporation, a subsidiary of the International Telephone and Telegraph Company. As introduced, these selenium rectifier cells were limited to a maximum AC input voltage of about 14 volts, root-mean-square. Improvements in the barrier layer during the early 1940's permitted an increase in the applied AC voltage to 18 volts, rms per cell. Subsequent work during World War II resulted in present (1956) cell rating of 26 volts rms.

The higher voltage rating per cell made practical what is known in the trade as miniature selenium rectifier assemblies — in contrast to the regular power selenium rectifier assemblies. These miniature selenium rectifiers provide an easy and economical solution to DC power problems in radio and television receivers. The demand for these miniature selenium rectifiers made it necessary to achieve true mass production and stocking of a range of rectifiers easily available from jobbers and distributors anywhere. This, compared to the custom production and poor availability of other type of rectifiers previous to this time, made the selenium rectifier quite popular.

The selenium rectifier's electrical characteristics, long life, light weight, availability, and potential for improvement have given it a meteoric rise since its introduction and at the present time it occupies the number one position in popularity and demand.

Production

Selenium rectifier cells use a circular or rectangular base plate of steel or aluminum. The aluminum base plate is generally preferred because of lightness, better heat dissipation, and the elimination of the rust problem. The surface of the base plate is roughened by sandblasting or chemical etching so as to provide a good bond between it and the semiconductor which is to be applied. Then the roughened base plate is nickel plated to reduce the electrical contact resistance between it and the semiconductor. The next step is the application of the semiconductor; purified selenium powder with a trace of bromide, chlorine, or iodine is dusted upon the roughened surface of the base plate and this combination is heated and simultaneously subjected to a pressure of about 1000 pounds per square inch. The resulting selenium layer, of an amorphous nature, is reduced to a crystalline form by further heat treatment to improve its electrical conductivity.

The adherence of the selenium semiconductor layer on the roughened base plate is a function of the thickness of the layer as well as its coefficient of expansion relative to that of the base plate. Better adherence is achieved with a thinner layer of selenium semiconductor — the limit to the thinness of the selenium layer being porosity or pin holes in the selenium and low reverse resistance of the rectifier cell. In practice, the usual thickness of the selenium layer ranges between 0.003 to 0.005 inch.

The base plate is now placed into a mask and the selenium surface is sprayed with a low melting-point alloy (selenium melts at about 217 degrees Centigrade). The whole surface of the selenium layer is covered with the exception of a narrow ring at the center and at the periphery of the base plate. The purpose of these rings is to provide insulation between the alloy front electrode and the metal base plate electrode. The sprayed alloy surface constitutes the front or counter-electrode of the selenium rectifier cell and is its cathode (rectification polarity). The alloy usually comprises from 15 to 20 per cent cadmium, the rest being bismuth and tin; the plastic temperature of the alloy is around 95 degrees Centigrade and its melting temperature varies from 110 to 170 degrees Centigrade depending upon the percentage of its contents.

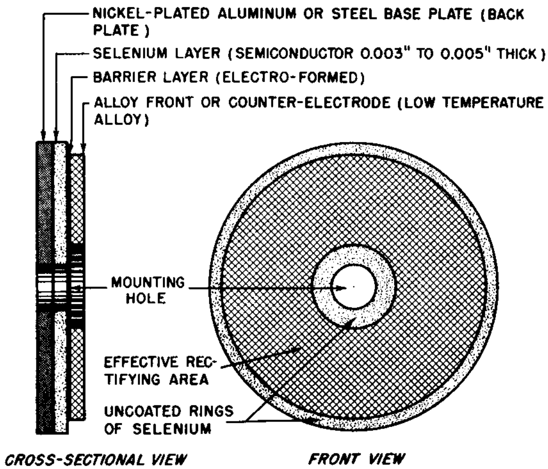


Fig. 5-1. Front and Cross-Sectional View of the Selenium Rectifier Cell.

In Fig. 5-1 is shown a sketch of a selenium rectifier cell in plan and cross-sectional view. The central hole is used for mounting purposes when the cell is assembled into rectifier stacks. The uncoated selenium peripheral and inner rings which insulate the front electrode from the base plate are shown in the front view sketch. The layer of selenium and the front electrode are very thin in practice; these layers are represented to an exaggerated scale in the cross-sectional view. The barrier layer between the selenium and the alloy front electrode is only a few molecules thick. The effective rectifying area of the selenium cell is equal to the area of the front electrode.

The electrical connection to the selenium rectifier cell of Fig. 5-1 is made to the back surface of the base plate and to the front surface of the front electrode. When a DC potential is applied to the cell so that the base plate is polarized positive and the front electrode is polarized negative, a much larger current will flow through the cell than when the polarity of the cell is reversed. The current flow through the cell is in a direction normal to the plane of the cell disc. The magnitude of the current flow depends directly upon the effective rectifying area of the cell and upon the applied voltage, although the relationship between the voltage and current is not linear.

Thus each selenium rectifier cell as pictured in Fig. 5-1 forms a complete, half-wave, rectifying element with the back plate acting as a support and one electrode, and the alloy surface acting as the other electrode, the combination presenting a one-piece rectifier requiring no high pressure contact for rectification.

In assembly of these rectifier cells into a stack, contact with the base plate is made by a metal washer or terminal member while contact to the front electrode or alloy layer is made by means of a spring contact plate. The amount of pressure exerted by this contact plate is determined by the thickness of an insulating washer placed between the cell and the contact plate.

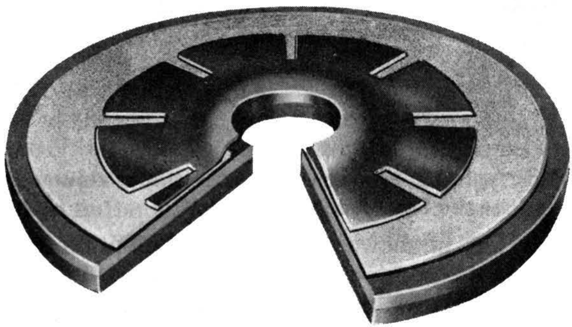


Fig. 5-2. Cut-Away View of a Selenium Rectifier Cell. (Courtesy of General Electric Co.)

Fig. 5-2 is a photograph of a General Electric selenium rectifier cell using the construction described. The cut-away permits a view of the cross-sectional nature of the cell. The first layer at the left of the photograph is the aluminum backplate. The next layer is the selenium semiconductor. The succeeding, spotted white layer is the alloy front or counter-electrode. Between the selenium and the alloy layer is positioned the blocking or barrier layer which is formed by heat treatment and electroforming. The petal-like spring contact engaging the front electrode is the last element of the selenium rectifier cell shown.

Another type of selenium rectifier cell construction secures the same advantage of assembly and front electrode contacting without the petal-like spring contact.

The reverse resistance of the previously described selenium rectifier cell falls off too rapidly to permit the cell to be put into practical service; to make a practical cell, it must be further processed — electroformed and heat treated. The barrier layer between the front electrode and the selenium semiconductor is electroformed by applying a rectified AC or a pulsating DC voltage in the reverse direction while the rectifier cell is heated in an oven which is regulated closely in temperature. Further heat treatment and seasoning at critical temperatures completes and stabilizes the barrier layer. At the beginning of the electroforming the applied voltage is low so as to prevent overheating the cell; as the reverse resistance builds up, the applied voltage is increased until its maximum value is a few volts over the rated voltage of the cell. The theory is that the electroforming increases the thickness of the barrier layer to a small extent and performs an electrical cleaning of the selenium surface adjacent to the front electrode by removing the surplus electrons. The process has little effect on the forward characteristic of the cell except to slightly increase the forward resistance.

The selenium rectifier cell thus processed is ready for assembly into rectifier stacks. The cell is generally made in disc form in diameters ranging from 7/8 inch to 4 3/8 inches, square plates ranging from 1/2 inch to 5 inches or in rectangular plates up to 6 1/4 x 7 1/4 inches. Special rectifier discs for high voltage or high frequency applications as small as 1/4 inch in diameter are commercially available.

Construction

For practical application of the rectifier cells discussed previously, it is necessary to assemble them in the required number and sequence into rectifier stacks in the manner described in Chapter 3. For such rectifier stacks to be stable, it is necessary that its constituent cells be firmly assembled together, that is, mechanical pressure be permanently applied to hold the cells in place. If, however, this mechanical pressure is applied to the active surface of the selenium cells, either the cell reverse resistance may be greatly reduced (poor efficiency due to increased leakage current) or a short circuit in the cell may result. Hence, two different schemes are commercially used to avoid these risks. This results in two physically different types of selenium rectifier cells currently used for assembly into the rectifier stacks. Consequently, stacks using one or the other type of selenium rectifier cell will be slightly different in physical structure. The principal difference between the two types of rectifier cells is in the method of contacting the front electrode or alloy surface. In the first type of rectifier cell, no front electrode is applied near the mounting hole (inner ring of Fig. 5-1) and the stack assembly pressure is applied to this area by a bakelite washer. A spring washer makes electrical contact with the front electrode surface at a pre-determined and limited pressure. This spring washer may be in the form of a petal or solid spring washer. The photograph of the General Electric selenium rectifier cell, shown in Fig. 5-2, clearly illustrates an example of the petal spring washer contact to the front electrode.

When this first type of rectifier cell is assembled into a rectifier stack, the required number are placed in the proper sequence upon a threaded and insulated stud. A metal terminal or washer makes electrical contact with the rear of the base plate of each cell and connection to the front electrode is made by the described spring washer. The predetermined pressure exerted by this spring washer is controlled by the thickness of an insulating, bakelite washer placed between the alloy surface of the cell and the adjacent inner surface of the spring washer. The advantage of this construction is that the electrical characteristics of the stack are not disturbed by the degree to which the terminal assembly nuts of the threaded stud are tightened. The reason for this is clear, when it is recalled that no front electrode is applied to the center ring of the rectifier cell and consequently no pressure sensitive barrier layer is present here to be affected. This permits mechanical pressure to be applied to the spacing and pressure limiting washers for stack assembly purposes without affecting the reverse resistance of the rectifier.

The second type of selenium rectifier cell does not require the contacting spring to the front electrode. Electrical connection to the front electrode is achieved by means of a metal washer or terminal strap in the rectifier stack assembly. To avoid electrical shorting to the base plate and reduction of the cell reverse resistance because of rectifier stack assembly pressure, the inner, uncoated ring of selenium is coated with an insulating varnish, then the selenium surface is sprayed with the low temperature alloy. This alloy surface does not extend to the edge of the plate or circular disc but is usually applied with a slight margin to eliminate the possibility of direct shorts to the base plate. This accounts for the outer or peripherial ring of uncoated selenium shown in the plan view of the cell in Fig. 5-1 and in the cut-away photograph of Fig. 5-2. The selenium layer is now insulated from the front electrode over the area where pressure will be applied when the rectifier stack is assembled and electrical connection to the front or counter electrode can be made by means of a metal washer or terminal strap as required in the stack assembly.

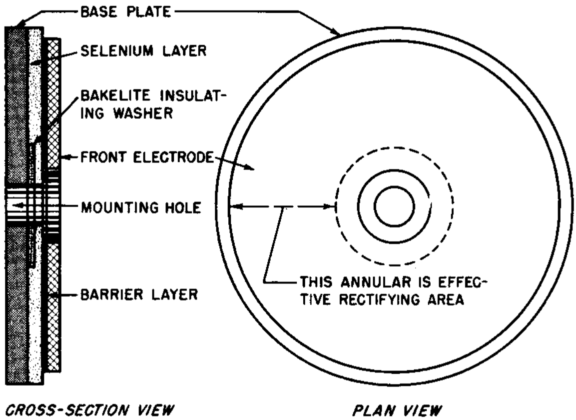
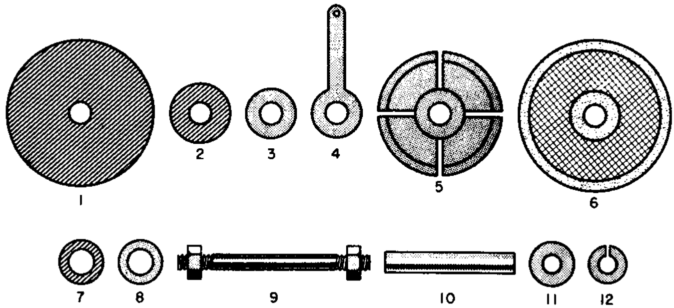


Fig. 5-3. Cross-Sectional and Plan View of Selenium Rectifier Cell Using Insulating Washer Principle.

Another scheme to obtain the same result for the second type of selenium rectifier cell is shown in Fig. 5-3. To one face of the aluminum or steel base plate there is applied an insulating washer, concentric with the mounting hole. Then the selenium layer is applied and processed. Over the selenium layer is applied the low-temperature alloy to constitute the front electrode. The front electrode, as described before, has an inner and outer margin to prevent shorting of the front surface with the metal base plate. The effective rectifying area is the area which the front electrode and the base plate have in common, that is, less the area of the insulating washer.

The advantage of the insulating washer type of selenium rectifier cell is that somewhat better cooling of the cell is achieved when it is assembled into a stack, for the cell face is not covered by a spring contact member. Moreover, the insulating washer type of selenium rectifier cell can be freely dipped into insulating varnish without the risk of the varnish penetrating between the front electrode and contact plate.

Having selected the selenium rectifier cell type and prepared the cells, it is necessary to grade them (described in Chapter 3) before assembly into rectifier stacks. Fig. 5-4 shows the elements of the contacting spring washer type of selenium cell stack assembly. The assembly of these ele-



1. END INSULATOR
2. INSULATING WASHER
3. STEEL WASHER
4. TERMINAL LUG
5. PETAL CONTACT SPRING
6. SELENIUM RECTIFIER CELL
7. BAKELITE SPACER
8. CONDUCTING SPACER
9. MOUNTING STUD WITH NUTS
10. INSULATING TUBE
11. STEEL END WASHER
12. LOCK WASHER

Fig. 5-4. The Elements of a Selenium Rectifier Stack Using the Contact Type Cell.

ments into a full-wave bridge with one cell per arm is illustrated in Fig. 5-5.

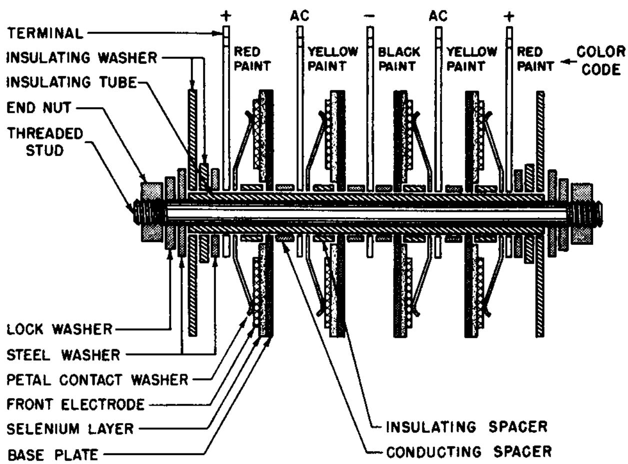
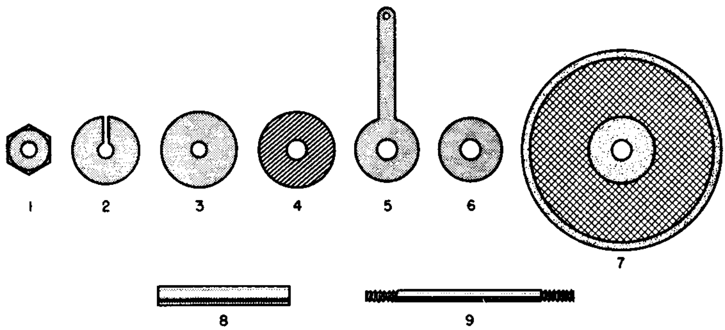


Fig. 5-5. Selenium Rectifier Stack Construction. Full-Wave Bridge, Using Contact Type Cell.

In Fig. 5-6 are shown the elements of the selenium rectifier stack using the insulated washer type of cell. Fig. 5-7 shows in cross-section the selenium rectifier stack using the components of Fig. 5-6 in a full-wave bridge, utilizing one cell per arm of the bridge.



1. STACK NUT
2. LOCK WASHER
3. STACK END WASHER
4. INSULATING WASHER
5. TERMINAL LUG
6. CONDUCTING AND SPACER WASHER
7. SELENIUM RECTIFIER CELL
8. INSULATING TUBE
9. THREADED STUD

Fig. 5-6. The Elements of a Selenium Rectifier Stack Using the Insulating Washer Type Cell.

Please note again that the cross sectional studies of the selenium rectifier cells in both Figs. 5-5 and 5-7 are grossly

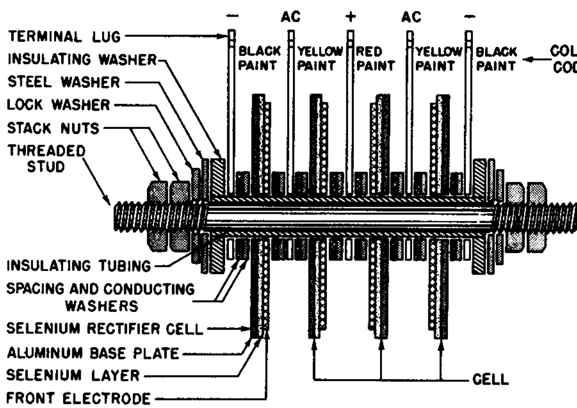


Fig. 5-7. Selenium Rectifier Stack Construction. Full-Wave Bridge, One Cell per Arm. Cells are of the Insulating Washer Type.

exaggerated as to the thickness of the layers constituting the cell. This is done so that the individual layers can be easily identified; normally, the whole cell may be less than 0.05 inch thick.

After the assembly of the rectifier stack, the whole stack is given one or more coats of insulating varnish and, if required, a fungus treatment.

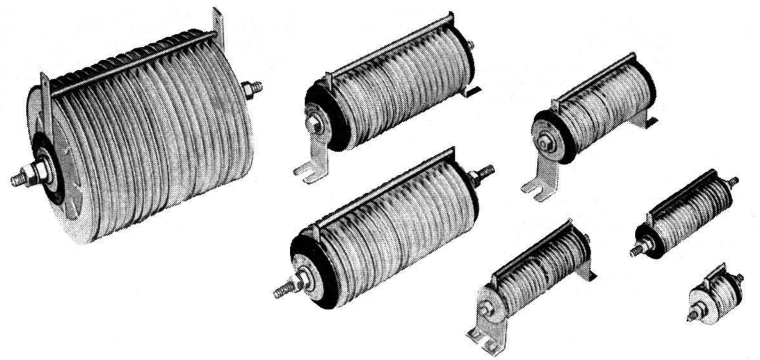


Fig. 5-8. Selenium Rectifier Stacks Manufactured by General Electric Company. (Courtesy of General Electric Co.)

The terminals of a selenium rectifier stack are color coded in the following manner: the yellow coded terminals are the AC input terminals, the red coded terminal is the positive terminal,and the black coded terminal is the negative terminal of the DC output. Should the rectifier stack constitute a half wave rectifier, then one terminal is imprinted + or painted red.

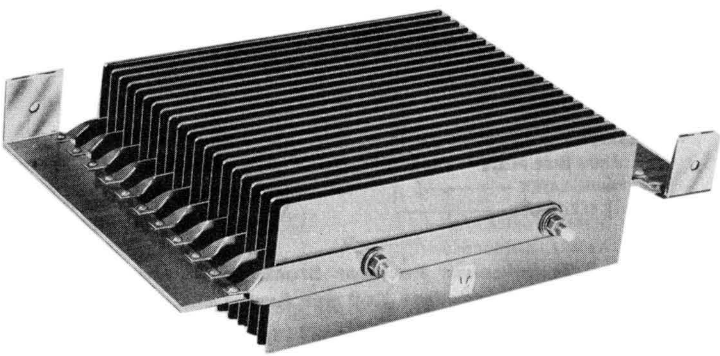


Fig. 5-9. Heavy Duty Selenium Rectifier Stack Using Rectangular Cell Plates. (Courtesy of Vickers, Inc.)

Examples of commercial selenium rectifier stacks are shown in the photograph of Fig. 5-8. Fig. 5-9 is a photograph of a rectangular selenium rectifier cell stack manufactured by

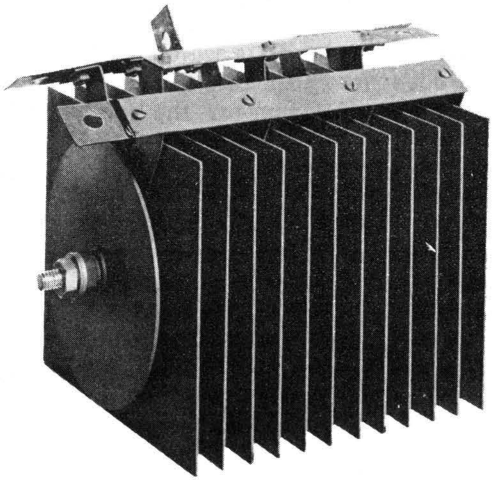


Fig. 5-10. A Three-Phase Bridge Selenium Rectifier. Fan Cooling, 24 Volts AC Input, 60 Amperes DC Output. (Courtesy of Seletron Division of Radio Receptor Co., Inc.)

Vickers, Inc. of St. Louis. This heavy duty selenium rectifier stack is 4 1/8 inches high, 18 inches wide, and 12 inches long. Six of these stacks carefully finished to withstand high humidity and corrosive atmospheres are used to deliver 18 kilowatts DC at 12 volts, 1500 amperes, in electroplating service. Fig. 5-10 is a photograph of a three-phase bridge selenium rectifier stack.

Elements of the Selenium Rectifier Cell

Previously, in Chapter 2, it was stated that all known metallic rectifiers can be represented by a generalized rectifier cell and shown to comprise four elements; these cell elements are:

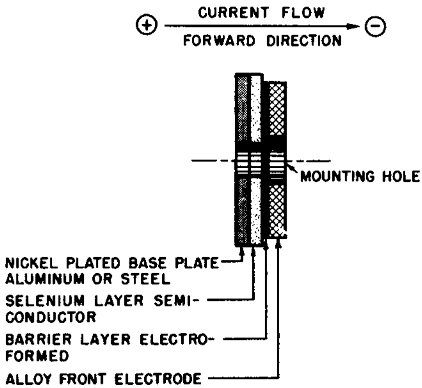
1. Base or support plate.
2. Semiconductor.
3. Barrier layer.
4. Front or counter electrode.

This description of the generalized rectifier cell applies to the selenium rectifier cell studied in this chapter. It has an aluminum or steel disc or plate which is the support plate; this base plate does not enter into the rectification process but serves as a stable platform for the semiconductor and is one electrical terminal of the rectifier cell. The selenium layer is the semiconductor; it is especially processed to possess good electrical and mechanical bond to the support plate. The barrier or insulating layer is electroformed between the selenium layer and the front electrode by electrical and heat treatment. The front electrode adjacent to the barrier layer is a metallic alloy more abundant in free electrons than is available in the selenium semiconductor. This combination behaves as a half-wave rectifier cell, for, when the applied polarizing potential is directed from the selenium to the adjacent metal front electrode across the barrier layer, the current flow is much more abundant than for the reverse potential. That is, current flows more freely through the selenium cell when the base plate is polarized positive and the front electrode is polarized negative.

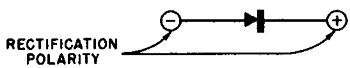
This condition of the base plate acting as the anode while the front electrode acts as the cathode of the selenium cell for current flow, is opposite to the condition described for the copper-oxide rectifier cell in Chapter 4. For example, Fig. 4-7 shows that the forward direction here is obtained when the copper base plate is positive and the lead front electrode is negative. It appears then that the copper-oxide and the selenium rectifier cells rectify in an opposite sense. But note that the reason for this difference is in the position of the barrier layer. In the copper-oxide rectifier cell the barrier layer is adjacent to the support plate, whereas in the selenium rectifier cell the barrier layer is adjacent to the front electrode.

If the general rule is used to determine the forward direction, no confusion results because of physical differences in the construction of the various metallic rectifier cells. This general rule states that the forward direction is that resulting from the potential difference being directed from the semiconductor to the adjacent metal electrode across the barrier layer; that is, polarizing the semiconductor positive and the adjacent metal electrode across the barrier layer negative.

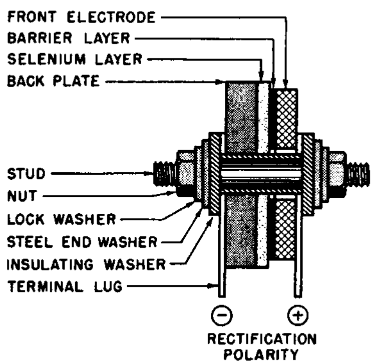
Following this rule the polarity for the forward direction is readily determined and the rectification in "opposite sense" for selenium and copper-oxide rectifier cells is no longer confusing.



(A) Exaggerated Cross-Sectional View of Selenium Rectifier Cell.



(B) Schematic Diagram Showing Rectification Polarity.



(C) Exaggerated Cross-Sectional View of Half-Wave Selenium Rectifier.

Fig. 5-11. Elements of Selenium Rectifier Cell.

In Fig. 5-11A the generalized metallic rectifier as exemplified by the selenium type is specified. The forward direction as defined in the foregoing is also shown. In Fig. 5-11B the electrical symbol for this rectifier cell is shown. The arrow points toward the forward direction; however, when the cell is used as a half-wave rectifier the rectification polarities are as shown here. (Refer to Chapter 3.) In Fig. 5-11C a sketch is given to show how the selenium cell may be assembled into a practical half-wave rectifier.

Volt-Ampere Characteristics

The principal function of a rectifier cell is to freely pass current in one direction (forward) while blocking or greatly limiting its passage in the opposite direction (reverse). If the rectifier cell freely passes current in the forward direction, this implies that the resistance to current flow in this direction is low; hence, the resulting forward voltage drop across the cell must also be low. If the current in the reverse direction is blocked or held to a minimum value, the reverse resistance must be large; hence, the voltage drop across the cell for the reverse direction of current flow must be large. The maximum value of reverse voltage drop is limited by the breakdown potential of the barrier layer of the cell.

Pursuing these thoughts further may lead to saying that a quality of merit for a rectifier cell may be considered to be a low voltage drop across the cell in the forward direction, and, in the reverse direction, a minimum leakage current. From this thought it can be understood that the volt-ampere curves of a metallic rectifier cell are essential, if an intelligent appraisal of the cell is to be made, for the volt-ampere curves present in graphical form the above described information. These curves are obtained by applying a DC voltage to the rectifier cell and observing, without delay, the corresponding current flow. The tabulated results from these observations are then plotted to produce the volt-ampere curves.

The volt-ampere curves for a selenium rectifier cell are shown in Fig. 5-12. The characteristics of the cell shown here are identified as static characteristics since all the values are measured by DC meters. See Chapter 2 for the technique employed in these measurements. Moreover, the curves are designated as typical characteristics for a selenium rectifier cell because such characteristics for the cell are not fixed but are dependent upon temperature, life of cell, and past history. Furthermore, even cells of the same age and history (same production run) may have considerable variation from the typical volt-ampere characteristic curves shown.

For the curves (forward and reverse) shown in Fig. 5-12 the horizontal axis is graduated in positive and negative volts corresponding to the forward and reverse potentials. The vertical axis or the ordinate is graduated in hundreds of milliamperes per square inch above the horizontal axis to correspond with the forward current; below the horizontal axis the ordinate is graduated in milliamperes per square inch to correspond to the leakage current. These current values are approximate and are based on a rectifier cell having an effective area of one square inch and operating at a temperature of 25 degrees Centigrade (about 77 degrees Fahrenheit).

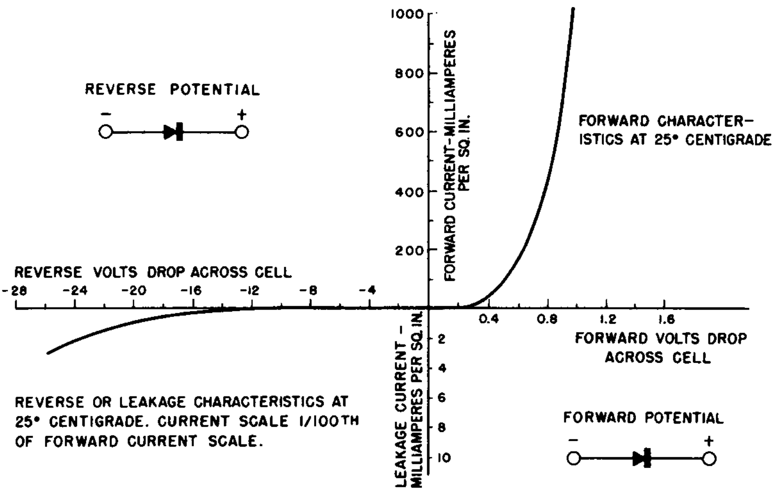


Fig. 5-12. Volt-Ampere Characteristic of a Selenium Rectifier Cell at 25 degrees Centigrade.

Plotting the ordinate of these curves in milliamperes per square inch makes the characteristics representative for all sizes of selenium rectifier cells. The lower current scale has been multiplied by a factor of 100 times the upper current scale, since the reverse current is usually so much smaller than the forward current that this scale enlargement is necessary to enable comparison of the forward and reverse properties of the cell.

The normal current loading in the forward direction for the naturally-cooled selenium rectifier cell is about 250 milliamperes per square inch, corresponding to a forward potential drop across the cell of about 0.6 volt DC at an operating temperature of 25 degrees Centigrade. Much higher current loadings can be obtained by the employment of fins, artifical cooling, or a combination.

In the reverse direction the maximum working voltage commercially employed at present (1956) is 26 volts rms. One manufacturer, however, advertises cell ratings of 33 volts rms. At an applied voltage of 26 volts rms, the leakage current is approximately 3 milliamperes per square inch at an operating temperature of 25 degrees Centigrade.

The volt-ampere curve for the reverse direction is the characteristic which requires prompt observation during the experimental run. The reason for this is that this characteristic is materially affected by the degree of formation that exists in the cell before the experimental run; it is also affected by any additional forming that may occur while the curve is being obtained.

Temperature Characteristics

The selenium rectifier cell has a negative temperature coefficient in the forward direction; that is, as the cell temper-

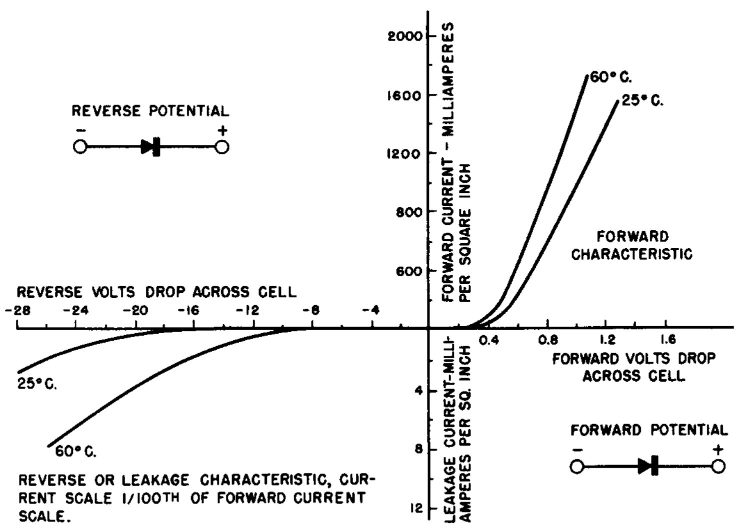


Fig. 5-13. Effect of Temperature on the Volt-Ampere Characteristic of a Selenium Rectifier Cell.

ature is increased the forward resistance decreases. Hence, for the same voltage drop across the rectifier cell the forward current increases as the cell temperature increases. The relationship between cell current versus cell voltage in the forward direction, for two cell temperatures as parameters, is presented in Fig. 5-13. These are static characteristics for a selenium rectifier cell having unit area of one square inch. Note, for example, that at 1.0 volt drop across the cell the forward current at 25 degrees Centigrade is about 1000 milliamperes per square inch, while at a cell temperature of 60 degrees Centigrade the forward current for the same voltage drop is 1400 milliamperes per square inch. This clearly illustrates the negative temperature coefficient of the selenium rectifier cell in the forward direction.

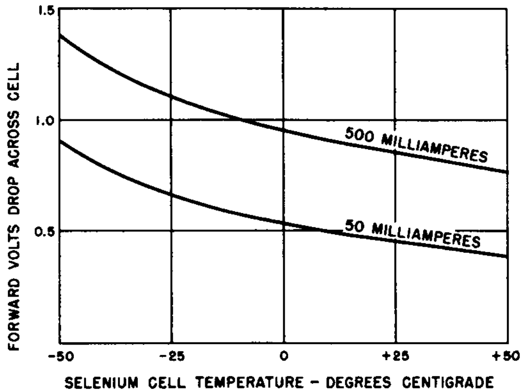


Fig. 5-14. Temperature Characteristics of the Selenium Rectifier Cell.

Another way to present the effect of temperature on the selenium rectifier cell is illustrated by Fig. 5-14. This graph represents the voltage drop across the rectifier cell versus cell temperatures for two values of constant current in the forward direction. Again, it can be seen from this that the forward resistance of the selenium cell decreases as the cell temperature increases.

The net result of temperature on the selenium rectifier cell in the reverse direction is also given in Fig. 5-13. For example, the leakage current at minus 20 volts is greater at 60 degrees Centigrade than at 25 degrees Centigrade. However, the effect on the reverse resistance due to the temperature is not quite as simple as that described for the forward resistance. Whether the temperature coefficient is negative, positive, or constant is dependent upon the applied reverse voltage and cell temperature. Refer to Fig. 5-15; note that, for an applied reverse voltage of 18 volts to the selenium rectifier cell, the leakage current is almost constant over the temperature range of minus 50 to plus 75 degrees Centigrade. This is a desirable property as the heating due to the leakage current is less at the higher operating temperature.

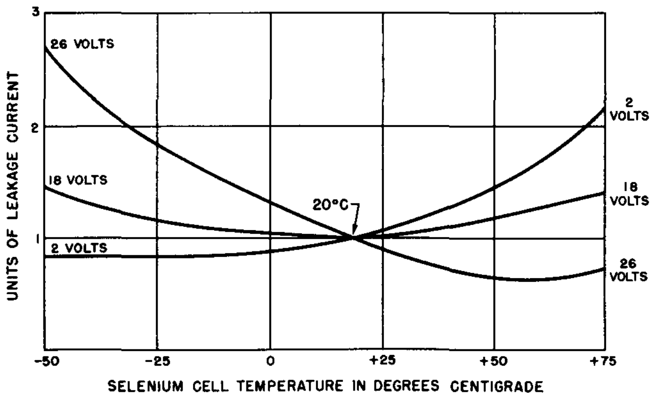


Fig. 5-15. Leakage Current versus Cell Temperature for Rated and Reduced Applied Voltages.

For an applied reverse voltage of 2 volts to the selenium rectifier cell the temperature coefficient becomes positive in the temperature range of 0 to plus 75 degrees Centigrade. This 2 volt operating voltage is, of course, not practical but the curve is presented to illustrate the complicated nature of the reverse resistance characteristic with temperature.

For a reverse voltage of 26 volts applied to the selenium rectifier cell, its rated voltage, the temperature coefficient is essentially negative over the whole temperature range showing an increase of leakage current for a decrease in temperature and a dĕcrease in current for an increase in cell temperature.

In practical rectifier circuits these resistance changes in either the forward or reverse direction are of little importance as the resistance of the rectifier is only a small part of the total circuit resistance (about 1/10th), so the effect of the temperature change on the rectified output is quite small.

Voltage-Resistance Characteristics

A satisfactory metallic rectifier cell must present a very low resistance to the passage of electrical current in the forward direction and a very high resistance to current flow in the reverse direction. The perfect metallic rectifier has zero resistance in the forward direction and infinite resistance in the reverse direction. This perfection has not been achieved in metallic rectifier cells; all commercial metallic rectifiers have some resistance in the forward direction and the resistance in the reverse direction is not infinite. The greater the ratio of the reverse to the forward resistance, the better the electrical performance of the rectifier cell.

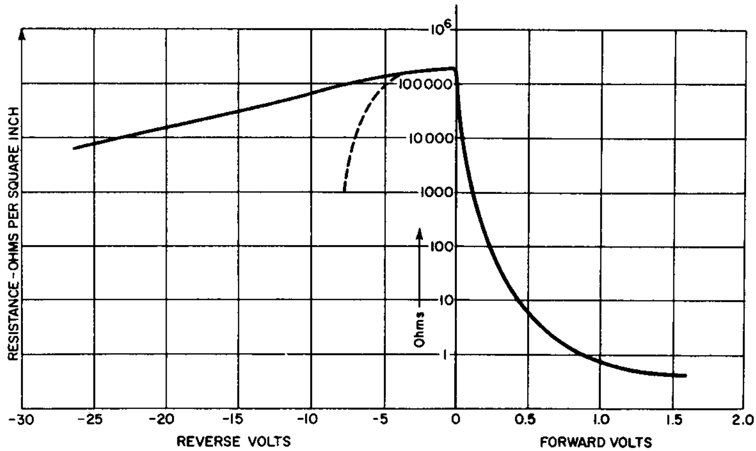


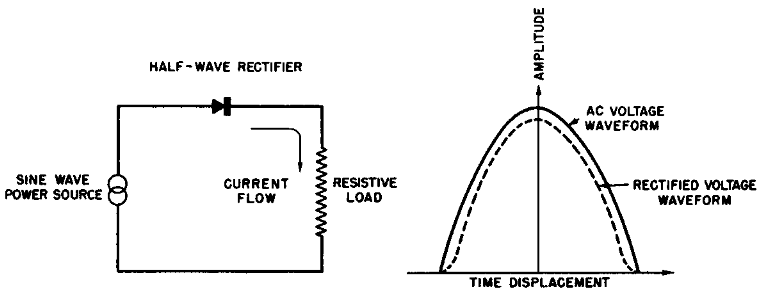
Fig. 5-16. Static Resistance Curve for Selenium Rectifier Cell.

In the selenium rectifier cell the forward and reverse resistance is not fixed or linear but varies with the magnitude of the applied potential. Refer to Fig. 5-16; this is the graphical presentation of the resistance of a unit area of a selenium rectifier cell versus the various applied potentials in the forward and reverse directions. The horizontal axis of this graph is graduated in positive and negative voltage increments representing the forward and reverse applied potentials respectively. The vertical axis or the ordinate of the graph is graduated in ohms in logarithmic increments because the resistance range is too great to otherwise properly display the resistance change.

The information displayed in Fig. 5-16 is obtained at an operating temperature of 25 degrees Centigrade for a selenium rectifier cell having an effective area of one square inch. It can be observed from this voltage-resistance graph that the cell has a finite resistance value of about 150,000 ohms. As the applied voltage is increased in the forward direction, the cell resistance decreases rapidly at first up to an applied voltage of one volt, after which the resistance tends maintain a constant, low value.

As the applied voltage is increased in the reverse direction, the cell resistance also decreases but much more slowly — if the applied voltage is kept within the cell's rating. Within the cell's voltage limits the reverse resistance curve is approximately logarithmic.

The graph of Fig. 5-16 applies to a selenium rectifier cell of unit area in which the reverse resistance has been previously formed electrically in the manner discussed previously. If the selenium rectifier cell has not been electrically formed, its reverse resistance will not be large nor will its barrier layer withstand as large an applied reverse voltage. Such an unformed rectifier cell has a reverse resistance which substantially follows the graph of Fig. 5-16 until the reverse resistance reaches 3 or 4 volts; beyond that voltage the reverse resistance falls off very sharply, as shown by the dotted curve in the reverse resistance section of the graph.



(A) Half-Wave Rectifier Circuit.

(B) Voltage Waveform Across Resistive Load.

Fig. 5-17. Waveform Distortion Due to Resistance Change of Selenium Rectifier Cell.

Oddities in the operation of a metallic rectifier, such as the selenium rectifier cell, are caused by the fact that the resistance of the cell is not constant but decreases as the current through the cell increases. A good example of an operational oddity is illustratéd by the Fig. 5-17. In Fig. 5-17A an AC power source, having a sinusoidal voltage waveform is applied to the series combination of a selenium rectifier cell (half-wave rectifier) and a pure resistive load (no inductive component). The voltage developed across the resistive load is not a rectified sine wave because the voltage drop across the rectifier cell will be relatively greater when the current flow through the cell is small than when it is at its rated maximum. This is shown in Fig. 5-17B. Here the solid curve represents the applied voltage of sinusoidal waveform; the dotted curve represents the rectified voltage drop developed across the load as a result of current flow through the rectifier cell. The effect of the non-linear resistance of the rectifier cell is to change the form factor of the voltage waveform across the load from its theoretical value of 1.11 to about 1.15. Form factor is defined as the ratio between the rms and the average value of a waveform. The form factor of a sine wave is 1.11.

Voltage Rating of the Cell

Voltage rating of a rectifier cell is defined as the root-mean-square value of the AC voltage applied to the cell. Selenium rectifier cells are presently operated at 26 volts rms, although one manufacturer advertises cell ratings of 33 volts rms.

If the selenium rectifier voltage rating is taken as a criterion, the rate of developmental improvement of this type metallic rectifier is quite phenomenal. After World War II, these rectifiers were being marketed at 18 volts rms per cell. In less than five years the rated voltage was pushed up to 26 volts rms, and the end is not yet in sight.

The voltage rating is based on an ambient temperature of 35 degrees Centigrade. Voltage ratings are derated above ambient temperatures of 50 degrees Centigrade (122 degrees Fahrenheit).

Current Rating of the Cell

The current rating of a metallic rectifier cell is the maximum current that may be passed through it in the forward or low resistance direction within the cell's thermal rating. This current is expressed as the average DC amperes as read on a D'Arsonval type ammeter. For the selenium rectifier cell the current rating is about 250 milliamperes per square inch at 35 degrees Centigrade for a self-cooled stack (no fins or artificial cooling). Above an ambient of 35 degrees Centigrade the current rating must be derated.

Current rating is, of course, dependent upon stack design and upon the cooling methods employed. With forced cooling in a 35 degree Centigrade ambient temperature, it is regular practice to operate selenium rectifiers up to 250% of normal rating or about 650 milliamperes per square inch.

Voltage Regulation

Since the selenium rectifier cell is essentially a resistive device, it has a property described as voltage regulation. Voltage regulation is defined as the ratio of the difference between the output voltage at no load and full load to the full load output voltage — expressed in percent. (Refer to Chapter 4.) The difference between the no load and full load voltage is the potential drop across the selenium rectifier in the forward direction occasioned by the cell's forward resistance. Thus, the voltage regulation of the selenium rectifier cell is a function of its forward resistance. If was found previously in this chapter that the selenium rectifier possesses a non-linear forward resistance, that is, the cell's forward resistance decreases as the forward current through it increases. This property partially counter-balances the increase in voltage drop across the rectifier cell as the load through the cell increases, resulting in a forward voltage drop which remains practically constant and low over a wide range of load current.

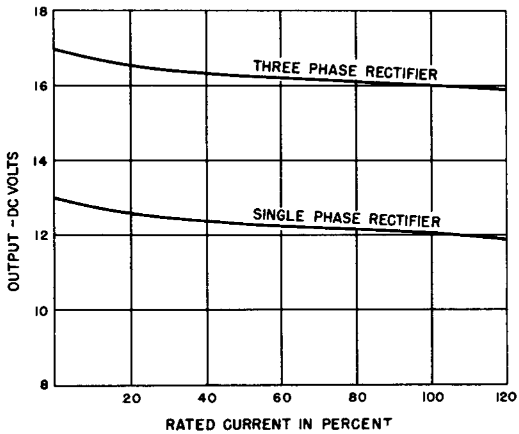


Fig. 5-18. Voltage Regulation Curves for Selenium Rectifier Cell for Single-and Three-Phase Circuit Feeding Resistive Load.

At full rated output and at normal temperature (35 degrees Centigrade) the voltage regulation of the selenium rectifier feeding a resistive load is 10 to 15 percent. About half of the output voltage regulation occurs from zero to 20 percent load; this makes possible good regulation of 5 to 10 percent over 80 percent of the load range.

If the voltage regulation requirements are critical, then the rectifier can be selected so that normal operation is secured between 20 and 100 percent load. This can be done by

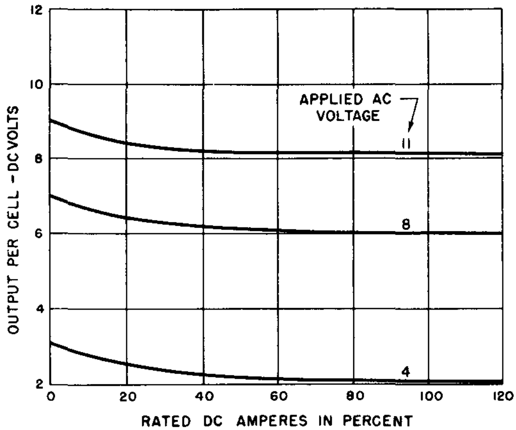


Fig. 5-19. Voltage Regulation of Single-Phase, Selenium, Bridge-Rectifier on Resistive Load.

obtaining a rectifier for the application, having the proper electrical capacity so that the minimum load on the rectifier

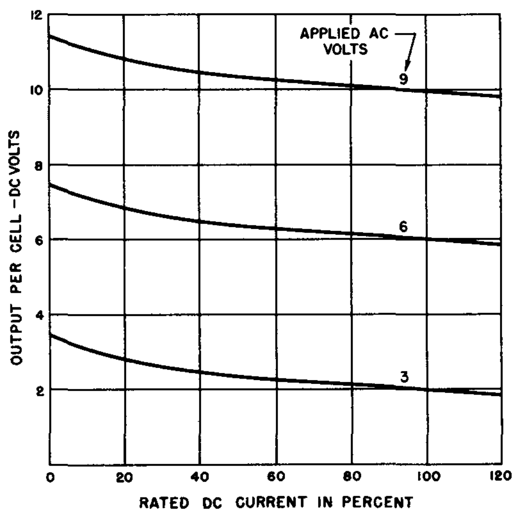


Fig. 5-20. Voltage Regulation of Single-Phase, Selenium, Bridge-Rectifier on Battery Load.

will be about 20 percent. If the minimum load is below 20 percent and close voltage regulation is necessary, the minimum load may be artificially boosted by an auxiliary constant load.

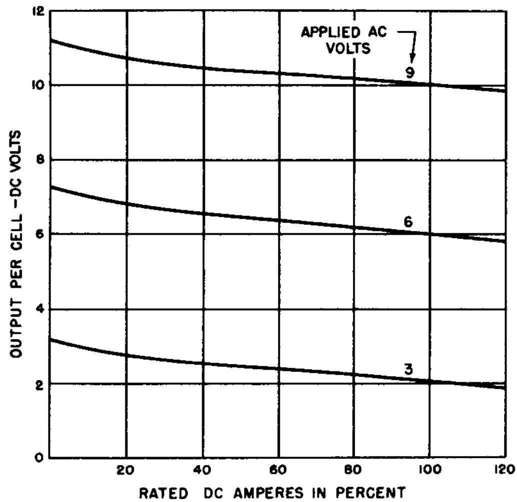


Fig. 5-21. Voltage Regulation of Three-Phase, Selenium, Bridge-Rectifier on Resistive Load.

Fig. 5-18 displays the voltage regulation curve for a selenium rectifier cell on single and three-phase circuit. Extended loading is used to clearly show the flatness of the regulation beyond the 20 percent load.

Fig. 5-19 presents the voltage regulation curves for a single-phase selenium bridge rectifier feeding a resistive load. Three different values of applied AC input voltages are shown.

Fig. 5-20 gives the voltage regulation curves for the same rectifier feeding a battery load.

Fig. 5-21 illustrates the voltage regulation of a three-phase bridge rectifier feeding a resistive load. The three curves represent three different values of AC voltage applied per cell. The voltage regulation of a three-phase rectifier on battery load is so close to that of the resistance load of Fig. 5-21, that this graph can be used for either type of loading.

With an inductive load, the regulation is dependent on the ratio of inductance to resistance and is generally higher than with a resistance load. In the case of the three-phase circuit the regulation is about 10% regardless of the type of load.

Efficiency

The selenium rectifier is a resistive device at power frequencies and so has electrical losses in operation which make 100 percent efficiency impossible. The efficiency of the selenium rectifier is a function of its combined losses — that due to the forward and the leakage currents. In the form of an equation the efficiency may be expressed as:

$$\text{Efficiency in \%} = \frac{\text{DC output volts x DC output current}}{\text{DC output volts x DC output current} + W_F + W_R}$$

where

W_F = loss in watts due to forward current.
W_R = loss in watts due to leakage current.

These electrical losses in the forward and reverse direction are the I^2R losses in the forward and reverse direction.

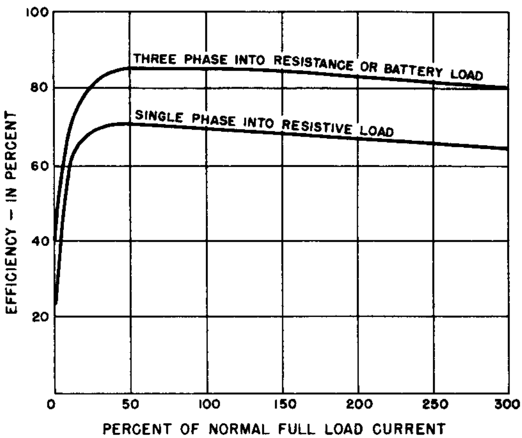


Fig. 5-22. Typical Efficiency Curves of a 26 Volt Selenium Rectifier Cell Operating at Full Voltage.

The loss associated to the reverse direction is practically constant if the applied voltage is constant. The loss in the forward direction behaves in a pecular manner resulting in high and constant efficiency for rectifier loadings from 20% to 100% of full load. This constant, maximum efficiency over the wide range results because of the non-linear variation of the forward resistance with current in the selenium rectifier.

Because of this, the forward electrical losses do not increase in direct proportion to the square of the forward current, as would be the case if the rectifier were a linear resistance device. It is correct that the forward electrical losses of the selenium rectifier are still equal to I^2R, but R (the forward resistance) decreases with increasing forward current causing the product I^2R (representing the forward electrical losses) to increase at a diminishing rate. Thus, the efficiency remains practically constant over the wide range of 20% to 100% of full load.

Fig. 5-22 shows the efficiency performance of the selenium rectifier operating at full voltage. The lower curve is that of a rectifier feeding a resistive load and operating from a single-phase circuit. The upper curve is that of a selenium rectifier feeding either a resistive load or a battery charging load and operating from a three-phase circuit. In the first case the efficiency is 65 to 70% over the wide range of 20 to 300% of full load current. In the second case the efficiency is 80 to 85% for the same wide range. The selenium rectifiers used to obtain these curves had normally spaced stacks. The 100% or normal full load current is the rated current for a rectifier assembled with such standard cell spacing.

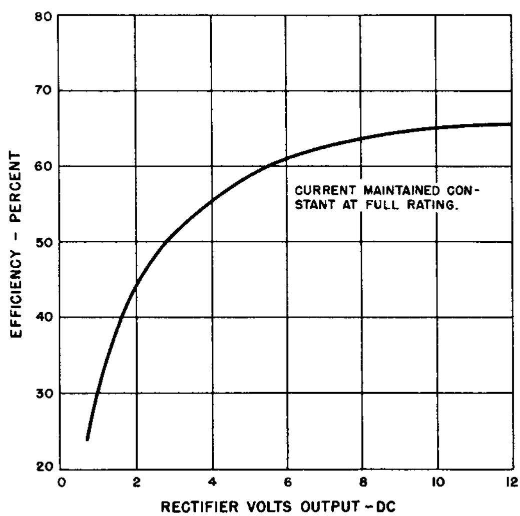


Fig. 5-23. The Efficiency of a Single-Phase Selenium Rectifier is a function of Output Voltage and Current.

Increasing the cell spacing on the rectifier stack or adding cooling fins to the stack permits increasing the amount of current that the rectifier will carry for the same temperature rise. The continuous duty rating for stacks which employ extra spaced cells or cooling fins may be increased up to 250% of the normal full load current rating.

As can be seen from the efficiency curves of Fig. 5-22, the main effect of increased current over the 100% full load condition is a reduction of the efficiency and also poorer voltage regulation.

Statements concerning efficiency should specify the particular voltage and current at which the rectifier is operating. For example, Fig. 5-23 shows the change in efficiency that takes place as the output voltage is varied and the current load maintained at 100%.

In general, a single-phase full wave rectifier operating into a resistive load will have an efficiency at rated output of 60 to 70 percent. In a similar circuit with a battery charging load, the efficiency will be from 70 to 75 percent. In three-phase operation, efficiencies of 85% can be obtained at full rated output for either a resistive or battery charging load.

Power Factor

Power factor, defined as the ratio in percent of the AC watts input to the product of the AC volt-ampere input, is practically unity for the selenium rectifier when it is used on low frequency power sources, such as commercial power lines. When the selenium rectifier is used in a commercial power circuit, the overall power factor will be determined by other equipment associated with the rectifier. For example, if the selenium rectifier is used with a line-isolating or step-down transformer and feeds a resistive load or a battery on charge, the power factor is usually 90 to 95% or better.

At higher frequencies the inherent shunting capacitance of the rectifier cells alters the power factor to something less than unity — the exact value being a function of the applied frequency and the associated load of the rectifier. This reduction of the power factor for the selenium rectifier becomes predominant for frequencies greater than 1000 to 2000 cycles per second.

Frequency Characteristic

The selenium rectifier cell was described previously in this chapter as comprising two electrodes separated by a semiconductor and a barrier or insulating layer. This causes an inherent capacitance effect for the rectifier cell which becomes apparent at high frequencies. This capacitance of the rectifier cell is similar in its behavior to a small physical capacitor shunted across the perfect rectifier cell. The adverse effect of the capacitance across the rectifier cell is to reduce the reverse impedance. The exact value of this capacitance is a function of the area of the rectifier cell and is roughly 0.1 microfarad per square inch. The value of the capacitance is not constant for a particular cell but depends upon the applied polarizing voltage.

The chief limitation due to this inherent capacitance of the selenium rectifier cell is to restrict the rated characteristics to frequencies below 1000 to 2000 cycles per second.

If selenium rectifiers are required for operation above 2000 cycles per second, they must be especially processed to reduce the shunting capacitance discussed above. The most effective method to reduce the shunting capacitance is to reduce the rectifier cell area. To achieve an economical method of manufacturing small area selenium rectifier cells, small discs are punched from large sheets which are coated with selenium, heat treated, and have the small diameter front electrodes properly masked concentric to the proposed punched area. These small discs are then assembled into an insulated tube and spring-loaded to maintain the proper pressure upon the discs. Though this type of construction completely encloses the rectifier cells, the heat radiating surface is large in contrast to the effective working area of the cell resulting in a rated current density (amperes per square inch) which is larger than for the open construction described. Of course, the working voltage per cell remains the same. The enclosed type of construction also makes possible compact rectifier assemblies for high voltage application.

Effect of Idleness and Speed of Operation

The barrier layer in the selenium rectifier cell is electrically formed. This forming is part of the manufacturing process and commercial rectifiers are completely formed before being sold to the consumer. In use, the formation of the barrier is continually maintained by the normal applied voltage. In periods of idleness, when no voltage is applied to the rectifier, some degree of formation is lost or the rectifier becomes partially unformed. Upon application of the voltage, however, reforming occurs; this process is normally completed within one or two seconds. The only noticeable effect in operation during this reforming process is a transient increase in leakage current due to the less effective barrier layer resulting from idleness. This transient has no significant effect on the rectifier output.

The speed of operation of the selenium rectifier is instantaneous. A DC output is instantly available as soon as the AC power is applied to the input of the rectifier.

Aging and Life

The operation of a selenium rectifier is considered to be electronic in character and, as long as it is operated within its voltage, current, and temperature ratings, its life is stated to be indefinite. In commercial circles such rectifiers have been tested under many conditions for tens of thousands of hours. Moreover, in practice, many practical applications of the selenium rectifier have exhibited more than twelve years of trouble-free operation. It is true that if the rectifier has been idle for some time it may show a slight loss of rectification efficiency when the AC power is first applied. Its original electrical ratings are restored within a few seconds after the AC power is applied due to the reforming of the blocking layer.

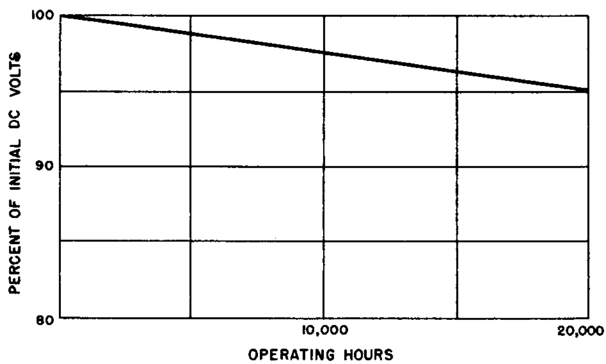


Fig. 5-24. Aging Characteristics of Selenium Rectifiers.

Fig. 5-24 shows a representative selenium rectifier performance aging curve with respect to hours of operation, for a number of rectifier stacks. The rectifier stacks under the test were single-phase bridges feeding resistive loads. An ambient temperature of 35 degrees Centigrade and the electrical ratings of the rectifier stacks were maintained during the tests.

It will be noted that the DC voltage output at the end of twenty thousand hours was about 95% of the initial value. This decrease in output voltage with hours of operation is due to a small increase in the forward and reverse resistance. The increase in the forward resistance, of course, decreases the output voltage; the increase in the reverse resistance improves the rectifier characteristics. If it is necessary to maintain the output voltage constant, then some means to compensate for the increased forward resistance must be provided. One means to accomplish this is to provide additional increments of AC voltage input by having available taps on the supply transformer.

In general, then, selenium rectifiers tend to show a small decrease in the output voltage due to an increase in the forward resistance. This increase of the forward resistance is not progressive but stabilizes after 10,000 to 20,000 hours of continuous service and the net decrease of the output voltage is of the order of 5 to 10%, if the rectifier is kept within its temperature and electrical ratings. The actual time required to reach full stability is a function of electrical loading, the temperature of operation, the circuit type, the duty cycle, or a combination of these factors. Idle rectifiers do not exhibit an appreciable aging effect.

Threshold Voltage

Fig. 5-25 represents the static forward characteristics of a selenium rectifier cell operating at an ambient temperature of 35 degrees Centigrade. It will be noted that approximately 0.4 volt DC must be applied before forward current is observed. Under dynamic conditions, that is, with the cell operating as a half wave rectifier with an AC input voltage, approximately 0.3 volt rms must be applied before forward current is detected in the rectifier load circuit. Thus, the threshold voltage of the selenium rectifier cell is of the order of 0.3 to 0.4 volt depending upon temperature and circuit conditions.

Operating Temperature and Derating

The electrical ratings of a selenium rectifier are specified at an ambient temperature of 35 degrees Centigrade. Selenium rectifiers are capable of operation over a wide range of temperatures — at a reduction of efficiency and electrical ratings. Over the temperature range of minus 40 to plus 70 degrees Centigrade the percent change in output voltage is held to less than 10%.

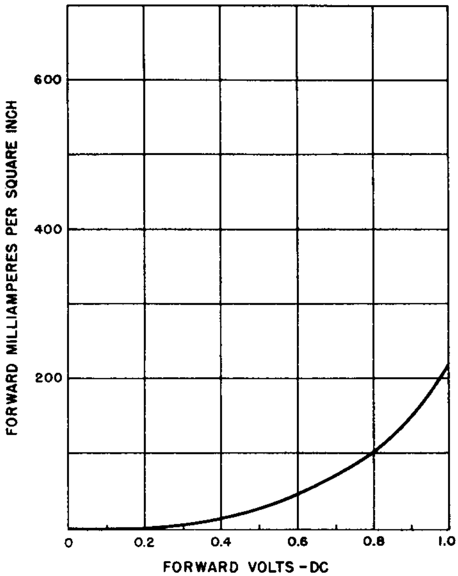


Fig. 5-25. Static Forward Characteristic of a 26 Volt Selenium Rectifier Cell.

At low temperature operation the forward resistance is increased resulting in a diminishing of output voltage and efficiency. The increase of losses at low temperatures is partly offset by the heat generated in the unit which increases the temperature above the ambient temperature. Selenium rectifiers have been experimentally operated at temperatures as low as minus 65 degrees Centigrade (minus 85 degrees Fahrenheit); after this exposure the forward resistance is permanently increased by 25% and the efficiency at this low temperature is 13% less than at 25 degrees Centigrade.

At the high end of the temperature range, that is, above an ambient of 35 degrees Centigrade, the selenium rectifier cannot be operated at its normal ratings. The output must be decreased in either voltage, current, or both. A typical derating curve for high-temperature operation is given in Fig. 5-26.

To operate in an ambient temperature above 35 degrees Centigrade, the rectifier losses must be reduced so that the safe operating temperature is not exceeded. If the applied voltage is reduced, the reduced leakage losses may permit an increased forward current at an operating temperature above

35 degrees Centigrade. The jags in the current curve of Fig. 5-26 represent this option — for example, if the applied AC voltage to the selenium rectifier is reduced 20% at 50 degrees Centigrade, the current rating may be increased about 5% over the normally diminishing current rating.

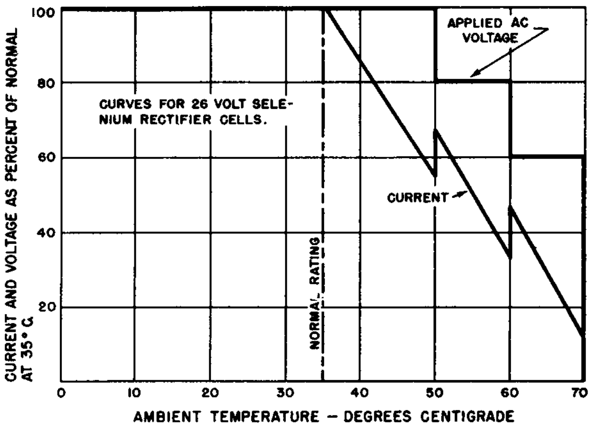


Fig. 5-26. Current and Voltage Derating Curves to Maintain Constant Operating Temperature for Ambients above 35 Degrees Centigrade.

At an ambient of about 75 degrees Centigrade the average selenium rectifier is derated to zero. The derating curve is based on continuous duty. Better ratings at higher temperatures can be obtained for intermittent operation, the value of these ratings being dependent upon duty cycle.

Ambient Conditions Other Than Temperature

Selenium rectifiers, like most electrical equipment, are sensitive to corrosive dust, moisture, fumes, and tropical conditions. Generally, insulating varnishes protect the rectifier from moisture and dust. Fungus treatment protects it from tropical conditions; and special multiple-layer finishes protect it from mercury vapor, against which the selenium rectifier is particularly weak. One manufacturer of selenium rectifiers warns his customers not to use or store selenium rectifiers where mercury vapor is present.

Future Outlook

Selenium rectifiers were introduced with cell ratings of about 14 volts rms. In less than five years this voltage rating was increased to 26 volts rms. The present effort is to increase the voltage rating to much higher levels of the order of 50 to 70 volts per cell. On a laboratory basis, cells have been developed that operate at 70 volts rms. Besides trying to improve the voltage rating, effort is being expended to extend the upper temperature rating from 70 to 75 degrees Centigrade to 125 to 150 degrees Centigrade. Here the limitation will be the softening temperature of the selenium semiconductor.

CHAPTER 6

The Magnesium-Copper Sulfide Rectifier

Introduction

The next type of metallic rectifier to be discussed in this book is the magnesium-copper sulfide rectifier. This type in conjunction with the other two types (copper-oxide and selenium) already discussed have, up to the present time, serviced the bulk of the rectifier applications in the United States.

The magnesium-copper sulfide rectifier is not as widely used as the copper-oxide or the selenium rectifiers already described, but it has several important properties which has kept it in demand. First of all, it is the only commercial rectifier that will operate successfully above 200 degrees Centigrade. The second desirable property is its current rating. As an example: for design purposes selenium and copper-oxide rectifiers are considered to have a current of less than one ampere per square inch, while the magnesium-copper sulfide rectifier is rated at 35 amperes per square inch.

It appears from a study of the patent literature that the magnesium-copper sulfide rectifier also had an early beginning. It would be extremely interesting to determine whom to credit with the invention of the first metallic rectifier and to learn the rectifier type. It seems that the copper-oxide and the magnesium-copper sulfide rectifiers were developed concurrently. For example, United States Patents numbered 1,649,741, 1,649,742, 1,649,743, 1,649,744, 1,723,525, and 1,751,359, all issued to Samuel Ruben, clearly outline the magnesium-copper sulfide type of rectifier. The first patent of the above list has an application file date of September 27, 1924, whereas the last number has an application file date of August 20, 1925.

From a study of the trade literature it appears that Samuel Ruben's magnesium-copper sulfide rectifier patents are implemented chiefly by P. R. Mallory Company of Indianapolis, Indiana, for this is the principal source of this type of rectifier. The second, and only other source for the magnesium-copper sulfide rectifiers is Electronic Rectifiers, Inc., also of Indianapolis.

Production

The principal components of a magnesium-copper sulfide rectifier cell, before electroforming, are a magnesium or magnesium alloy plate or disc having a slightly oxidized active surface and a cupric sulfide plate or disc. Rectification can be secured by placing these two plates in contact with each other; however, stable and dependable rectification characteristics demand bonding between the two electrodes which can be obtained by the electroforming process to be described.

Magnesium as the base plate metal has the advantage of good electrical conductivity as an electrode and it helps form a barrier layer of limited thickness. In manufacturing the magnesium-copper sulfide cells, the magnesium is processed in strip form and then the washers or plates are punched from this strip and prepared for assembly with the copper sulfide elements.

The copper sulfide as the front electrode also possesses the advantage of good electrical conductivity; it also has a low temperature coefficient for its resistance and supplies one of the components for the formation of the barrier and semiconductor layers integral with the front and base electrodes.

The barrier and semiconductor layers are formed electrically by the interfacial reaction of the above two electrodes. Thus, the actual physical materials which are required to produce the magnesium-copper sulfide cells are a pure magnesium disc or plate as the base metal and a pure and dense cupric sulfide disc for the front electrode.

Besides these physical requirements for the production of magnesium-copper sulfide cells, it is necessary that the magnesium disc or plate have on its active surface a very superficial layer of oxide; this is required so as to limit the initial electroformation currents to small areas reducing the heating, electric arcing, and the electrical energy which would be required if the entire cell junction were formed simultaneously.

The superficial oxide film upon the active surface of the magnesium electrode may be produced electrochemically or may be formed by treating the magnesium with a chemical solution; the film should possess a voltage breakdown characteristic of a few volts (about 4 volts), the exact value being somewhat critical.

The cupric sulfide disc must also be chemically pure to produce a stable rectifier cell; moreover, since it must have a smooth surface to assure a good mechanical contacting area with the magnesium electrode for the electroforming operation, it must have great mechanical strength to withstand the grinding operation necessary to achieve this smooth surface.

Sulfide discs processed from pure copper are not satisfactory because they are too soft and fragile for the grinding operation. In commercial practice the copper sulfide element of the magnesium-copper sulfide rectifier cell is generally formed from a brass disc which possesses about 15% zinc. This brass disc, which is to become the copper sulfide element of the rectifier cell, is treated with liquid sulfur which removes the zinc from the surface of the brass disc leaving on the outer surface of this disc pure cupric sulfide (CuS) and a center of zinc and copper sulfides. Another method used to produce the front electrode consists of exposing the copper or brass discs to sulfur vapor at about 400 degrees Centigrade for various periods of time. By this treatment the copper is converted to either cupric sulfide, CuS, or cuprous sulfide, Cu_2S. Front electrode washers obtained by the sulfiding process are very dense and mechanically strong; they lend themselves to the grinding operation necessary to provide a highly smooth and finished surface for contacting the magnesium element.

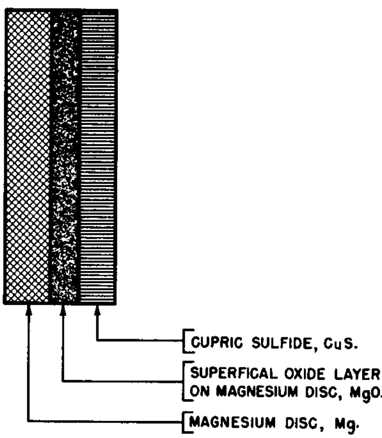


Fig. 6-1. Grossly Exaggerated Cross-Sectional View of Magnesium Disc in Contact with Cupric Sulfide Electrode Previous to Electroformation to Produce Magnesium-Copper Sulfide Cell.

To electroform the magnesium-copper sulfide cell, the magnesium and the cupric sulfide electrodes are placed together, either as cells in special forming fixtures or in the ultimate rectifier stack. Fig. 6-1 shows in cross-sectional form the layout of the unformed magnesium-copper sulfide rectifier cell. It can be seen from this figure that the unformed rectifier cell comprises a disc of magnesium, Mg, with a superficial layer of magnesium oxide, MgO, on its active surface adjacent to which is placed the cupric sulfide disc, CuS. Then an alternating voltage is applied to the cell. The peak value of this alternating voltage exceeds the breakdown voltage of the superficial oxide film on the active surface of the magnesium electrode (about 4 volts) and causes a current to flow through the weakest part of the oxide film.

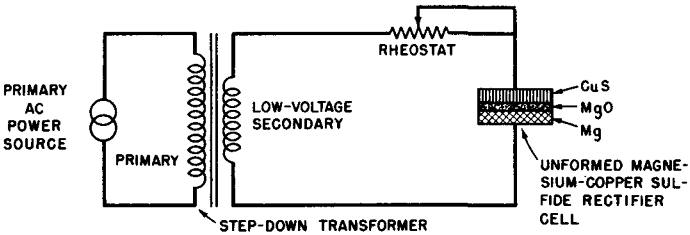


Fig. 6-2. Electrical Circuit Suitable for Electroforming the Magnesium-Copper Sulfide Discs into a Magnesium-Copper Sulfide Cell.

A simple circuit suitable for this process is shown in Fig. 6-2. Here, a primary source of AC electrical energy is reduced in voltage by means of the step-down transformer shown. The secondary of this transformer supplies the unformed magnesium-copper sulfide cell in series with a current-controlling rheostat. This rheostat is adjusted so that the forming current is limited to about 2.5 amperes per square inch of the active cell area.

In each half cycle of the applied AC voltage when the magnesium disc is polarized positive and the cupric sulfide disc negative, that is, when the cell's reverse voltage exceeds the breakdown voltage of the magnesium oxide film, electroformation of the junction takes place. This electroformation continues until all of the magnesium surface of the cell has been converted into magnesium sulfide.

When the electroforming process is completed, the magmesium-copper sulfide cell has a cross-sectional layout as shown in Fig. 6-3. It will be observed that the active surface of the metal base electrode, the magnesium disc, is covered with a layer of magnesium sulfide, MgS, while the cupric sulfide surface layer of the copper sulfide electrode adjacent to the magnesium disc is converted into cuprous sulfide, Cu_2S, and bonded to the magnesium sulfide film which constitutes the rectifier cell's barrier layer. The cuprous sulfide layer is the rectifier cell's semiconductor layer.

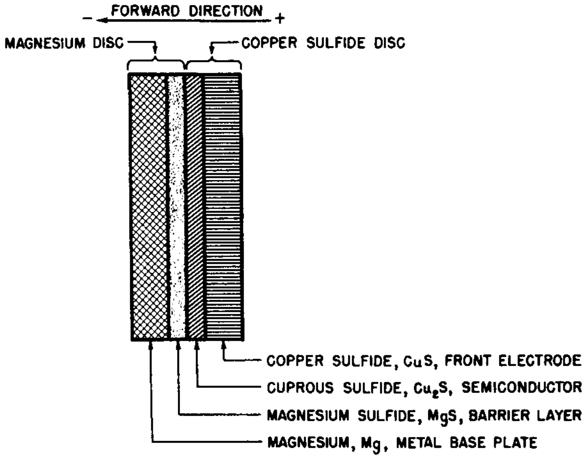


Fig. 6-3. Exaggerated Cross-Sectional View of Magnesium-Copper Sulfide Cell After Electroforming Operation.

The normal operating range of the magnesium-copper sulfide rectifier cell is 3.5 volts and the forming voltage is of the order of 4 to 6 volts. A forming voltage greater than that required to produce the barrier film results in sparking due to the breakdown of the insulating layer of magnesium sulfide and the decomposition of the cuprous sulfide into copper or copper-oxide. This copper-oxide in contact with the magnesium increases the forward resistance and decreases the reverse resistance which increases the leakage current.

The inventor of the magnesium-copper sulfide rectifier, Samuel Ruben, has a concise explanation for the process of the electroformation and his explanation, derived from the "Transactions of the Electrochemical Society", Vol. 87, 1945, page 248, is given below.

"The action that occurs in the process of formation following the initial puncture of the MgO film may be explained as follows: When the cupric sulfide electrode is the negative terminal in the forming circuit, the current flow to it from the contacting magnesium electrode through the localized point area will reach a value where there will be an insufficient number of electrons available from the surface of the cupric sulfide. At this point there is a rise in potential at the sulfide surface, which at a sufficient value causes disruption of the cupric sulfide into cuprous sulfide and a free sulfur ion. Under the influence of the electric field, the sulfur ion combines with the magnesium, forming a polarized layer of magnesium sulfide. As soon as the blocking effect of the reacted area exceeds the breakdown voltage of the superficial MgO layer, adjacent areas puncture and form until the entire junction area is uniformly reacted.

"When the layer of MgS, which integrally bonds the electrodes, is built up to a value at which the potential gradient becomes distributed over it, instead of at the electrode interface, the current decreases to a leakage value and no further increase of the barrier layer thickness occurs. If the potential were to be continuously increased to a point above the critical breakdown voltage of the magnesium sulfide layer, instead of increasing the thickness of the layer, continuous sparking by disruption and oxidation of the electrode surfaces would occur."

From this description it can be understood that the forming operation is somewhat critical and must be done under carefully controlled conditions of cell mechanical pressure, temperature, applied voltage, and current.

At the conclusion of the electroforming process the magnesium and the copper sulfide elements are cemented firmly together by the thin film of magnesium sulfide which is formed from the original elements of the cell under the influence of temperature and the electric current.

Cells electroformed in this manner have the property of asymmetric current conductivity with the electric current flowing more readily from the copper sulfide to the magnesium than in the reverse direction. The thin film of magnesium sulfide serves as the barrier layer of the rectifier cell, the magnesium element serves as the metal base electrode, and the copper sulfide element serves both as a source of sulfur to contribute to the production of the barrier and semiconductor layers and as a front electrode.

Fig. 6-4 is a cross-sectional and front view of a magnesium-copper sulfide rectifier cell. The interfacial details are not repeated — these can be studied in Fig. 6-3. The dimensions which are given are representative of a typical commercial cell rated at 100 amperes maximum DC, when it is used in a single-phase, full-wave bridge circuit. This maximum current rating applies when forced draft cooling employing an air flow of 500 cubic feet per minute is used. For natural convection cooling this cell is rated at 15 to 16 amperes DC. The effective rectifying area of the cell shown is about

2.65 square inches and the thickness dimension given does not include the non-polarizing disc.

The central hole is used for mounting purposes when the cell is assembled into rectifier stacks. The base plate is magnesium or magnesium alloy and in commercial practice it has been found that its thickness may be varied appreciably without altering the rectifying properties of the cell to any great extent.

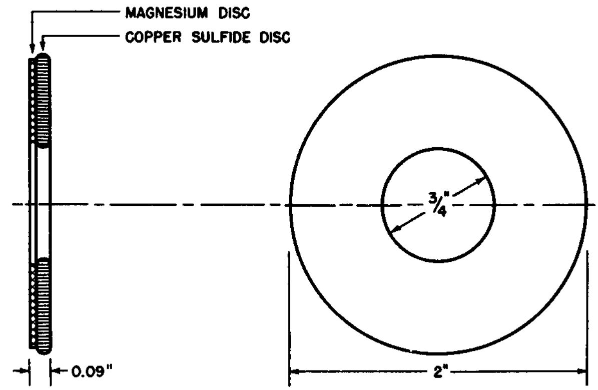


Fig. 6-4. Cross-Sectional and Front View of a Typical Magnesium-Copper Sulfide Rectifier Cell Without Non-Polarizing Disc.

The front electrode of the magnesium-copper sulfide rectifier cell is the copper sulfide disc; however, to maintain the original operating characteristics of the rectifier cell after the electroforming process, it is necessary to employ a counter electrode or non-polarizing contact to engage the inactive surface of the sulfide electrode. The reason for this is that all common metals which might be used to contact the sulfide electrode will sulfide in time under the influence of the cell voltage drop and the chemical effects. Sulfide formation on the surface of the copper sulfide adjacent to the contacting electrode will increase the internal resistance of the rectifier cell and cause polarization which results in a continuous decrease in efficiency. The use of a thin carbonized nickel or iron disc as a counter electrode or non-polarizing electrode eliminates this difficulty and maintains the desired low resistance contact to the copper sulfide disc. Often the front electrical connection to the copper sulfide surface is achieved by contact with the nickel plated surfaces of spacer washers or radiator and terminal plates of the rectifier stack.

Another condition which is required to maintain the original operating characteristics of the magnesium-copper sulfide cell is the exclusion of moisture. Although the cell junction is bonded and electrically stable by virtue of the electroforming process, it is still subject to adverse reactions in the presence of moisture. The combination of MgS and water yields magnesium oxide and hydrogen sulfide which causes progressive blocking off of the effective rectification area by the production of a magnesium oxide layer. This moisture effect is eliminated by the application of several layers of waterproof and heat-resisting varnishes to the entire surface of the rectifier unit and then thoroughly baking the finish.

The forward current flow in the magnesium-copper sulfide cell is in a direction normal to the plane of the cell disc and its magnitude is dependent upon the effective rectifying area of the cell and upon the applied voltage in a manner to be described later in this Chapter.

In commercial practice the magnesium-copper sulfide cell is generally made in disc form and in diameters which range from 1/2 to 2 inches.

Construction

In the practical application of the magnesium-copper sulfide rectifier cells, it is necessary to assemble these cells in the required number and sequence into rectifier stacks in the manner discussed in Chapter 3.

Actually, in the case of the magnesium-copper sulfide rectifiers, the cells may be electroformed either before or after being assembled into stacks. The rectifier stacks are assembled under pressure of about 2500 pounds per square inch upon threaded studs or bolts and consist of the required number of cells and their associated heat dissipating and terminal plates, spacer washers, and non-polarizing discs. These non-polarizing discs are inert conductors, such as carbonized materials or nickel plated spacer washers or radiator plates and terminal plates; the job intended for the non-polarizing discs is to prevent counter rectification at the outer surface of the copper sulfide disc which would decrease the rectifying properties of the cell.

The radiator plates besides providing electrical connection to the cells facilitate cooling of the cells both for convection or forced draft cooling mode of operation.

The necessary components to fabricate a commercial magnesium-copper sulfide rectifier stack are shown in Fig. 6-5. These components are required so as to assemble the individual rectifier cells in series, parallel, or series-parallel arrangements to provide the voltage and current specifications of the stack. As each rectifier is rated at about 3.5 volts rms, it is necessary to assemble the required number of cells upon an insulated and threaded stud or bolt passing through the hole in the center of the cell. The rectifier stack also requires radiator plates, terminal plates, non-polarizing discs or the optional nickel-plated spacer washers, insulators, end washers, spring washers, and assembly nuts.

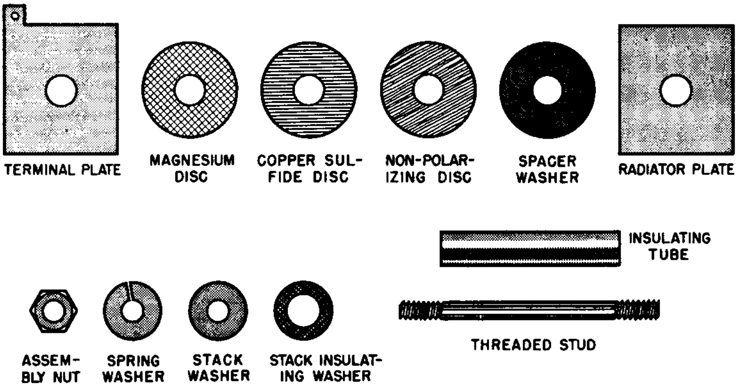


Fig. 6-5. Elements of the Magnesium-Copper Sulfide Rectifier Stack.

In practice, the length of the rectifier stack is limited to about 40 cells — about 10 to 12 inches long. The cells require the processing treatment already described which limits their diameters from a minimum of 1/2 inch to a maximum of 2 inches. Thus, heavy current rectifiers require one or more of the large size cells in parallel and forced draft cooling.

Paralleling of the cells is frequently accomplished on common radiating and terminal plates; or, if desired, separate stack assemblies may be paralleled externally.

Fig. 6-6 illustrates a cutaway view of a single-phase, full-wave bridge rectifier using two magnesium-copper sulfide rectifier cells per leg.

A typical single-phase, full-wave magnesium-copper sulfide bridge rectifier employing the 2 inch diameter cells and operating under forced draft cooling of 500 cubic feet per minute, has the following approximate specifications:

Maximum AC volts rms, no load	10.5
Maximum AC volts rms, loaded	9.75
DC volts at maximum resistive load	4.8

Maximum DC current into resistive load, amperes	100
Maximum DC current into resistive load, convection cooling, amperes	16
Number of cells per leg of bridge	3
Total number of cells in rectifier stack	12
Overall Dimension of stack	4x5x7 inches
Weight of stack	6 1/2 pounds

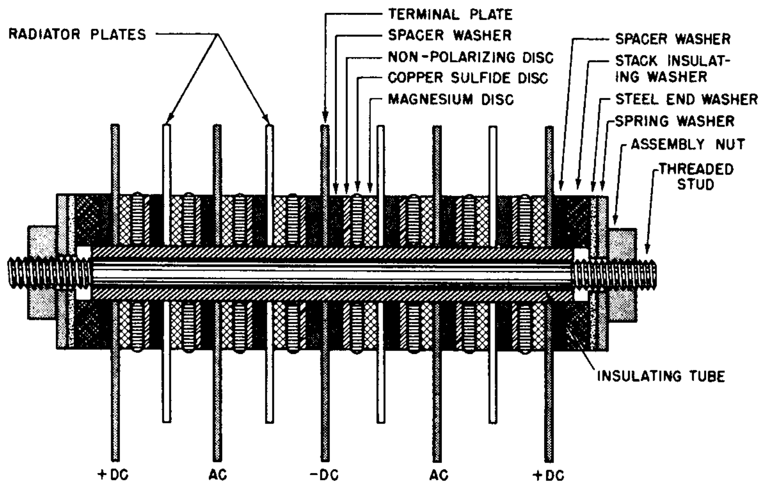
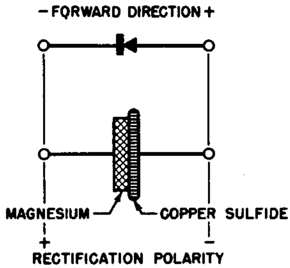


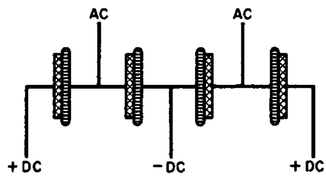
Fig. 6-6. Cutaway View of a Magnesium-Copper Sulfide Bridge Rectifier, Single-Phase, Full-Wave.

As can be seen from Fig. 6-6 the central terminal of the rectifier stack is the negative output connection whereas the two end terminal plates are the positive terminals of the DC output; thus, it is necessary to strap these two terminal plates together to complete the bridge connections. The situation is clarified in schematic form in Fig. 6-7. Fig. 6-7A shows the simplified schematic for the magnesium-copper sulfide rectifier cell, identifying both the forward direction polarity and the rectification polarity as previously defined in this book. Fig. 6-7B shows the magnesium-copper sulfide stack circuit as represented by the physical layout of Fig. 6-6 except that for simplicity only one cell per leg is displayed; and the bridge circuit is completed by strapping the two DC terminals together in Fig. 6-7C. See the dotted line connections.

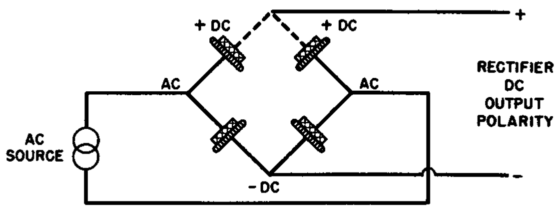
Of course, if it is desirable, there is nothing to prevent the magnesium-copper sulfide cells being so placed upon the stack assembly that the central terminal is positive and the outer terminals, which must be strapped together to complete the rectifier bridge, are negative.



(A) Magnesium-Copper Sulfide Rectifier Cell.



(B) Single-Phase, Full-Wave Bridge Rectifier Without Positive Terminals Strapped Together.



(C) Single-Phase, Full-Wave, Bridge Rectifier With Positive Terminals Strapped Together by Dotted Line.

Fig. 6-7. Schematics of Single-Phase, Full-Wave Magnesium-Copper Sulfide Rectifier.

Elements of the Magnesium-Copper Sulfide Rectifier Cell

Chapter 2, of this book defined the generalized metallic rectifier cell as comprising four elements listed below:

1. Metal base or support plate.
2. Semiconductor layer.
3. Barrier layer.
4. Front or counter electrode.

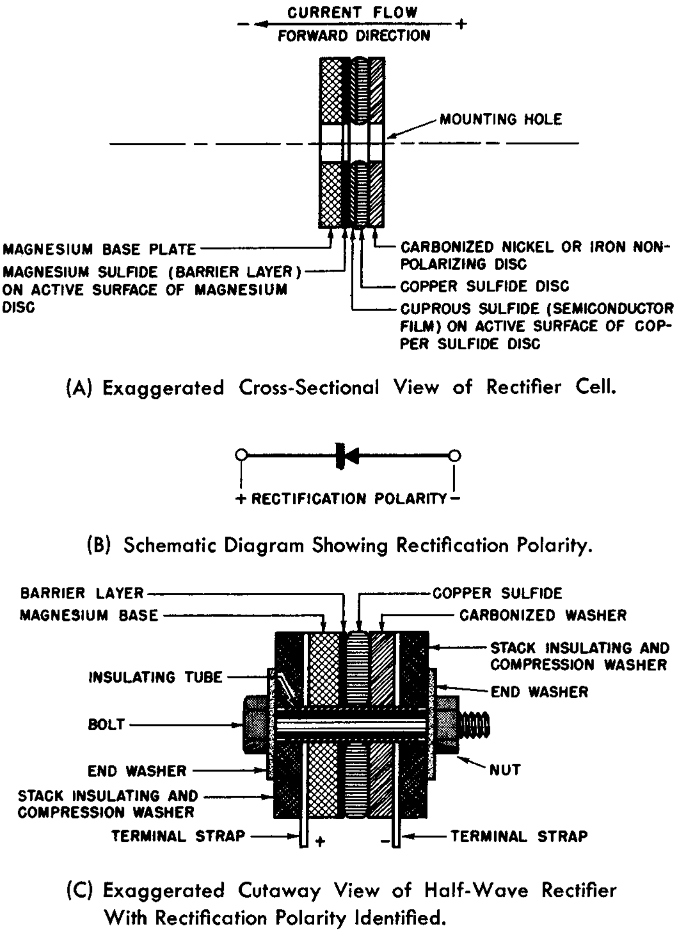
This description of the generalized metallic rectifier cell also applies to the magnesium-copper sulfide rectifier cell discussed in this chapter. By reference to Fig. 6-3, which illustrates the magnesium-copper sulfide rectifier cell after it has been electroformed, it can be seen that the metal base plate here is the magnesium or magnesium alloy disc or plate. The semiconductor layer is the cuprous sulfide film on the active surface of the copper sulfide disc, placed there as a result of the electroforming operation previously described. The barrier layer is the magnesium sulfide film on the active surface of the magnesium electrode, also placed there by the electroforming process. Moreover, this barrier layer bonds or cements the magnesium and copper sulfide elements together upon the completion of the electroforming process. The front electrode is the copper sulfide disc and, to prevent sulfide action between it and the contacting terminal electrode, a contacting electrode of carbonized iron or a nickel plated washer is used which serves as the electrical connection to the inactive surface of the copper sulfide and in addition prevents counter rectification at this surface. Thus, electrical connection to the rectifier cell is obtained by one terminal to the magnesium plate and the other terminal to the carbonized disc which makes electrical contact to the surface of the cuprous sulfide, semiconductor, through the low-resistance copper sulfide.

Easy flow of electric current occurs when the magnesium is made negative with respect to the copper sulfide. This is the forward direction of the magnesium-copper sulfide rectifier cell and follows the general rule which defines the forward direction as that resulting from the potential difference being directed from the semiconductor (cuprous sulfide) to the adjacent metal electrode (magnesium) across the barrier layer (magnesium sulfide).

An exaggerated cross-sectional view of the magnesium-copper sulfide cell is shown in Fig. 6-8A. The forward direction is also shown. Although from Fig. 6-8A it would appear that the magnesium-copper sulfide rectifier cell has five elements, the combination of the copper sulfide disc and the carbonized washer may be considered as the front electrode, since the only purpose for the carbonized washer is to prevent sulfiding and a gradual deterioration of the rectifier properties.

In Fig. 6-8B the electrical symbol for this rectifier cell is given. The arrow points towards the forward direction; however, when the cell is used as a rectifier, the rectification polarity is as shown here. (Refer to Chapter 3.)

In Fig. 6-8C a sketch is given to show how the magnesium-copper sulfide rectifier cell may be assembled into a practical half-wave rectifier. Radiator plates are omitted for simplicity and are not needed for low-current capacity stacks.



(A) Exaggerated Cross-Sectional View of Rectifier Cell.

(B) Schematic Diagram Showing Rectification Polarity.

(C) Exaggerated Cutaway View of Half-Wave Rectifier With Rectification Polarity Identified.

Fig. 6-8. The Magnesium-Copper Sulfide Rectifier.

Volt-Ampere Characteristics

Previous sections have stressed the importance of the volt-ampere characteristics of rectifier cells. It also has been stated that two methods are available for obtaining this information — the DC or static characteristics technique and the AC or dynamic characteristics technique. For details of these two systems of measurement refer to Chapter 2.

Inconsistent results are obtained in an effort to determine the volt-ampere characteristics of the magnesium-copper sulfide rectifier cell by the DC or static characteristics method because of the interrelationship of time and internal temperature with the primary variables of voltage and current.

However, the dynamic or AC characteristics at power line frequencies (preferably at 60 cycles per second) produce a more accurate indication of the operating relationships as they actually exist during rectification. Moreover, these dynamic characteristics are stable and reproducible, showing insignificant change with time or mean temperature.

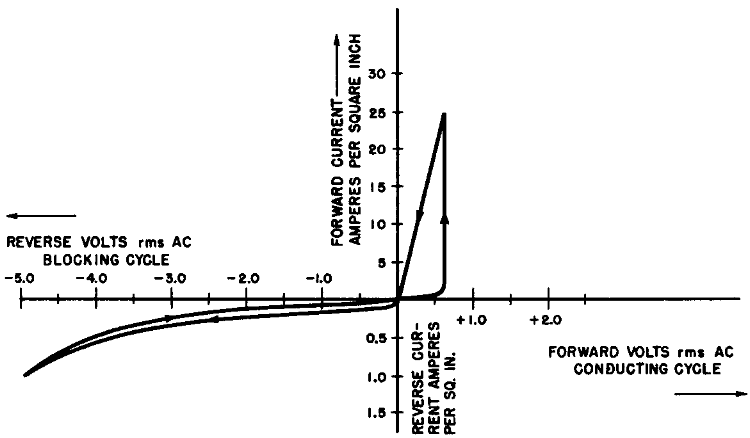


Fig. 6-9. Dynamic Volt-Ampere Characteristics of a Typical Magnesium-Copper Sulfide Rectifier Cell.

Fig. 6-9 is a graphical presentation of the dynamic voltage-current characteristics of a typical magnesium-copper sulfide cell. Note that the forward or conducting voltage axis is plotted in increments of 1/2 volt; the reverse voltage axis is also plotted in 1/2 volt increments. To expand the rectifier characteristics, the forward current axis is plotted in 5 ampere increments, while the reverse or leakage current axis is plotted in 1/2 ampere increments.

From a study of these curves it will be seen that increasing the forward voltage from zero results in an insignificant forward current until a critical voltage of about 0.6 volt rms is reached; after this initiating voltage is applied to the magnesium-copper sulfide rectifier cell the forward current rises abruptly to a relatively high value with little increase in the forward voltage. When the forward voltage is decreased from this critical conducting voltage value, the forward current decreases in approximately linear fashion.

On an alternating voltage excitation the conducting cycle of the magnesium-copper sulfide rectifier consists of a short period during which the current flow is negligible, until the applied voltage reaches about 0.8 volt peak value (0.6 x 1.4). From this point the current increases to a maximum value at practically constant voltage drop (note the vertical ascent of the current) and then decreases from the maximum value to zero at substantially constant resistance with reference to the value of resistance obtained at maximum current.

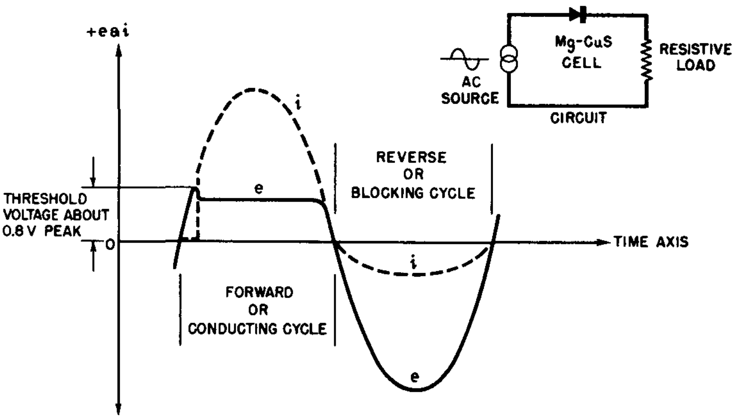


Fig. 6-10. Applied Voltage and Resulting Current Versus Time as Seen on an Oscilloscope for a Magnesium-Copper Sulfide Rectifier Cell.

The lower curve in the section which displays the blocking cycle shows the leakage current as a function of the voltage as the applied reverse voltage is increased. The upper curve in this same section of the graph shows the leakage current as a function of reverse voltage as this voltage is reduced to zero. Both reverse voltage curves are non-linear. The arrows on the curves point in the direction which indicates the direction in which the applied voltage is increasing or decreasing.

This type of volt-ampere characteristic wherein the forward and retrace properties are not the same, that is, there is a pronounced difference in forward and reverse conductance for increasing voltage as compared to decreasing voltage, is identified as a hysteresis effect.

Another way of exhibiting the voltage-ampere characteristics of the magnesium-copper sulfide rectifier cell is to display the functions of voltage and current against a common time base upon an oscilloscope screen. Such a presentation is given in Fig. 6-10. Here the voltage waveform which represents the voltage applied to the magnesium-copper sulfide cell is shown by the solid line curve. The resultant current through the rectifier cell, forward as well as leakage, is given by the dashed line curve. Again it can be clearly seen that the applied voltage in the forward direction must exceed a critical value of about 0.5 to 0.6 volt rms before current conduction initiates. Upon the initiation of the forward current it assumes large magnitudes with negligible forward voltage drop across the rectifier cell. For example, note the horizontal nature of the forward voltage waveform after conduction is initiated. In the reverse direction the magnesium-copper sulfide cell is different from the other two types of rectifiers studied previously in that appreciable reverse current flows, namely about 0.5 ampere per square inch for a reverse voltage across the cell of the order of 3 to 5 volts peak value.

Temperature Characteristics

The magnesium-copper sulfide rectifier cell may be operated over a wide range of temperatures with little change

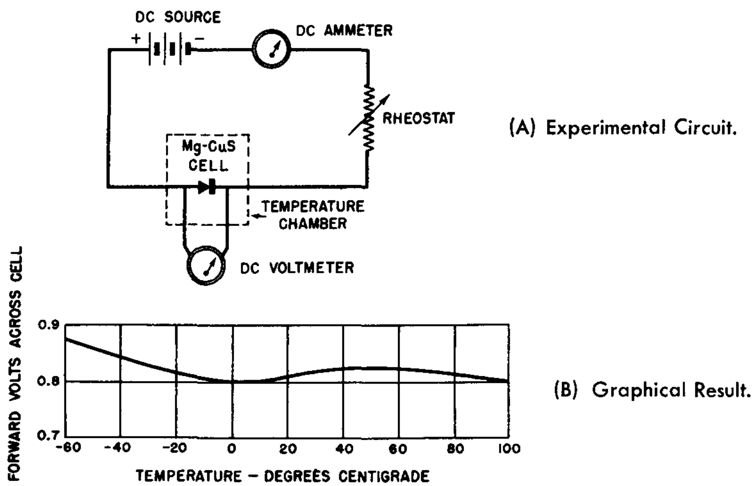


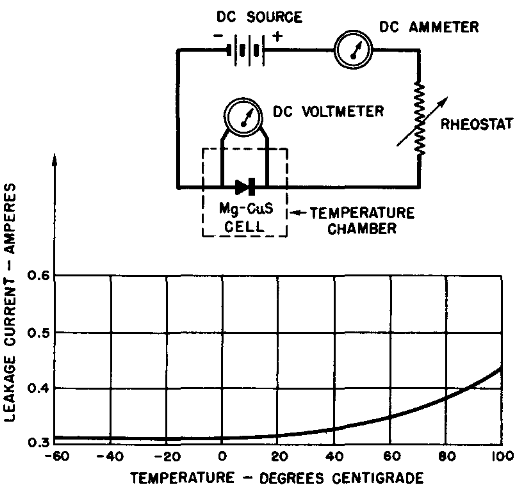
Fig. 6-11. Voltage-Temperature Characteristics of a Magnesium-Copper Sulfide Cell.

in internal resistance because its junction components have negligible resistance temperature coefficients.

The stability of the magnesium-copper sulfide rectifier cell from temperature effects may be experimentally demonstrated in a number of ways. For example, a constant current may be passed through the rectifier in the forward direction and the resulting forward voltage drop measured as the cell is exposed to a wide change in temperature. Any change in the forward voltage drop represents a change in the forward resistance with the changing temperature.

The experimental set-up for this test is shown in Fig. 6-11A which shows a DC source of electricity; a rheostat by which to maintain the forward current constant, say at 5 amperes; a DC ammeter to indicate the value of the forward current; and a magnesium-copper sulfide rectifier cell all wired in series. Note that the DC voltage is applied to the cell in the forward direction. The cell is placed within a chamber in which the temperature can be varied over a wide range.

The experimental result from such a test is graphically presented in Fig. 6-11B. It can be easily seen that the change in forward resistance is negligible over the temperature range of -60 degrees to +100 degrees Centigrade (212 degrees Fahenheit), for the forward voltage across the cell varies less than 0.1 volt over this temperature range. The slight increase at



(A) Experimental Circuit.

(B) Graphical Result.

Fig. 6-12. Reverse Current-Temperature Characteristics of a Magnesium-Copper Sulfide Cell.

the -60 degrees Centigrade end of the curve indicates a small increase in the forward resistance for this end of the temperature spectrum.

To determine what happens to the magnesium-copper sulfide cell's reverse or blocking resistance over the same temperature range, the circuit of Fig. 6-12A may be employed. Here a DC voltage is applied in the blocking direction of the magnesium-copper sulfide cell; the rheostat in the circuit is adjusted to maintain the blocking voltage constant at about 3 volts over the range of temperature change employed. The series ammeter measures the resulting leakage current flow through the rectifier cell which is placed within the temperature chamber for this test. The graphical presentation of the results are shown in Fig. 6-12B. Again the actual leakage resistance change as indicated by the value of the leakage current is very small for the wide temperature change experienced by the magnesium-copper sulfide rectifier cell. This time the largest change of reverse resistance occurs at the high end of the temperature spectrum and the increasing leakage current here indicates a slight decrease in the blocking resistance.

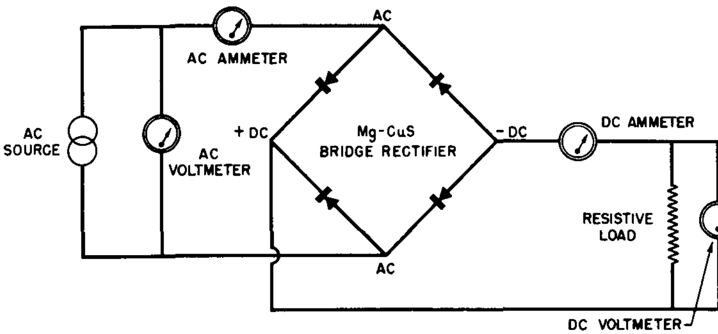


Fig. 6-13. Experimental Setup for Single-Phase, Full-Wave, Magnesium-Copper Sulfide Bridge Rectifier.

The last experimental set-up to be described in connection with the temperature effects of the magnesium-copper sulfide rectifier cell gives the over-all effect of temperature upon the cell's rectified output. The circuit employed is given in Fig. 6-13 and shows a single-phase, full-wave bridge rectifier using magnesium-copper sulfide cells; this bridge is excited by a constant AC voltage of 12.8 volts rms. The output of the magnesium-copper sulfide bridge rectifier feeds a constant resistance load of 0.75 ohm. The resistive load is shunted by a DC voltmeter to indicate the DC output voltage while a DC ammeter in series with the output indicates the DC output current. In a like manner, an AC voltmeter across the AC source measures the applied input voltage and an AC ammeter in series with the rectifier input measures the AC current drawn by the rectifier.

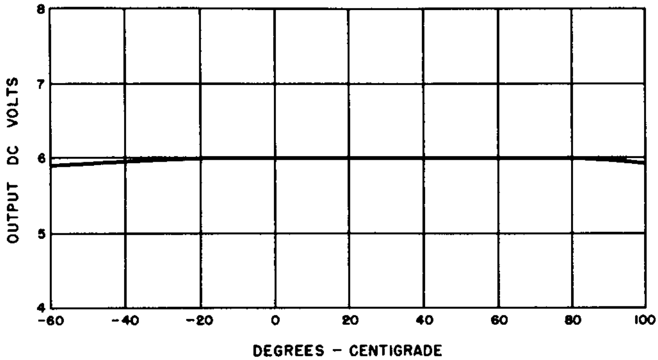


Fig. 6-14. DC Output Voltage of Single-Phase, Full-Wave, Magnesium-Copper Sulfide Bridge Rectifier Versus Temperature.

Again the rectifier is placed within a temperature chamber and exposed to a wide range of temperatures. Fig. 6-14 presents graphically the DC output voltage as a function of temperature. As one would expect from a study of previous experiments in Figs. 6-11 and 6-12 which indicated negligible resistance change in the cell, the output voltage of the magnesium-copper sulfide bridge rectifier is remarkably constant over the wide temperature range of -60 to +100 degrees Centigrade; there is but a slight dip at the temperature extremes.

The experimental set-up of Fig. 6-13 also permits one to determine how the efficiency of the magnesium-copper sulfide rectifier varies with temperature. Efficiency of the rectifier is defined by the following formula:

$$\text{Efficiency} = \frac{E_{DC} \times I_{DC}}{E_{AC} \times I_{AC}}.$$

This information is obtained experimentally by the set-up of Fig. 6-13 and the result is plotted graphically. Fig. 6-15 displays the curve. Here one will note that the efficiency is a minimum of 31% at -60 degrees Centigrade; the efficiency is a maximum of 37% at +60 degrees Centigrade; and it is about 36% at +100 degrees Centigrade. Using the efficiency figure of 36%, which it is at 20 degrees Centigrade, as a reference (this temperature is that considered as normal) the tempera-

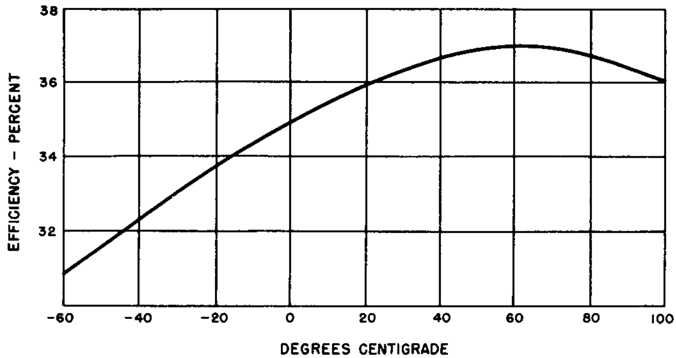


Fig. 6-15. Efficiency Versus Temperature for a Single-Phase, Full-Wave, Magnesium-Copper Sulfide Bridge Rectifier Feeding A Resistive Load.

ture extremes then cause a 5% decrease at -60 degrees Centigrade and a 0% increase at +100 degrees Centigrade.

Voltage-Resistance Characteristics

In the forward direction the magnesium-copper sulfide rectifier cell exhibits a very large resistance to forward current flow until the applied voltage (copper sulfide polarized positive and the magnesium base polarized negative) exceeds the critical initiating voltage of about 0.8 volt DC or AC peak value. When the initiating voltage is applied to the cell the forward resistance drops abruptly to a low value and decreases as the forward current increases. As the applied voltage is lowered from the initiating value for the magnesium-copper sulfide cell the forward resistance of the cell is maintained at a constant value.

In the reverse direction the resistance is not infinite as substantial leakage current flows during this part of the cycle. It can be seen from the voltage-amperage curves of Fig. 6-9 that the resistance change with the applied reverse voltage is not linear and it is more nearly coincident than in the forward direction.

Because of the heavy leakage current and the hysteresis effects exhibited by the magnesium-copper sulfide cell in its voltage-resistance properties, it is not suitable for instrument or control applications. Its adverse voltage-resistance characteristics are not objectional for the application for which the magnesium-copper sulfide rectifier is most suited — heavy current, low-voltage rectification.

Voltage Rating of the Cell

The voltage rating of the magnesium-copper sulfide rectifier cell is 3.5 volts rms. This low voltage rating for this cell makes it necessary to place too many cells in series in order to achieve high voltage ratings for rectifier stacks. For this reason magnesium-copper sulfide rectifier stacks having voltage ratings greater than 50 to 60 volts rms are not economical unless high temperatures or other unusual requirements justify the higher cost.

Current Rating of the Cell

The magnesium-copper sulfide rectifier cell has a higher current rating than the two types of metallic rectifiers previously described. It will be recalled that current rating is a function of heat dissipation, thus, such ratings as are given must be qualified as to the cooling methods used. When forced draft cooled, the magnesium-copper sulfide rectifier cell has a current rating as high as 50 amperes per square inch. When the same cell is convection cooled the current rating drops to about 15 to 16 amperes per square inch. For design purposes a conservative figure of current rating to remember is about 35 amperes per square inch under forced draft cooling. All these current ratings are for an ambient of 40 degrees Centigrade.

Voltage Regulation

In the conducting direction the magnesium-copper sulfide rectifier stacks have an extremely low internal resistance which decreases as the current increases. This property of the rectifier promotes good DC output voltage regulation over a wide range of heavy load conditions. The regulation of a single-phase, full-wave magnesium-copper sulfide bridge rectifier depends upon the type of load it is feeding. A resistive load provides the best regulation, the full-load voltage being 75 to 80 percent of the no-load voltage. The inductive load provides the next best regulation and the capacitive load the poorest regulation.

The voltage regulation of the magnesium-copper sulfide rectifier stack is not favorable when compared with the previous types of metallic rectifiers described, but the reader must remember the much heavier load currents involved. If closer voltage regulation is desired, it is possible to use simple compounding schemes to provide more nearly constant output voltage over the load range.

Efficiency

The efficiency of the magnesium-copper sulfide rectifier is practically constant with respect to hours of use, wide range of load, and ambient and operating temperatures. As a single-phase, full-wave rectifier, its efficiency is in the neighborhood of 35 to 40 percent when it is feeding a resistive load or an inductive load, and 40 to 45 percent when feeding a capacitive or storage battery load. As a three-phase full-wave rectifier the magnesium-copper sulfide rectifier's efficiency is independent of the type of load and is between 50 to 60 percent.

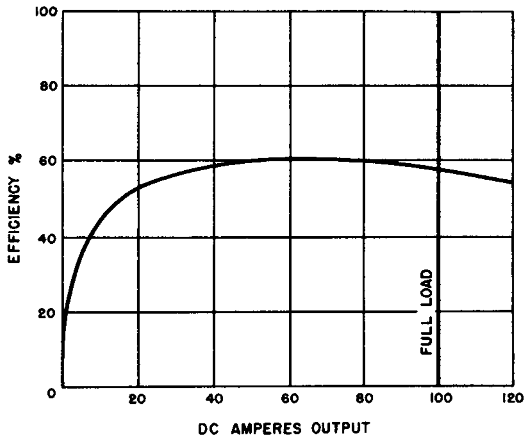


Fig. 6-16. Efficiency Characteristics of a Magnesium-Copper Sulfide Rectifier Employed in a Three-Phase, Full-Wave Bridge Circuit.

It will be recalled that the forward voltage drop across the magnesium-copper sulfide rectifier cell is practically constant regardless of current density. It is this property along with the excessive leakage current which limits the wattmeter efficiency of this rectifier to about 60 percent. Fig. 6-16 shows in graphical form the DC efficiency curve with respect to load. It will be observed that after the 20 percent loading of the three-phase, full-wave bridge rectifier, the efficiency remains practically constant up to 120 amperes output, this output representing 20 percent overload.

To study the change of efficiency with respect to temperature refer to Fig. 6-15.

Power Factor

In common with the other two types of metallic rectifiers described previously, the magnesium-copper sulfide rectifier is essentially a resistive device at power frequencies. Because of the other properties already described, this rectifier can not be used for signal detection or control valve purposes, hence, it is limited to power frequencies where full advantage may be taken of its heavy current rating. At power frequencies its power factor is unity. In practical circuit application the power factor will be determined by its associated circuit components.

Frequency Characteristics

The heavy current rating and the peculiar threshold properties limit the use of the magnesium-copper sulfide rectifier to power frequencies.

At 60 cycles per second this rectifier's full current rating may be utilized. At 25 cycles per second, it is necessary to reduce the current rating by 25 percent, while at 400 cycles per second the maximum current rating may be increased by 50 percent.

Effect of Idleness and Speed of Operation

Over the temperature range of -70 to +130 degrees Centigrade (-94 to +265 degrees Fahrenheit) the speed of operation of the magnesium-copper sulfide rectifier is practically instantaneous. When the rectifier has been stored or has been idle for an appreciable period of time some deformation of the rectifying cells may occur. However, the cells will reform rapidly, when the rectifier is placed into service.

Ambient Temperature Effects

An outstanding feature of the magnesium-copper sulfide rectifier is that it will operate in high ambient temperatures which will destroy the copper oxide and selenium types of metallic rectifiers.

Magnesium-copper sulfide rectifiers may be operated continuously in ambient temperatures as low as -70 degrees Centigrade (-94 degrees Fahrenheit) or as high as 120 degrees Cenitgrade (248 degrees Fahrenheit) with slight change in efficiency or output voltage over operation secured at room temperature, 20 degrees Centigrade (68 degrees Fahrenheit).

The magnesium-copper sulfide rectifier stack ratings are based upon a 40 degree Centigrade (104 degrees Fahrenheit) maximum ambient temperature.

Aging of Magnesium-Copper Sulfide Rectifiers

Aging, as interpreted by the definition as a change in the rectifier characteristics with time and usage is negligible in the magnesium-copper sulfide rectifiers. One advantage of this property of this rectifier is that designers of metallic rectifier power supplies using the magnesium-copper sulfide rectifier do not have to include transformer taps for adjustment of the input voltage to the rectifier to compensate for rectifier aging. This feature is especially convenient for manufacturers of electrical equipment who are reluctant to have non-technical people in the field make adjustments or changes on their equipment.

Life and Operating Temperature

Originally the magnesium-copper sulfide was considered to have a definite life span; however, improvements in the technique of manufacturing and a better understanding of its characteristics have now made it possible to state that if this rectifier's ratings are not exceeded, it, like the selenium and copper-oxide rectifiers, has unlimited life.

The temperature of the magnesium-copper sulfide rectifier stack for maximum life is about 85 degrees Centigrade (185 degrees Fahrenheit). Magnesium-copper sulfide rectifiers operated in applications where the longest possible life is not a requisite, a stack operating temperature of 130 degrees Centigrade (265 degrees Fahrenheit) is permissible. At this temperature many magnesium-copper sulfide rectifiers, on duty continuously, have been in operation in excess of 10,000 hours.

Operation at temperatures of 200 degrees Centigrade or over, although successful and only achieved by the magnesium-copper sulfide rectifier, reduces its life to 500 to 1500 hours depending upon current and voltage factors.

Another factor besides the operating temperature of the magnesium-copper sulfide rectifier stack is the current density of the cells. Current density of the cell is defined as the DC amperes per square inch of the active rectifying area. Where longest life of the rectifier is required, it is necessary to derate the current rating from its maximum value.

Threshold Characteristics

A study of the voltage-ampere characteristics (see Fig. 6-9) reveals that the magnesium-copper sulfide rectifier cell has a pronounced threshold voltage. This threshold voltage is in the conducting direction and has a value of 0.5 to 0.6 volt rms or about 0.8 volt DC or AC peak value.

That the magnesium-copper sulfide rectifier is not suitable for instrument rectifier applications and that its efficiency is limited to 60 percent maximum even for three-phase operation can be acredited to this threshold effect.

Future Outlook

It appears unlikely that there will be any revolutionary improvements in the properties of the magnesium-copper sulfide rectifier since it has seen many years of intensive development in the past. Although it is the only commercial rectifier which will operate successfully above 200 degrees Centigrade, with reduced life, of course, its chief limitations are the low voltage per cell, about 3.5 volts rms, and the low conversion efficiency of 35 to 40 percent for single-phase, and from 50 to 60 percent for three-phase operation.

Because of its high temperature properties the magnesium-copper sulfide rectifier is under further development by the sponsorship of the Armed Forces for low-voltage, cathode heater supplies for electronic equipment.

The most recent improvement applied to the magnesium-copper sulfide rectifier for high temperature application has been hermetic sealing. For, although this rectifier operates successfully at 200 degrees Centigrade (with reduced life), full advantage of this property has not been exploited in the past because of the lack of protective coatings which would withstand the high temperature operation. The new solution to this problem is the hermetic sealing.

This technique involves electroformed magnesium-copper sulfide cells assembled upon a bolt and soldered into a bath-tub can such as used for hermetically sealed capacitors. Terminal connections are secured through glass-to-metal or ceramic-to-metal seals. To facilitate cooling of the sealed rectifier stack, the bath-tub can is coated black. The outside dimensions of the hermetically sealed rectifiers developed thus far is 1 3/8 inches long, 1 1/4 inches high, and 1 13/16 inches wide. A rating for a typical hermetically sealed magnesium-copper sulfide rectifier for a resistive load are listed as follows:

AC input voltage	16
Normal output amperes DC	0.7
Normal output volts DC	8.4
Rated output amperes DC @ 200 C.	0.9
Rated output volts DC @ 200 C.	6.7
Maximum load amperes, any condition	1.5

The normal rating is at 35 to 40 degrees Centigrade with a life rating of 10,000 to 20,000 hours to unlimited life, whereas the operation at 200 degrees Centigrade results in a rectifier life of 1000 to 1500 hours.

CHAPTER 7

Comparison of the Three Types of Rectifiers

Introduction

Up to this point in this book the reader has become acquainted with the need for an effective device for changing alternating current electricity into direct current electricity and has studied in some detail the elements, the properties, and the electrical characteristics of three types of metallic rectifiers; namely, the copper-oxide, the selenium, and the magnesium-copper sulfide.

In a very few metallic rectifier applications the type of rectifier which is used is not of any particular consequence, but in general some property of one particular type makes it especially suitable for a given application. How then is one to determine which rectifier type to use in a specific application? A comparison of the properties of the three types will perhaps reveal the advantages and limitations of the rectifiers under discussion. Such is the purpose of this chapter.

Comparison of Volt-Ampere Characteristics

The reader has learned from past sections of this book that the volt-ampere characteristic of a metallic rectifier is a valuable and quick way to evaluate its potential merits. What we are principally looking for in these characteristics in the forward direction is the required forward voltage drop across the cell for the permitted forward current flow, and the amount of current flow in amperes per square inch. In the reverse direction we are interested in the maximum value of reverse applied voltage before breakdown of the barrier layer or before substantial leakage current results, and the magnitude of the leakage current. The reverse voltage of the rectifier cell gives us an idea as to the potential voltage rating permitted for the cell. Of course, the comparison characteristics should be at the same temperature for we have learned that the characteristics under study are not independent of temperature.

In Fig. 7-1 is drawn a comparison graph of the volt-ampere characteristics of the three types of metallic rectifiers — drawn to a common volt-ampere scale and representative for each type at 20 degrees Centigrade. The magnesium-copper sulfide curve was a little awkward to draw since the current response is so much greater than for the other two types for both directions of current flow. Moreover, we learned in Chapter 6, that the static or DC characteristics of this type rectifier is highly variable and that the hysteresis nature of the volt-ampere property produces a closed loop curve for both directions of current flow. The magnitude of the magnesium-copper sulfide rectifier curve in the forward direction is of the order of 25 to 50 amperes per square inch; the curve runs off the graph. The forward current values shown in this graph are for comparison purposes only — not operating values; at the values shown the rectifier cells would overheat unless forced cooling were employed.

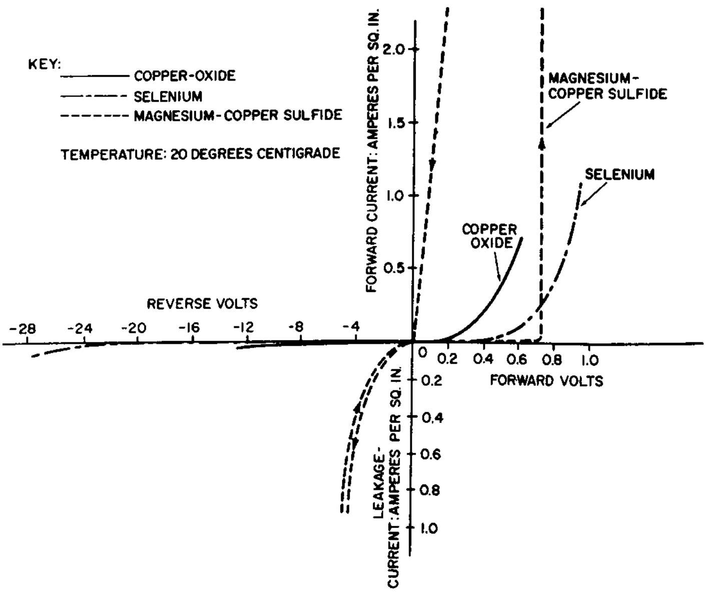


Fig. 7-1. A Comparison of the Volt-Ampere Characteristics of the Three Types of Rectifiers.

On a comparative basis it is easy to see from Fig. 7-1 that the copper-oxide rectifier has no forward threshold voltage, while the threshold voltage for the selenium is about 0.2 volt and that for the magnesium-copper sulfide is a pronounced 0.7 to 0.8 volt. Moreover, the forward current for the copper-oxide and the selenium rectifiers is of the order of one ampere per square inch compared to the 25 to 50 amperes per square inch for the magnesium-copper sulfide rectifier. Additionally, the forward voltage drop at a given current density is approximately one-half as great for the copper-oxide rectifier as for the selenium rectifier.

In the reverse or leakage current direction one can see from Fig. 7-1 that the applied voltage to the rectifiers must be limited to about 3 1/2 volts for the magnesium-copper sulfide, 8 volts for the copper-oxide, and 26 volts for the selenium type. At these values of reverse applied voltage the leakage current for the copper-oxide and the selenium rectifiers is about 2 to 4 milliamperes per square inch, while for the magnesium-copper sulfide it is an excessive 1 ampere per square inch.

Comparison of the Voltage-Temperature Characteristics

The curves of Fig. 7-2 illustrate the variation of the forward voltage drop across the rectifier cell as a function of temperature. It will be noted that although a greater forward voltage drop is required, namely 0.8 to 0.9 volt, this drop is maintained practically constant in the case of the magnesium-copper sulfide cell.

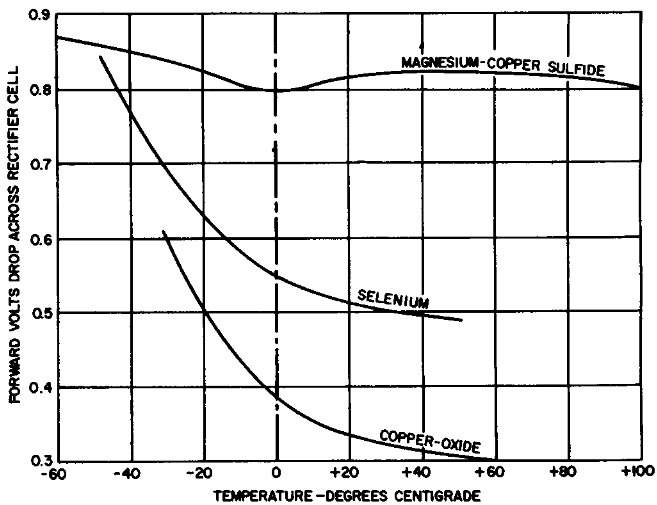


Fig. 7-2. Forward Voltage-Temperature Characteristics of Rectifier Types.

The selenium and copper-oxide rectifier cells shows a large increase in the forward voltage drop across the cell as the temperature is decreased.

The behavior of the three rectifiers in the reverse direction is somewhat more difficult to give graphically. The over-all response of the rectifier is dependent upon this as well as upon the current density of the cells, but, in general, the over-all response is similar to Fig. 7-2 — the magnesium-copper sulfide type being less dependent upon the temperature and over a greater temperature range. Refer to Fig. 6-14 as further illustration of this statement.

Comparison of the Voltage Ratings

In line with the discussions in previous chapters of this book, the voltage rating of the three types of rectifier cells at their rated temperatures and current densities is as follows:

Type	Volts per Cell.
Magnesium-copper sulfide	3.5
Copper-oxide	8.0
Selenium	26.0

This information is given pictorially in Fig. 7-3 and represents a rectifier type selection chart on the basis of voltage rating.

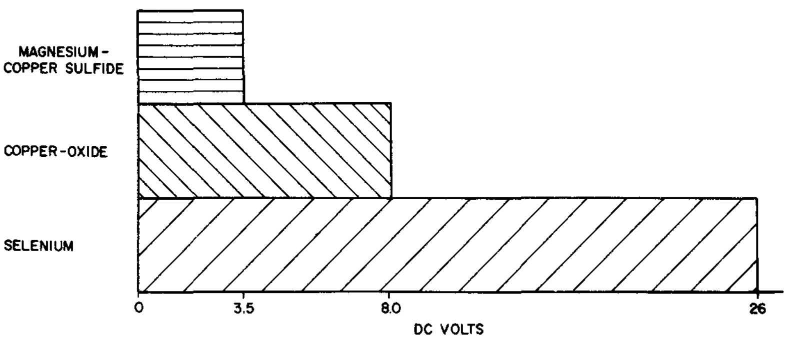


Fig. 7-3. Selection Chart on Basis of Expected DC Volts Required.

For example, if the proposed application calls for a rectified output of 20 volts, the economical cell type to select is the selenium, for, in a half-wave circuit but one such cell is required; in a full-wave bridge circuit four such cells are required. If the copper-oxide type cell is selected, the half-wave circuit requires 3 cells whereas the full-wave bridge requires 12 cells. Thus, on the basis that the more economical and efficient rectifier stack uses the least rectifier cells, the selenium type is the choice and the chart of Fig. 7-3 makes possible an easy selection of the rectifier type on the basis of voltage requirements alone. Other considerations may alter the selection.

For economical selection on the basis of volts output alone, up to 3.5 volts, the choice of the three types of rectifiers is optional; from 3.5 to 8 volts, the magnesium-copper sulfide drops out and the selection is between the copper-oxide or selenium; beyond 8 volts the selenium is the one to use. If the required rectified voltage is greater than 26 volts, two or more selenium rectifier cells in series are required. (Refer to Chapter 3.)

Selection On the Basis of Current Ratings

For the convection cooled rectifier cell at an ambient temperature of 35 to 40 degrees Centigrade, the copper-oxide rectifier cell is rated at 1/10 ampere per square inch, the selenium rectifier cell is rated at 1/4 ampere per square inch, and the magnesium-copper sulfide rectifier cell is rated at 15 amperes per square inch. This information is pictured graphically in Fig. 7-4 which forms a convenient rectifier type selection chart on the basis of current rating alone. We have

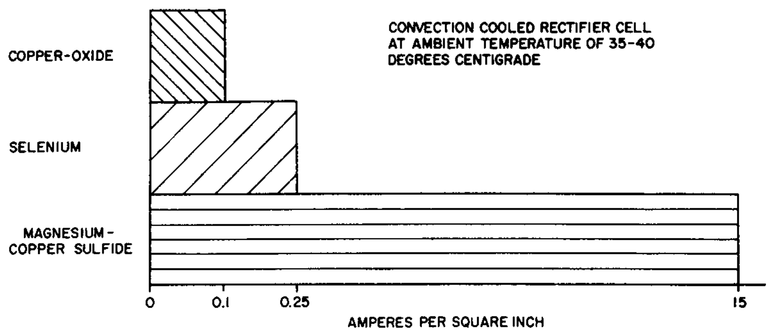


Fig. 7-4. Comparison of Rectifier Types on Basis of Ampere Per Square Inch Current Flow Permissible.

learned that physically these rectifier cells are limited to certain dimensions (refer to chart on page 142 of this chapter). Thus to achieve large current ratings for the copper-oxide or selenium rectifier types requires paralleling rectifier stacks. On the basis of current requirements alone Fig. 7-4 makes for easy selection of the rectifier type.

Comparison of Efficiency

The curves of Fig. 7-5 make possible the comparison of the efficiency of the three types of rectifiers. These curves are based upon using the rectifiers in a three-phase circuit which feeds a resistive load. On the basis of efficiency alone then, the selenium type rectifier is best with the copper-oxide rectifier a close second.

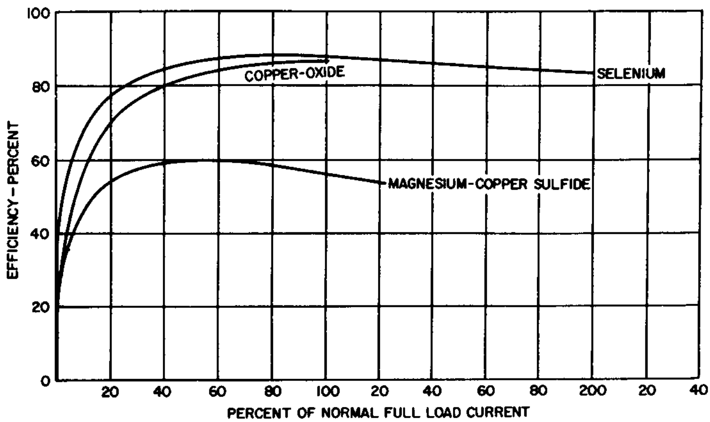


Fig. 7-5. Efficiency Curves for the Three Types of Rectifiers—Three-Phase Circuit, Resistive Load.

Comparison of Operating Temperatures

Fig. 7-6 presents a metallic rectifier comparison chart on the basis of operating temperatures alone. It confirms our past discussion that the magnesium-copper sulfide rectifier

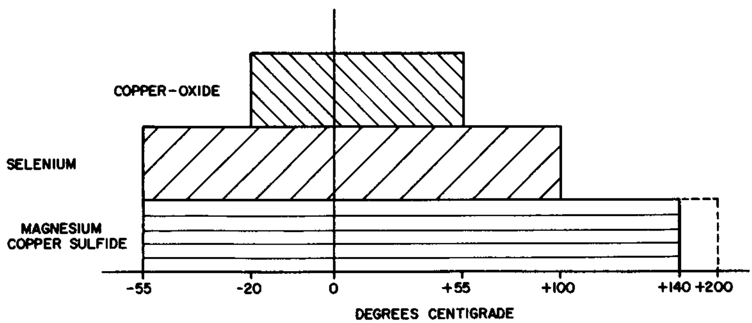


Fig. 7-6. Operating Temperature Range for the Three Rectifier Types.

type covers the widest temperature ranges and is the only rectifier which works satisfactorily above 125 degrees Centigrade to over 200 degrees Centigrade.

The selenium rectifier has the next best temperature range, while the temperature range of the copper-oxide type rectifier, by comparison with the other two types, is quite restricted, indeed.

Actually, the temperature range over which satisfactory operation is secured must be qualified by the desired life expectancy. Thus, with some reduction of life, selenium power rectifiers may operate up to 125 degrees Centigrade while the magnesium-copper sulfide rectifiers will operate in excess of 500 hours in temperatures of 200 degrees Centigrade or over.

Temperatures below zero degrees Centigrade limit the electrical properties of all three types of metallic rectifiers and all three types can be operated for a short time at temperatures as low as minus 70 degrees Centigrade.

The Comparison Chart

Many of the properties of the three types of rectifiers are not easily compared graphically because of dependency upon other factors. Moreover, the best solution for an application is not usually dependent upon a single factor such as efficiency, voltage rating, current rating, etc. It then becomes necessary to present a chart with the pertinent properties listed in such a fashion as to permit comparison. This chart is given on page 142; knowing the operating conditions of an application this chart should ease the selection of the rectifier type.

Conclusions

The conclusions which one can draw from the preceding comparision discussion may be briefly summarized as follows:

1. Where the application calls for heavy current, moderate voltage output up to 50 to 60 volts and/or operating temperatures over 125 degrees Centigrade, consider the magnesium-copper sulfide type of rectifier.

2. Where the application calls for moderate to low currents, high stability, and reproducible characteristics, such as for instrument or control purposes, use the copper-oxide type of rectifier.

METALLIC RECTIFIER COMPARISON CHART

Property		Copper-Oxide	Selenium	Magnesium-Copper Sulfide
Elements	Base Plate	Copper	Aluminum or Steel	Magnesium
	Semi-Conductor	Cuprous-Oxide	Selenium	Cuprous Sulfide
	Barrier Layer	"Perfect" Cuprous-Oxide	Electro-Formed	Magnesium Sulfide
	Front Electrode	Lead	Low Temperature Alloy	Copper Sulfide
Direction of Forward Current		From Lead to Copper Base	From Aluminum to Front Electrode	From Copper Sulfide to Magnesium
Rectification Polarity		Copper Plate Is Positive	Aluminum Is Negative	Magnesium Is Positive
Current Rating, Amperes Per Sq. Inch		1/10 DC	¼ DC	15 DC
Voltage Rating, Volts Per Cell		8-10 rms	26 rms	3.5 rms
Ambient Temperature °C.		35°	35-40°	35-40°
Power Factor		Unity	Unity	Unity
Life		Indefinite	Indefinite	Indefinite
Volt. Regulation, Single Phase, Resistive		15-25%	10%	20-30%
Approx. Temperature Range, °C.		—20 to +55	—55 to 100°	—55 to 140 to 200°
Threshold Voltage, Volts		Zero	About 0.2 to 0.4	About 0.8
Efficiency	1 phase	65%	65-70%	35-40%
Resistive Load	3 phase	85%	85%	50-60%
Cell Size	Min.	3/16 Inch in Diameter	3/16 Inch in Diameter	½ Inch in Diameter
	Max.	1½ Inches in Diameter	6¼ x 7¼ Inch Plates	2 Inches in Diameter
Approx. Frequency Response		Power Rectifiers 0-1000 cycles Instrument Rectifiers 0-Kilocycles	0-2000 Cycles	0-400 Cycles

3. Where the application calls for high efficiency, moderate to heavy current, rectified voltages greater than 50 to 60 volts, use the selenium rectifier.

CHAPTER 8

Classification of Metallic Rectifiers

Introduction

Metallic rectifiers are used in many diverse applications; that is, a huge installation may supply 100,000 ampere at 50 volts for an electro-plating process, while in the other extreme a small rectifier, easily inserted into a thimble, converts a DC meter into an AC indicating meter and operates in the milliwatt range at a few volts and milliamperes.

It becomes evident that no one company can specialize is all types of rectifiers suitable to bridge this wide gap. Moreover, most organizations usually manufacture but one type of rectifier (that is, the selenium, the copper-oxide, or the magnesium-copper sulfide) although a few manufacture two out of the three types of rectifiers.

The application field for metallic rectifiers has become so complex and broad that some classification of metallic rectifiers is necessary. As a preliminary step we might divide metallic rectifiers into two broad groups: those suitable for power rectification, and those suitable for small current applications. The rectifiers included in the power class comprise those operating at levels of, say, over one ampere, while those in the small current group include those operating under one ampere. This one ampere demarcation line is arbitrary but it does seperate metallic rectifiers into two convenient groups.

Power Rectifiers

The rectifiers in the first or power group may utilize any one of the three rectifier types discussed, namely, copper-oxide, selenium, or magnesium-copper sulfide. When the required rectified output voltage is low and the current requirement great, the chances are that the magnesium-copper sulfide rectifier type will do the job best. When the required rectified output voltage is greater than 50 to 60 volts and the current requirements are moderate to moderately heavy, the better efficiency of the selenium type nominates this type of rectifier for the job. For heavy current control or signalling applications, for example, in railway or elevator work, the reliability and stability of the copper-oxide type recommends it for the job.

Small Current Rectifiers

Rectifiers under the small current classification in themselves cover so broad a field of application that further division of this group is necessary. This may be done as follows:

a. Radio and television rectifiers.
b. Instrument rectifiers.
c. Valve or control rectifiers.
d. High voltage rectifiers.

Radio and Television Rectifiers

This group includes small-current rectifiers, usually, of the half-wave type which are specifically designed and in-

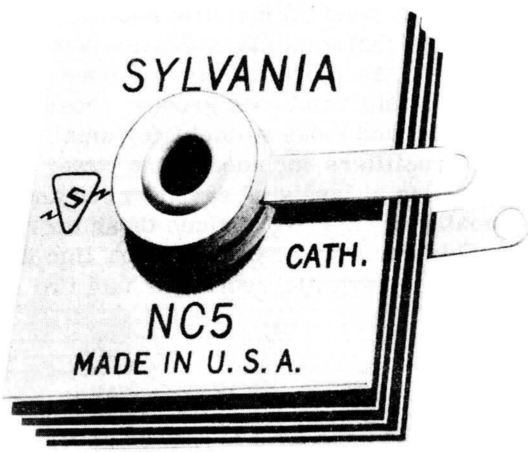


Fig. 8-1. A Small Current, Half-Wave, Selenium Rectifier Rated at 130 Volts rms, 100 Milliamperes, DC. (Courtesy of Sylvania Electric Products, Inc.)

tended for use in radio and television receiver applications. The bulk of these rectifiers are of the selenium type, principally due to the higher voltage requirements, and the current ratings of the rectifier stacks cover the range of approximately 25 to 1000 milliamperes. Fig. 8-1 gives a photographic view of a selenium, half-wave rectifier for this application. This half-wave rectifier is rated at 130 volts rms maximum input and will deliver a rectified current of 100 milliamperes DC. In later chapters of this book we shall learn how to use such rectifiers.

Instrument Rectifiers

This group of small-current rectifiers is characterized by stability, wide frequency range, and a current range from 500 microamperes to about 50 milliamperes. Up to the present day the most successful of the metallic rectifiers to fit this application has been the copper-oxide type. Its stability, reproducibility, and zero threshold voltage have earned it a place for this job.

Valve or Control Rectifiers

The third group in the small-current rectifier listing includes valve or control rectifiers. The properties most valuable for these applications usually are the non-linear characteristics of the volt-ampere curve, the threshold voltage characteristic, or the "one-way" valve action. In this type of usage both the selenium and the copper-oxide types of rectifiers are useful. Although the magnesium-copper sulfide type of rectifier has a pronounced threshold voltage, its non-reproducibility and severe leakage current usually preclude it from valve or control applications.

High-Voltage Rectifiers

The last group of small-current rectifiers listed in the foregoing is high-voltage rectifiers. The principal need for this type is for rectified output voltages of the order of 1000 to 30,000 volts DC at current levels of a few milliamperes. Such ratings are typical requirements for cathode-ray instruments, x-ray equipment, television receivers, and the like. The most suitable rectifier type for this application is the selenium.

CLASSIFICATION CHART OF METALLIC RECTIFIERS

Classification	Typical Applications	Voltage Range	Current Range	Suitable Type
1. Power Rectifiers	Electro-Plating Elevator Control Electric Transportation	1-500 Volts	1-100,000 amperes	Magnesium- Copper Sulfide Copper-Oxide Selenium
2. Small Current Rectifiers				
a. Radio, Television	Radio FM Receivers TV Equipment	100-300 Volts	25-1000 ma.	Selenium
b. Instrument	Signal Detection Meter Applications Modulators	0-100 Volts	0-50 ma.	Copper-Oxide
c. Valve or Control	Instruments Regulators Duplex Systems	0-100 Volts	0-50 ma.	Copper-Oxide Selenium
d. High Voltage	Oscilloscopes X-Ray TV	1000-30,000 Volts	0-50 ma.	Selenium

The Classification Chart

Summarizing the material in this chapter, the metallic rectifiers under discussion can be classified as shown in the chart on page 148.

CHAPTER 9

Rectifier Circuits

Introduction

Now that the reader has become acquainted with the three types of metallic rectifiers and their properties as discussed in the preceding chapters of this book, he will want to learn how they may be employed. Although rectifiers are used in many types of applications involving control or measurement circuits, some of which will be described later, this chapter will deal exclusively with the primary purpose for metallic rectifiers — their use in circuits for conversion of AC to DC.

There have been many rectification circuits which have been developed throughout the years; however, a number of these circuits have become standard practice for all types of applications. These circuits can be divided into three major groups as follows:

1. Single-phase rectification circuits.
2. Voltage-multiplier rectification circuits.
3. Three-phase rectification circuits.

In the succeeding sections of this chapter only the more useful rectification circuits in each group will be described.

Single-Phase Rectification Circuits

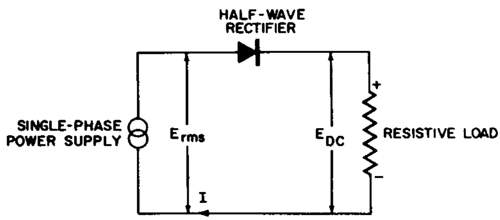
Single-phase rectification may be divided into the following four groups:

a. Single-phase, half-wave rectifier circuit.
b. Single-phase, half-wave circuit with capacitor.
c. Single-phase, full-wave center-tap circuit.
d. Single-phase, full-wave bridge circuit.

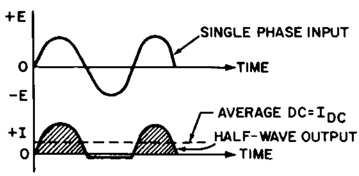
The circuits to be described in connection with these four groups are the most used in radio, television, light duty domestic, and industrial applications.

Single-Phase, Half-Wave Rectifier Circuit

This circuit is shown in Fig. 9-1A. In this figure a single-phase power source, for example the conventional 60 cycle source, feeds a simple series circuit consisting of a half-wave rectifier and a resistive load. As far as AC to DC power conversion is concerned, the circuit of Fig. 9-1A is not an



(A) Schematic Diagram



(B) Performance Graph

E_{rms} = 2.3 E_{DC} + DROP ACROSS RECTIFIER (rms)

I_{rms} = 1.8 I_{DC}

RIPPLE FREQUENCY = APPLIED INPUT FREQUENCY

RIPPLE IN RECTIFIER OUTPUT = ABOUT 120 %

(C) Equations

Fig. 9-1. A Single-Phase, Half-Wave, Rectifier Circuit.

efficient or useful rectification circuit. A discussion of it, however, provides a convenient stepping stone to the more effective rectification circuits. Later in the book the reader will encounter the principal use of this simple circuit in special control applications.

Fig. 9-1B shows that although a single-phase AC voltage is applied to the simple series circuit, the resulting current flow is practically unilateral; this current flow is represented by the shaded sinusoids directly below the portion of the input voltage waveform which causes the rectifier to conduct. Thus, during one half of the input cycle, current conduction takes place in the series circuit; while during the other half cycle, negligible current conduction takes place. During this latter cycle only the reverse or leakage current flows and we have learned from previous discussion that this reverse current may have a value somewhere between 1/100 to 1/1000 of the forward current. (In the case of the magnesium-copper sulfide rectifier this ratio may be about 1/25.) Because the current flows during only one half of the input cycle the arrangement derives its name "half-cycle" rectifier.

A DC ammeter in series with the rectifier and the resistive load will not respond to the rise and fall of the rectified current, if the applied frequency is about 50 to 60 cycles or higher. The meter will indicate the average rectified current flow in the circuit. The dashed horizontal line in the current waveform of Fig. 9-1B represents this average DC current value.

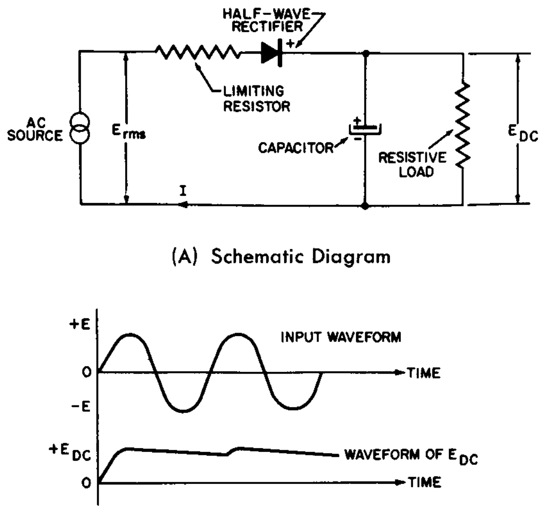
Since the rectified output is not a steady flow of direct current, it can be represented as a steady current with an alternating component super-imposed upon it. The frequency of the alternating component is the same as the applied frequency, that is, the ripple frequency in the rectified output is the same as that of the applied alternating input.

In Fig. 9-1C the significant equations for the circuit are given. The applied input voltage in root-mean-square, the value as read by an AC voltmeter, is equal to 2.3 times the DC voltage as measured across the resistive load plus the voltage drop across the half-wave rectifier in root-mean-square. The root-mean-square current drawn from the power source is equal to 1.8 times the value of the rectified current as indicated by a DC ammeter in series with the resistive load. The ripple component in the rectifier output is greater in magnitude than the steady current and in percent is about 120 to 125. This percentage is determined by the following equation:

$$\text{Percent ripple} = \frac{\text{AC ripple voltage (rms)} \times 100\%}{\text{Average DC voltage}}.$$

Single-Phase, Half-Wave Rectifier With Capacitor

The single-phase, half-wave rectifier circuit of Fig. 9-1A becomes practical with the addition of one capacitor in shunt with the resistive load. This arrangement is illustrated in Fig. 9-2A. The circuit is quite similar to that described for Fig. 9-1A with the important addition of an electrolytic capacitor of large capacitance across the resistive load. A refinement consists of a limiting resistor is series with one line to protect the rectifier against excessive capacitor charging currents.



(A) Schematic Diagram

(B) Graphs

$E_{DC\ Max.} = 1.41\ E_{rms}$

RIPPLE FREQUENCY = APPLIED FREQUENCY

% RIPPLE = FUNCTION OF CAPACITOR AND LOAD

(C) Equations

Fig. 9-2. A Single-Phase, Half-Wave, Rectifier Circuit With Capacitor.

To describe the function of the electrolytic capacitor and why it improves the half-wave rectifier, consider first that the resistive load is temporarily removed. Connected as shown, the rectifier in this circuit conducts only when the upper AC input terminal is positive at which time the capacitor is charged to the peak value of the AC input voltage less the conducting voltage drop across the rectifier of about 5 volts for a radio type selenium rectifier rated at 130 volts rms.

That is, starting from an input voltage of zero value and letting this voltage increase sinusoidally in the positive direction to the peak level, the capacitor is charged substantially to this peak value of voltage also, because the forward resistance of the half-wave rectifier is small. When the input waveform decreases to zero, the capacitor keeps its charge because it can not discharge through the half-wave rectifier in the reverse direction (assuming a perfect rectifier with zero leakage).

When the load resistance is applied to this charged capacitor, and/or when the rectifier is imperfect because of leakage current, current is withdrawn from the charged capacitor continuously, so each conductive cycle must make up the loss and the capacitor voltage rises and falls each cycle to a degree dependent upon the value of the capacitor in farads and the resistance of the load in ohms. The product of these two factors is called the time constant of the circuit and equals numerically to R x C where R is expressed in ohms and C is expressed in farads.

In this circuit, then, the ripple frequency is the same as the applied frequency and the percent of ripple is a function of the time constant and the output voltage level is a function of the load.

Fig. 9-2B graphically shows the waveform of the applied voltage and the waveform of the rectified output when a small amount of current is drawn from the charged capacitor. The output waveform starts from zero, at time equals zero, to illustrate the initial conditions when the circuit is first powered. The first positive half-cycle charges the capacitor to peak value. Since current is being drawn from it because of the shunting resistive load, the voltage across the load decreases until the next positive half-cycle recharges the capacitor.

CURRENT RATING OF HALF-WAVE SELENIUM RECTIFIER	APPROXIMATE PEAK LIMITING RESISTANCE IN OHMS
50 MILLIAMPERES	47
100 MILLIAMPERES	22
200 MILLIAMPERES	4.7
500 MILLIAMPERES	4.7

Fig. 9-3. Chart for Selecting Proper Peak-Limiting Resistor.

To limit the peak charging current to a safe value so as to protect the rectifier, it is necessary to connect a peak current limiting resistor of the appropriate size in series with the supply voltage as shown in Fig. 9-2A. Current flowing through this resistor produces a voltage drop across the resistor; rectifiers with higher current ratings will require less peak limiting resistance to produce a given IR drop. The value of this peak limiting resistor will depend upon the current rating of the rectifier used. It will range from 4 or 5 ohms for a rectifier rated at 500 to 1000 milliamperes to about 50 ohms for a rectifier rated at 50 milliamperes. The required wattage of the peak limiting resistor varies from 2 to 3 watts for the 50 milliampere rectifier to 5 watts for the 1000 milliampere rectifier. Fig. 9-3 presents a chart showing the appropriate peak limiting resistor to use with a selenium half-wave rectifier of a given current rating when this rectifier is used in the circuit of Fig. 9-2A.

An important characteristic of any power supply is its voltage regulation. This refers to the amount by which the DC output voltage drops from its no-load terminal value to its value at full-rated output current. Voltage regulation is expressed as a percentage and is equal numerically to:

$$\text{Percent voltage regulation} = \frac{100\% \, (E1 - E2)}{E2}$$

where,

E1 is the no-load terminal DC voltage.

E2 is the DC output voltage at full current drain.

CURRENT RATING HALF-WAVE SELENIUM RECTIFIER	VALUE OF C IN MICROFARADS	PERCENT VOLTAGE REGULATION AT FULL RATED CURRENT
50 MA	20	23
	40	18
100 MA	20	37
	100	21
200 MA	20	68
	100	17
500 MA	100	37
	200	28

Fig. 9-4. Voltage Regulation Chart.

Best voltage regulation for the circuit of Fig. 9-2A is obtained when the capacitor across the load is a large value of capacitance in microfarads. An illustration of the function of this capacitor on the voltage regulation is given by the chart of Fig. 9-4 which shows the percent voltage regulation to expect for various values of capacitance, when using the half-wave selenirectifiers listed, at their full-rated current values.

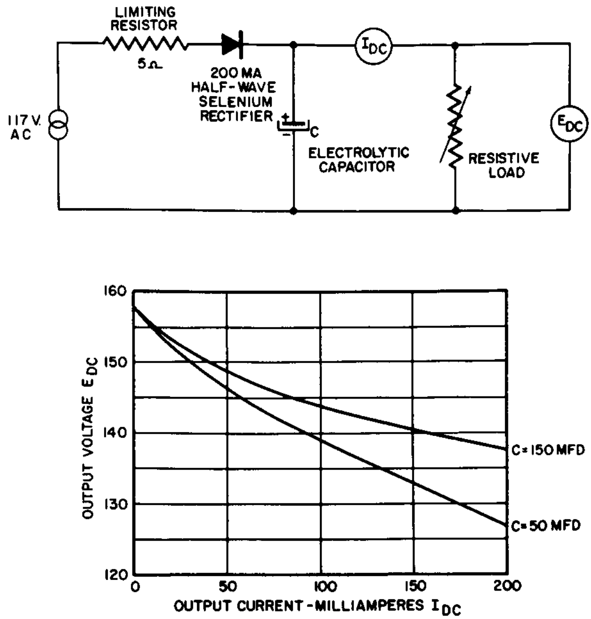


Fig. 9-5. Circuit and Voltage Regulation Curves for Half-Wave Rectifier Circuit, With Capacitor.

Fig. 9-5 gives a practical adaptation of the half-wave rectifier circuit with capacitor using the selenium type of metallic rectifier, including circuit details and illustrating the effect of the value of the capacitor upon the rectified voltage output versus current delivered to the load — in other words, the voltage regulation of the circuit as a function of the shunting capacitor.

As neither the rectifier nor the electrolytic capacitor is "perfect", the rectified voltage at the zero load current value is not quite 1.414 times 117 volts AC. This peak value as shown on the graph is about 158 volts. The regulation of the circuit is better with the larger capacitor, for, at this value, the output falls but 21 volts for a current ranging from 0 to

200 milliamperes. When the shunting capacitor is reduced to 50 mfd, the voltage fall is 31 volts for the same load range.

One can see from Fig. 9-5 that the regulation of the circuit described is not excellent, yet in many cases this is not required, for, the load may be fixed. Moreover, because compact, inexpensive electrolytic capacitors are available with large capacitance ratings, this type of circuit serves well for small current requirements. Furthermore, it makes possible rectified output voltage equal to or greater than the applied line voltage at rms value without the use of a step-up transformer. This feature is popular for the AC-DC type of radio and TV receiver.

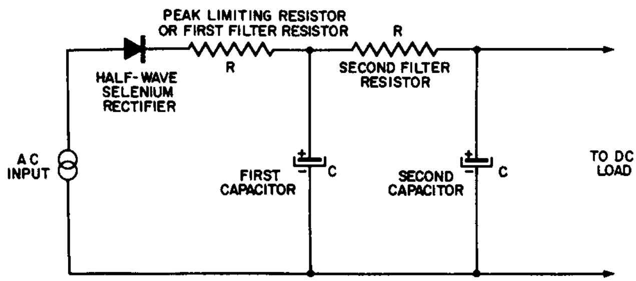
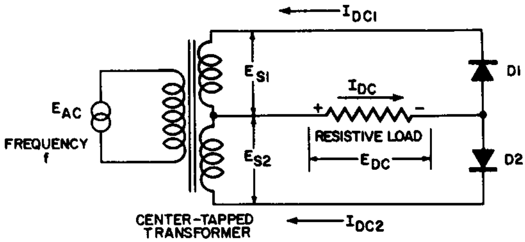


Fig. 9-6. Adding a Second Stage of R-C Filtering to the Half-Wave Rectifier Circuit.

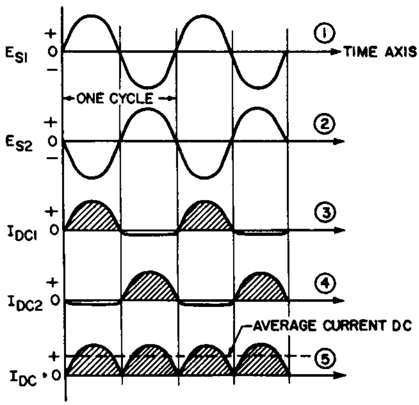
In the half-wave rectifier circuit with capacitor, a second stage of R-C (resistance-capacitance) as shown in Fig. 9-6 will augment the smoothing action of the ripple component of the DC output at the expense of poorer voltage regulation. It is desirable that the second capacitor have the same value of capacitance in microfarads as the first capacitor and that both have the same minimum DC working voltage ratings equal to the peak value of the applied AC supply voltage. The value of the resistor R is a function of the load and the output voltage required. The larger it is in ohms, the better will be the filtering action. A value of 100 to 1000 ohms is typical in some power supplies. When very low ripple is desired in the output, several identical filter stages may be cascaded.

Single-Phase, Full-Wave, Center-Tap Rectifier Circuit

We have seen that the half-wave rectifier circuit of Fig. 9-1A suffers from poor voltage regulation and excessive ripple voltage because the power is transferred from AC to DC only during half of the alternating cycle. To improve upon this performance, a capacitor was utilized in the second arrangement described to act as a fly wheel during the non-conducting cycle of the half-wave rectifier and give up part of its electrical charge to sustain the steady flow of current. The better voltage regulation of this system is greatly dependent upon the use of large values of capacitance and, even then, the system is limited to rectified currents of small values, certainly not greater than one ampere and usually to currents of the order of a few milliamperes to about 500 milliamperes.



(A) Schematic Diagram



(B) Graphs

$E_{S1} = E_{S2} = 1.15\, E_{DC}$ + VOLTAGE ACROSS RECTIFIER (rms)

$I_{AC} = 0.8\, I_{DC}$

RIPPLE FREQUENCY = 2f

RIPPLE = 47–52%

(C) Equations

Fig. 9-7. A Single-Phase, Full-Wave, Center-Tap Circuit.

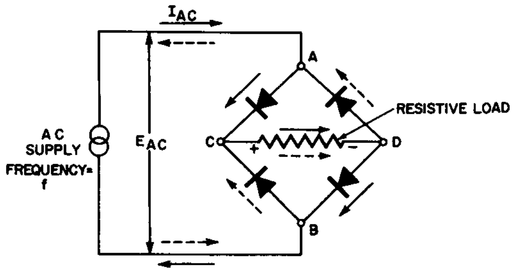
To improve this performance it is necessary to extract rectified power during both halves of the alternating input. This may be accomplished by the use of a center-tapped transformer and two half-wave rectifiers. The arrangement and the details are given in Fig. 9-7. The use of the center-tapped secondary on the transformer, coupling the rectifier circuit to the AC source, provides two equal and opposite voltages as referred to the center-tapped connection. These voltages are designated as E_{S1} and E_{S2}. Their time and magnitude relationships are shown by the first two waveforms of Fig. 9-7B. The two half-wave rectifiers, D1 and D2, and the common resistive load are connected as shown in Fig. 9-7A and the arrangement provides a full-wave direct current delivery to the load because rectifier D1 delivers a half cycle of direct current on one alternation, while rectifier D2 delivers its equal share of current during the succeeding alternation. See Fig. 9-7B, waveforms 3 and 4, and then correlate waveform 3 with waveform 1 and waveform 4 with waveform 2. The current flow through the resistive load is the summation of I_{DC1} and I_{DC2} which equals I_{DC}; this is shown graphically by waveform 5. The dashed line through this waveform represents the average value of the rectified current flowing through the load as indicated by a DC ammeter.

The equations of Fig. 9-7C illustrate that the secondary voltage required in rms is equal to 1.15 times the rectified voltage across the load plus the voltage drop across the rectifier in rms. The AC input in rms to the rectifier circuit proper equals 0.8 times the rectified current in the load. The ripple frequency of this circuit is double that of the input frequency; for a verification of this statement study waveform 5 with 1 in Fig. 9-7B. The percentage ripple is of the order of 47 to 52 percent.

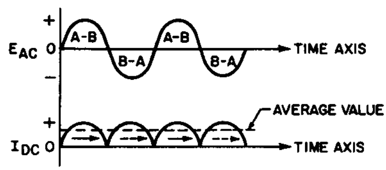
Although this arrangement is better than the previous systems described because it is of the full-wave rectification type resulting in better voltage regulation, and lower ripple (more uniform DC output); the transformer design is not efficient as each half of the secondary still works half of the time. Thus, this arrangement is most useful when full-wave rectification is required and the design is limited to two half-wave rectifiers; it is principally economical when low DC voltage is required — approximately 8 to 10 volts. Where the requirement for the DC output is greater than 10 volts, it is necessary to have two rectifiers in series where but one cell is shown in Fig. 9-7A. For this reason the center-tap circuit loses advantage when the output voltage requirement necessitates two half-wave rectifiers in each rectifier branch. When several rectifier cells must be used in series, the center-tap transformer design is no longer economical because of its half duty cycle and center-tap requirements. The choice then falls upon the single-phase, full-wave, bridge rectifier.

Single-Phase, Full-Wave Bridge Rectifier Circuit

The most popular single-phase rectifier which uses both rectifier and transformer components efficiently is the full-wave bridge arrangement. Efficiencies of the order of 60 to 70 percent are obtained because both halves of the input cycle supply the load. The circuit is shown in Fig. 9-8A. It will be



(A) Schematic Diagram



(B) Voltage and Current Waveforms

$E_{AC\,rms} = 1.15E_{DC}$ ACROSS LOAD + 2(VOLTAGE DROP ACROSS RECTIFIER, rms)

$I_{AC\,rms} = 1.15 I_{DC}$

RIPPLE FREQUENCY = 2f

RIPPLE IN OUTPUT VOLTAGE = 47-52%

(C) Equations

Fig. 9-8. A Single-Phase, Full-Wave, Bridge Rectifier Circuit.

found that four half-wave rectifiers are connected in a manner to provide full-wave rectification. When the input alternation is such that terminal "A" of the bridge is positive and terminal "B" is negative, the direction of the resulting current flow is given by the solid arrows. When the alternation of the input voltage wave is such that junction "B" is positive and junction "A" is negative, the current flow direction is indicated by the dashed arrow lines.

It is important to note that although two sets of rectifiers are used, resulting in different paths for the current flow through the diagonals of the bridge for the positive and negative alternation of the input voltage, the direction of the current flow through the load is the same for both alternations providing full-wave power to the resistive load. These details are shown graphically in Fig. 9-8B, while Fig. 9-8C provides the necessary equations. See Chapter 3 of this book for other details of the single-phase, full-wave bridge rectifier.

Voltage-Multiplier Rectification Circuits

This group of single-phase rectification circuits have such a unique property that they may be separately classified under the above title. This property of the circuits to be described is the ability to supply rectified or DC potentials exceeding the peak value of the applied alternating voltage and to achieve this greater voltage without the need for bulky, expensive, power transformers. Generally the higher voltage rating of these circuits requires the use of the selenium type of metallic rectifiers. In replacing the power transformer and the conventional rectifier tubes used, selenium metallic rectifiers have made available low cost, compact, light weight TV receivers. In one application, the TV chassis, redesigned to use metallic rectifiers in voltage multiplier circuits to obtain the required B+ voltage, weighs as little as the power transformer alone used in the previous design of the TV receiver providing the same operational characteristics.

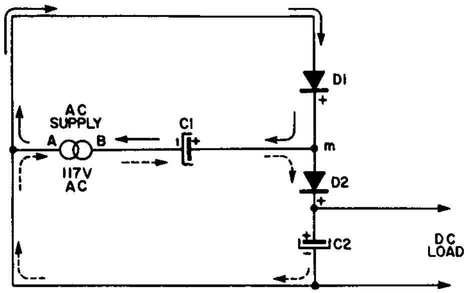
Using the principles of the voltage multiplier rectification circuits, there is no theoretical limit to the maximum voltage which can be obtained; however, the most popular applications limit the use of these circuits to arrangements providing 3 to 4 times the peak value of the applied line voltage, or about 500 volts DC for a 117 volts, 60 cycle input.

Voltage multiplier rectification circuits which require the application of half-wave rectifier assemblies may be divided into five groups as follows:

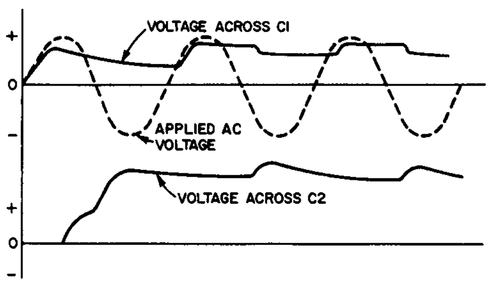
a. Voltage doubler, half-wave.
b. Voltage doubler, full-wave.
c. Voltage tripler.
d. Voltage quadrupler.
e. Ladder Circuit.

Half-Wave Voltage-Doubler Circuit

The voltage doubler, half-wave rectification circuit is the most frequently used transformerless voltage multiplier. The no-load DC output voltage of this circuit is 2 x 1.414 or about 2.82 times the rms value of the AC supply voltage. Thus, a voltage doubler rectification circuit powered from a 117 volt AC line will deliver a no-load DC output voltage of approximately 330 volts, neglecting the voltage drop across the rectifiers in its circuit. As output current is drawn, the DC voltage will fall; this decrease of output voltage is a function of the DC load and the value of the capacitors of the circuit.



(A) The Circuit



(B) Voltage Graphs

Fig. 9-9. A Half-Wave Voltage Doubler.

The half-wave voltage doubler circuit is shown in Fig. 9-9A. By examining the circuit, the reader can determine that it consists of a series loop comprising two half-wave rectifiers D1 and D2 and an electrolytic capacitor, C2. The rectifiers are connected in series additive, that is, the positive terminal of D1 is connected to the negative terminal of D2. Since it is customary to use polarized electrolytic capacitors in these circuits for reasons of economy, the proper connection for C2 is to connect its positive terminal to the positive terminal of rectifier D2 as shown.

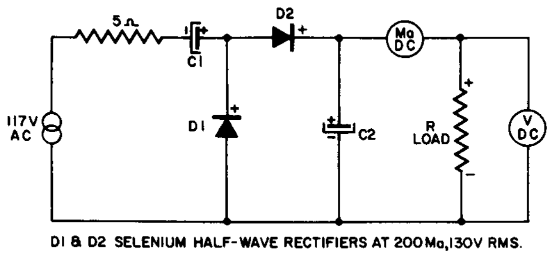
The positive terminal of the first capacitor C1 is connected to point m at the junction of the two rectifiers. The alternating voltage power supply has one terminal B connected to the remaining terminal of the electrolytic capacitor C1, while its other terminal A is connected to the junction between rectifier D1 and the negative terminal of electrolytic capacitor C2.

The principle of operation of this circuit will be understood by the reader by following the circuit performance for one alternation of the AC input. First, assume that portion of the input alternation in which terminal A of Fig. 9-9A is positive with respect to terminal B of the AC supply. For this condition of the circuit rectifier D1 will be conductive and rectifier D2 will be non-conductive and charging current will flow in the direction shown by the solid arrows to charge capacitor C1 until it assumes a voltage equal to the peak potential of the line. (In this case this will be 1.414 x 117 volts.) In the next half cycle, as terminal B becomes positive with respect to terminal A, the charge of capacitor C1 will add its potential to that of the peak value of the AC supply voltage and the current flow will be through rectifier D2 (this current flow is indicated by the dashed arrows) charging capacitor C2 to a potential equal to that of the peak line voltage plus the voltage across C1. The voltage across C2 is thus equal to twice the peak line voltage — at no load. The load, of course, is applied across C2. Under this load, capacitor C2 recharges but once during a complete alternation of the AC input, so the ripple frequency is the same as the line frequency and the voltage regulation of the system is poorer than that obtained from the full-wave voltage doubler to be described next.

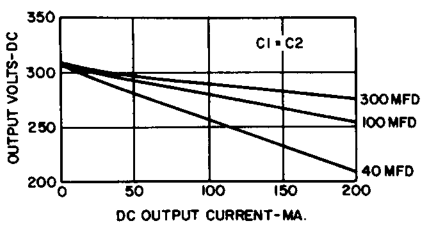
In Fig. 9-9B the upper portion of the voltage graph shows in dashed lines the sinusoidal waveform of the applied AC input. During the positive alternations, rectifier D1 conducts and charges capacitor C1; during the negative alternations the charge in C1 partially discharges into C2, accounting for the fall of potential shown by the solid line curve marked "voltage across C1".

During the negative alternation of the AC input, rectifier D2 conducts and the charge of C1 plus the line voltage in additive fashion charge C2 to approximately twice the peak value of the applied line voltage. The resultant voltage waveform, for a light load across C2, is shown by the lower solid line curve of Fig. 9-9B.

Although the voltage regulation and the ripple frequency of the half-wave voltage-doubler circuit is inferior to the full-wave voltage-doubler circuit to be described, it is the circuit more widely used because one terminal of the rectified output is common to the AC input source tending to reduce AC hum and stray pickup problems because this common junction between input and output may be grounded.



(A) Schematic Diagram



(B) Voltage Regulation Curves for Different Values of Capacitors.

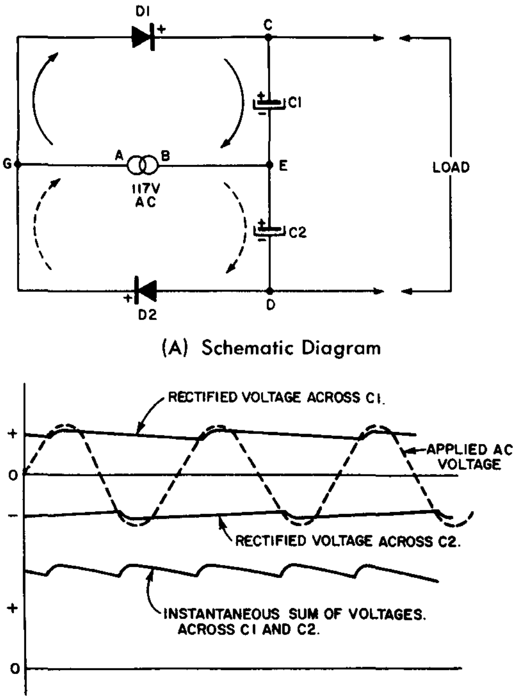
Fig. 9-10. A Practical, Half-Wave, Voltage-Doubler Rectifier Circuit.

In a practical circuit the two rectifiers used are identical as are also the two capacitors. Capacitor and rectifier polarities must be observed. The voltage regulation of the circuit is improved by use of large capacitance values for the two capacitors. For example, when using half-wave rectifiers of the selenium type rated at 200 ma, 130 volts rms, the voltage regulation is about 50 to 60 percent when the capacitors have a value of 40 microfarads and 20 to 30 percent when the capacitors are increased to 100 microfarads.

Fig. 9-10 gives a practical, half-wave voltage-doubler, rectifier circuit with typical component values. The voltage regulation graph shows the performance to be expected for different values of capacitances. The function of the 5 ohm resistor is to act as a limiting resistor to the initial current surge while the capacitor is being charged and to act as a fuse in the event that a short circuit occurs in the DC load.

Full-Wave Voltage-Doubler Circuit

The full-wave voltage-doubler circuit is shown in Fig. 9-11A. It involves the same number of components as the half-wave voltage-doubler circuit discussed previously but the arrangement and performance are different. In this circuit the outer loop consists of two rectifiers and two capacitors. The two rectifiers, connected in series additive (positive terminal of one to the negative terminal of the other), are wired in series with the two capacitors also connected in series additive.



(A) Schematic Diagram

(B) Voltage Graphs

Fig. 9-11. A Full-Wave Voltage-Doubler Circuit.

Terminal A of the AC power supply is wired to the junction between the two rectifiers (see junction G) and terminal B is wired to junction E between the two capacitors. The load for the rectified voltage is applied across the two capacitors C1 and C2.

The principle of operation of this circuit is as follows: When terminal A of the AC supply voltage is positive with respect to terminal B, current flow represented by the solid arrows passes through rectifier D1 and charges C1 to peak line voltage with point C positive with respect to junction E. In the next half-cycle, when terminal B of the AC source becomes positive with respect to terminal A, capacitor C2 is charged (represented by the current flow line shown by the dashed arrows) so that terminal D is negative with respect to junction E. At no-load then, the rectified output potential across terminals C to D is twice the peak line voltage at the end of a full cycle of alternation. With no-load then, the rectified output voltage across the two capacitors is equal to 2.82 times the AC supply voltage measured in rms. With load the capacitors lose part of their charge during the cycle and the output voltage is a function of load current and the rating of the capacitors in farads.

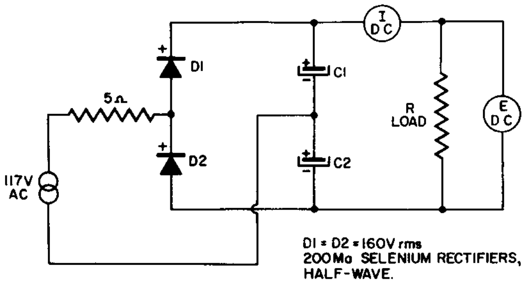
Fig. 9-11B graphically presents the applied AC voltage (in dashed waveform), the resulting rectified output voltage waveforms across C1 and C2, and the instantaneous summation of the voltage waveforms across C1 and C2, as seen by the load. One can see that the capacitors in this full-wave circuit are charged alternately on each cycle of the AC input and then discharge additively into the load. For this reason the full-wave voltage-doubler has better voltage regulation and a lower ripple component in the rectified output than the half-wave voltage-doubler circuit.

SELENIUM HALF-WAVE RECTIFIER RATED AT:	VALUE OF CAPACITORS IN MICROFARADS (C1 = C2)	VOLTAGE REGULATION PERCENT
100 MA 130Vrms	40	24
	100	21
200 MA 130Vrms	40	28
	100	19

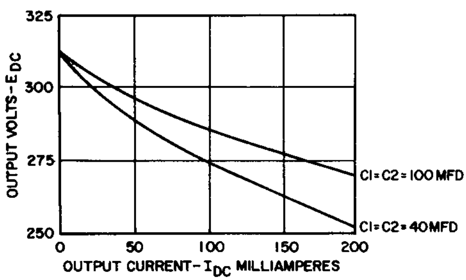
Fig. 9-12. Voltage Regulation Characteristics of the Full-Wave Voltage Doubler.

The chief disadvantage of the full-wave voltage-doubler circuit is that neither output terminal can be "grounded" for neither output terminal is common to the AC terminals. AC hum and stray pick-up will be a greater problem when using this type of power supply with sensitive amplifiers and receivers but this difficulty is partly offset by the lower ripple component and the better voltage regulation.

The chart of Fig. 9-12 illustrates the voltage regulation to expect from the full-wave voltage-doubler circuit at two half-wave rectifier ratings and for two values for the capacitors; identical capacitors and rectifiers are used for each respective circuit.



(A) Schematic Diagram



(B) Voltage Regulation Graph

Fig. 9-13. A Practical Full-Wave, Voltage-Doubler Rectifier Circuit.

Fig. 9-13 gives a practical circuit which employes the full-wave voltage-doubler principle. The accompanying graphs show the voltage regulation to expect at various loads up to the rating of the rectifier. In this circuit, polarities of the rectifiers and the electrolytic capacitors must be observed and C1 and C2 must be equal. The current and voltage ratings of the half-wave rectifiers, D1 and D2, should also be equal. The familiar peak limiting resistor is also included.

The Voltage-Tripler Circuit

The voltage-tripler rectifier circuit is a transformerless voltage-multiplier which has a no-load DC output equal to three times the peak applied AC voltage or 3 x 1.414 or 4.242 times the rms value of the AC supply voltage. When this circuit is powered from a conventional 117 volt AC power line, the no-load DC output voltage will be approximately 496 volts if the potential drop across the rectifiers is neglected. When the output terminals are loaded, the DC voltage will decrease as a function of the load and the size of the capacitors used.

Three identical rectifiers and three identical electrolytic capacitors are employed in the voltage-tripler circuit. The larger the capacitors the better the voltage regulation of this circuit.

SELENIUM HALF-WAVE RECTIFIER RATING (D1=D2=D3)	CAPACITANCE IN MFD (C1=C2=C3)	VOLTAGE REGULATION PERCENT
200 MA 130V rms	40	40
200 MA 130V rms	100	27

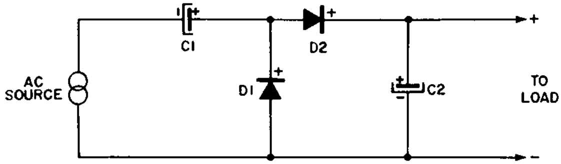
Fig. 9-14. Voltage Regulation Chart for Voltage-Tripler Circuit.

This function of the capacitors in the voltage-tripler circuit is shown by the chart of Fig. 9-14 which shows what may be expected for two values of capacitors in a tripler circuit using three selenium half-wave rectifiers rated at 130 volts rms, 200 milliamperes.

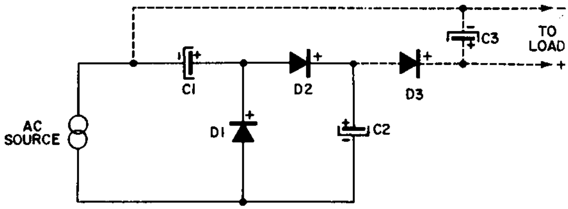
To understand the circuit and principle of operation of the voltage-tripler rectifier arrangement, consider first the half-wave voltage-doubler circuit of Fig. 9-9A and confirm that it can be redrawn as shown in Fig. 9-15A.

The principle of operation of this circuit which was discussed previously can be extended to higher orders of voltage multiplication. The voltage across C2 can be added to a succeeding rectifier-capacitor stage to provide an output voltage which is equal to three times the peak value of the applied line voltage and, if desired, this latter capacitor voltage can be added to still another rectifier-capacitor stage and so on until the desired voltage multiplication is achieved.

Fig. 9-15B shows the schematic diagram of the half-wave, voltage-tripler as an extension of the half-wave, voltage doubler circuit of Fig. 9-15A. The dashed lines in Fig. 9-15B show the rectifier-capacitor stage which was added.

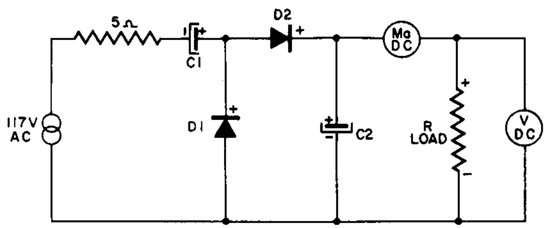


(A) Half-Wave Voltage-Doubler Circuit



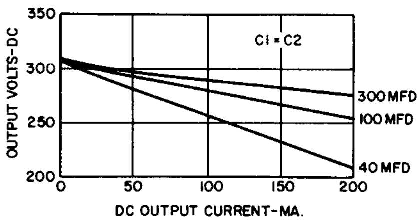
(B) Voltage-Tripler Circuit

Fig. 9-15. The Development of the Half-Wave, Voltage-Tripler Circuit.



D1 & D2 SELENIUM HALF-WAVE RECTIFIERS AT 200Ma,130V RMS.

(A) Schematic Diagram



(B) Voltage Regulation Curves

Fig. 9-16. A Practical Voltage-Tripler Circuit.

The schematic diagram of the practical half-wave voltage-tripler rectification circuit is given in Fig. 9-16A, while Fig. 9-16B shows the voltage regulation curves for two values of circuit capacitors. Again the polarities of the electrolytic capacitors and the half-wave rectifiers must be observed and the capacitors must be equal and so must the rectifiers. By comparing the circuit of Fig. 9-16A with Fig. 9-15B the reader can verify that the arrangements shown are equivalent electrically.

The Voltage-Quadrupler Circuit

As an extension of the principle discussed in the foregoing, that is, by adding rectifier-capacitor stages in the proper manner, the voltage multiplication factor of the circuit may be advanced to any practical level desired. Fig. 9-17 shows the half-wave voltage-quadrupler rectification circuit which results when one additional rectifier-capacitor stage is added in the proper manner to the voltage-tripler circuit of Fig. 9-16A.

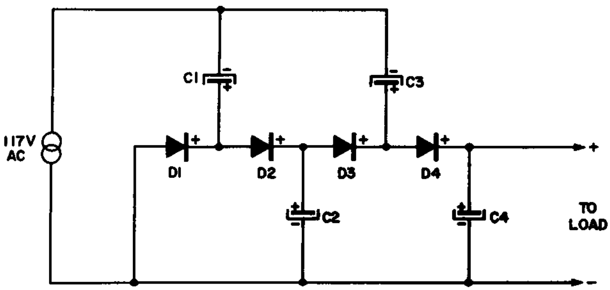
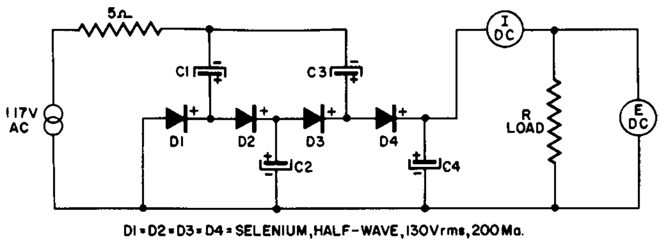


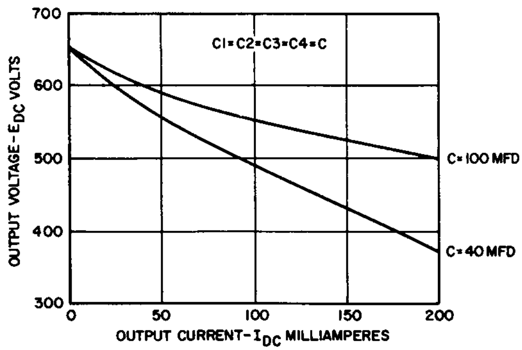
Fig. 9-17. A Voltage-Quadrupler Rectification Circuit.

This circuit is especially useful for low-powered electronic equipment; a study of the circuit shows that it simply comprises two half-wave voltage doubler rectification circuits in series. This circuit delivers a no-load, DC terminal output voltage equal to 4 x 1.414 times the rms value of the AC supply voltage. Thus, a voltage-quadrupler rectification circuit operating from a 117 volt AC power line will deliver a no-load DC output voltage of about 660 volts. As output current is drawn, the DC output voltage will decrease to a value dependent upon the load and the size of the circuit capacitances. Four identical rectifiers and four identical capacitors are required for this circuit and the polarities must be observed.

The voltage regulation of this circuit employing four half-wave selenium rectifiers rated at 130 volts rms, 200 ma and four capacitors at 40 mfd is about 89 percent; when the capacitors are increased to 100 mfds, the voltage regulation is about 36 percent.



(A) Schematic Diagram



(B) Voltage Regulation Curves

Fig. 9-18. A Practical Voltage-Quadrupler Rectification Circuit.

Fig. 9-18 shows the details of a practical voltage-guadrupler rectification circuit with voltage regulation curves.

Yet another means to obtain a voltage-quadrupling rectification circuit is to connect two half-wave voltage-doubler circuits similar to that shown in Fig. 9-15A with the AC input circuits in parallel and the DC output circuits in series additive. The circuit diagram for this arrangement is drawn in Fig. 9-19. Again the no-load DC output voltage is 4 x 1.414 times the rms alternating current input voltage. With an input of 117 volts AC, the DC output voltage at no load is equal to approximately 660 volts when the potential drop across the rectifiers is neglected.

The voltage regulation of this circuit is 85 to 90 percent when the capacitors are identical and equal to 40 mfd; when the capacitors are equal to 200 mfd, the voltage regulation is

35 to 40 percent. The rectifiers are all identical and rated at 130 volts rms, 200 ma, selenium, half-wave.

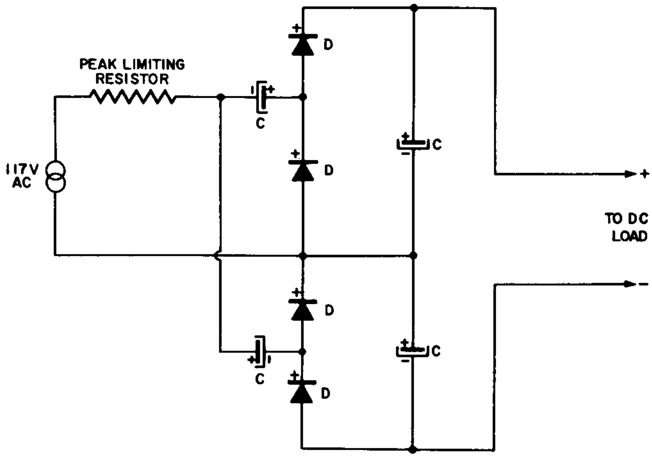


Fig. 9-19. Another Voltage-Quadrupling Scheme.

The Ladder Circuit

Another circuit powered from the single phase AC source provides voltage multiplication in its DC output. The configuration of this circuit's diagram provides it with its fancy name of the Ladder voltage multiplier circuit. This voltage multiplier rectification circuit provides a multiplier factor which is a function of the number of rectifier-capacitor stages.

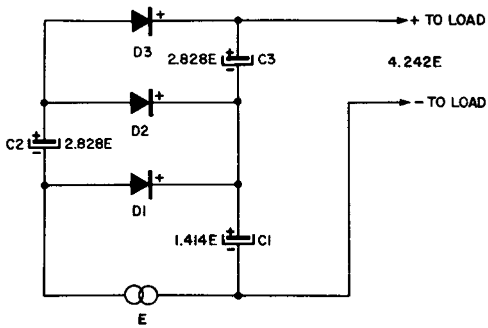


Fig. 9-20. The Ladder Voltage Multiplier Circuit.

The diagram of the circuit is given in Fig. 9-20, which shows a three stage arrangement to provide a DC output voltage which is equal to 3 x 1.414 times the rms value of the AC input.

In this circuit the capacitors may progressively decrease in capacitance with the distance from the AC source. The current ratings of the half-wave rectifiers may also be decreased in the same fashion.

In operation if we can assume that each capacitor is very large in comparison with the capacitor in the succeeding stage then the first half cycle of alternation charges C1 to 1.414E. In the next half cycle of alternation C2 is charged to 2.828E; and finally in the third half cycle of alternation C3 charges to 3 x 1.414E or 4.242E. In succeeding cycles of alternations the voltages across these capacitors are maintained. It can be seen, then, that the voltage of C1 is additive to that of C3 making the DC output voltage as seen by the load 3 x 1.414E.

The multiplification factor of the ladder circuit can be extended with additional rectifier-capacitor stages to obtain enormous DC potentials from the primary 117 volt AC line. Such high voltage power sources are very useful for X-ray and cathode-ray equipment.

Three-Phase Rectification Circuits

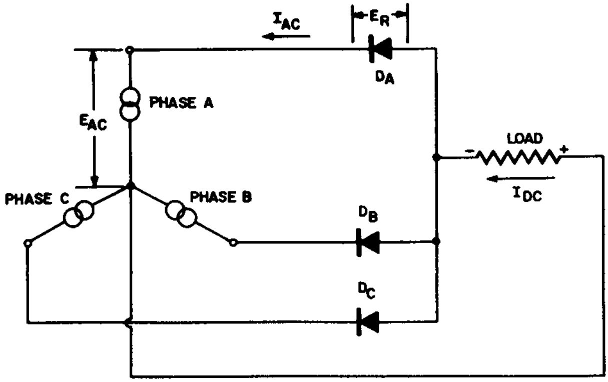
Three-phase rectifier circuits are but an extension of the single-phase rectification circuits already studied. These three-phase circuits are chiefly used for heavy current applications in which the better efficiency and the lower ripple component become important. The higher efficiency and the lower ripple component in the three-phase circuit results because each phase contributes current in turn only while the applied voltage is near the peak value. For this reason, in a three-phase rectifier circuit capacitors or filter circuits are not needed to achieve smoothness of rectified output which can not be approached by single-phase circuits without the use of such auxiliary components.

Of the large number of three-phase rectifier circuits devised, this book will only deal with the following more useful ones:

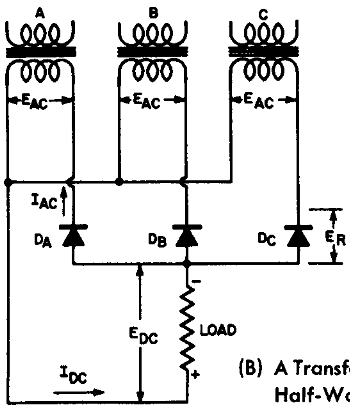
a. Three-phase, half-wave rectifier circuit.
b. Three-phase, full-wave center-tap rectifier circuit.
c. Three-phase, full-wave bridge rectifier circuit with Y connected AC source and Delta connected AC source.
d. Three-phase, full-wave rectifier circuit with interphase or balancing transformer.

Three-Phase, Half-Wave Rectifier Circuit

This circuit is similar in principle to the single-phase, half-wave rectifier circuit previously discussed. The improvement in the performance of the three-phase circuit over that of the single-phase circuit is due to the overlapping of the three-phase rectified current, resulting in an output current throughout the entire cycle. The ripple frequency is three times the applied frequency of the power source and its magnitude is held to about 18 percent.



(A) A Three-Phase, Half-Wave, Rectifier Circuit Connected Direct to Y Connected Source.



$E_{AC} = 0.86 E_{DC} + E_{R\,rms}$

$I_{AC} = 0.58 I_{DC}$

RIPPLE FREQUENCY = 3f

THEORETICAL RIPPLE = 18%

THEORETICAL EFFICIENCY = 96%

(C) Equations

(B) A Transformer-Coupled, Three-Phase, Half-Wave Rectifier Circuit.

Fig. 9-21. The Three-Phase, Half-Wave, Rectifier Circuit.

Fig. 9-21 gives the pertinent facts about this circuit. Fig. 9-21A represents the schematic diagram of the circuit when the power is obtained directly from a Y connected power source. Fig. 9-21B represents the schematic diagram of the circuit when the power is obtained from the secondary of transformers whose primaries are connected to a three-phase power source of either the Y or delta type; and Fig. 9-21C gives the more important formulas for the circuits shown.

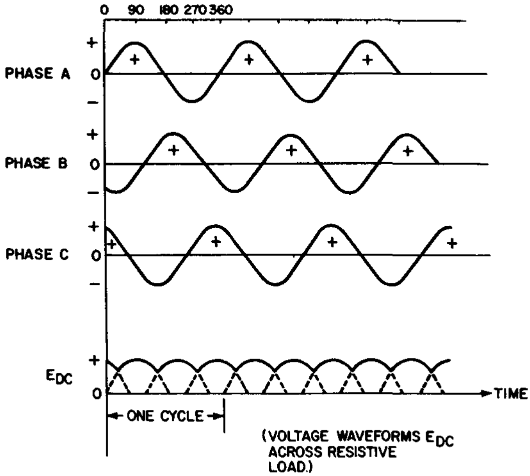
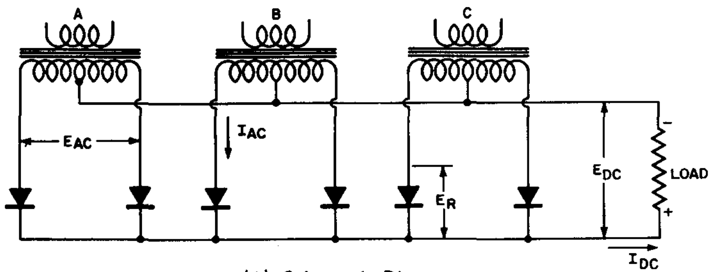
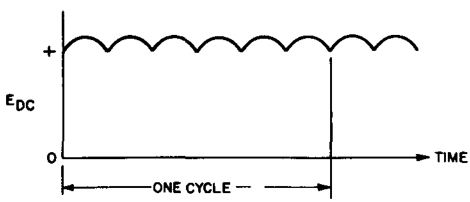


Fig. 9-22. Waveform Graphs for Three-Phase, Half-Wave, Rectifier Circuit.



(A) Schematic Diagram



$E_{AC} = 1.44 E_{DC} + E_{Rrms}$
$I_{AC} = 0.41 I_{DC}$
RIPPLE FREQUENCY = 6f
RIPPLE MAGNITUDE = 4%
EFFICIENCY = 99% (THEORETICAL)

(B) Output Voltage Waveform Across Resistive Load (C) Formulas

Fig. 9-23. A Three-Phase, Full-Wave, Center-Tapped Rectifier Circuit.

Fig. 9-22 shows graphically the voltage waveform of the three-phase input and the resultant waveform of the output voltage across a resistive load.

Three-Phase, Full-Wave, Center-Tap Rectifier Circuit

This circuit is derived from the single-phase, full-wave center-tap circuit and is particularly useful when heavy rectified currents at low voltage are required. A center-tap on each phase winding of the coupling transformer secondary is required. The complete details are shown in Fig. 9-23.

Three-Phase, Full-Wave, Bridge Rectifier

The three-phase, full-wave bridge rectifier circuit is one of the most useful and economical circuits for heavy recti-

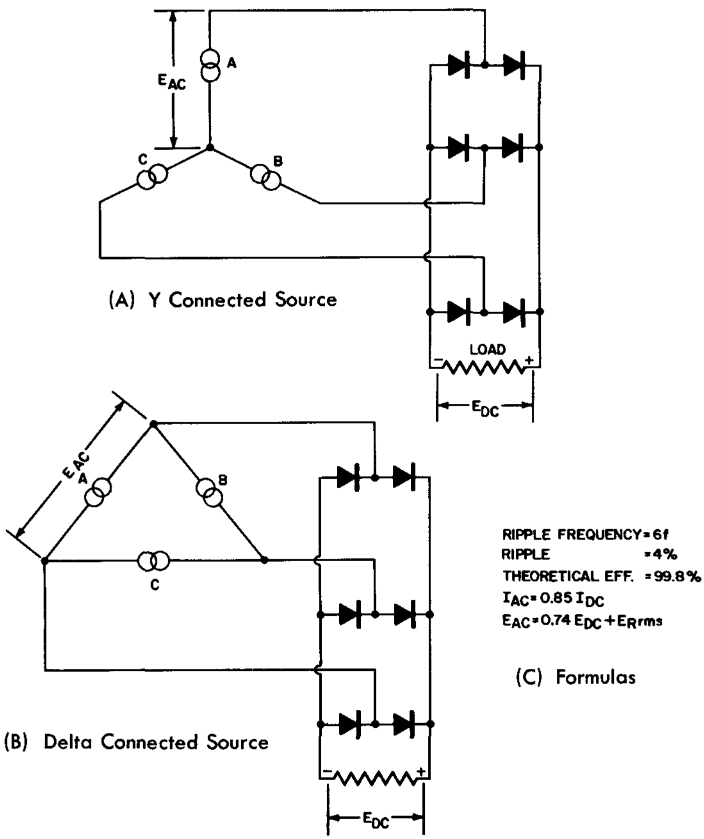


Fig. 9-24. The Three-Phase, Full-Wave Bridge Rectifier.

fied current requirements. It has a high theoretical efficiency of 99 percent and the rectified output contains only 4 percent of ripple component. The frequency of this ripple is six times the applied frequency.

This circuit can be used without coupling transformers when the line voltage is of the proper level and the resulting DC output across the resistive load is approximately the same as the AC voltage supply level. Either a delta or a Y connected power source may be used. The details are shown in Fig. 9-24.

Three-Phase, Full-Wave Rectifier With Inter-Phase Transformer

Fig. 9-25 represents a three-phase, full-wave rectifier circuit with an inter-phase or balancing transformer connecting the two sets of secondary circuits. Without this trans-

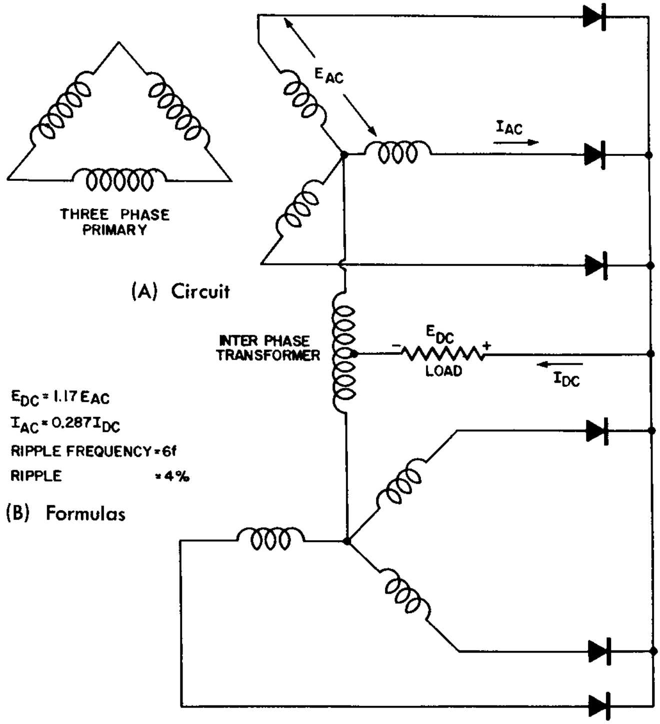


Fig. 9-25. A Three-Phase, Full-Wave, Rectifier Circuit With Inter-Phase Transformer.

former, the circuit becomes a standard six-phase connection and the current conduction occurs during 1/6 of the cycle; with the inter-phase transformer included in the circuit as in Fig. 9-25, the current conduction period is increased to 1/3 of a cycle, thus increasing the current rating of the rectifier output.

CHAPTER 10

Applications of Power Rectifiers

Introduction

The chief application of metallic type, power rectifiers is the conversion of alternating current into direct current for any useful direct current operated device or process requiring a substantial amount of DC power. For this use power rectifiers require only the rectifying property of the metallic rectifier assembly. The DC output ratings of such structures range from a few volts up to several hundred volts and from an ampere up to several thousand amperes. The power rectifier assembly generally contains cooling fins and the assembly may use natural convection or forced air cooling; sometimes the rectifier assembly may even be immersed in an oil bath cooling system.

In power rectifier application we usually associate the metallic rectifier with its AC line coupling transformer, output control means, switch gear, and, perhaps, a metering system. Moreover, we often think of these systems as low voltage systems — operating at outputs of a few volts. In truth, however, metallic rectifier power installations often become quite elaborate and can supply much larger output voltages at substantial power. For example, the photographs of Figs. 10-1, 10-2, 10-3, and 10-4 show some details of a particularly well engineered rectifier system. Fig. 10-1 illustrates one of the three parts combined to form the DC rectifier system shown in Fig. 10-2. This system of Fig. 10-2 has a continuous DC capacity of 1200 amperes at 125 volts. It has been installed at the H. J. Heinz Co. of Pittsburg as a source of power for elevator motors. The photographs of Figs. 10-3 and 10-4 are close-ups of some of the supervisory and automatic devices incorporated in this equipment which employs selenium rectifier stacks. The rear view of this equipment, also showing the rectifier stacks, may be viewed in the frontispiece photograph of this book.

Power applications in which metallic rectifiers are employed are so numerous and cover so broad a range of electri-

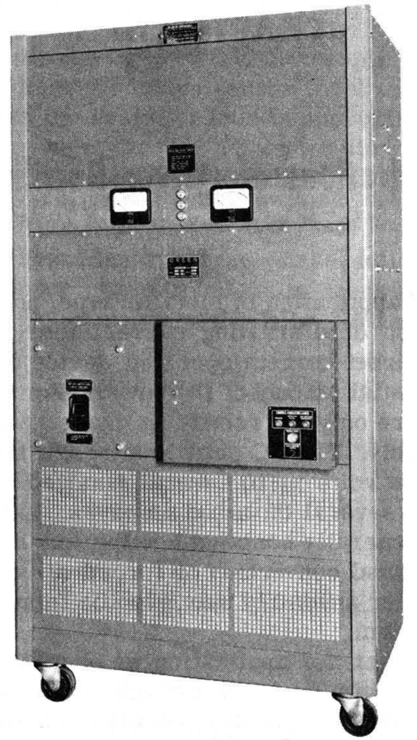


Fig. 10-1. A Front Cabinet View of a Selenium Power Rectifier System. (Courtesy of W. Green Electric Company.)

cal engineering in the DC field that a complete discussion is not only impossible, but, not necessary because it is self-evident. However, several power applications have proven very popular and their discussion should adequately cover this type of application for metallic rectifiers. These popular applications for power rectifiers are as follows:

a. Storage battery eliminators.
b. Storage battery chargers.
c. Rectifier supply for electroplating.
d. Rectifier supply for DC motor operation.
e. Rectifier supply for automotive use.
f. Cathodic protection against corrosion.

Storage Battery Eliminator

There are many DC applications wherein the use of a metallic rectifier assembly of the power type can eliminate

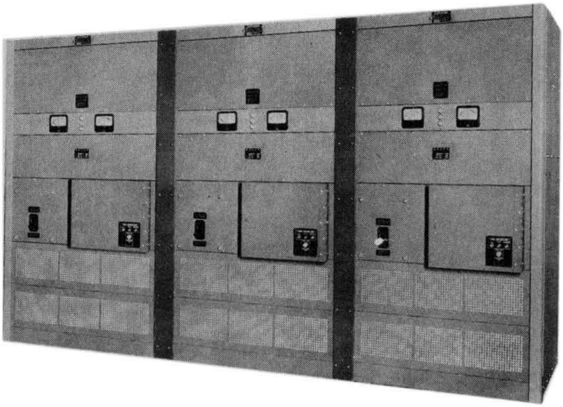


Fig. 10-2. A Selenium Power Rectifier System Using Three of the Units Shown in Fig. 10-1. (Courtesy of W. Green Electric Company.)

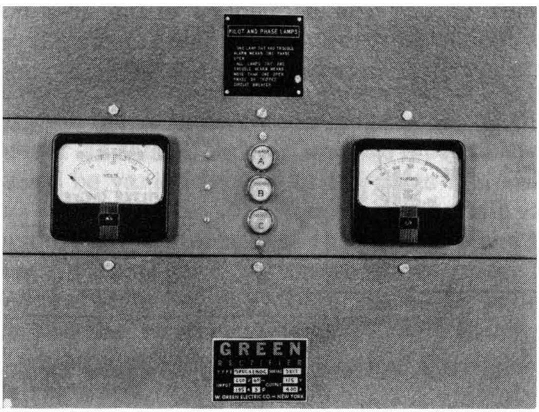


Fig. 10-3. Front View of Supervisory Controls on Rectifier System Shown in Figs. 10-1 and 10-2. (Courtesy of W. Green Electric Company.)

the troublesome storage battery if a source of AC power is conveniently nearby. Fig. 10-5 gives an example of a battery eliminator for use on private telephone systems, signalling equipment, hospital signal systems, or fire alarm systems.

The AC voltage from the power line is reduced in potential to the required level by means of the step-down transformer T,

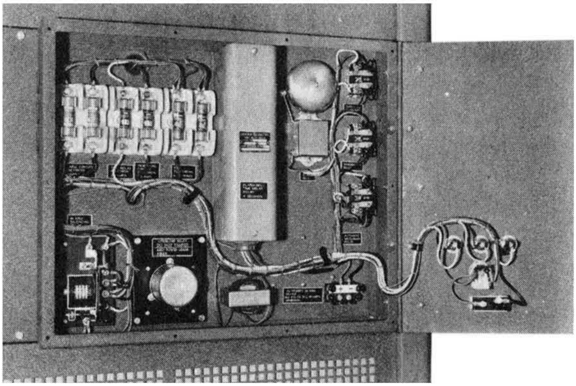


Fig. 10-4. Interior View of Supervisory and Automatic Controls On Rectifier System Shown in Figs. 10-1 and 10-2. (Courtesy of W. Green Electric Company.)

which also serves to isolate the DC equipment from the AC line by virtue of the inductively coupled primary and secondary transformer coils. The secondary of the step-down transformer is connected to the AC terminals of the full-wave rectifier. This rectifier may be of the magnesium-copper sulfide

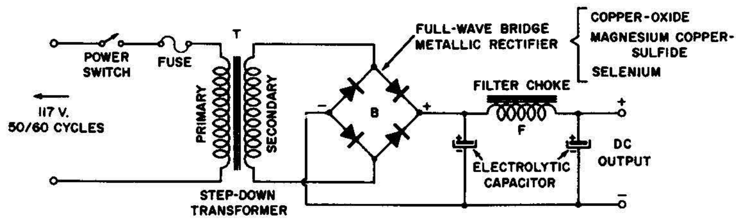


Fig. 10-5. A Storage Battery Eliminator Circuit.

type, if low output voltage and heavy current are required or of the selenium or copper-oxide type, if moderate currents and low to medium values of DC output voltage are needed. The DC output of the bridge rectifier is in turn wired to a filter circuit consisting of a filter choke and two large electrolytic capacitors. Thus, the output terminals of the battery eliminator provide well filtered DC power, isolated from the power line and having an output voltage and current capacity predetermined by design.

The circuit design of Fig. 10-6 has an additional refinement permitting a control over the output voltage from zero

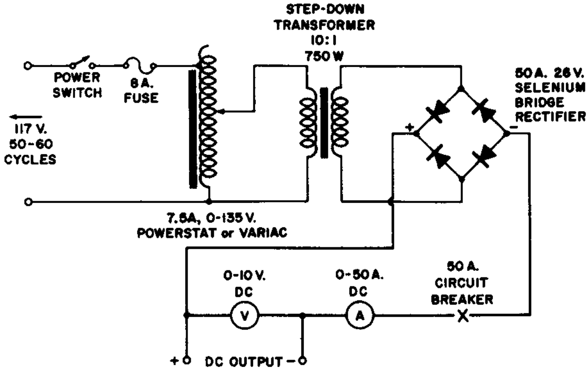


Fig. 10-6. A Battery Eliminator Circuit With a Variable DC Output Voltage of 0 to 10 Volts, Current Capacity, 50 Amperes.

to the maximum desired value. This control is accomplished without the use of rheostats or potential dividing resistances which are wasteful of electrical power, heat generating, and are one of the causes of poor voltage regulation in the power supply. This source of variable DC output voltage which possesses high efficiency and good regulation is attained by means of a variable auto-transformer of the Powerstat or Variac type connected between the AC source and the primary of the step-down transformer as shown. In this way the input to the rectifier system may be varied from 0 to 135 volts in an efficient and continuous manner. Since the control device is a variable auto-transformer, no wasteful heat is generated and the regulation of the system is good from zero to full load. Typical circuit values are given for a system which can provide an output of 0 to 10 volts at 50 amperes DC. The filter circuit can be added to the output terminals shown if a smoother output voltage is reguired.

Storage Battery Charging

Storage battery charging is another interesting and profitable application for power rectifiers of the metallic type. For this application a heavy current output at low voltage (6, 12, or 24 volts DC) is needed. A basic battery charging circuit using a magnesium-copper sulfide rectifier is given in Fig.

10-7. The primary power is derived from an AC source such as a convenience outlet of a lighting circuit at 117 volts, AC.

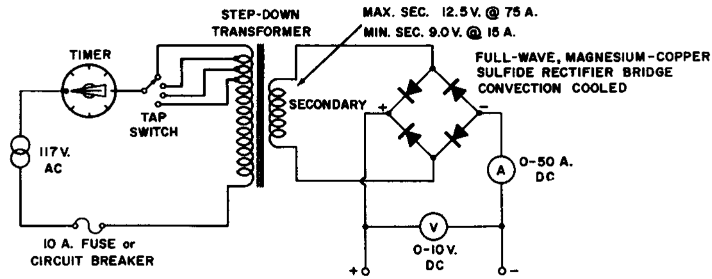


Fig. 10-7. The Basic Battery Charging Circuit, Low Amperage, Convection Cooling.

The timer in the primary circuit predetermines the length of the charge while the tapped primary permits adjusting the charging rate. The basic circuit gives values for components which are suitable for a low amperage, convection cooled type of installation.

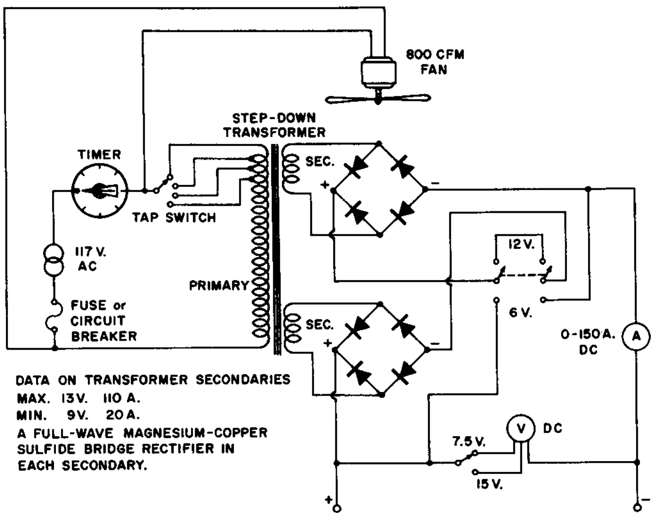


Fig. 10-8. A More Elaborate Battery Charging Circuit.

The circuit shown in Fig. 10-8 is an elaborate version of a storage battery charger; besides having all of the features of the previous basic model, it has a switching system in the output circuit to permit charging either 6 or 12 volt batteries.

At 6 volts the circuit's capacity is 150 amperes; at 12 volts the current capacity is 75 amperes. For this installation forced air cooling is necessary in order to maintain the rectifier operating temperature within safe limits. The electric fan is rated at 800 cubic feet per minute.

TABLE FOR LEAD-ACID TYPE STORAGE BATTERY

DC CHARGING RATE CONTROLLED BY PRIMARY TRANS. TAPS.
MAX. DC CURRENT BASED ON 2.35 VOLTS PER CELL PLUS I VOLT DROP IN CONNECTING LEADS.
MIN. DC CURRENT BASED ON 2.2 VOLTS PER CELL PLUS I VOLT DROP IN CONNECTING LEADS.

No. of Lead-Acid Cells	Nominal Battery Voltage	DC Charging Rate – Amps		Transformer Secondary Data Voltage Range			
		Max.	Min.	Max.	Min.	Max. No. Load Top Tap	Amps
						10.5	0
2	4 V.		10		6.8		
		80		9.7			110
						14	0
3	6 V.		10		9.3		
		80		13			110
						17	0
3	6 V.		10		10.5		
		100		15.5			140
						20	0
4	8 V.		10		13.5		
		100		18.5			140
						28	0
6	12 V.		10		19		
		180		25			140
						30	0
6	12 V.		10		20.5		
		100		27.5			140

Fig. 10-9. Charging Rate Table With Transformer Secondary Data.

An interesting storage battery charging table is given in Fig. 10-9 correlating the battery voltage against maximum and minimum charging rate and the required transformer secondary data. This design data is intended for use with the magnesium-copper sulfide type rectifiers.

DC Supply for Electroplating

The use of metallic rectifiers in DC power supplies for electroplating, electrocleaning, and anodizing was somewhat new before World War II, but "three-shift" operation during the war and their expanded usage after has firmly established them a place in this field.

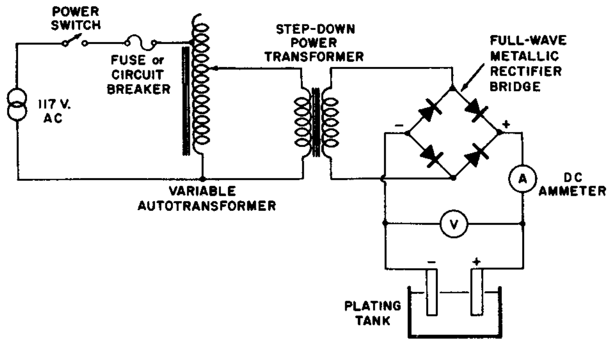
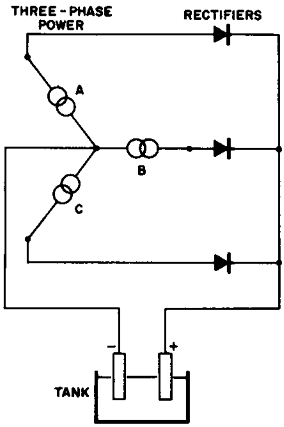


Fig. 10-10. A Single-Phase, Full-Wave Electroplating Circuit.

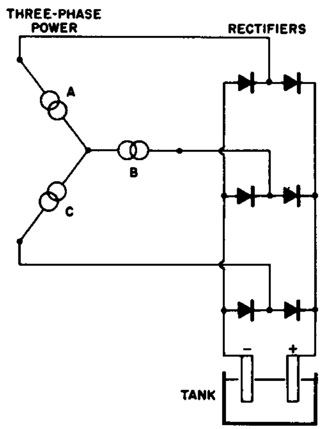
For this electro-finishing application the single-phase, full-wave rectification circuit of Fig. 10-10 is satisfactory for small jobs. It simply involves a means to control the output (the variable autotransformer), a power transformer to reduce the line voltage down to the required lower voltage, a full-wave metallic rectifier, and an ammeter and voltmeter to measure the DC output. Such an arrangement can be compact, noiseless, and simple to use. A portable unit can easily have a rated output of 6 volts at 25 amperes, DC. Other single-phase electro-plating power units are being manufactured with current capacities of up to 150 amperes at 6 volts and with reduced current ratings at the higher voltages of 12, 18, 24, and 48 volts.

Single-phase, full-wave rectification power units are satisfactory for most electroplating, cleaning, and anodizing; often in hard chrome plating which usually requires high current densities and less AC ripple in the output, three-phase type power rectifier circuits are used. Electro-plating rectifiers with DC output ratings over one kilowatt are also manufactured in the three-phase design so as to attain efficient and balanced connection to the factory three-phase power supply of 220, 440, or 550 volts AC.

Fig. 10-11A shows the diagram of the three-phase, half-wave rectification circuit; and Fig. 10-11B the three-phase bridge circuit. Louis W. Reinkin, chief engineer of W. Green Electric co., N. Y. in his series of articles entitled "Rectifiers for Electro-plating", starting with the February, 1947, issue of the magazine "Metal Finishing"*, stresses a good point when he states that he prefers to call the circuit of Fig. 10-11A a three-phase star circuit rather than a three-phase, half-wave rectification circuit. His reason for this preference is that it is common to associate poor efficiency and performance with half-wave circuits of the single-phase type. A three-phase star circuit (three-phase, half-wave) is entirely satisfactory for electrofinishing and is considerably more efficient than a single-phase full-wave bridge circuit. The three-phase bridge circuit of Fig. 10-11B requires six rectifier arms in place of the three half-wave assemblies of the star circuit of Fig. 10-11A for the same output current, but twice the output voltage of the star circuit can be obtained.



(A) Three-Phase, Half-Wave or "Star" Circuit.



(B) Three-Phase Bridge Circuit.

Fig. 10-11. Three-Phase Electrofinishing Circuits.

In three-phase applications of the metallic rectifier, either circuit of Fig. 10-11 is satisfactory for electrofinishing and the final choice is dependent upon the rectifier type selected and the DC output voltage required.

If the plating power supply uses copper-oxide or magnesium-copper sulfide type rectifiers, the three-phase bridge circuit is commonly employed because the lower voltage ratings of these rectifiers make it necessary to use the same total number of rectifier plates for the star circuit and the star transformer is more expensive to build. When selenium rectifiers are employed for the plating power plant, their higher

*Published by The Finishing Publications Inc. Westwood, N. J.

voltage ratings per plate (26 volts rms) permit the efficient application of the star circuit for DC outputs up to 6 to 8 volts, since the bridge type circuit requires twice as many plates and would be less efficient than the star circuit. Above 8 volts DC output the desirable choice for any type of rectifier is the bridge circuit.

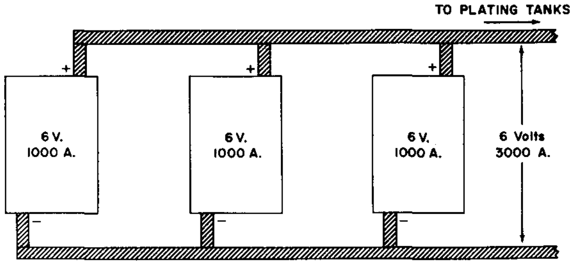


Fig. 10-12. Method of Paralleling Rectifiers for Greater Current Capacity.

Power rectifier assemblies for electrofinishing are available in a wide variety of voltage ratings and current capacities; the 6 volt rating is the most widely used. At this voltage rating units are available with current capacities from 1000 to 5000 amperes. Higher current capacities may be obtained by connecting two or more of these rectifier power supplies in parallel. Fig. 10-12 illustrates the proper polarities to observe when paralleling rectifier units and applies for a system having an output rated at 6 volts, 3000 amperes DC, obtained from three unit assemblies rated individually at 6 volts, 1000 amperes DC.

The series connection of two or more identically rated rectifier power supplies is useful when an output voltage higher than the rating for the individual unit is required. For example, if a DC output of 18 volts at 1000 amperes were necessary, this could be secured by connecting the three power units of Fig. 10-12 in series in the conventional fashion of positive terminal to negative terminal and so on. Series connected rectifiers are particularly useful for anodizing where the final operating voltage for the process is required to range between 40 and 48 volts.

Electrofinishing equipment has to be carefully designed to protect the operator from electrical shock hazards and the power supply components from the corrosive liquids and atmosphere common to such operations. The installations can become somewhat elaborate too, with the switch gearing, meters and the automatic controls. Electric timing meters, which are preset by experience, may be employed for timing the electro-finishing process or amperehour controls may be used which shut off the plating current after a predetermined quantity of amperehours has elapsed rather than an arbitrary time interval. Amperehour control is more desirable for if the voltage, bath temperature, and bath composition are maintained reasonably constant, then the plating thickness can be closely controlled by the setting of the amperehour meter.

Power Supply for DC Motor Application

There are many fields of application for an adjustable speed motor. Although it might appear that this need could be fulfilled by means of a variable autotransformer of the Variac or Powerstat type feeding an AC motor of the series or repulsion type, experience has proven that this arrangement while satisfactory at constant loading will produce wide changes in speed under varying load.

DC motors, particularly the DC shunt or compound type, provide better speed regulation and wider speed range as adjustable or variable speed drives. The problem then is a DC power supply to drive the shunt or compound motor. Again the metallic rectifier lends a hand with the help of the variable autotransformer to facilitate an economical answer to the problem described above. In these arrangements of variable speed motors an adjustable autotransformer of the Variac or Powerstat type feeds a full-wave rectifier bridge to supply thereby a variable armature voltage of 0 to about 125 volts DC to a DC shunt or compound motor. The field of this motor is usually maintained at a constant value with full excitation over the speed range. Sometimes, this field excitation may be reduced to a lower constant value to provide another and higher speed range. Such a system as described provides a speed range of 15 to 1 to as much as 50 to 1. The commercially available variable speed power units fulfilling this system control motors up to 1/3 horsepower and are compact enough to be conveniently installed on the bench near the device to be operated by the variable speed motor.

Applications for which this type of motor controls are especially suitable are: coil winding machines, small lathes, drill presses, and other light machine tools where easily controlled shaft speeds are a requirement or a convenience. Where timing of an operation must be adjustable over a wide range as in electroplating, blue printing machines, and photographic developing; this type of motor control is suitable. In variable speed systems where the load is practically constant, the motor speed will be maintained very close even for small line voltage variations. The reason for this is that in a shunt motor the change in the field excitation partly compensates the armature variation.

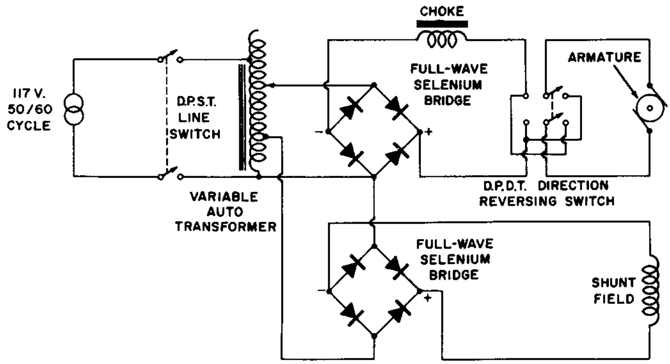


Fig. 10-13. A Speed Control Circuit for a DC Motor Fed From an AC Source.

Fig. 10-13 shows the circuit connections for a metallic rectifier speed control suitable to power a DC shunt or compound motor. You will note that separate full-wave bridge rectifiers are used to supply the armature and shunt field independently. In this way the armature voltage may be varied from 0 to about 125 volts DC, while the shunt field voltage is kept constant over the speed control range. The double-pole double-throw switch provides a means to reverse the direction of rotation of the motor armature while the choke in series with the armature serves to maintain a low ripple current in the armature circuit as well as improve the speed regulation.

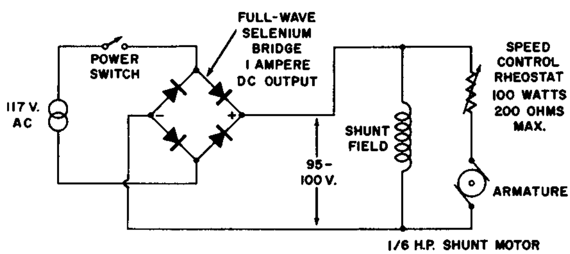


Fig. 10-14. A Simple Variable-Speed Drive Circuit.

A simpler circuit for controlling the speed of a DC motor retains most of the previous advantages but its speed range and regulation are impaired somewhat. It is more ecomical of rectifier bridges and does not use a variable autotransformer but a less expensive rheostat. This circuit is shown in Fig. 10-14 and has been successfully employed with shunt motors of 1/6 horsepower over a speed range of 5 to 1 without compensation for the voltage loss through the full-wave rectifier bridge. The full-wave rectifier is rated at 135 volts rms maximum. At 117 volts rms it has a DC output of 100 volts at 1 ampere. In continuous application both the motor and the rectifier run cold at any position of the speed control.

Rectifier Supply for Automotive Use

This application does not fulfill the statement in the introduction of this Chapter — that of being a current popular use for power rectifiers of the metallic type, but it is likely to prove an important factor in the automotive field in the near future. It is well known that all of the electrical equipment on automotive vehicles is powered from the storage battery and DC generator; the generator also serves to maintain the battery's charge. Recently the electrical demand upon this battery-generator system has increased so greatly that it is becoming more difficult to design economical DC generators which can handle the needs of the new electrical accessories mounted upon the vechicles. The commutator and brushes of the DC generator are especially expensive to build — along with the increased maintenance problems.

The idea being tested which involves the metallic rectifier is to use an alternator whose output is rectified by a full-wave bridge type rectifier. This combination offers economical design, less rotating and moving parts to maintain (for there are no brushes and commutators), automatic and better voltage regulation with varying engine rpm, and automatic reverse current protection. In addition, it is feasible to use the AC output directly for such electrical equipment as the radio, lights, electric gauges, heater, and windshield wiper with beneficial results in cost and service.

By careful design of the alternator, it is possible to obtain almost constant voltage output without the troublesome electro-mechanical voltage regulator used with the present DC generator and storage battery combination. This feature alone results in longer electric light life and simple design for the electrical fuel, oil pressure, and engine temperature gauges.

A simplified circuit presenting the basic idea of the full-wave metallic rectifier applied in the automotive field is given in Fig. 10-15. This figure is self-explanatory; however, it is to be noted that the rectifier bridge because of its unilateral conductivity acts as a reverse current cut-out relay, since it prevents the storage battery from discharging back into the stator windings.

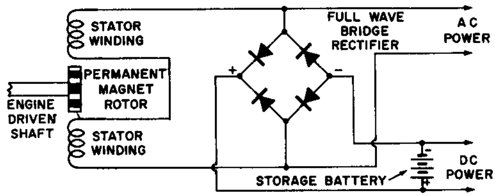


Fig. 10-15. Metallic Rectifier Application in Automotive Vehicles.

Several of the large automotive vehicle manufacturers have been running road tests on cars equipped with metallic rectifier systems similar to that described above and there is a good possibility that this versatile power rectifier may soon invade the automotive field.

Cathodic Protection Against Corrosion

The last application of metallic rectifiers of the power type to.be discussed in this section is cathodic protection against corrosion. This is the protection of metallic structures which have to be buried in soils or immersed in water, for example, oil and gas pipe lines, bottoms of metal storage tanks, lead sheathed cables for telephone and electric power work, water tank installations, submerged portions of building structures, and the like.

Any metallic structure buried in soils or immersed in water is subject to corrosion because destructive electric currents which are generated by chemical action between structures and the surrounding electrolytes strip off minute particles of the metal until the buried metallic structure, pipe, steel beam, or metal surface becomes so weakened that it is eventaully destroyed. Hence, corrosion of buried or submerged metal is the result of electrical current flowing from the metal into the surrounding soil or water. This current flow carries metal particles of the structure away from it in minute quantities and the result is corrosion or electrolysis. Over a period of time this electrolytic action will result in leaks in pipes or disintegration of metallic structures which have to be buried or submerged. This electrolytic corrosion can be overcome if direct current can be induced to flow from the surrounding soil or water toward the metal pipe or structure being protected instead of away from it. This type of protection is called cathodic protection and involves the flow of direct current through the soil or water to the entire exterior of the structure or a current flow direction opposite to that of the corroding current.

For this type of protection a continuous and economical source of DC is required; this is easily secured from metallic rectifiers, particularly of the selenium type. Usually, the installations for this type of service operate at a voltage of 2 to 12 volts and at a current capacity of from 10 to 1000 amperes depending upon the surface area to be protected.

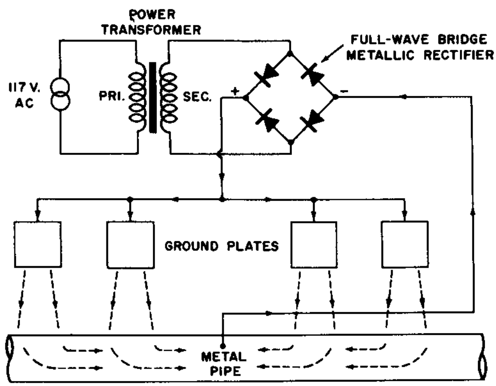


Fig. 10-16. Cathodic Protection of Buried Metal Pipe.

Fig. 10-16 illustrates an installation designed to protect a section of metallic pipe buried in the soil and carrying oil, for example. The corrosion of this pipe can be caused by stray or electrolytic DC currents flowing away from this pipe. This galvanic action may be counteracted by making the pipe negative (cathodic). To do this requires an external source of electric potential applied between the pipe and earth, forcing the pipe potential below the earth potential and maintaining it there. To do this, an AC source is coupled to a power transformer, to the secondary of which is connected a full-wave metallic rectifier. The positive terminal of the rectifier is connected to a number of grounding plates, while the negative terminal is connected to the pipe as shown. Direct current flows from the rectifier to the ground plates buried at a suitable distance from the protected pipe, through the earth to the pipe and back to the rectifier again. This system renders the pipe cathodic to the soil electrolyte and protects it against corrosion.

CHAPTER 11

Applications of Small Current Rectifiers

Introduction

Small current or power rectifiers have been classified as those having a DC output of one ampere or lower. While these metallic rectifiers can be any one of the three types previously discussed (copper-oxide, magnesium-copper sulfide, or selenium) and of the half-wave or full-wave structure, they are generally designed for single-phase operation. The most popular type employed for applications requiring this current capacity is the selenium. Compactness, light weight, low cost, and satisfactory voltage rating are the chief reasons for this

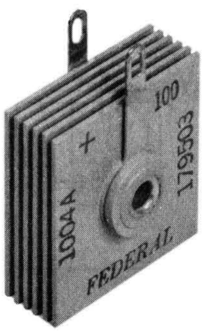


Fig. 11-1. A Small Selenium Power Rectifier. (Courtesy of Federal Telephone and Radio Corp.)

choice. The photograph of Fig. 9-1 displayed one example of such rectifier assemblies. If the structure is selenium, stock assemblies rated at 130 volts rms maximum, half-wave, single-phase, are easily and economically available from most electronic supply dealers and cover current capacities of 25 to 1000 milliamperes. As an example, the physical size of a 500 milliampere selenium rectifier assembly consisting of a 5 plate structure is 1 1/2 x 3 inches with a stack height of 1 5/16 inches. Fig. 11-1 illustrates a single-phase, half-wave selenium rectifier rated at 130 volts rms maximum, with a current capacity of 100 milliamperes DC. It consists of 6 selenium plates assembled upon an insulated bushing with two terminal members so arranged that soldering the rectifier into an application circuit will not damage the active rectifier areas by overheating. The physical size of the plates are 1 x 1 inch and the overall stack height is about 3/4 inch. This type of power rectifier is used in great numbers in power supplies for radios, television receivers, amplifiers, and other electrical devices requiring small amounts of DC power. A few examples from some of the more useful applications will illustrate their deserved popularity.

DC Power Supply for Electric Shavers

Most electric shavers use AC to power the internal electric motors which are designed to operate on either AC or DC. If a DC supply were always available these shavers could provide a more smoother, comfortable shave because the speed

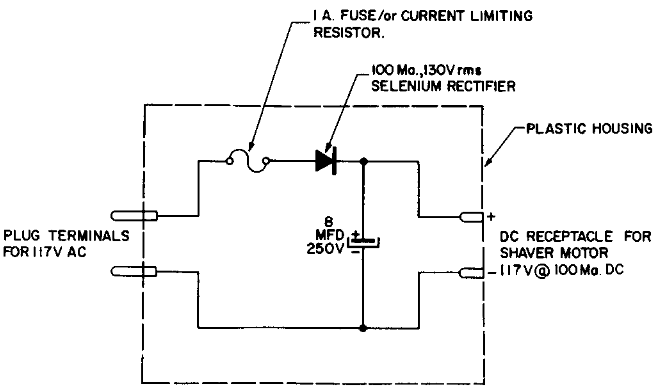


Fig. 11-2. A Selenium Rectifier Power Converter for Electric Shavers.

and performance of the shaver motor can be improved by a factor of as much as 25% by applying DC in place of the usually available AC. Any converter device for this application would have to be inexpensive, compact, and immediately ready for operation upon the application of AC power. The small selenium rectifier has provided a suitable solution to this problem. The shaver converter is available in a compact plastic housing which has means to plug into the convenience outlet of a 117 volt AC supply. A receptacle in this plastic housing is the DC source of power for any AC/DC shaver and about 115 volts at 100 milliamperes of rectified and filtered DC is supplied under load conditions to a typical shaver motor. The circuit is given in Fig. 11-2. As shown in this diagram, the fuse and current limiting resistor may be combined. The purpose of the 8 mfd 250 volt electrolytic capacitor is to provide smooth delivery of DC power over both the conducting and non-conducting half-cycles of the applied input in the manner discussed in Chapter 9.

DC Power Supply for Phonograph Amplifier

Most compact electrical phonographs are designed to contain in a suitable housing about the size of a typewriter case the motor driven turntable, a tone arm carrying a crystal cartridge with its stylus structure, an electronic amplifier, and the loudspeaker. The device is intended for operation on AC because the shaded pole motor used in such applications runs the turntable at approximately the 78 rpm despite line voltage changes of reasonable magnitude. The electronic amplifier, however, even though it may involve only one radio tube, will need DC voltages to polarize and power its electrode elements.

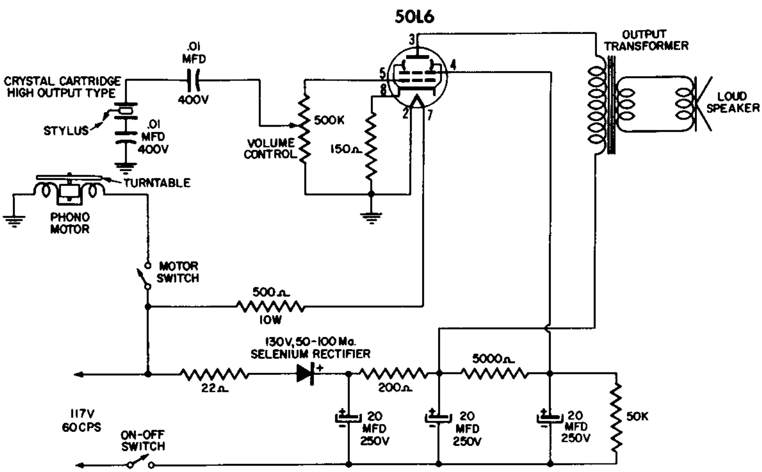


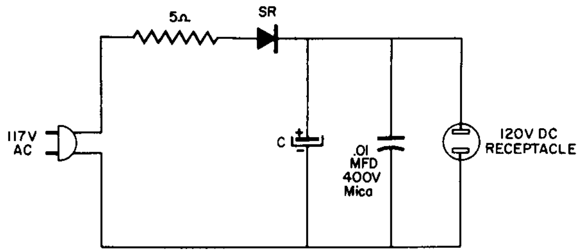
Fig. 11-3. A Phono Amplifier Using a Selenium Rectifier Power Supply.

This DC supply should be inexpensive, compact, and efficient so as to minimize heat dissipation within the confined cabinet. A selenium type small power rectifier will be suitable and a typical diagram of such an application is shown in Fig. 11-3.

The turntable motor is driven by the 117 volts AC input of suitable frequency, usually 60 cycles per second. The electronic amplifier, however, requires DC potentials which are obtained by means of the half-wave selenium rectifier which is rated at 130 volts rms at a current capacity of 50 to 100 milliamperes. The output of the rectifier is well filtered by means of two stages of resistance-capacitance filters to minimize electrical hum in the loudspeaker. This well filtered DC source then powers the elements of the tube which drives the loudspeaker when the electrical signals from the crystal cartridge are applied to the control grid of the tube.

Power Supply for Small Electrical Devices

Frequently, it is necessary to power some DC actuated device when the only convenient power source is the AC line.



SELECT SELENIUM RECTIFIER SR WITH ADEQUATE CURRENT RATING FOR DESIRED CURRENT OUTPUT.

SELECTION CHART FOR CAPACITOR C
ELECTROLYTIC RATED AT 250V

CURRENT OUTPUT DC	REQUIRED C IN MFD
250 Ma.	40
300 Ma.	50
350 Ma.	60
400 Ma.	70

Fig. 11-4. A Selenium Rectifier Power Supply Suitable for Small Electrical Devices.

Such devices may be small motors, DC electromagnets, relays, and the like. A suitable power conversion device for these applications giving the appropriate circuit constants for a number of current capacities is given by Fig. 11-4. The arrangement uses the familiar half-wave selenium rectifier consisting of a 5 plate assembly and has a DC output rating of about 120 volts. The 0.01 mfd mica capacitor which is shunted across the DC output terminals is not absolutely necessary for the proper functioning of this power supply, but it does minimize line carried electrical disturbances of impulse or high frequency character which may upset the operation of the DC device powered from this supply. Otherwise, the operation of this circuit is as described in Chapter 8, under the heading "Single-Phase, Half-wave Rectifier with Capacitor".

DC Supply for Magnetic Chucks

Grinding and polishing machines require magnetic chucks to hold the work pieces in place during these operations. A metallic rectifier system for supplying the DC power necessary has the advantage of simplicity, no waiting time for heater warm-up (as in tube type rectifiers), compactness, and practically zero maintenance. A satisfactory circuit to supply 280 volts at 500 milliamperes DC is diagrammed in Fig. 11-5.

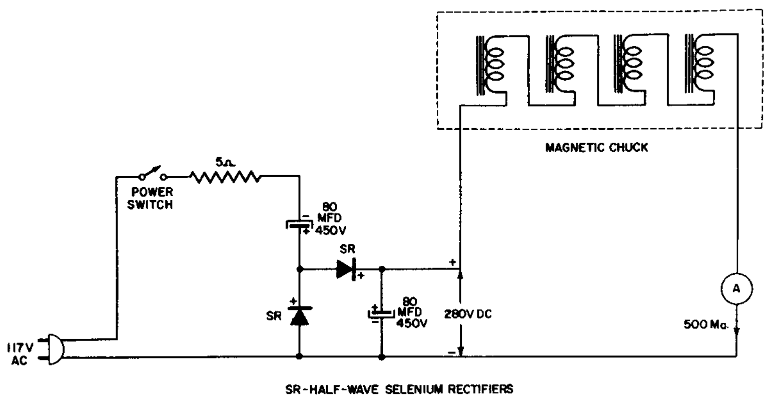


Fig. 11-5. Selenium Rectifier Power Supply for a Magnetic Chuck.

This circuit uses the principle of the voltage doubler scheme previously discussed to secure an output voltage greater than the AC input without the use of step-up transformers.

AC-DC Radio Power Supply

The next application of small power rectifiers of the metallic type to be discussed here involves radio receivers, usually, of the "table" type which are so designed to operate on either an AC or DC supply of 117 volts without switching or relay devices. With this type of universal supply on DC it is only necessary to be sure that the plug on the end of the power cord is inserted into the line receptacle correctly so as to match the positive polarity of the power line with the positive polarity of the plug terminal. No damage is done if the plug is reversed on the first try except that the radio will not operate after the usual warm-up time has elapsed. It is then necessary to "reverse" the plug in the line receptacle to ensure proper operation on the DC supply. The rectifier which is used in this type of circuit serves no useful function on the DC supply. If the same plug is now inserted into an AC receptacle, the AC-DC radio receiver still operates properly and in this case the rectifier and its associated filters are doing

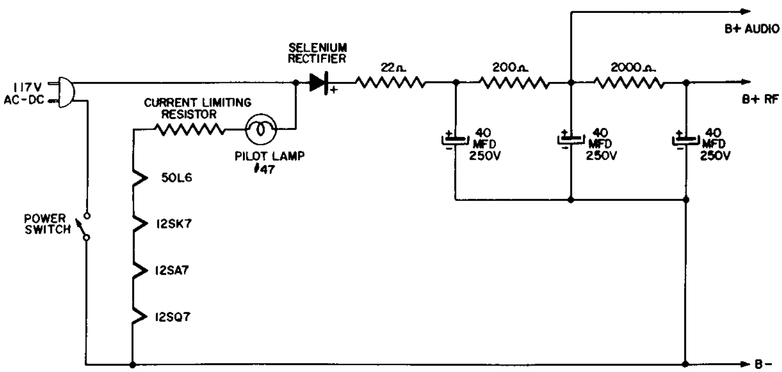


Fig. 11-6. An AC-DC Radio Power Supply Using Selenium Rectifiers.

the work to make this possible. The circuit is given in Fig. 11-6. The heaters of the four conventional radio tubes used for radio reception are wired in series with a current limiting resistor, and pilot light across the power line when the power switch is actuated.

Television Power Supplies

A power supply commonly used in television receivers is a half-wave, voltage-doubler circuit using two selenium rectifiers. A circuit employing this method is shown in Fig. 11-7. In this circuit, a filament transformer is used to supply one 12.6- and two 6.3- volt sources for tube filaments.

The 5- ohm resistor R1 functions as a current limiter which opposes the initial surge current occurring when capacitor C1 first charges. This resistor also acts as a fuse and protects some of the more expensive components in case a short circuit develops across the output load.

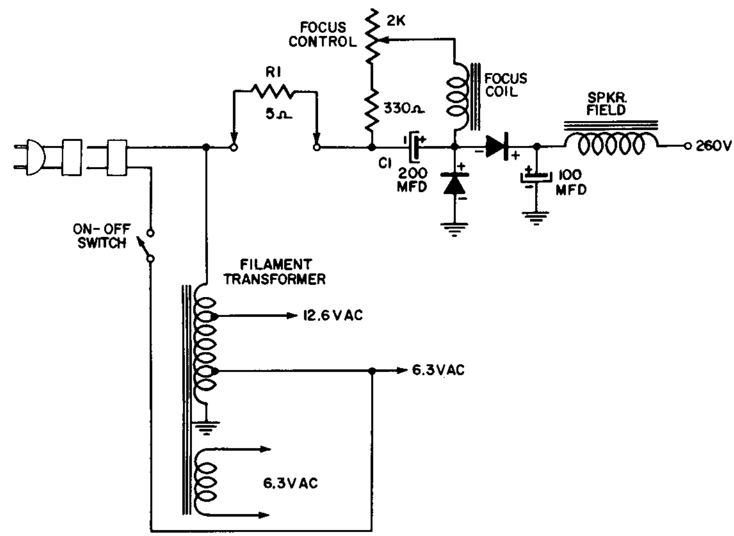


Fig. 11-7. Half-Wave, Voltage-Doubler Circuit Employing Selenium Rectifiers, Used in Television Power Supplies.

One of the simplest and perhaps the most popular low-voltage power supply used in TV receivers is the half-wave

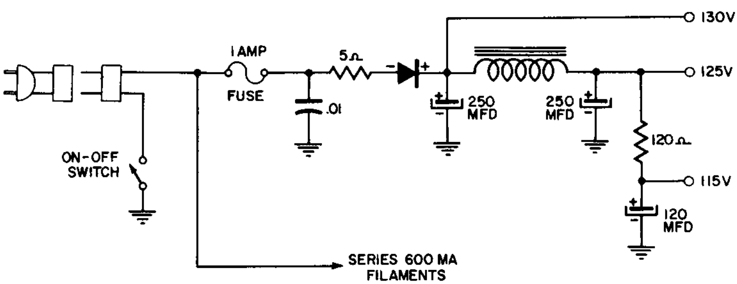


Fig. 11-8. Conventional Half-Wave Rectifier System Using Selenium Rectifiers.

rectifier system shown in Fig. 11-8. Somewhat larger values in the filter network are required for a circuit of this design. The receiver used in this example employs a series filament string; and is typical of the newer chassis designs.

Sarkes Tarzian, Inc. has made available a unit which will enable the service technician to plug selenium rectifiers into a set in the same manner that tubes are inserted. This conversion chassis Model CC-1, together with a pair of typical selenium rectifiers may be seen in Fig. 11-9.

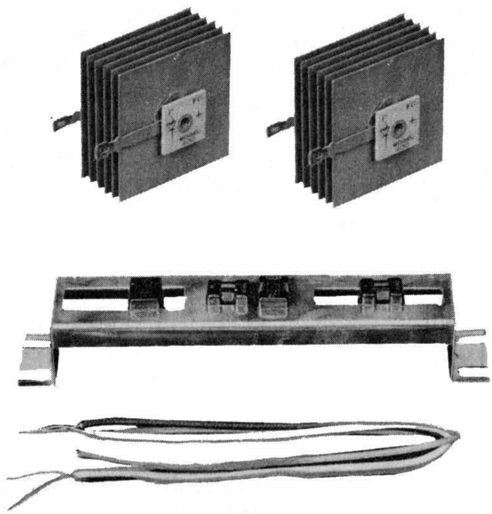


Fig. 11-9. A Pair of Selenium Rectifiers Together with Conversion Chassis Model CC-1 Made by Sarkes Tarzian, Inc.

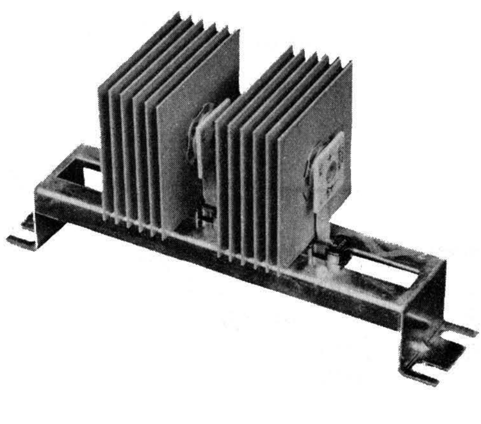


Fig. 11-10. View of Conversion Chassis with Rectifiers in Place.

Fig. 11-10 shows the rectifiers after they have been plugged into the conversion chassis. The only step necessary before the rectifiers can be plugged in is to twist the positive terminal on each rectifier 90 degrees. Twisting the lug in this way ensures that the rectifier will always be in the correct polarity when it is inserted.

CHAPTER 12

Instrument Rectifiers

Introduction

The usual type of instrument used in the measurement of voltage and current in alternating current circuits depends upon the moving iron vane principle. In this type of measuring instrument the voltage or current to be indicated energizes a solenoid within the instrument case which in turn reacts upon a pivoted iron vane carrying with it the instrument pointer. Although such instruments are rather accurate (1 to 2%) and are commonly used for measurements in AC circuits, there are three major limitations accompanying their usage: first, considerable power must be "robbed" from the circuit in which it is desired to make the measurement, that is, the instrument sensitivity is poor; second, as compared with the linear scale properties of DC instruments, the scale of commonly used AC instruments is nonlinear and rather crowded at the lower end. Fig. 12-1 shows a comparison of the linear scale of a 0 to 1 volt DC voltmeter to that of an AC voltmeter of the moving vane type covering the same voltage range. The third limitation of commonly used AC measuring instruments is the narrow frequency range; the frequency response of the moving vane type AC meter is limited to a few hundred cycles at most – usually about 125 cycles per second.

Fig. 12-1. Scale Comparison of AC and DC Meters.

These disadvantages, namely, excessive power consumption, nonlinear scale spread, and limited frequency response may be overcome by using the more sensitive meter movement of the D'Arsonval type equipped with instrument type metallic rectifiers to permit operation on AC circuits. It is true that the accuracy of this type of AC meter is not as good as that obtained from the moving vane type and that means must be provided for compensation of certain conditions, yet for many electronic and communication circuits, the loading presented by moving vane instruments allows no readings at all or readings in error by several hundred per cent. Hence, the 3 to 5% error normally attributed to rectifier meter type of AC instruments becomes quite attractive.

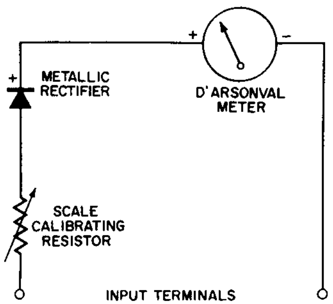


Fig. 12-2. Rectifier Type AC Voltmeter.

Fig. 12-2 shows a simple circuit for converting a D'Arsonval meter movement into an AC measuring instrument — in particular an AC voltmeter. The arrangement consists of a calibrating resistor, half-wave metallic rectifier, and a D'Arsonval meter, all connected in series. The rectifier converts the alternating current into pulsating direct current, the moving coil meter indicates the average value of this current, and the calibrating resistor establishes the value of the AC input potential necessary to deflect the meter pointer to full scale.

Using Fig. 12-2 as our pattern for rectifier type AC measuring instruments, we can see that they consist essentially of a device for rectifying the alternating current and a moving coil meter to indicate the value of the rectified direct current supplied by the rectifier. The moving coil meter is a current operated device, commonly a microammeter or milliammeter movement, wherein the deflection of the indicating pointer is proportional to the current flow through the moving coil. Therefore, the sensitivity of the rectifier meter combination is determined by the ratio of the forward to reverse current that the rectifier is capable of producing in the moving coil of the meter. This ratio depends upon the rectifier type selected and upon the circuit in which the rectifier is used.

Some Required Properties of an Instrument Rectifier

The metallic rectifiers used in rectifier type AC meters are called instrument rectifiers; although they operate on the same basic principle of unidirectional conductivity common to all metallic rectifiers, their successful operation for instrumentation purposes requires certain properties not necessarily important in other rectifier applications. The more important of these properties are: no threshold effects, permanence in characteristics, and high efficiency and stability. Without getting too involved into the ideal requirements of an instrument rectifier, we know that the above considerations limit our selection of the type to that of the copper-oxide rectifier.

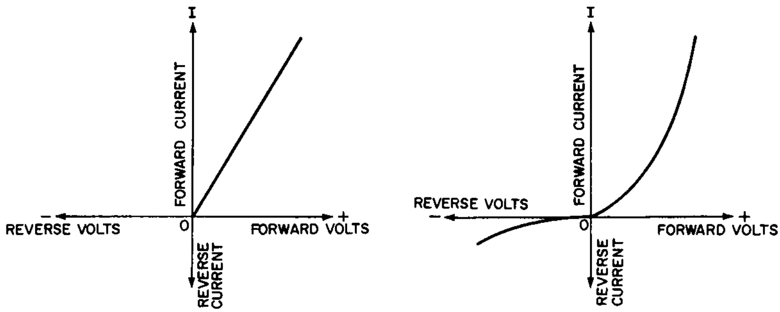
This type metallic rectifier is the only one of the three types previously discussed which does not exhibit some threshold effect, that is, it does not require a critical value of input or applied voltage before current conduction results.

By requiring permanence of characteristics as a property in the desired rectifier for instrument application, we mean minimum "aging" or changes in the electrical properties of the rectifier after it has been applied and calibrated into the meter circuit.

By high efficiency we desire a high ratio of forward to reverse direct current; and by stability we desire minimum changes in rectifier properties due to external effects, such as temperature, atmospheric conditions, and the like.

From our previous study of metallic rectifiers we learned that the process of rectification depended upon the property known as unidirectional or unilateral conductively; moreover, we found that this "unilateral conductivity" is not perfect — that there is always some current flowing through the rectifier in the reverse direction when the applied potential is reversed, as when applied in an AC circuit. Thus, whereas the ideal instrument rectifier should have the volt-ampere characteristics shown in Fig. 12-3A, in practice this characteristic is more nearly like Fig. 12-3B.

The ideal characteristic shows no leakage or reverse direction current flow, no threshold effects, and a linear forward current flow with the applied forward potential. The characteristic of available instrument rectifiers show that as the reverse potential is increased, an increasing amount of leakage current flows and that, although there is no practical threshold effect, if the copper-oxide type of rectifier is used, the forward characteristic is not linear; for equal increments of applied voltage more current flows at higher levels of potentials than for lower levels of potential. The undesirable leakage current of the practical rectifier reduces its efficiency and complicates its application in multi-range instruments. The non-linear forward characteristic makes it more difficult to approach linear AC scales and conformity of scales between ranges of multi-range AC meters; however, both of these effects can be compensated in instrument applications.



(A) Ideal Characteristic. (B) Practical Characteristic.

Fig. 12-3. Characteristics of Theoretical and Practical Instrument Rectifiers.

By requiring permanence in the instrument rectifier, we want minimum drift or aging in the rectifier so that the factory calibration of the rectifier meter combination will be retained. Aging in metallic rectifiers can be caused by mechanical damage, chemical action, improper processing during manufacture, or overheating the active areas when soldering the rectifier into the application circuit.

The reader will recall that the unidirectional conductivity of the copper-oxide rectifier is due to the copper-oxide barrier layer; this layer is of a crystalline nature. All crystals are solids and their forms can not be changed by mechanical means without fracturing the crystal. In the crystalline layer which represents the rectifying or barrier junction in the metallic rectifier, any mechanical stresses which cause even slight deformation of the rectifier disc will tend to produce minute cracks in the crystals forming the barrier layer. These minute cracks or fractures in the crystalline layer cause permanent changes in the electrical properties of the rectifier. For this reason, rough handling, subjection to mechanical stresses, or inaccurate dimensions in manufacture, which result in areas of uneven compression upon the assembly of the rectifier discs, are to be minimized in instrument rectifiers if "aging" or permanent changes in the electrical properties of the rectifiers are to be avoided.

Chemical action also causes aging. This chemical action can be the result of incorrect or incomplete processing during the manufacture of the rectifier or due to external chemical action from contamination in the atmosphere. The presence of rubber insulation in the proximity or contact with the rectifier is detrimental too. An adequate lacquer coating is usually sufficient protection against atmospheric contamination but sulfur compounds in the rubber are more difficult to counteract.

Overheating metallic rectifiers when soldering them into circuits can also cause aging or change in its electrical properties. For this reason most instrument rectifiers are provided with flexible, multi-stranded wire leads so as to preclude direct soldering to the rectifier terminals. These flexible leads are soldered to the terminal plates before the rectifier is processed and assembled; in this way direct soldering to the rectifier terminals is avoided for such procedure can cause intense localized heating resulting in uneven expansion of the rectifier discs common to the terminals and thus cracking the crystalline rectifying junctions. This brings about loss of rectifying efficiency and change in the electrical characteristics of the instrument rectifier.

Physical Description of Instrument Rectifiers

Instrument rectifiers are the specialized class of metallic rectifiers having disc areas much smaller than those used for conventional power supply units. The smaller physical size serves three useful purposes. First, the reduced active area provides less shunting capacitance; this helps improve or extend the high frequency response of the rectifier. Second, the reduced active area increases the current density of the rectifier helping to reduce its forward resistance. Third, the smaller physical size makes more practical the special processing required in instrument rectifiers to obtain the necessary electrical properties. One such special process is the thin layer of pure gold which is sputtered on the cuprous oxide film and upon the reverse side of the rectifier disc to improve the electrical conduction and to protect the active surfaces.

Sketches of two types of instrument rectifiers are shown in Fig. 12-4. They represent the full-wave bridge structure although instrument rectifier assemblies may also be obtained in half-wave or special combinations of rectifier discs. In the rectifier shown in Fig. 12-4A the disc diameter is about 1/2 inch and the active area of each disc is about 0.15 square inch. Usually 2 to 3 inches of braided, tinned, copper leads are furnished already soldered to the cell terminals. Nickel plated end plates and an insulated machine screw hold the assembly together. The whole assembly is coated with one or more layers of clear lacquer as a protection against atmospheric conditions. In a conventional bridge arrangement such an instrument rectifier has a continuous electrical rating of 5 to 10 volts rms input and a DC output current of 30 milliamperes. This type of rectifier is suitable for the operation of less sensitive or more robust meter movements, relays, and other electrical devices requiring more than one milliampere of rectified output. It is also suitable for all commercial and lower audio frequency applications and will operate up to 50,000 cycles per second in arrangements where the accuracy of the meter reading is not important.

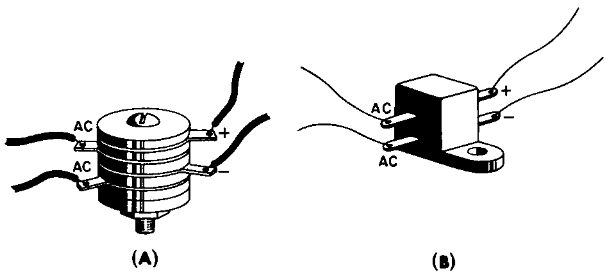


Fig. 12-4. Instrument Rectifiers.

The instrument rectifier shown in Fig. 12-4B has a disc diameter of approximately 0.15 inches and an active area of 0.02 square inches. This rectifier is also furnished with 2 to 3 inches of stranded, tinned, copper leads. The assembly structure is not evident because it is sealed in a moisture proof compound. This type rectifier is suitable for extended frequency range with a meter, relay, or other device requiring less than one milliampere of current for operation. With special circuitry and care, frequency response up to 15,000,000 cycles per second can be attained with the type rectifier shown in Fig. 12-4B. Its normal continuous electrical rating is 2 to 5 volts rms input and it can supply up to 5 milliamperes output current.

The Half-Wave Instrument Rectifier Circuit

The simple circuit of Fig. 12-2, which illustrates the application of a half-wave instrument rectifier to a moving coil DC meter along with the calibrating resistor to provide us with a rectifier-type AC voltmeter, will serve if we are not too critical of the linearity of the instrument scale and if we do not propose to make it into a multi-range instrument as shown in Fig. 12-5. For example, suppose we wish to construct a two range, rectifier-type AC voltmeter patterned after Fig. 12-5 and covering the full scale ranges of 5 and 100 volts rms. Having selected a suitable half-wave copper-oxide rectifier and a 0 to 1 DC milliammeter it is first necessary for us to decide upon the value of the series multiplier resistor to be used in the 5 volt range. If the input were 5 volts DC and we did not use the rectifier, we would know at once that the multiplier resistor should be 5000 ohms. How would we know this? For an input of 5 volts DC we desire a full scale indication of the milliammeter pointer (which requires 1 milliampere). The multiplier resistance R, equals E/I or 5 volts divided by 0.001 ampere or 5000 ohms, the proper value for the multiplier resistance for the low range.

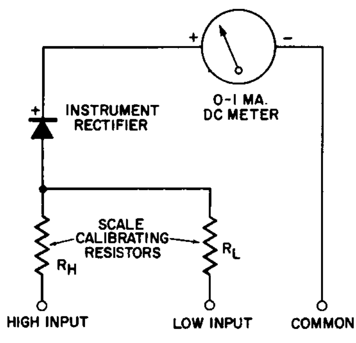


Fig. 12-5. Multi-Range Rectifier-Type AC Voltmeter.

Another way of saying the same thing is to say that the DC voltmeter just described has a sensitivity of 1000 ohms per volt.

When we apply the half-wave rectifier to the voltmeter circuit to permit measurements in AC circuits, this value of 5000 ohms for the 5 volt range is too much. One reason for this is that in the half-wave rectifier circuit, current flows during every other half cycle of the input in the manner previously explained; the other reason is that we have neglected to take into account the waveform of the alternating input.

If our AC input were rectangular as shown in Fig. 12-6, the half-cycle flow of current would necessitate the reduction of the 5000 ohms resistance by one half to secure full scale indication on a half-wave circuit. This multiplier resistance of 2500 ohms assumes that the input is alternating but of a rectangular waveform, for we have assumed that the 5 volts full scale input was applied during the whole half-cycle period.

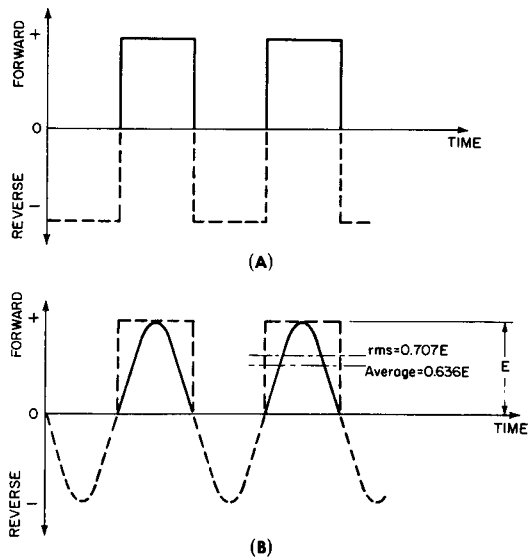


Fig. 12-6. Rectangular and Sine Waveforms.

We know that when 5 volts AC is applied to our meter (for which we desire a full scale indication), we mean 5 volts root-mean-square. We also know from previous explanations of alternating current circuits that the peak value of a sine wave is 1.414 time the rms value or if the peak value is E then the rms value is 0.707E, that is, E divided by 1.414. Furthermore, we know that the average value of a sine wave is 0.636E. Thus, when we apply 5 volts rms to our rectifier type voltmeter, the peak value of the voltage applied is 5 times 1.414 or 7.070 volts; and the average value of this voltage is 7.070 times 0.636 or approximately 4.5 volts. We are interested in this average voltage for this is the value of the potential which causes the average current to flow — the value of current which is indicated by our moving coil meter. The average value of voltage, 4.5, divided by the average full scale current, namely 0.001 ampere, would indicate a multiplier resistance of 4500 ohms, and since this average voltage is present but half of the time (due to the half-wave rectification of the AC input), we must halve the series multiplier resistance if we desire the full scale current to be 0.001 ampere; hence, it appears that the value of this multiplier resistance is 2250 ohms.

One additional factor must be included in our computations to approach the ultimate value of this multiplier resistance; the forward resistance of the half-wave rectifier must be considered. Correcting for the voltage drop across the forward resistance a value of about 2000 ohms for the multiplier resistance for the 5 volt range is just about right; and for the 100 volt range one would say that 20 times 2000 ohms or 40,000 ohms was correct. These computations have neglected the resistance of the moving coil of the meter which is in series with the multipliers. For a typical 0 to 1 milliampere DC meter this resistance may range from 50 to 200 ohms and must be considered as part of the multiplier. This factor and the lengthy discussion as to why the multiplier resistance amounts to about 400 ohms per volt instead of the familiar 1000 ohms per volt are given so that the reader will better understand some of the problems in the commercial application of the instrument rectifier. Here however, we want to see chiefly why the rectifier's reverse current gets us into difficulty when we attempt to construct a multi-range AC voltmeter such as that shown in Fig. 12-5.

We have tried to design a two range, half-wave rectifier type AC voltmeter having the ranges of 5 and 100 volts AC rms. We have computed the values of the multiplier resistances in the foregoing and found them to be 2000 ohms and 40,000 ohms respectively. Upon testing the newly designed circuit we find that when we apply 5 volts we obtain a full scale pointer deflection when using the 5 volt range of the instrument. However, when we use the 100 volt range and apply 100 volts AC rms to the input, we find that the pointer deflects only about 50 percent of full scale. The reason for this discrepancy is that our computations for the multiplier resistance have been based upon forward current alone — assuming that the reverse resistance of the rectifier was infinite. Actually this reverse resistance of the half-wave rectifier may be for example, 50,000 ohms resulting in a reverse or leakage current of 0.1 milliampere on the 5 volt range and 2 milliamperes on the 100 volt range; these results are obtained by using Ohm's law to determine the full scale reverse current. The full scale forward current is fixed for the two ranges and is 5 volts divided by our multiplier resistance of 2000 ohms or 2.5 milliamperes for the low range and

100 volts divided by 40,000 ohms or again 2.5 milliamperes for the high range. The forward to reverse current ratio on the low range of our simple voltmeter is 2.5/0.1 or 25, whereas for the high range it is 2.5/2 or 1.25. This decrease of current ratio as a result of an increase of reverse direction voltage decreases the rectification efficiency causing a reduced pointer deflection for the 100 volt range. This experience clearly shows that for more uniform full scale pointer deflection in multi-range, rectifier-type AC voltmeters someway must be devised to reduce the reverse voltage across the half-wave rectifier.

The Half-Wave Instrument Rectifier Circuit With Resistance Shunt

An arrangement which will hold the reverse voltage to a low value is obtained by shunting the series combination of the meter and the half-wave rectifier with a resistance. A circuit using this idea in a two-range AC voltmeter is given in

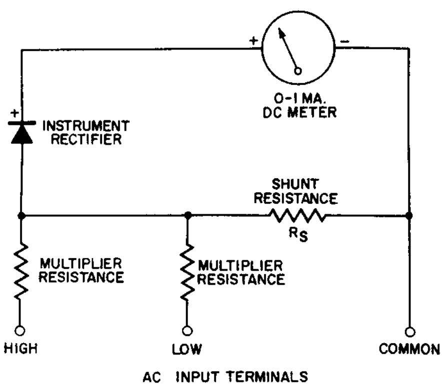


Fig. 12-7. Rectifier-Type AC Voltmeter Using Resistive Shunt.

Fig. 12-7. The reader will note that it is similar to the previously discussed circuit of Fig. 12-5 but with the addition of Rs the shunting resistor. This shunting resistor, in conjunction with the active multiplier resistance, provides a voltage divider arrangement so that the voltage drop across the rectifier-meter combination is held to the same low voltage on all ranges of the voltmeter when the input potential has reversed its polarity (as during the non-conducting half cycle on an AC source). By this circuitry, the value of the reverse or leakage current through the rectifier and meter has the same value for both ranges of the voltmeter.

With the forward to reverse direction current ratio fixed by this shunt resistance scheme, the rectifier efficiency and the meter scale curvature are alike on both ranges.

The value of the shunt resistance has two limits: infinity, as in the example of Fig. 12-5 wherein we ran into the scale trouble on the two desired ranges; and short-circuit, in which case no useful meter indication can be obtained. Between these two limits we can experimentally find a value of shunt resistance which will make the scale of the two ranges of our voltmeter about uniform. Say that a typical value for this shunt is about 1000 ohms. Having applied this value of shunt resistance we find that for our gain in uniformity of scale between the two ranges, we must pay by a reduction of meter sensitivity in the form of decreased values for the multiplier resistors — or in a lower "ohms per volt".

Moreover, the scheme of holding the reverse direction voltage to low values by this shunt circuit also works in a like manner for the forward direction voltage; that is, the shunt circuit maintains the forward voltage to a low value at full scale regardless of which range is used. At half scale the voltage developed across the shunt (which is part of the voltage divider circuit when considered in conjunction with the active multiplier) is one half that required for full scale indication and the same proportion holds for any partial scale voltage. Operated under these conditions the current density property of the rectifier causes the AC meter scale to depart from linearity resulting in bad crowding towards the zero end of the scale. This current density property is the familiar characteristic of the rectifier in which the forward resistance is not fixed but decreases as the current through the rectifier increases. This forward resistance has a maximum value for small magnitudes of forward current and reduced values for larger forward current flow. When the rectifier input voltage is maintained fixed by a resistive shunt as in Fig. 12-7 to a value proportional to the voltage impressed across the instrument terminals, the resistance increase in the rectifier causes less current to flow in the rectifier meter circuit which further increases the rectifier resistance because of its current density property, until an equilibrium is reached at a point on the meter dial substantially below the point on the linear scale corresponding to the voltage being measured.

We can see that the shunting resistor idea of Fig. 12-7 has made possible uniform AC scales for the two (or more, if desired) ranges of our voltmeter but the price we have to pay for this advantage is reduced sensitivity and a crowded graduation for the lower portion of the meter scale.

The Half-Wave Instrument Rectifier Circuit With Rectifier Shunt

If we could devise a shunt which would be active during the nonconductive cycle of the input potential to the meter, and inactive during the conducting cycle of the input potential to the meter, we might approach our ideal of uniform scales between ranges, a linear scale, and suitable sensitivity. This thought suggests using a half-wave rectifier similar to the meter rectifier as the shunting element of the voltage divider of the circuit shown in Fig. 12-7. This new arrangement is given in Fig. 12-8.

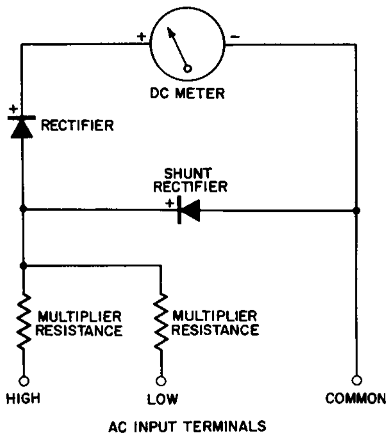


Fig. 12-8. Half-Wave Rectifier-Type AC Voltmeter with Rectifier Shunt.

We are now in the fortunate position of having a shunt which is active during the reverse polarity half-cycle of the input and this reverse direction voltage is held to a lower value than can be realized by any practical resistive shunt scheme. Other advantages of the method of Fig. 12-8 are: the shunt rectifier is not active during the forward half-cycle with the result that the input voltage to the rectifier-meter combination approaches the linear DC scale, and the higher sensitivity of the circuit of Fig. 12-5 is recovered.

The Full-Wave Instrument Rectifier Circuit

The three instrument rectifier circuits discussed thus far are half-wave operated and are suitable at input frequencies higher than say 50 or 60 cycles per second. As the frequency of the input is reduced or where the input is of a lower frequency, say 25 cycles per second, the above circuits are no longer satisfactory. Their failing is that at lower frequencies the inertia of the meter movement is not sufficient to reduce or "snub" the pointer vibration caused by the half-cycle flow of current. That is, the period of no-current conduction is long enough at low frequencies to cause the hair springs of the meter moving system to partly restore the meter pointer towards zero. During the next conductive half-cycle, a pulse of forward current pushes the pointer up again.

At 50 to 60 cycles per second these periods of activity and inactivity occur so fast that the inertia of the coil and pointer system average out the vibration. Another reason that the half-wave circuits described may not be satisfactory even at medium frequencies is that more instrument sensitivity may be required. We can approximately double the sensitivity and at the same time reduce the pointer quiver by eliminating the non-conducting half-cycle if we can devise a full-wave instrument rectifier circuit to overcome these limitations. A full-wave circuit is shown in Fig. 12-9.

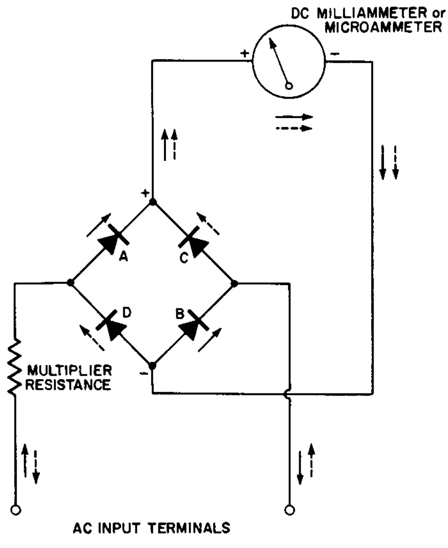


Fig. 12-9. A Full-Wave Rectifier-Type AC Voltmeter.

The DC output terminals of the full wave instrument rectifier are applied directly to the corresponding polarity terminals of the DC meter whereas the AC input is applied to the AC terminals of the bridge rectifier with one branch of the input having a suitable multiplier resistance in series. By this method not only is the instrument sensitivity on AC input doubled over the half-wave circuits and pointer quiver minimized at low frequency inputs, but in addition there is no requirement for resistive or rectifier shunt circuits to permit uniformity of meter scales on multi-range meters because both halves of the input cycle are utilized for the operation of the meter. On one half of the input cycle the two rectifiers A and B pass the current through the meter, and during the next half cycle the two rectifiers C and D pass current through the meter. During the inactive half cycle some reverse current does flow through the "non-conducting" rectifiers. Upon comparison with the diagram of Fig. 12-8 it will be noted that this scheme of Fig. 12-9 is the full wave version of the half-wave circuit shown in Fig. 12-8. The full-wave version is superior over the half-wave circuit because of improved sensitivity and minimized pointer quiver at frequencies below 50 cycles per second.

The Full-Wave Instrument Rectifier Circuit Using Two Rectifiers

If economy in the full-wave operation of the instrument circuit is necessary, this can be obtained at some loss of linearity and sensitivity by replacing two of the half-wave rectifiers in the full-wave bridge by resistors. There are two such arrangements, the first of which is given in Fig. 12-10.

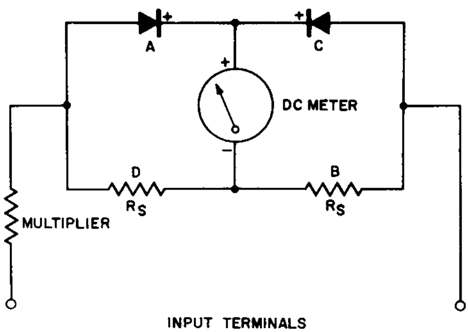


Fig. 12-10. A Full-Wave Rectifier-Type AC Voltmeter Using Two Rectifiers.

Upon comparison with the circuit of Fig. 12-9 it can be observed that half-wave rectifiers B and D have been replaced with two identical resistors. The arms of the full-wave bridge containing the identical rectifiers and the resistors are labeled after the same pattern as established for Fig. 12-9. The reader can trace the circuit mentally to verify that during one half cycle the forward current flows from the source through the multiplier resistance, through rectifier A, the meter coil, and thence through resistor B back to the AC source. During the succeeding and reverse half cycle the forward current from the AC source flows through rectifier C, the meter coil, and thence through resistor D, the multiplier resistance, and back to the source. During the conducting cycle each rectifier and its corresponding resistor behave in the manner described for the half-wave rectifier circuit with resistive shunt of Fig. 12-7; this circuit in Fig. 12-10 is essentially a full-wave version of Fig. 12-7. The full-wave version of Fig. 12-10 has the advantage over the half-wave version of Fig. 12-7 of almost twice the sensitivity and minimized pointer quiver for moderately low frequencies. Like the half-wave version, however, the full-wave circuit of this metering circuit has an AC scale which is crowded near zero and uniformity of scales for multi-range instrumentation is retained.

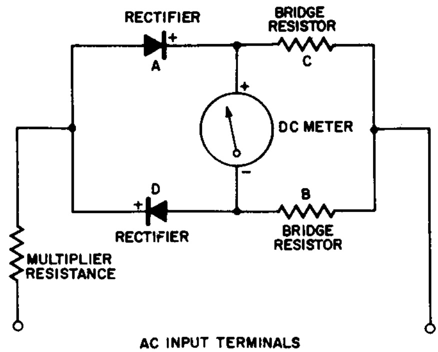


Fig. 12-11. Another Method of Connecting a Full-Wave Rectifier-Type AC Voltmeter Using Two Rectifiers.

The other full-wave meter circuit which reduces the pointer quiver at low frequency inputs but which has poorer sensitivity is drawn in Fig. 12-11. The chief advantage of this arrangement of rectifiers and their associated resistors in the full-wave bridge is that by proper experimental choice of these associated resistors the AC scale of the voltmeter can be made nearly linear.

Errors in Instrument Rectifiers

In our introductory material on instrument rectifiers we discussed avoidable causes which may result in errors in rectifier type AC meters; these, you may recall, were mechanical damage due to careless handling, chemical action due to improper processing or exposure to contaminating atmosphere, or overheating the active areas of the rectifier when soldering the rectifier assembly into the application circuit.

There are four properties of instrument rectifiers which can cause undesirable errors which cannot be avoided by processing or handling but most of which can be compensated for by suitable circuit design. These error properties may be listed as:

a. Waveform of input signal.
b. Frequency.
c. Ambient temperature.
d. Current density.

Waveform Error

We have described rectifier type instruments as indicating the average value of the alternating current. Usually this alternating current is of the sine-wave form and the meter scale is calibrated to read rms values of the sine wave although its indication is proportional to the average value of the waveform, namely 0.636 times the peak value of the applied sine wave. For this reason when distorted sine waves, for example, alternating voltages of essentially sine characteristics but rich in harmonics, or alternating current waveform other than sine such as triangular or square wave are applied to the input terminals of the rectifier-type meter, the indications are no longer correct — the meter pointer deflection is proportional to the average value of the applied waveform but the rms reading is no longer correct. That is, the rms value of the unknown waveform which is not a true sine wave is not related to its average value by the same ratio as that of the sine-wave form. In the sine wave, the rms value is related to the average value by the ratio 0.707 to 0.636 or 1.11, which is called the form factor of the sine wave.

There is no means for compensating for this type of waveform error but fortunately, if the problem is recognized the operator need not be led astray. In most cases where rectifier type AC instruments are applied the waveform is sinusoidal and the meter readings are accurate.

Frequency Error

We have already discussed the difficulties encountered when measuring alternating potentials having frequencies below 30 cycles per second when using rectifier-type AC measuring instruments. If the rectifier circuit involved is half wave, a serious pointer quiver precludes accurate measurement below 20 to 30 cycles per second. This condition is minimized or practically overcome for this frequency range by the application of full-wave rectification. When the input potential is of a still lower frequency, say 5 to 10 cycles per second, even the full-wave circuit will not eliminate an objectional and cyclic pointer oscillation. If the rectifier type AC instrument is to be used only for low frequency, and a small delay in pointer indication after the voltage is applied or changes its level is not objectional there are two easy ways to overcome this low frequency pointer oscillation. In the first method the meter moving system (coil and pointer assembly) is specifically designed to have considerable mechanical inertia so that its period of oscillation will be low and the pointer system will give the desired average indication rather than an oscillation about the mean indication. A way to accomplish this is to add an aluminum vane to the pointer system and enclose this vane in a chamber with a predetermined vent; this scheme is equivalent to the pneumatic dash-pot idea of snubbing mechanical oscillations.

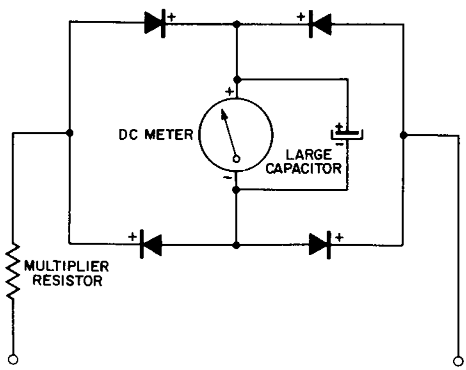
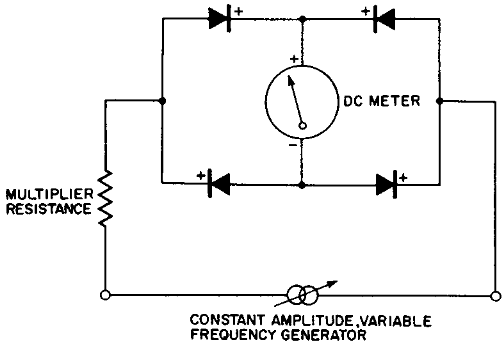


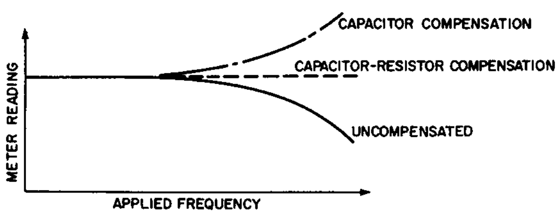
Fig. 12-12. A Rectifier-Type AC Meter Circuit for Low Frequency Work.

The second method of damping pointer oscillation of a rectifier type AC meter at the lower input frequencies is illustrated by the diagram of Fig. 12-12. Here the familiar full-wave, rectifier type AC meter circuit has a large capacitor shunted across the DC meter. This capacitor acts as a large reservoir or tank for the rapidly varying DC potentials impressed across its terminals and across the shunted DC meter. It functions to average out the oscillation potential and present to the meter terminals an averaged potential. This is desired to cause an average current indication and the addition of this capacitor smoothens out the pointer response at low frequencies. The value of this capacitor depends upon the meter and the circuit constants and may have a capacitance of from several hundred to several thousand microfarads; especially processed electrolytic capacitors have been used.

As the frequency of the applied potential of constant amplitude to a conventional rectifier type AC meter is increased the pointer deflection, which should remain constant, begins to decrease and at some high value of applied frequency the indication may be zero.



(A) Test Circuit.



(B) Rectifier-Type Meter Reading Versus Applied Frequency.

Fig. 12-13. Frequency Response of Rectifier-Type AC Meters.

Fig. 12-13A shows a test circuit which may be used to obtain the frequency response of the rectifier type AC meter. A variable frequency generator, having its output voltage set at a constant level of say 10 volts, is varied over the frequency range of particular interest, say, 20 to 50,000 cycles per second. A typical frequency response is shown by the solid curve of Fig. 12-13B. It can be seen that as the applied frequency increases, the meter reading decreases at the higher frequencies even though the input is maintained constant.

This loss of meter reading at the higher frequencies is the result of the following factors:

a. Capacitance effect of the rectifier assembly.
b. Impedance of meter coil and multiplier.

The capacitance property of the rectifier is equivalent to the effect obtained when the ideal rectifier is shunted by a small capacitance. See Fig. 12-14. With this picture of the equivalent circuit it is easy to see that at high frequencies the rectifier becomes less efficient, for the reverse resistance is reducedby the decreasing reactance of the shunting capacitor across it. It is true that the smaller disc area of the instrument type rectifiers is conductive to less shunting capacitance and therefore, this type rectifier is more efficient at the higher frequencies.

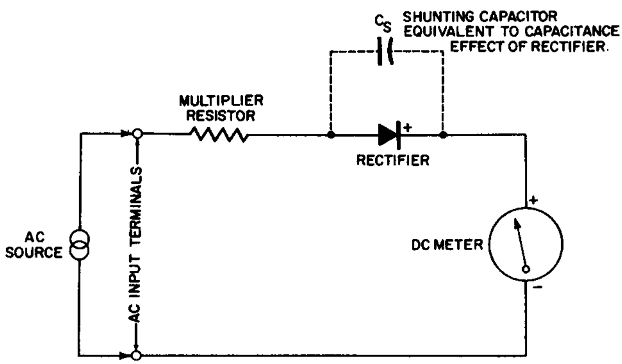


Fig. 12-14. Equivilant Circuit Illustrating Capacitance of Rectifier at Higher Frequencies.

Another factor which causes reduced meter readings at the higher frequencies is the meter coil impedance. The reader will remember that the moving coil of the meter is essentially equivalent to a small inductance in series with the coil resistance through which the rectified current pulses must pass. This equivalent circuit is shown in Fig. 12-15. There are small stray capacitance effects due to the moving coil structure also; as these are effective at frequencies much higher than that in which we are interested, they are neglected here.

Naturally, as the input frequency increases the impedance of the moving coil increases because of the inductive component of the moving coil — again causing a reduction in the current through the meter. The simplified equivalent circuit of the meter moving coil resistive and inductive components is given in Fig. 12-15. If the multiplier resistance is wire wound, this element of the rectifier type AC meter will also have an increasing impedance tending to further decrease the meter current at input frequencies of higher order.

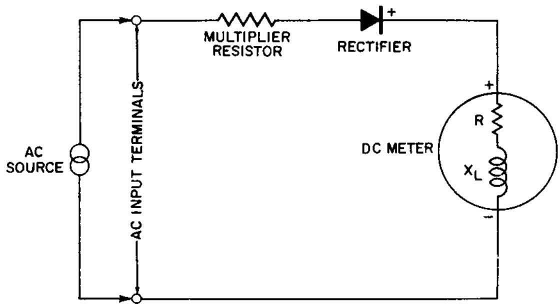
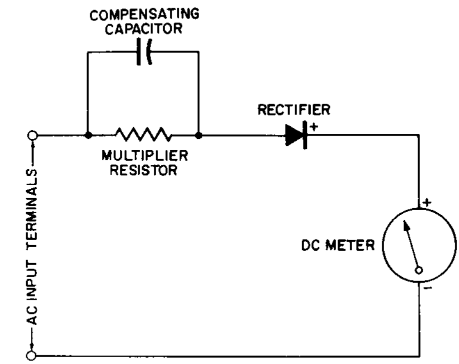


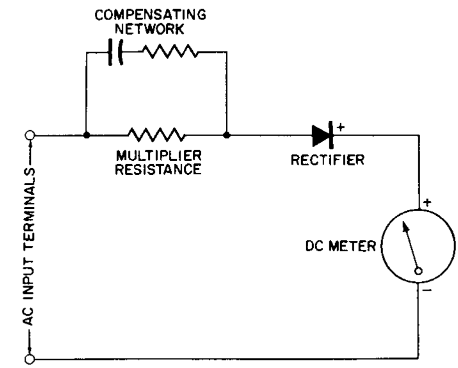
Fig. 12-15. Simplified Equivalent of DC Meter Coil at High Frequencies.

Fig. 12-16 shows circuit compensation means to overcome this type of decrease in meter reading. In Fig. 12-16A the multiplier is shunted by a small capacitor which decreases in reactance as the input frequency increases. This idea makes it possible to reduce the impedance of the shunt circuit, consisting of the multiplier resistance and the capacitor, which is in series with the rectifier and the DC meter. Over a range of frequencies this reduction of circuit impedance can compensate for the increasing meter coil impedance and that of the multiplier, and for the decreasing rectifier efficiency because of its capacitance effect.

A rise in the frequency response curve may take place by this compensation scheme because the multiplier shunting capacitor is over-compensating the other errors. See the dot-dashed curve of Fig. 12-13B. This over-compensation may be minimized by adding a suitable value of resistance in series with the shunting capacitor as in Fig. 12-16B. This resistor limits the amount of compensation possible with any given shunting capacitor, and by the proper selection of capacitance and resistance, a flatter response at higher frequencies may be obtained as represented by the dashed curve of Fig. 12-16B. The problem is not easily represented by simple equivalent circuits, so that values for the capacitance and the resistance will have to be determined by trial; moreover, the response curve at best may not be flat over the entire high-frequency range, but may have dips and humps which are caused by the stray capacitances combining with



(A) Capacitor Compensation.



(B) Capacitor-Resistor Compensation.

Fig. 12-16. Compensation for High-Frequency Errors in Rectifier-Type AC Meters.

the circuit inductances to cause series or parallel resonance conditions at certain frequencies.

Ambient Temperature Error

Ambient temperature errors are caused by changes in the forward and reverse direction resistance in the rectifiers used in rectifier-type AC meters when the temperature changes. In the copper-oxide type of rectifier both the forward and reverse direction resistance decrease with increasing temperature. This represents a negative coefficient of resistance. This resistance change causes errors in the meter circuit which are dependent upon the circuit type used and upon the operating conditions selected for the rectifier. In instrument circuits similar to that of Fig. 12-8 or Fig. 12-9 the temperature error is directly proportional to the rectifier resistance change. This error will be most noticeable on the low voltage range where the series multiplier will not have a large enough ohmic value to swamp out resistance changes of the series rectifier. The temperature error will be quite small on the high voltage ranges, where the series multiplier resistance is so large that moderate ohmic changes of the rectifier, because of temperature changes, will be negligible.

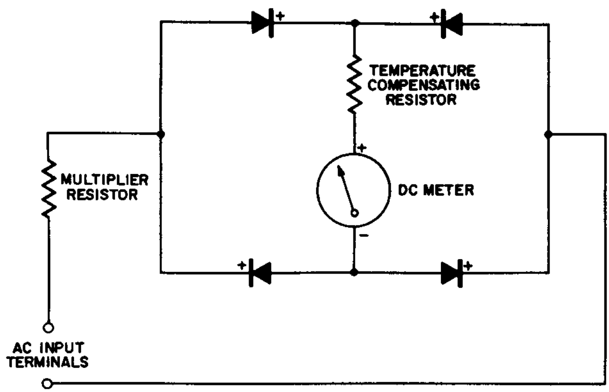


Fig. 12-17. Compensating Resistor in Series With Meter for Temperature Effects.

One way to compensate for temperature errors is to include an additional resistance in series with the meter as shown in Fig. 12-17 for the full-wave circuit. This circuit trick increases the reverse direction voltage drop across the rectifier so that enough reverse current flows at the higher temperatures to compensate for the increased forward current. This scheme also improves the AC scale linearity but the limit to the ohmic value of this series resistance is approached when the maximum reverse direction voltage reaches the safe operating limits of the rectifiers used.

Another scheme to compensate for temperature effects in rectifier-type AC meters is to use positive temperature coefficient multipliers in conjunction with the positive coefficient of the moving coil to compensate or minimize the negative coefficient of the rectifiers. This only gives partial correction at low voltage ranges of the meter because the negative coefficient of the rectifier is greater than that obtained for commercially available positive temperature coefficient multiplier resistors.

Current Density Error

We have learned that the forward resistance of rectifiers is not constant but is dependent upon the value of the forward current; for large values of forward current this forward resistance is low; for small values of forward current this forward resistance is large. The reverse direction resistance remains constant at any given temperature. This dependency of the ohmic value of the forward resistance upon current flow causes multi-range instruments to track poorly on a common scale because this rectifier resistance change is a substantial percentage of the multiplier resistance value on low voltage ranges and almost negligible on higher voltage ranges. Conant Laboratories have devised a shunt circuit using rectifiers for the shunting elements. This type of circuit provides almost exact compensation for errors due to current density variation. It also corrects errors due to temperature changes and partially corrects frequency errors.

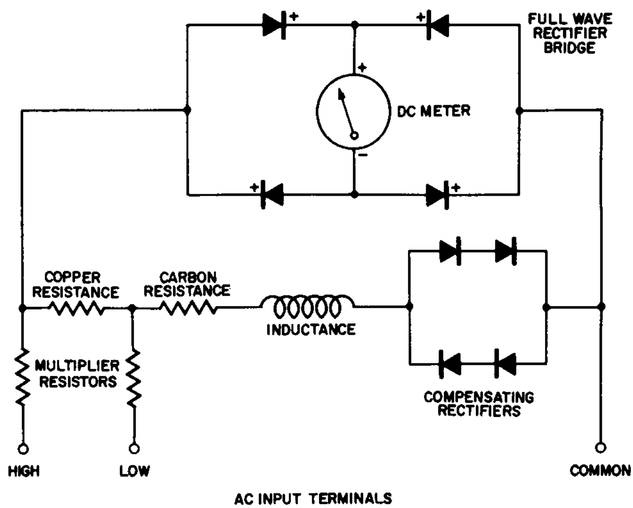


Fig. 12-18. Compensated Rectifier-Type AC Voltmeter.

The completely compensated circuit after this pattern is drawn in Fig. 12-18. For further information, the reader can refer to "Instrument Rectifiers" by H. B. Conant, Conant Laboratories, Lincoln 5, Nebraska.

CHAPTER 13

Metallic Rectifiers as Electrical Valves

Introduction

There are a number of interesting and important applications for an electrical device which permits current flow in one direction but obstructs the current flow in the reverse direction when the polarity of the applied potential is reversed. This can be accomplished electromechanically by means of a polarized relay but the more elegant solution is the application of the property of unilateral conduction of a metallic rectifier. When used for this kind of application, metallic rectifiers are called electric valves.

Selenium and copper-oxide types of metallic rectifiers have both been successfully used as electric valves; each new application requires specific consideration to determine which set of rectifier properties can be used to best advantage. For example, in an arrangement wherein the current flows through a selenium type electric valve in the forward direction most of the time and rarely is the polarity of the applied voltage reversed, then, at these rare intervals when the applied potential is reversed the reader will recall that there will be a high reverse leakage current until the rectification junction has had an opportunity to reform. This high reverse leakage current is of very short time duration and it may or may not be objectional in the problem considered. If the electric valve actuated device has a reasonable mechanical or thermal inertia then this surge of reverse current is of little harm. If the actuated device is a fast acting electro-mechanical relay, this leakage current may cause a false actuation of this relay resulting in improper operation of subsequent controlled circuits. This momentary reverse current may have a magnitude of 10 to 20 percent of the normal forward current when the rated DC voltage is applied per rectifier junction. If this value of reverse current causes improper actuation of the circuit, the reverse direction voltage per rectifier junction may be reduced by adding more plates to the selenium type electric valve, until satisfactory performance is attained. Or it may be that a copper-oxide type rectifier is better for the job considered because of its better electrical stability and no need for electro-forming.

In circuit applications of metallic rectifiers as electric valves in which there is a cyclic change of the applied potential, there is no difficulty from the electroforming current effect, and selenium type rectifiers may be used.

Where the manufacturer's tables, or specifications, give the DC ratings of the rectifier plates (these ratings are the most useful for electric valve problems), the reader will find that these DC ratings are somewhat higher than the ratings of the same plates when used as conventional rectifiers; the reason for this is that the absence of alternating current in these valve applications precludes heating due to leakage currents on a continuous basis.

A few examples of the application of metallic rectifiers as electric valves will be given in this Chapter to illustrate these possibilities.

Metallic Rectifiers as Voltage Surge and Arc Suppressors

Metallic rectifiers can be used as electric arc suppressors to preserve contact life of switches and relays used in circuits having inductive loads. This application is shown in Fig. 13-1.

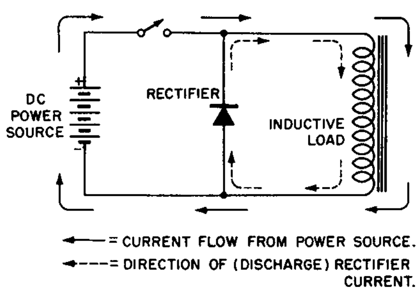


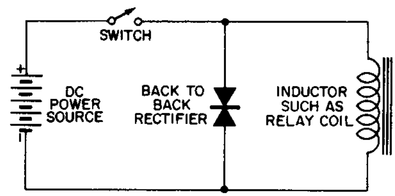
Fig. 13-1. Metallic Rectifier as an Arc Suppressor.

Here, the use of the metallic rectifier as a device for absorbing inductive energy so as to prolong switch contact life is dependent upon the unidirectional property of the half-wave rectifier used as an electric valve.

As shown in this figure the rectifier is connected in parallel with the inductive load which may be a motor, solenoid, a relay, or an electromagnet. When the switch contacts are closed (these contacts may be that of a manually operated switch or the control contacts of a sensitive relay), the current flow from the power source is through the inductive load with little or practically no current flow through the rectifier because the applied polarity is in the high resistance or reverse direction.

When the switch is opened, the load current still tries to flow in the same direction as before and now it is possible for it to do this because of the shunting rectifier which provides, by its low forward resistance, a suitable discharge path as represented by the dotted arrows. Because the rectifier presents a low resistance circuit, a discharge path is provided for the stored inductive energy and the inductive voltage rise across the load is suppressed. This helps preserve the switch contacts from the detructive arcing normally present and the stressing and ultimate breakdown of the coil insulation by the induced surge voltages.

Fig. 13-2. An Improved Arc Suppressor Circuit Using Two Rectifiers.



An additional improvement on this voltage surge or arc suppression circuit using metallic rectifiers as electric valves has been developed by Federal Telephone and Radio Corporation and its affiliates. This development uses selenium type rectifiers and may also be applied to relays, contactors, magnets, solenoids, or any inductive device powered by a DC source. The principle of this development is also to limit the self-induced voltage in these inductive devices, and thereby increase contact and wire insulation life. Fig. 13-2 shows the improved version of the application of the electric valve action of metallic rectifiers.

In the original surge suppression circuit, see Fig. 13-1, a half-wave selenium rectifier is used to provide contact protection in DC circuits by shunting the inductive device. The valve action of the metallic rectifier blocks the flow of current from the DC source when the coil is energized, but offers little resistance to the reverse or induced current when the circuit is opened by the relay or actuator contacts.

The new type voltage surge suppressor, Fig. 13-2, uses two or more selenium rectifier cells connected "back-to-back".

The basic idea here is to employ the rapidly decreasing resistance of the selenium rectifier cell with the increasing reverse voltage as shown in Fig. 13-3.

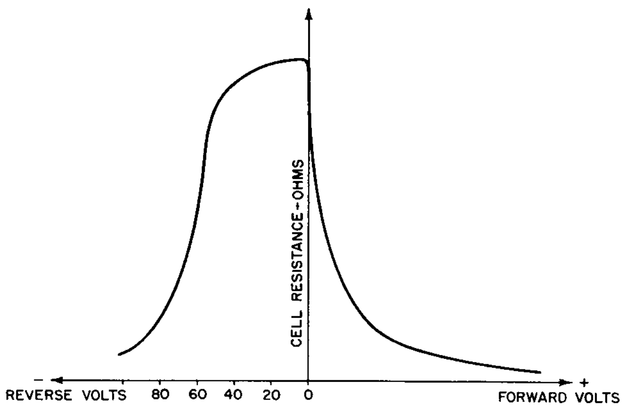


Fig. 13-3. Reverse Voltage Versus Rectifier Cell Resistance for Selenium Type Cell.

The reader can verify from the voltage-resistance curve that the reverse resistance at minus 10 volts is many times greater than that at minus 80 volts. When an electric valve fashioned of selenium rectifier cells mounted back-to-back is connected across an inductive load, one of the rectifier cells blocks the current from the battery or DC source, while the other rectifier cell effectively limits the self-induced voltage rise across the coil when the work current is interrupted as by opening the relay or actuator contacts. In this way the magnetic energy stored in the inductance is dissipated in the resistance of the selenium rectifier and the coil. An advantage obtained by this circuit is that radio frequency interference is reduced because oscillatory discharge is suppressed.

Another advantage of this circuit is that because of the back-to-back construction the reverse resistance to the supply voltage is greater and the normal leakage current from the DC source is low resulting in economy of operation where the suppressor is used across the power source on a continuous duty basis.

One other advantage of this circuit is that it reduces the release time of the system when the inductive device is a relay. When the original circuit involving the half-wave selenium rectifier is used the self-induced voltage surge is minimized but the release time is excessive. The new circuit arrangement for reducing voltage surge may improve the release time by a factor of 5 to 1.

For voltage surge applications involving telephone relays, magnetic clutches, or like devices, protectors of the type shown in Fig. 13-2 are available in a packaged unit 5/8 inch long by 3/8 inch in diameter. When the work circuit involves 120 volts DC and the inductance device uses 1/2 ampere, the surge suppressor is about 1 inch long and 1/2 inch in diameter. In external appearance these voltage surge suppressors look like paper capacitors.

Metallic Rectifiers as Relay Devices

A common application of the metallic rectifier as an electric valve is as a cut-out or reverse current relay in battery charging circuits. See Fig. 13-4. While the generator is operating, it is able to supply current to charge the storage battery and help carry the DC load, whenever its output voltage

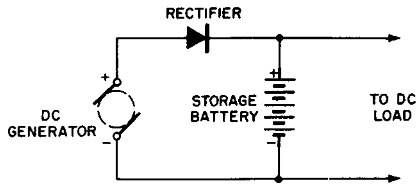


Fig. 13-4. Reverse Current Relay Circuit.

is great enough. When its output voltage drops or the generator stops, the battery can not discharge through the generator windings because of the valve characteristics of the metallic rectifier cell. The rectifier behaves as a reverse current cut-out relay without physical contacts which are subject to vibration, pitting, or burning.

Duplex Operation of Controls

It is often desirable to actuate two independent controls at the end of a single, two wire control line, where ordinarily a three or four wire line would be necessary. A solution to this problem has been offered by the skillful application of the unilateral conduction or valve action of two half-wave rectifiers and two relays, as shown in Fig. 13-5. In this circuit relay RE1 can be closed when the double-pole, double-throw switch engages the set of contacts "B". In this position the lead common to the rectifiers is positive and the current passes from the source through rectifier D1, thence through relay coil RE1, through the lead common to the relays, and back to the negative terminal of the DC power source. With the double-pole, double-throw switch in position "B", current can not flow through rectifier D2, therefore, relay No. 2 remains open.

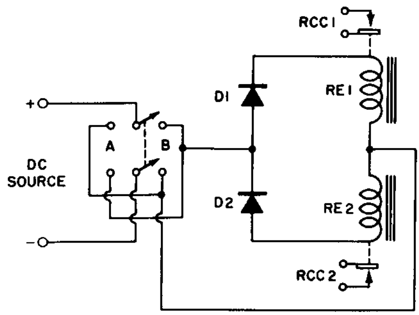


Fig. 13-5. Duplex Operation from a DC Source.

When the double-pole, double-throw switch is positioned to engage the set of contacts labeled "A", the lead common to the rectifiers is connected to the negative terminal of the DC power source; now the current flows through rectifier D2, through relay coil RE2, thence through the lead common to the relays and back to the positive terminal of the DC power source. It is to be noted that now the current cannot flow through rectifier D1; therefore, relay RE1 remains open. Hence, with the duplex circuit of Fig. 13-5 either relay control circuit RCC1 or RCC2 may be closed when desired by properly positioning the double-pole, double-throw switch.

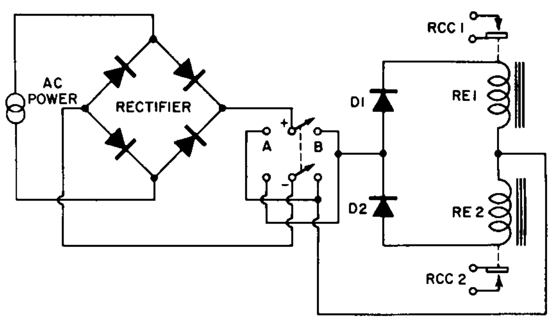


Fig. 13-6. Duplex Operation from an AC Source.

When the power source is alternating, another metallic rectifier assembly may be used to convert the alternating current into direct current to make possible the operation of the above scheme from the ordinary commercial AC power lines. This "all AC" arrangement is pictured in Fig. 13-6.

The AC duplex operation of the control relays may be further simplified by the elimination of two of the half-wave rectifiers at the sending or control end of the line. See Fig.

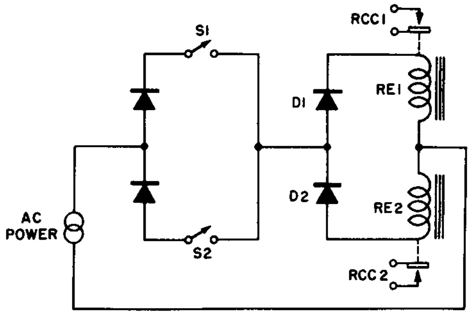


Fig. 13-7. Simplified Method of Obtaining Duplex Operation from an AC Source.

13-7. The principle of the operation is the same as before with individual control over relays RE1 and RE2 being obtained at the sending end of the two lines by closing either switch S1 or switch S2. A further advantage secured by this simplification is that, when switches S1 and S2 both are closed, both control relays may be actuated simultaneously from the sending end of the two lines.

Square Wave Operation by Metallic Rectifiers

For circuit testing purposes it is necessary to have available a "square" waveform of potential. For example, a cathode-ray oscilloscope voltage calibrator uses a square wave source as a means of calibrating the amplitude of the unknown waveforms seen on the oscilloscope screen.

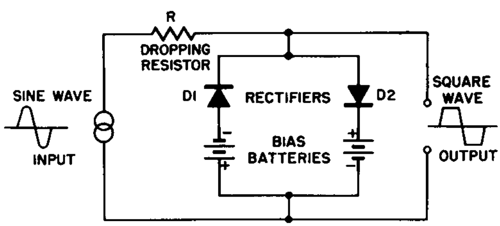


Fig. 13-8. Square Wave or Clipping Circuit Using Metallic Rectifiers.

By utilizing the electric valve property of the metallic rectifier, but delaying its action by means of bias potentials, it is possible to obtain "square-wave" voltages from sine wave sources. See Fig. 13-8.

On either sine wave alternation, rectifier elements D1 and D2 do not conduct until the sine wave voltage exceeds the biasing potential shown; after this point in the voltage rise the rectifiers conduct causing a heavy voltage drop in the common dropping resistor R. This results in an effective "chopping" off of the tops of the sine wave alternations, giving an output appearing similar to a "square wave".

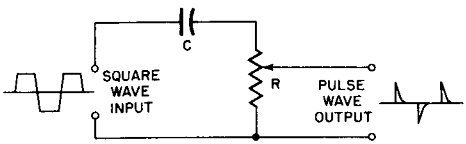


Fig. 13-9. Circuit for Obtaining a Pulse Waveform from a Square Wave Input.

By passing this square wave through a differentiating circuit (see Fig. 13-9) comprising a small capacitor in series with a large resistor, the voltage waveform obtained across the resistor consists of pulses which are useful in the laboratory for tripping thyratron circuits or for control purposes in electronic circuits.

CHAPTER 14

Other Applications of Metallic Rectifiers

Introduction

There are a number of applications of metallic rectifiers which do not fall under the previous classifications. These miscellaneous, but important, jobs for metallic rectifiers will be described in this chapter.

Metallic Rectifiers for Magnetic Amplifiers

Since World War II magnetic amplifiers have become exceedingly popular for many control problems. This type of amplifier, which is extremely reliable and permits substantial power amplification, does not use electronic tubes, but a combination of saturable core reactors and metallic rectifiers. Because of this combination, this type of amplifier is ready to operate as soon as power is applied — there is no warm-up time. It is so rugged that it can be applied to fire control problems and it will easily withstand the shock. Moreover, when using this type of amplifier, the replacement and maintenance problems are greatly minimized.

The chief disadvantage of the present magnetic amplifiers is that the frequency range is usually limited to a few hundred cycles per second, or at best through the audio frequency range with special circuit arrangements. Ultimately, with better saturable core materials and metallic rectifiers, the frequency range may be extended into the radio frequency range. A further disadvantage of present magnetic amplifiers is that they consume some power from the signal source.

Within the limitations of frequency range and power consumption from the signal source, the magnetic amplifier provides stable and ample power amplification for AC and DC usage. It is particularly useful for motor controls, regulated power supplies, non-mechanical power relays, and the like.

Figs. 14-1 and 14-2 illustrate two practical applications of magnetic amplifiers. Fig. 14-1 shows the rear view of a

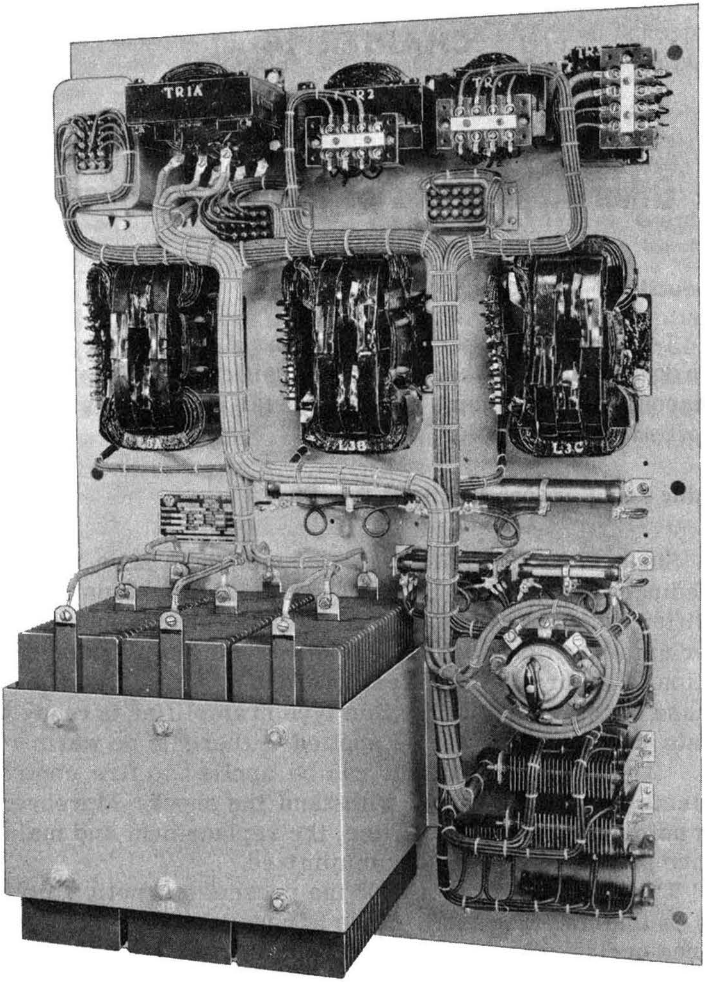


Fig. 14-1. Magnetic Amplifier Type Voltage Regulator for 200 KVA Generator Using Three-Phase Metallic Rectifiers. (Courtesy of Vickers, Inc.)

magnetic amplifier type generator voltage regulator for a 200 kva generator. This magnetic amplifier uses three-phase, full-wave rectifiers. The rectifiers are of the selenium type, convection cooled, and deliver 3.2 to 4.8 kw DC.

The power rectifiers of the magnetic amplifier can be seen in the bracket mounting in the lower left-hand corner of

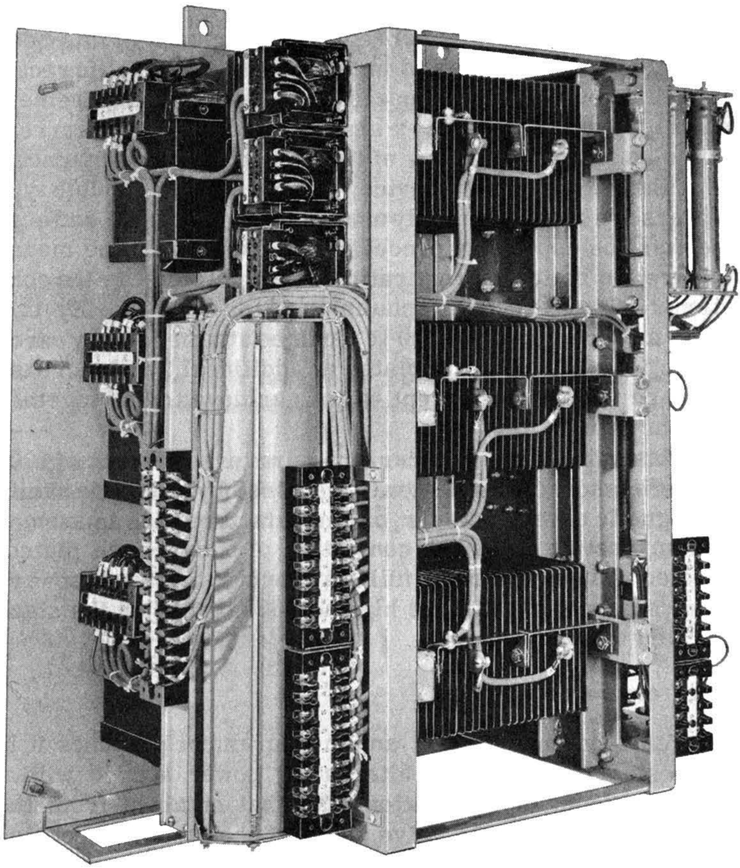


Fig. 14-2. Magnetic Amplifier Type Voltage-Regulator for 100 KVA Generator. (Courtesy of Vickers, Inc.)

the control panel. Other and smaller selenium rectifier stacks are also used as components for the preamplifier stages of this magnetic amplifier.

Fig. 14-2 is a view of a generator voltage regulator for a 100 kva generator. It also uses three-phase, full-wave selenium rectifiers. These are convection cooled and deliver 2.1 to 4 kw DC, and are located in the right-hand portion of the control panel, mounted one above the other.

In this book we are not going to deal with the circuitry of magnetic amplifiers because this subject is a big field all its own. In an elementary manner this subject is discussed in the writer's book entitled "Saturable Core Devices" to which the interested reader is referred.* Our concern in this book is with metallic rectifiers and in particular with metallic rectifiers suitable for magnetic amplifiers. The chief requirement for this type of application is a high forward to reverse current ratio so as to make best use of the properties of the magnetic core of the saturable core device. Currently, the selenium type rectifiers are most commonly used in this application and even these must be especially processed and selected. One means to secure the better current ratio needed is to derate the conventional 26-volt rectifier plates to 16 or 20 volts. By this scheme a current ratio of 500 to 1 can be attained and by careful selection of the rectifier plates an additional 2 to 1 increase in forward to reverse current ratio is achieved or all together a current ratio of 1000 to 1.

This ratio of forward current to reverse current of 1000 to 1 is still short of the ideal ratio required by presently available magnetic cores; however, one manufacturer has announced selenium rectifiers stacks consisting of 5 by 6 inch plates, connected as a single-phase, full-wave bridge that have forward to reverse current ratios as high as 4000 to 1 when the stack is derated to 16 volts.

Power Frequency Multipliers

For experimental test and measurement purposes it is often desirable to have an alternating power source with a higher frequency of alternation than that obtained from the power line. By using the valve action of the metallic rectifier it is possible to double and quadruple the fundamental power frequency by simple circuits.

Fig. 14-3 shows a frequency doubler circuit. Fig. 14-4 indicates the magnetizing current, flux set-up, and the voltage output. The solid arrows in Fig. 14-3 shows the flux setup by coil No. 1 when terminal M of the power supply voltage is positive. For this polarity of applied voltage, primary No. 2 is carrying a negligible current because of the oppositely connected rectifier D2, hence negligible magnetizing force. In the next half cycle, indicated by the dashed line portion of the applied voltage curve, primary No. 2 magnetizes the core in the direction shown by the dashed-line arrow.

*Published by the Scientific Book Publishing Co. Vincennes, Indiana.

Despite the reversal of the applied voltage the rectifiers behave as commutating devices to cause the current to flow in

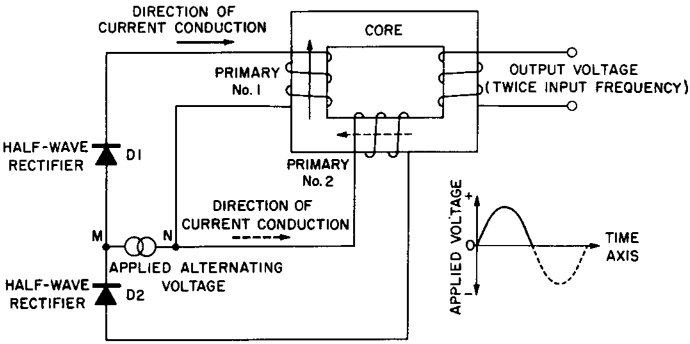


Fig. 14-3. A Frequency Doubler Circuit Using Two Primaries and Two Rectifiers.

such a direction as to setup flux in the same direction. This is clearly shown in Fig. 14-4B where in waveform No. 1 is the

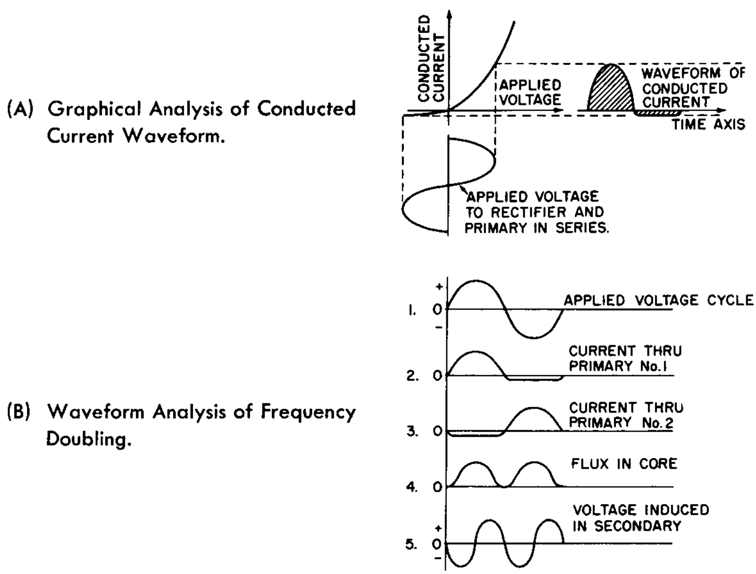


Fig. 14-4. Analysis of Frequency Doubler Circuit.

applied voltage; waveform No. 2 shows that during the positive half cycle only coil No. 1 is energized; waveform No. 3 shows that only coil No. 2 is energized during the negative half cycle of the applied voltage. Coils No. 1 and No. 2 are so poled on the core that the flux is set up in the same direction as shown in waveform No. 4. The rate of change of this flux curve will produce the voltage generated according to Lenz's law. This voltage curve is shown in waveform No. 5 in Fig. 14-4B.

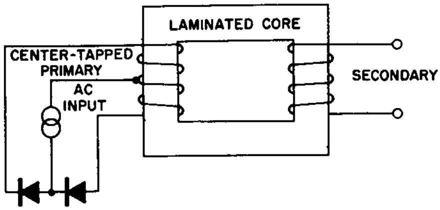


Fig. 14-5. Frequency Doubler Circuit Using Two Rectifiers and a Center-Tapped Primary.

The arrangement may be simplified, for example, it is seen that coils No. 1 and No. 2 of Fig. 14-3 have a common connection. Hence, if but a single coil provided with a center-tap were mounted on the core, in place of the two coils shown, the results would be equivalent to that described but the apparatus would be simplified. This form of the doubler is shown in Fig. 14-5.

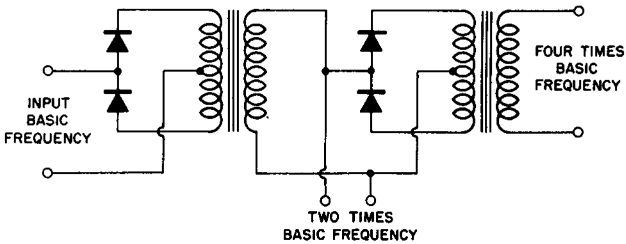


Fig. 14-6. A Frequency Quadrupler Circuit.

In rectifier-transformer frequency doublers there will be two full waves produced in the secondary for each half wave

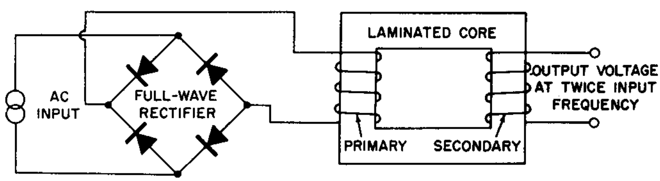


Fig. 14-7. A Frequency Doubler Circuit Using Full-Wave Rectifiers.

in the primary. The frequency can be doubled as often as desired by increasing the number of rectifier-transformer circuits. Fig. 14-6 shows a schematic circuit in which the basic frequency is first doubled then quadrupled by the use of two rectifier-transformer arrangements each using a tapped coil primary.

Fig. 14-7 displays the apparatus designed to use a full-wave rectifier, involving four half-wave elements, in the manner shown to achieve unidirectional current flow through the primary; the double primary coil of Fig. 14-3, or the tapped primary of Fig. 14-5 is replaced by a single coil. A study of this circuit will show that the basic idea is the same as that described in connection with the previous circuits.

Actuation of Vibrating Power Tools

Metallic rectifiers are used in numerous power applications where it is necessary to produce rapid mechanical oscillation or vibration. The following electric hammer description is illustrative of one manner in which this principle is applied to the power field.

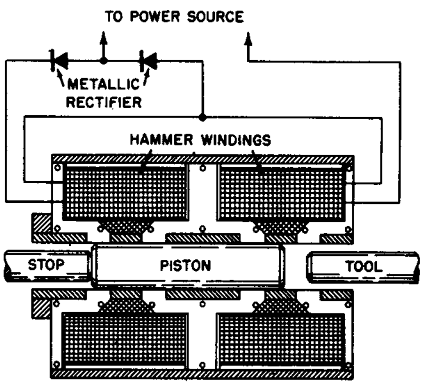


Fig. 14-8. Cutaway Section of an Electric Hammer Designed for Operation With Metallic Rectifiers.

Electric hammers are somewhat similar to air hammers in design, with a free piston that strikes a positive blow on the shank of the tool being used — 3600 blows per minute when operated on a 60 cycle circuit. Fig. 14-8 is a drawing of the hammer, piston, windings, and rectifier circuit connections of the hammer.

The piston is the only working part and is pulled back and forth by two powerful magnets wound around the barrel of the hammer.

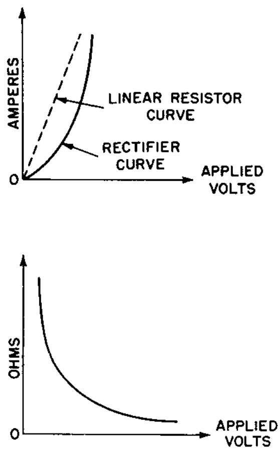
The magnets are energized alternately by pulsating currents derived from a metallic rectifier circuit that is a part of the hammer outfit.

Due to the simple magnet principle operated by rectifiers, this type of electric hammer will work continuously through the toughest jobs without breakdown or time out.

Due to the rectifier control, this type of electric hammer is very powerful. It strikes thousands of sharp blows every minute, drilling, cutting, channelling, scaling, bushing, or any of its other uses, and one of these electric hammers will do the work of several men.

Metallic Rectifier as Voltage Regulator

The metallic rectifier may be employed in simple circuits to help maintain load voltages more constant. In this application the nonlinear resistance characteristics of the rectifier in the forward direction is utilized. Referring to the voltage-current curve of the metallic rectifier which has been reproduced in Fig. 14-9A, it will be noted that the rectifier



(A) Rectifier and Linear Resistor Curves.

(B) Forward Resistance of a Rectifier.

Fig. 14-9. Rectifier Curves.

does not obey Ohm's law — for if it did, its curve would be linear as represented by the dotted line. However, at any point on the curve the voltage drop across the rectifier divided by the current through the rectifier produces the forward resistance for that operating point.

It is interesting to learn in what manner the rectifier resistance varies. The curve giving this information can be derived from the voltage-current curve of Fig. 14-9A by obtaining its reciprocal. This operation yields the forward resistance curve of the rectifier as shown in Fig. 14-9B or this curve may be obtained experimentally.

It is to be noted that the resistance change is rapid for initial applied voltage changes but that larger values of applied voltage yield almost constant resistance.

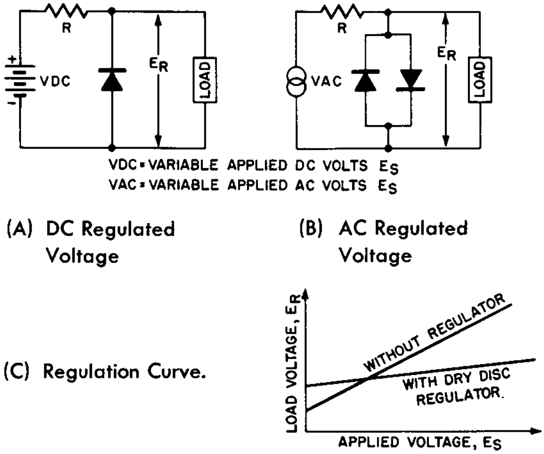


Fig. 14-10. Voltage Regulator Circuits.

Taking advantage of this nonlinear resistance property of the metallic rectifier in conjunction with the use of a fixed resistor, circuits may be devised to regulate load voltage for both AC or DC circuits. Fig. 14-10 shows the circuit configurations and the regulation obtained.

As the applied voltage increases the current increases more rapidly at first because of the nonlinear characteristic of the metallic rectifier; hence a series current-limiting resistor R which absorbs the increasing applied voltage in the form of an IR drop tends to maintain the load voltage more nearly constant.

Since in alternating current circuits the polarity of the load leads periodically reverse, it is necessary to use two rectifier assemblies "back-to-back" to obtain regulation over both parts of the alternation.

Full-Wave Rectification Without Transformer for Use in Control Circuits

A unique application of a center-tap coil as shown in Fig. 14-11 may be employed in the control of relays and other solenoid actuated devices whereby full-wave rectification is obtained with half the rectifiers that would be required for operation of a conventional type coil. The conventional type coil and circuit arrangement is shown in Fig. 14-12. In the center tap

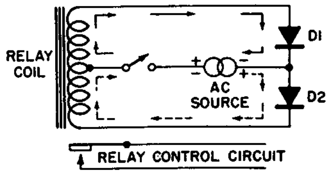


Fig. 14-11. Full-Wave Rectification Without a Transformer.

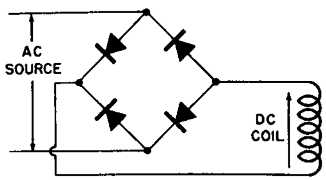


Fig. 14-12. Conventional Type Coil Used in Relays.

coil arrangement the coil is wound with a center tap and connected into the circuit so that both halves of the coil winding are additive as shown in Fig. 14-11. During one-half cycle current flows through the upper half of the coil and through rectifier D1 and back to the source as shown by the solid line arrows. When the current reverses polarity current flows (in the direction shown by the dash line arrows) through rectifier D2 thence through the lower half of the coil to the source. A very important feature of the circuit is that this type of relay is highly efficient since the rectifier acts as a shunt on the half of the coil not receiving current thereby permitting its stored up electromagnetic energy to be returned to the circuit as the other coil current is increasing from zero thus preventing the current ever reaching zero during the off half of the cycle.

In certain applications of the center-tap coil arrangement, it may be important that the pull exerted by either of the two coils be exactly equal. In this instance, the conventional type of center-tap coil would not meet this specific requirement because the magnetic pull of the two coil halves will not be exactly equal due to the fact that the inner half of the winding (being nearer the core) will have a smaller diameter than the outer half of the coil; therefore, its resistance will be greater and it will pass a smaller current.

To overcome the above difficulty the coil may be wound in the manner shown in Fig. 14-13, here the coil is shown as wound of two wires (of the same size) in parallel; therefore, the two coil halves will be exactly equal in length and have exactly the same resistances. The direction of current flow

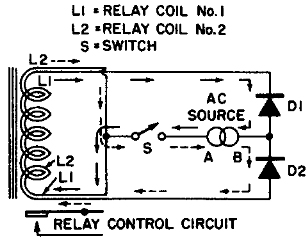


Fig. 14-13. Special Type of Relay Coil to be Used for Full-Wave Rectification.

through this type of coil is shown in Fig. 14-13. When point A of the AC source is positive and point B is negative the current flow through the coil and circuit will be as indicated by the solid line arrows. When the polarity changes so that point B becomes positive then the current flow through the coil and circuit will be as shown by the dash line arrows.

CHAPTER 15

The Silicon Rectifier

EDITOR'S NOTE

At the time of completion of the preceding 14 Chapters, which constituted the original manuscript of "Metallic Rectifiers, Principles and Applications," the use of silicon as the semiconductor in rectifiers was announced. In order to include information on silicon rectifiers, we have included this chapter which discusses the basic concepts of design and application of this new type rectifier. We wish to thank Mr. George Eannarino, Director of the Rectifier Division of Sarkes Tarzian, Inc., for his co-operation in making this information available.

Introduction

The silicon rectifier is a new development recently introduced in the field of power conversion and semiconductors. The silicon rectifier exhibits several properties which make its future outlook perhaps brighter than the three types previously discussed.

The semiconductor properties of silicon have been known for many years. As early as 1904, point contact (cats whiskers) detectors made of silicon were used in radio receivers. With the advent of the vacuum tube, interest in the point contact detector decreased and it was not for many years that interest was again revived.

In the 1930's research workers began the study of shorter radio wavelengths. They found that ordinary vacuum tubes were of little use in this region and some new type of detector was needed. In the search for a new detector, the properties of the old point contact silicon detector were evaluated.

In an attempt to improve the old detectors, methods of producing purer silicon were developed. Improvements came rapidly and the silicon detector became a practical device, thus making radar practical during World War II.

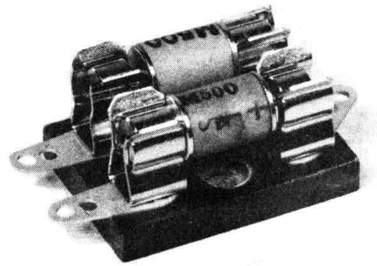


Fig. 15-1. The Sarkes Tarzian M500 Silicon Rectifiers Being Used in Television Receivers.

Through further experiments during and after World War II, the silicon transistor was developed in 1948. Continuing research lead to the introduction in 1956 of the silicon power rectifier which is shown in the photograph of Fig. 15-1.

Theory of Operation

Silicon, as used in silicon rectifiers, is a nearly perfect single crystal of pure metal to which has been added an element from either Group III or Group V of the Periodic Table. (Silicon is in Group IV.) Silicon doped with a Group III element conducts electrical current by means of holes, and is designated as "P" type. Silicon doped with a Group V element conducts current by means of electrons, and is designated as "N" type. Actually, since the introduction of all undesired elements is impossible to control, there are both Group III and Group V elements present and the overall effect is that of the net difference. Thus, in "N" type silicon, the difference in the number of Group V atoms minus the number of Group III atoms determines the number of conduction electrons. The most numerous carriers are designated as majority carriers; for example, electrons are majority carriers in "N" type silicon and holes (positive charges) are minority carriers.

The silicon junction rectifier or diode consists of a "P" - "N" boundary within the lattice of a single crystal of silicon. In silicon area type rectifiers, the body of the wafer generally consists of "N" type silicon on which a very thin layer of "P" is formed by either alloying or diffusing a suitable material. The boundary or barrier layer thus formed is very thin, less than 10^{-3} centimeters; therefore, on a junction capable of blocking a potential of 1000 volts, the space charge across the barrier layer is greater than 10^6 volts per centimeter. It is obvious, that to produce high voltage junctions, extreme care must be taken to eliminate all unwanted impurities that tend to ionize at high potentials.

At zero bias, diffusion effects of electrons and holes are opposed by an electrostatic space charge and the junction is at equilibrium; however, as an external voltage is applied, the junction exhibits unilateral characteristics of current flow. Current flows readily when a positive potential is connected to the "P" side of the junction, and very low currents flow when the potential is reversed. This unilateral effect defines the area of usefulness of a silicon rectifier, and the ratio of conductive to blocking resistance establishes the rectification ratio of the rectifier cell. Blocking resistances are as high as 10^9 ohms, while the forward resistances are measured in fractions of ohms; therefore, the rectification efficiency is greater than 99% with the forward drop contributing nearly the total loss.

Production of Silicon Rectifiers

Silicon does not readily lend itself to zone refining; therefore, the most popular methods to produce single crystals of pure silicon is crystal "pulling" where a seed of pure single crystal silicon is dipped into molten silicon, rotated slowly and withdrawn at a predetermined rate. A major problem in crystal "pulling" is to keep the resultant crystal free from contaminants. Molten silicon is very active and attacks the materials used in containers and holders. Quartz crucibles are commonly used and the entire process is conducted in an inert atmosphere to reduce the possibility of contamination. Temperature is also very important and plus or minus 0.1° C. at approximately 1430° C. must be maintained.

When it is determined that the crystal has resulted in the desired type (either "P" or "N"), and that the resistivity is within the range that will produce suitable voltage ratings, the crystal is cut into thin slices and finally into small wafers or dice of desired size and thickness.

After suitable etching and grading to separate wafers that do not conform to established thickness specifications, the dice are alloyed by a special process. Alloying is conducted at high temperatures and provides not only a "P" - "N" junction on one side of the wafer, but a low ohmic content on the base. Low resistance contacts are important, since once the internal space charge is overcome the resistance of the cell decreases exponentially and contact and lead resistances become factors limiting current flow.

Alloyed dice are brazed to a base and then hermetically sealed after a contact is provided to the alloyed side. Extreme care must be taken during the mounting and assembly operations to keep the surface free from contamination of any type since contaminants will ionize and shunt the junction.

Final electrical and mechanical tests are performed before and after successive heat cycles to make certain that the rectifier is stable under all conditions of temperature, humidity, altitude, and shock.

Forward Characteristics

The direction of low resistance or high current flow is defined as the "forward" direction of the silicon rectifier, and since the majority of the power losses within the device are concentrated in the conduction cycle we will consider this carefully. Fig. 15-2 shows the classic static forward-current

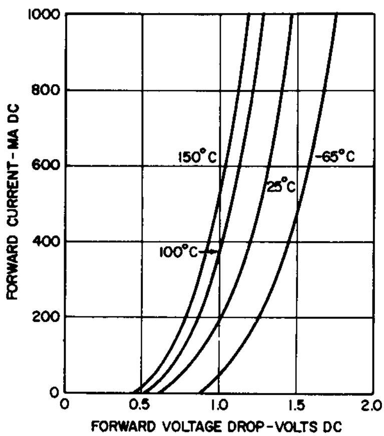


Fig. 15-2. Static Forward Current Vs. Applied Voltage.

characteristics versus applied voltage. The curve of Fig. 15-2 shows that the effect of the space charge establishes a threshold voltage at approximately 0.6 volts DC. Note that once the device starts to conduct, the current increases exponentially with small increments of voltage and then increases nearly linear on a very steep slope.

The current density of a silicon rectifier is very high and on present designs ranges between 600 and 750 amperes per square inch of effective barrier layer area. This depends to a great extent on the general construction of the enclosure and particularly on the ability of the heat sink to conduct heat from the crystal. A rectifier rated at one ampere DC and 15 amperes of peak surge current, contains a cell that has a total volume of .0000112 cubic inches. A rectifier rated at 15 amperes DC and 75 amperes of peak surge current, has a total cell volume of .000227 cubic inches. Peak currents are, therefore, extremely critical because the small mass of the cell will heat instantaneously and could conceivably reach failure temperatures within a time lapse of a few microseconds.

An increase in junction temperature increases efficiency as is shown by the curves of Fig. 15-2. Not only does an increase in cell temperature cause a general forward resistance decrease, but a relative decrease of threshold voltage also occurs. This decrease is caused by an increase in thermal energy and agitation which, in turn, raises the energy level of the holes and electrons, thus reducing the space charge.

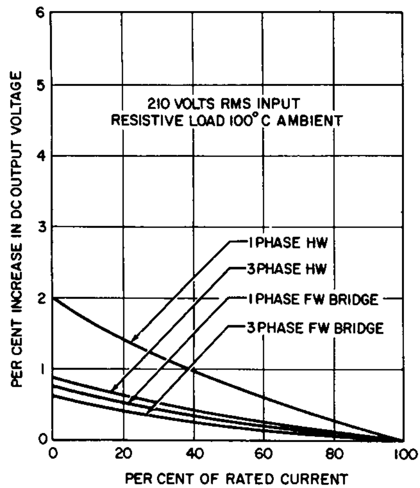


Fig. 15-3. Typical Regulation Curves for Various Circuits.

Typical regulation curves for various circuits are shown in Fig. 15-3. The three-phase bridge is the most efficient with a change of only 0.6% in output voltage as the load is varied from 0 to 100%. The single-phase half-wave circuit is the least efficient with a change of 2% in output voltage as the load is varied from 0 to 100%.

Reverse Characteristics

The reverse direction of a silicon rectifier is characterized by extremely high resistance, up to 10^9 ohms, below avalanche voltage; at the avalanche voltage, a very sharp break occurs and the resistance rapidly decreases. This characteristic, graphically illustrated in Fig. 15-4, shows typical reverse current versus reverse voltage. Note the initially low values of reverse current and the sharp break as the critical voltage is reached. Because of this it is good practice to rate the peak inverse working voltage at least 20% below the avalanche point to provide a safety factor.

The avalanche point varies between rectifiers produced from the same crystal and depends to great extent on two factors: (1) The resistivity of the segment of crystal from which the wafer is cut, with crystal resistivity depending on distributed impurities within the crystal lattice; and (2) surface contamination introduced during alloying, brazing, assembly, or sealing. Contaminants will ionize at relatively low voltages and shunt the junction.

In a high voltage silicon rectifier that is virtually free of surface contamination and with uniform distribution of impurities, the avalanche is caused by ionization of atoms within the crystal and the junction assumes characteristics similar to those that apply to ionization of gases.

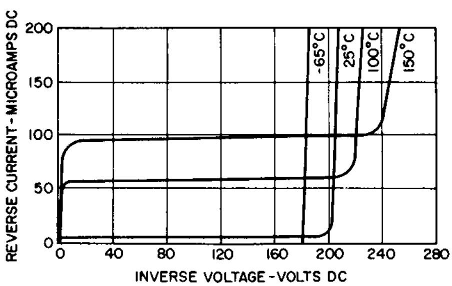


Fig. 15-4. Static Reverse Isothermal Curves for Sarkes Tarzian Type 15N1 Silicon Rectifier.

Isothermal reverse curves are shown in Fig. 15-4. These show that the avalanche voltage increases with an increase in temperature and a general softening of characteristics is noted. The avalanche voltage decreases by about 10% between room temperature and extremely low temperatures; however, since 20% is allowed on initial rating, a safety factor is provided. At temperatures higher than room temperature the avalanche voltage increases; therefore, there is no need for derating.

Efficiency of the Silicon Rectifier

Reverse losses represent a negligible factor of power dissipation because of extremely low back currents. The forward losses, however, contribute very nearly the total loss within a silicon cell. To illustrate the magnitude of difference, a typical 600-volt rectifier will pass approximately 5 microamperes of back current at rated voltage for a back resistance of 120 megohms and a power dissipation of .003 watts. The same rectifier rated at one ampere DC connected in a single-phase half-wave circuit, would have a forward voltage drop of 2.5 volts when operating at 100% rated current. The forward resistance of the cell would be 2.5 ohms and a power dissipation of 2.5 watts. In this case, the resistance ratio is approximately 120,000,000 to 1 and the forward to reverse power ratio is approximately 800 to 1. A rectifier rated at 600 volts peak inverse will deliver approximately 200 watts of power to a load, in a half-wave circuit, with internal losses of about 1 watt at an efficiency of 99.5%. This will become important as the fields of application extend to heavy current equipment.

Operating Temperatures

Silicon rectifiers are designed to operate in ambients from -55° C. to 100° C. without derating and to 150° C. with moderate derating. The maximum case temperature is 170° C. with a 20° C. thermal gradient anticipated between the case and the cell.

Parallel Operation

Silicon rectifiers are produced as half-wave units with maximum current limits; however, at times it is necessary to use individual rectifiers in parallel to obtain sufficient output. Because the forward resistance is very low once a silicon rectifier starts to conduct, any unbalance between threshold voltages or internal voltage drop would cause serious unbalance of load distribution and ultimate failure of the overloaded section. For this reason it is recommended that a small series resistance be used with each half-wave section operating in parallel.

Series Operation

No special precaution is required when silicon rectifiers are operated in series, provided that the sum of the peak inverse ratings is not exceeded. Fig. 15-5 shows the effect of operating rectifiers with unbalanced peak inverse ratings. Note that each unit will increase until its individual avalanche point is reached; at this point, there is a leveling off regardless of how much the source voltage is increased.

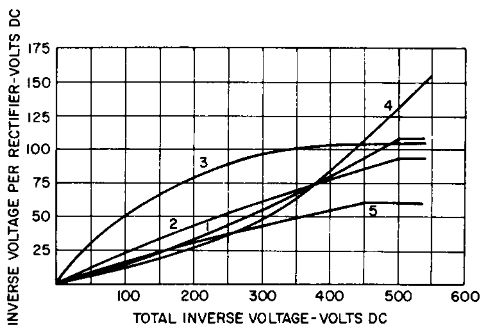


Fig. 15-5. Inverse Voltage Per Rectifier with Five Sarkes Tarzian "P" Type Silicon Rectifiers Connected in Series.

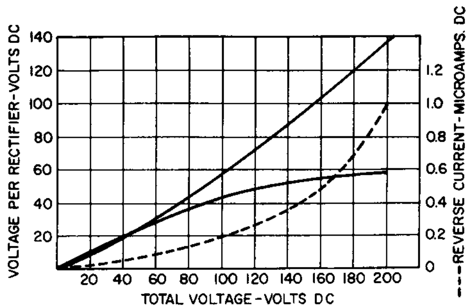


Fig. 15-6. Inverse Voltage Per Rectifier with Two Sarkes Tarzian "P" Type Silicon Rectifiers Connected in Series.

Fig. 15-6 shows reverse current versus voltage with unbalanced rectifiers operating in series. This data shows there is no tendency for the reverse current to increase sharply even though the peak inverse ratings of individual rectifiers are exceeded.

Conventional Circuits

Silicon rectifiers are generally produced as half-wave units; however it is possible to connect single units into a variety of single phase and polyphase combinations.

Single-Phase, Half-Wave

It is not necessary to use more than one unit per circuit unless load requirements for voltage and current exceed the ratings of a single unit. When an input capacitor filter is used, it is necessary to provide a few ohms of surge limiting resistance to prevent rectifier failure. Also, the peak voltage

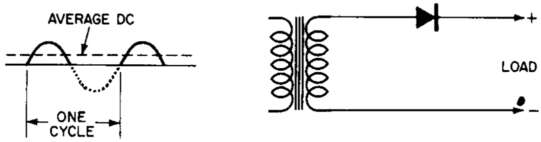


Fig. 15-7. Single-Phase, Half-Wave Rectifier Circuit.

rating of the rectifier should not be exceeded since the DC voltage contributes to the total back voltage. In the circuit of Fig. 15-7, a special transformer design is required because of core saturation effects of unidirectional current and high rms to DC ratios.

Single-Phase, Full-Wave Bridge

The circuit of Fig. 15-8 shows four half-wave silicon rectifiers used in a single-phase full-wave bridge circuit. Full wave output reduces ripple and increases efficiency.

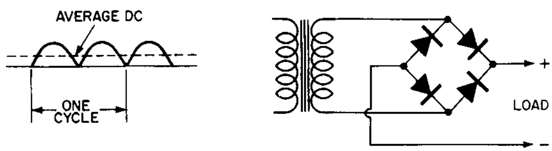


Fig. 15-8. Single-Phase, Full-Wave Bridge Type Circuit.

Transformer design is simplified since both halves of the input cycle are utilized. The transformer secondary voltage is approximately 1.25 times the DC output voltage.

Three-Phase, Half-Wave

Three single-phase, half-wave silicon rectifiers are required to obtain a three-phase, half-wave circuit. See Fig. 15-9. Better circuit utilization provides relatively high efficiency and low ripple at three times the fundamental frequency. The output voltage is approximately equal to the phase voltage; however, the rms voltage rating of each arm

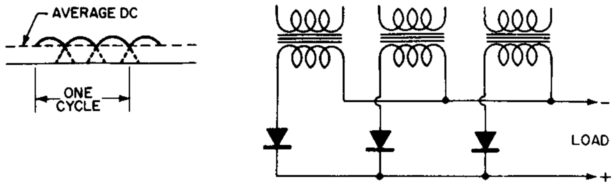


Fig. 15-9. Three-Phase, Half-Wave Rectifier Circuit.

of the rectifier must be equal to the line voltage which is 1.73 times the phase voltage.

Three-Phase, Full-Wave Bridge

The three-phase bridge circuit, shown in Fig. 15-10, requires six single-phase, half-wave units. This circuit delivers very high efficiency and is commonly used where DC power requirements are large. Due to overlapping of the three phases the ripple percentage is low, approximately 4%,

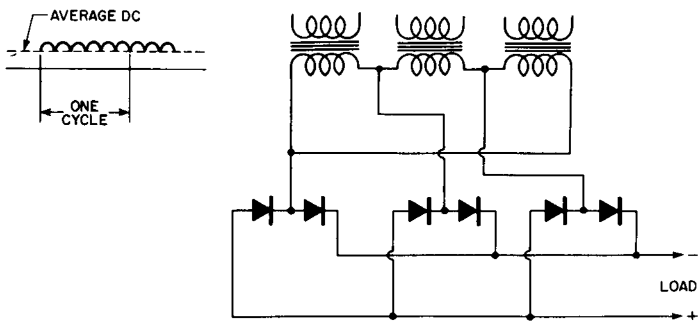


Fig. 15-10. Three-Phase, Full-Wave Bridge Type Circuit.

and though additional filtering may be required, the resultant ripple that is six times the fundamental source frequency is easily filtered. The DC output voltage is approximately 25% higher than the input phase voltage.

Comparison of Output Voltages of Silicon Versus Selenium Rectifiers

A typical full-wave voltage doubler circuit, commonly used in television receivers, is shown in Fig. 15-11. The charts shown in the following, compare the output voltage of the silicon rectifier with that of the selenium rectifier, using values of 4.2 ohms and 5.2 ohms for the series resistor R1.

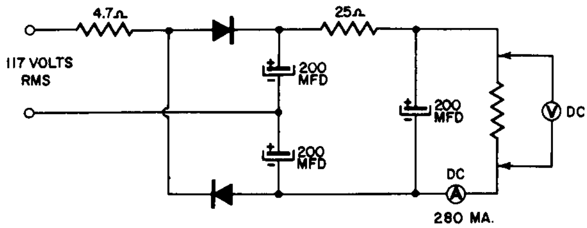


Fig. 15-11. A Typical Full-Wave, Voltage-Doubler Circuit.

SILICON RECTIFIER (SARKES TARZIAN M500)

RECTIFIER NO.	DC OUTPUT VOLTS	
	4.2 OHMS	5.2 OHMS
1 & 2	287	284
3 & 4	287	284
5 & 6	287	284

SELENIUM RECTIFIER (SARKES TARZIAN 300)

RECTIFIER NO.	DC OUTPUT VOLTS	
	4.2 OHMS	5.2 OHMS
1 & 2	266	262
3 & 4	266	262
5 & 6	267	264

The Model M500 silicon rectifiers produced by Sarkes Tarzian, Inc. are designed primarily for use in television receivers where-voltage doubler circuits operating directly off the line are in common use. Their small size, high efficiency, and low cost make them desirable for use in all types of commercial electronic equipment.

APPENDIX I

Some Electrical and Metallic Rectifier Terminology

Aging. Aging of a metallic rectifier is any persisting change (except failure) which takes place for any reason in either the forward or reverse resistance characteristic. (NEMA)

Ambient Temperature. Ambient temperature is the air temperature immediately around the metallic rectifier.

Asymmetrical Conductor. See rectifier cell.

Cell Combinations. The cell combination in a metallic rectifier is the arrangement of cells in a stack, stack assembly, or rectifier unit. The cell combination is described by a sequence of three numbers, written a-b-c, with the following significances:

a. Number of rectifying elements.
b. Number of cells in series in each rectifying element.
c. Number of cells in parallel in each rectifying element.

NOTE: The total number of cells in the rectifier is the product of these three numbers. (NEMA)

Cell Current Rating. The current rating of a metallic rectifier cell is the maximum current that may be passed through it in the forward or low resistance direction and maintain its thermal ratings.

Cell Voltage Rating. The voltage rating of a metallic rectifier cell is defined as the maximum rms value of an AC voltage to be applied to the cell.

Conductor. Substances in which the electrons are able to pass readily from atom to atom under the influence of a small applied potential are called conductors. Examples of conductors are silver, copper, aluminum, etc.

Conversion Efficiency of Metallic Rectifier. The conversion efficiency of a metallic rectifier equals the average DC volts times the average DC amperes output, divided by the AC watts input, in percent.

Dry Disc Rectifier. See metallic rectifier.

Dry Plate Rectifier. See metallic rectifier.

Electric Current Flow. The conventional direction of electric current flow in the circuit external to the applied potential is from the positive to the negative terminal.

Electron Flow. In a circuit the electron flow is from the negative terminal of the applied potential to its positive terminal.

Fin. A square or round metal plate which may or may not perform an electrical function in a rectifier stack, but is assembled therein for the purpose of dissipating heat.

Forward Current. The current which flows in the forward direction through a rectifier cell.

Forward Direction. The forward direction of a rectifier cell is the direction of lesser resistance to current flow through the cell.

Forward Resistance. The forward resistance of a metallic rectifier is the resistance measured at a specified forward voltage drop or forward current.

Forward Voltage Drop. The forward voltage drop is the potential drop in the rectifier cell as a result of the flow of forward current through the metallic rectifier cell.

Instrument Rectifier. An instrument rectifier is a specialized metallic rectifier having smaller disc area than conventional power supply units and being especially processed to have stability, permanence, and high efficiency.

Insulator. Substances in which the electrons are so tightly bound that it takes enormous electric potential to cause current flow are called insulators. Examples of insulators are ceramics, glass, and mica.

kva. A unit of apparent electrical power equal to 1000 volt-amperes, abbreviated from kilovolt-amperes.

kw. Abbreviation for kilowatts, equal to 1000 watts.

Metallic Rectifier. A metallic rectifier is a rectifier which has an asymmetrical conductive junction between solid conducting and semiconducting materials which permits current flow more readily in one direction.

Metallic Rectifier Unit. A metallic rectifier unit is an operable arrangement of a rectifier and essential auxiliaries such as transformers, filters, switchgear, etc. (NEMA)

Non-symmetrical Conductor. See metallic rectifier.

Power Factor (pf). Power factor is the ratio in percent of the AC watts input to the product of the AC volt-ampere input.

Rectifier. A rectifier is an electrical device which changes alternating current into direct current by its characteristic which permits the flow of current more readily in one direction.

Rectifier Assembly. A metallic rectifier stack assembly is an assembly of two or more stacks.

Rectifier Cell. A single junction rectifier which has one positive electrode, one negative electrode, and one rectifying junction and is operable as an elementary rectifier.

Rectifier Couple. See rectifier cell.

Rectifier Disc. See rectifier cell.

Rectifying Element. See rectifier cell.

Rectifying Junction. The rectifying junction is the region in a rectifying cell which possesses asymmetrical conduction. This junction is also called the barrier layer or blocking layer.

Rectifier Plate. See rectifier cell.

Rectifier Stack. A rectifier stack is an assembly of one or more rectifier cells. Rectifier stacks are usually made by assembling rectifier cells upon an insulated center bolt or stud.

Rectifier Valve. A metallic rectifier whose function is to block the reverse flow of direct current for control or similar purposes.

Reverse Voltage. The reverse voltage is the voltage which is applied in the reverse direction to a metallic rectifier cell.

Reverse Current. The reverse current is the current which flows in the reverse direction through the rectifier cell. It is also called the leakage current.

Reverse Direction. The reverse direction of a metallic rectifier cell is the direction of greater resistance to current flow through the cell.

Reverse Resistance. The reverse resistance of a metallic rectifier cell is the resistance measured at a specified reverse voltage or reverse current.

Root-Mean-Square (rms). The effective value of sinusoidal waveform of alternating current or voltage and equal to 0.707 times the peak value of the sine wave.

Semiconductor. Substances which are not good conductors and yet are not insulators are called semiconductors. Examples of semiconductors are carbon, metal oxides, and certain alloys.

Semiconductor Rectifier. See metallic rectifier.

Single-Phase. The form of distribution of alternating current commonly used for household purposes and small power applications.

Three-Phase. A form of distribution of alternating current commonly used for commercial and industrial purposes; the voltage across each phase is at an angle of 120 degrees to the voltage across the other phases.

Threshold Voltage. The threshold voltage of a metallic rectifier cell is the minimum value of alternating voltage applied to the cell before rectification takes place.

Unilateral Conductor. See rectifier cell.

Varistor. See metallic rectifier.

Voltage Regulation. Voltage regulation is the ratio of the difference between the no load voltage and the full load voltage to the full load voltage in percent.

Waveform Factor. The waveform factor is the ratio between the rms to the average value of the waveform. The waveform factor of a sine wave is 1.11.

APPENDIX II

Classified Sources for Metallic Rectifiers

To the potential electrical component buyer, designer, and professional engineer there are available a number of directories of sources for electrical merchandise. These directories, of course, contain sources for metallic rectifiers. However, the listings are generally mixed — no indication as to whether the source is for copper-oxide, selenium, or magnesium-copper sulfide rectifier. Worse yet, the listings generally contain references which are not primary sources for rectifiers but those who either purchase their rectifiers from primary sources and then manufacture rectifier power supplies or allied devices, and those who purchase the plates and assemble rectifiers to order.

In the listings to follow every effort has been made to include only primary sources for metallic rectifiers. This type of information puts the potential customer in direct contact with the source and avoids delays and extra charges when special rectifiers are required.

The first listing contains the names and addresses of these primary sources of metallic rectifier manufacturers. The second listing gives the names of the manufacturers of copper-oxide rectifiers; the third listing gives the names of the manufacturers of the magnesium-copper sulfide rectifiers. The fourth listing gives the names of the manufacturers of the selenium type rectifiers.

The remaining listings indicate where specialized metallic rectifiers may be obtained. These specialized listings cover instrument rectifiers, valve rectifiers, high voltage rectifiers, rectifiers for radio and television receivers, and high frequency rectifiers.

The writer has checked these listings very carefully and sincerely hopes that no errors or omissions are present but in a field which is undergoing change and rapid growth only a periodic revision can keep the listings up-to-date.

Bradley Labs, Inc.
170 G Columbus Ave.
New Haven 11, Conn.

Conant Labs
6500 O Street
Linclon 5, Neb.

Fansteel Metallurgical Corp.
2220 Sheridan Rd.
North Chicago, Ill.

Federal Telephone and Radio Corp.
88 Kingsland Rd.
Clifton, N. J.

General Electric Co.
Apparatus Sales Division
1 River Road
Schenectady 5, N. Y.

International Rectifier Corp.
1521 E. Grand Ave.
El Segundo, Calif.

International Resistance Co.
401 N. Broad Street
Philadelphia 8, Pa.

Mallory & Co., Inc., P. R.
3029 E. Washington Street
Indianapolis 6, Ind.

Radio Receptor Co.
251 West 19th Street
New York 11, N. Y.

Sarkes Tarzian, Inc.
415 N. College Ave.
Bloomington, Ind.

Syntron Co.
243 Lexington
Homer City, Pa.

Sylvania Electric Products, Inc.
1740 Broadway
New York 19, N. Y.

Vickers, Inc.
1815 Locust Street
St. Louis 3, Mo.

Westinghouse Electric Corp.
Pittsburg 30, Pa.

Manufacturers of Copper-Oxide Rectifiers

Bradley Labs, Inc.
Conant Labs
General Electric Co.
Westinghouse Electric Corp.

Manufacturers of Magnesium-Copper Sulfide Rectifiers

P. R. Mallory & Co., Inc.

Manufacturers of Selenium Rectifiers

Bradley Labs, Inc.
Fansteel Metallurgical Corp.
Federal Telephone and Radio Corp.
General Electric Co.
International Rectifier Corp.
International Resistance Co.
Mallory & Co., Inc.
Radio Receptor Co.
Sarkes Tarzian, Inc.
Syntron Co.
Sylvania Electric Products,Inc.
Vickers, Inc.
Westinghouse Electric Corp.

Manufacturers of Radio and Television Type Selenium Rectifiers

Bradley Labs, Inc.
Federal Telephone and Radio Corp.
General Electric Co.
International Rectifier Corp.
Mallory & Co., Inc.

Radio Receptor Co.
Sarkes Tarzian,Inc.
Sylvania Electric Products, Inc.

Manufacturers of Instrument Rectifiers of the Metallic Type

Bradley Labs, Inc.
Conant Labs.

Manufacturers of Valve-Type Rectifiers (Selenium and Copper-Oxide)

Bradley Labs, Inc.
Conant Labs.
Fansteel Metallurgical Corp.
Federal Telephone and Radio Corp.
General Electric Co.
International Rectifier Corp.
International Resistance Co.

Manufacturers of High-Voltage Metallic Rectifiers (Selenium)

Bradley Labs, Inc.
Fansteel Metallurgical Corp.
Federal Telephone and Radio Corp.
General Electric Co.
International Rectifier Corp.
Radio Receptor Co.
Sarkes Tarzian, Inc.

Manufacturers of High-Frequency Metallic Rectifiers

Bradley Labs, Inc.
Conant Labs.
International Resistance Company.

APPENDIX III

Classified Bibliography for Metallic Rectifiers

For the reader who is interested in delving deeper into the theory, as well as design and application of metallic rectifiers, this Appendix contains a classified bibliography for such study. The classification is divided into four parts. The first part of the classification contains references to theory as well as general material on metallic rectifiers. The remaining three parts cover references to the copper-oxide, magnesium-copper sulfide, and to the selenium rectifiers, respectively.

General References

1. "Principles and Applications of Semi-Conductors", E. D. Wilson, Electr. Mfg., p. 126, (Dec. 1946).

2. "The Physics of Electronic Semi-Conductors", G. L. Pearson, Trans. AIEE, Vol. 66, pp. 209-214, (1947).

3. "Crystal Rectifiers", H. C. Torrey and C. A. Whitmer, a book, Vol. 15 from the Radiation Laboratories Series by McGraw-Hill Book Co., New York, N. Y., (1948).

4. "Semi-Conductor Rectifiers", S. J. Angello, Electrical Eng. Vol 68, pp. 865-872, (Oct. 1949).

5. "Photo Effects in Semi-Conductors", J. A. Becker, Electrical Eng. Vol. 68, pp. 937-942, (Nov. 1949).

6. "Conductivity in Semi-Conductors", K. Lark and Horovitz, Electrical Eng. Vol. 68, pp. 1047-1065, (Dec. 1949).

7. "Electrons and Holes in Semi-Conductors", W. Shockley, a book published by D. Van Nostrand, Inc., New York, N. Y. (1950).

8. "Standards for Metallic Rectifiers" Publication No. MRi-1950, Dec. 1950 by National Electrical Manufacturers' Association, 155 E. 44th St., New York, N. Y.

9. "Military Specifications, Rectifiers, Metallic." MIL-R-15736 (Ships), 2 Jan. 1951.

10. "Advanced Developments in Metallic Rectifiers", W. F. Bonner and F. J. Oliver, Elect. Mfg., (Oct. 1951).

11. "Experiments With Rectifiers", from the book "Learning Electricity and Electronics Experimentally", Leonard R. Crow, Scientific Book Publishing Co., Vincennes, Ind.

12. "Rectifier Applications with Magnetic Amplifiers and Saturating Core Devices", from the book "Saturating Core Devices — Operating Principles and Applications", Leonard R. Crow, Scientific Book Publishing Co., Vincennes, Ind.

References On Copper-Oxide Rectifiers

1. "A New Type of Contact Rectifier", L. O. Grondahl, Physical Reviews, Vol. 27, p. 813, (1926).

2. "Theories of New Solid Junction Rectifiers", L. O. Grondahl, Science, Vol. 64, p. 306, (1926).

3. "The Copper-Cuprous-Oxide Rectifier and Photoelectric Cell", L. O. Grondahl, Review of Modern Physics, Vol. 5, p. 157, (1933).

4. "Fundamental Characteristics and Applications of Copper Oxide Rectifiers", C. C. Hamann and E. A. Harty, General Electric Review, Vol. 36, pp. 342-348, (Aug. 1933).

5. "Aging in Copper-Oxide Rectifiers", E. A. Harty, General Electric Review, Vol. 39, pp. 244-245, (May 1936).

6. "Semi-Conductor Theory of Blocking Layer and Point Contact Rectifier", W. Schottky, Zeitschrift für Physik, Vol. 113, p. 367, (1939).

7. "Applications of Copper Oxide Rectifiers", Electronics, p. 15, (July 1939).

8. "Metal Rectifiers", A. L. Williams and L. E. Thompson, Jour. IEE, Vol. 88, part I, pp. 353-371, (1941).

9. "Which Rectifier for Your DC-Operated Product?" Elect. Mfg., (Feb. 1942).

10. "Dry-Disc Rectifiers", Aerovox Research Worker, Vol. 15, No. 3, (March 1943).

11. "Principles and Applications of Semi-Conductor Rectifiers", E. D. Wilson, Elect. Mfg., p. 126, (Dec. 1946).

12. "Rectifiers — Selenium and Copper-Oxide", W. H. Falls, General Electric Review, Vol. 50, pp. 34-38, (1947).

13. "Twenty-Five Years of Copper-Copper-Oxide Rectifiers", L. O. Grondahl, AIEE Tech. Paper No. 48-66, (Dec. 1947), also Trans. AIEE, Vol. 67, pp. 403-410, (1948).

14. "The Copper Oxide Rectifier", I. R. Smith, Trans. AIEE, Vol. 67, p. 1051, (Nov. 1948).

15. "The Characteristics and Some Applications of Varistors", Frank R. Stansil, Proc. IRE, Vol. 39, No. 4, pp. 342-358, (April 1951).

16. "Advanced Developments in Metallic Rectifiers", W. F. Bonner and F. J. Oliver, Elect. Mfg., (Oct. 1951).

17. "Instrument Rectifiers", H. B. Conant, a booklet available from Conant Laboratories, Lincoln 5, Neb.

References On Magnesium-Copper Sulfide Rectifiers

1. "The Copper Sulfide Rectifier as a Source of Power for Projection Arc", C. A. Kotterman, Journal of the Society of Motion Picture Engineers, Vol. 32, pp. 558-567, (1939).

2. "The Magnesium-Copper Sulfide Rectifier Battery Charger for Railway Passenger Cars", C. A. Kotterman, Trans. AIEE, Vol. 58, pp. 260-265, (1939).

3. "Magnesium-Copper Sulfide Rectifier", Samuel Ruben, Trans. of the Electrochemical Society, Vol. 87, pp. 275-287, (1945).

4. "Magnesium-Copper Sulfide Rectifier Design Factors", R. O. Whitesell, Elect. Mfg., (Dec. 1945).

5. "Principles and Applications of Semi-Conductor Rectifiers", E. D. Wilson, Elect. Mfg., (Dec. 1946).

6. "AC Automotive Generator System for High Output", Tele-Tech., (Oct. 1947).

7. "Keeping Car Batteries Charged", A. D. Gilchrist, FM-TV, (Nov. 1951).

8. "High and Low Temperature Characteristics of Dry Disc Rectifiers", by P. R. Mallory & Co., Inc., Indianapolis, Ind.

References On Selenium Rectifiers

1. "Selenium Rectifiers", Karl Maier, Electrotechnische Zeitschrift, Vol. 55, No. 9, pp. 221-222, (March 1, 1934).

2. "Selenium Rectifiers", Karl Maier, Electrotechnische Zeitschrift, Vol. 56, No. 9, pp. 237-238, (Feb. 28, 1935).

3. "Selenium Rectifiers", E. Kipphan, Electrical Communications, Vol. 16, No. 1, pp. 21-29, (July 1937).

4. "Selenium Rectifiers", Communications, Vol. 18, No. 3, pp. 7-9, (March 1938).

5. "Some Industrial Applications of Selenium Rectifiers", S. V. C. Scruby and H. E. Giroz, Electrical Communications, Vol. 17, No. 4, pp. 366-374, (April 1939).

6. "Rectifier Power Plant for Transmission Systems", R. Kelley, Electrical Communications, Vol. 18, No. 1, pp. 60-64, (July 1939).

7. "Selenium Rectifiers for Signalling", Railway Signalling, Vol. 32, No. 12, pp. 673-675, (Dec. 1939).

8. "Selenium Rectifiers, Construction and Operation", W. O. Julius, Electrical Review, (May 17, 1940).

9. "Selenium Rectifier Characteristics, Applications and Design Factors", C. A. Clarke, Electrical Communications, Vol. 20, No. 1, (August 1941).

10. "Selenium Rectifiers for Closely Regulated Voltages", J. E. Yarmack, Electronics, (Sept. 1941).

11. "Selenium Rectifiers and their Design", J. E. Yarmack, Trans. Electrical Eng., Vol. 61, pp. 488-495, (July 1942) also paper 42-86.

12. "The Characteristics and Applications of the Selenium Rectifier", E. A. Richards, Inst, of Elect. Eng. Jour., (London), Vol. 88, part 3, No. 4, (Dec. 1941), see also Electrical Eng., (Oct. 1943).

13. "Characteristics and Applications of the Selenium Rectifier Cells", E. A. Harty, AIEE Trans, Vol. 62, pp. 624-629, (Oct. 1943).

14. "The Selenium Rectifier", Glen Ramsey, Electrical Eng., (Dec. 1944).

15. "Selenium Rectifiers for Cathodic Protection", W. F. Bonner, Federal Telephone and Radio Corp., Newark 1, N. J., (1946).

16. "Theory and Performance of Rectifiers", H. D. Holler, J. P. Schroat, Dept. of Commerce, Bureau of Stds., pp. 472-484.

17. "Transformer Calculations for Selenium Rectifier Applications", J. E. Hall, Elect. Mfg., (Feb. 1946).

18. "Selenium Rectifiers", J. Lobenstein, Communications, (Nov. 1946).

19. "Principles and Applications of Semi-conductor Rectifiers", E. A. Wilson, Elect. Mfg., (Dec. 1946).

20. "What Are Suitable Applications for Selenium Rectifiers?" Glen Ramsey, Elect. Mfg., pp. 106-110, 188-198, (May 1947).

21. "Rectifiers, Selenium and Copper-Oxide", W. H. Falls, General Electric Review, Vol. 50, pp. 34-38, (1947).

22. "Saturable Reactor Regulates Rectifier Voltage", P. C. Dolen, J. H. Hall, Elect. Mfg., (March 1949).

23. "Design, Application and Servicing of Selenium Rectifiers", I. Wolf, Service, (Nov. 1949).

24. "Vibration-Free Motor Drive", R. Somers, Elect. Mfg., (Aug. 1950).

25. "Surge Suppressor Lengthens Contact Life", Elect. Mfg. (March 1952).

INDEX

T

V

W