



Electronics

Radio

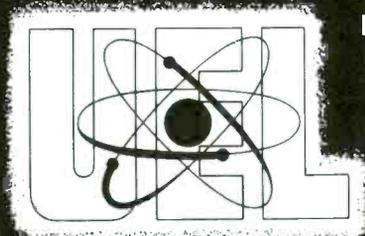
Television

Radar

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A-C METERS AND A-C POWER

ASSIGNMENT 19

ALTERNATING-CURRENT METERS AND ALTERNATING-CURRENT POWER

In Assignment 11, we studied in detail, the construction of d-c meters. We found that the D'Arsonval movement is used in a large percentage of d-c instruments. Figure 1 illustrates the D'Arsonval movement. Let us review some of the things which we have learned about this type of meter.

The action of the meter depends upon the inter-action of two magnetic fields. One of these magnetic fields, the fixed one, is provided by the permanent magnet; the other magnetic field, the variable one, is produced by passing the direct current through the coil which is pivoted and free to rotate between the poles of the permanent magnet.

When current is passed through the movable coil so that the polarity of the magnetic field about this coil is as indicated in Figure 1, the repulsion of this field, and the field of the permanent magnet will cause the coil to rotate, and move the pointer **up** the calibrated scale. The amount of rotation of the coil is determined by the amount of current passed through the coil. The rotation of the coil is opposed by the spring action of the two spiral springs located on either end of the shaft.

We also learned that this basic instrument could be used to indicate higher values of current than that for which it was designed, by using shunt resistors connected in parallel with the meter movement. We also learned how to compute the value of the shunt resistors necessary to indicate a desired full scale deflection, when the full scale current and the internal resistance of the meter were known.

This meter, we learned, can also be used to measure d-c **voltages** by using the proper values of series dropping resistors (voltmeter multiplier resistors) in conjunction with the meter.

Now let us see why we cannot use this meter, just as it is, to measure alternating currents. In an alternating current, of course, the current flows in first one direction and then in the other. On one of the alternations of the alternating current, the direction of the current flow through the coil would be such as to produce a magnetic field about the coil as shown in Figure 1. On the next alternation the current flow would be in the opposite direction, and therefore, the magnetic field built up around the coil would be in the opposite direction. The inter-action of this field, and the field of the permanent magnet, would cause the coil to rotate in a direction opposite to the previous direction, and the pointer would move **down** scale. Since an ordinary d-c milliammeter has its zero position at the left of the scale, this movement would be off scale, past zero.

It is possible to build a d-c meter with its zero position in the center of the scale, and reading positive values of current on the right of center and negative values of current on left of center. Such a meter is called a galvanometer.

If the frequency of the alternating current applied to a galvanometer were slow enough, the needle could be observed to swing from one side to the other as the polarity of the current changed. If the reversals were rapid enough, such as sixty hertz alternating current, in which there are 120 reversals per second, the changes would be so fast that the galvanometer needle could not follow them at all. The galvanometer would remain on zero, and would perhaps vibrate slightly. Obviously then, the D'Arsonval movement cannot be used for reading alternating current. Some type of meter is needed which will continue to turn in the same direction regardless of the polarity of the current causing the motion. Several basic types of a-c meters have been designed following this principle.

Siemens Dynamometer

Just as the D'Arsonval meter is the basic idea behind many of the direct current instruments, the Siemens Dynamometer is the underlying principle upon which many of the alternating-current instruments operate. This instrument is never used at the present time, except as a laboratory demonstration, but its operation is explained here because other practical a-c meters operate upon the same principle.

Figure 2 is a sketch showing a simple form of the Siemens Dynamometer. It consists essentially of two sets of coils. The coil "S" is stationary, and the coil "R", which is free to rotate through a relatively small angle, has its plane at right angles to that of coil "S" when there is no current passing through the coils. The rotating or moving coil "R" is suspended by the spiral spring "P" which opposes the direction of rotation, just as the coil of a direct-current meter is opposed by spiral springs. Current is led into the moving coil through two mercury cups, M_1 and M_2 . When this instrument is used as an ammeter, the two coils are wound with a few turns of heavy wire and are connected in series as shown in Figure 2. The important advantage of the Siemens Dynamometer is its action permitting alternating currents to be read.

The Siemens Dynamometer is in some respects similar to the D'Arsonval movement, but there is one fundamental difference. The D'Arsonval movement obtains its action due to the inter-action of two magnetic fields. One, the fixed field produced by a permanent magnet, the other a variable field produced by the moving coil. The movement in a Siemens Dynamometer is also due to the inter-action of two magnetic fields, but in this case the one magnetic field is produced by a fixed coil, the coil "S" in Figure 2, and the other field is produced by the movable coil "R". If Figure 2 is examined closely, it will be noticed that the two coils are in series; therefore, the same current flows through these two coils.

Figure 3 illustrates the principle of operation of the dynamometer. Figure 3(A) is a cross-sectional view of the two single turn coils of Figure 2 when their planes are at right angles. A and B are the cross-sections of the stationary coil "S". C and D are the cross-sections of the rotating

coil "R". When a-c is applied between point 1 and 2 of Figure 2, the magnetic lines of force will be as shown in Figure 3(A). Notice that the lines of force will have the same direction between A and C, and between B and D. This will strengthen the magnetic fields at these points. The lines of force are in opposite directions between B and C, and between A and D. This will weaken the fields at these points. These strengthened and weakened fields (torque) will cause the loop of wire, CD, (the one which is pivoted) to rotate clockwise as indicated by the arrow of Figure 3(A). When the current reverses direction (a-c) the lines of force around each conductor will reverse their direction as shown in Figure 3(B). This will keep the **torque** in the same direction as before, so the coil, CD, will keep on rotating in a clockwise direction. Notice that although the current flow is in the opposite direction, the movement of the pivoted coil is in the same direction as before. This meter will register a-c, and will reach the position shown in Figure 3(C) if enough torque is produced to overcome the frictional losses and the spring tension. Thus, we see that by replacing the fixed field in the D'Arsonval meter with a constantly reversing magnetic field produced by the fixed coil in the Siemens Dynamometer, we have produced a meter which will indicate the amount of a-c current flowing in the circuit. This same principle is used in a number of a-c indicating instruments. The indicating electro-dynamometer is an example of this type of construction.

Indicating Electro-dynamometer

Figure 4 shows a cross-sectional view of this type of instrument. Two fixed coils, F_1 and F_2 , are connected in series, so that their magnetic fields act in conjunction. These coils may be considered as being two parts of a single coil, open in the middle to allow the spindle of the moving coil "R" to pass through. "R" is a rotating or moving coil mounted on a vertical spindle. At each end of the spindle there is a hardened steel pivot which turns on jewelled bearings. Two spiral springs, similar to those used in direct-current meters, oppose the turning of the coil "R" and at the same time carry the current into and away from the coil. Since these springs can carry only a small current, the movable coil is wound with fine wire. A light indicating needle, or pointer, "N", is mounted on the spindle and is free to turn with the moving coil.

Assume that at some instant the direction of the magnetic field #1, which is due to the fixed coil, is from left to right as shown in Figure 4. At the same instant, the current in coil "R" produces a field, #2, and the direction of this field is shown by the arrows along the plane of the moving coil "R". Under this condition, the coils tend to align themselves so that the number of magnetic linkages in the system is a maximum. This is the same as saying that the two magnetic fields try to adjust themselves so that they will be parallel to each other. The moving coil "R", therefore, tends to turn in a clockwise direction so that its field will act in conjunction

with the #1 field, the field set up by the stationary coils, F_1 and F_2 . The turning action of "R" is opposed by the control springs on the spindle. The amount of motion of the moving coil in this instrument is proportional to the strength of the magnetic field set up in each coil, that is, field #1 and field #2, and to a certain extent is proportional to the angle between the planes of the coil "R" and the coils F_1 and F_2 . Now if the field strengths of each of these two coils is proportional to the current flowing through them, the torque is proportional to the product of the two currents. For this reason, the scale on this meter will not be a linear scale as in the direct-current D'Arsonval meters. That is, the scale division will be crowded on the low end of the scale (the end near zero), and will be spread out on the high end of the scale.

The dynamometer movement can be used for a voltmeter if the coils are made of fine wire and a series resistor is used to limit the current when the instrument is connected directly across the line. The current passing through the dynamometer is therefore proportional to the line voltage. The pointer in this case now moves over a scale calibrated directly in volts. At the lower end of the scale, the divisions are spaced together so closely that poor precision is obtained. The divisions at the middle and the upper portions of the scale however are usually of such magnitude that they may be read with a high degree of precision. The dynamometer type of voltmeter takes about five times as much current as the d-c voltmeter of the same rating and consumes an appreciable amount of power. As the moving coil is operated in a comparatively weak field, this type of instrument is very susceptible to stray fields. Unless the meter is well shielded, wires carrying current, inductive apparatus, and even iron alone if brought too near, may cause large errors in the readings. For this reason, these meters are surrounded by a laminated iron shield.

Inclined-Coil Instruments

The inclined coil instrument shown in Figure 5 operates on the same principle as the electro-dynamometer but will have a more uniformly spaced scale. The geometrical position of the moving coil provides more uniform changes in the spindle movement for corresponding changes in current through the instrument. The increased linearity of the scale permits a greater degree of accuracy to be maintained over the entire range of the meter.

Spreading-Vane Meters

The type of a-c meter which employs only one coil is shown in Figure 6. This type meter gets its name from the fact that motion in the meter is produced by the inter-action of the two flat pieces of soft iron commonly called vanes. One of these vanes is stationary and the other is free to swing on the spindle in a fashion similar to a book being opened. These two vanes are located on the inside of a coil wound of fine wire. A series

resistor is also used to limit the current when the meter is designed to read voltage. As current is passed through the coil in one direction the two iron vanes will be magnetized, as shown in Figure 6. Notice that adjacent ends of the two vanes have the same polarity, that is, the left end in the diagram of each is North and the right end is South. Since like magnetic poles repel, the movable vane will swing away from the fixed vane, and the amount of motion will be indicated on the calibrated scale. As current is passed through the coil in the opposite direction, the two iron vanes are again magnetized but in this case they are magnetized in the opposite direction, that is, the left end of each in the diagram will now be the South pole and the right end of each will be the North pole. In this case, the like poles of two magnets are still adjacent, consequently the movable vane will rotate away from the fixed vane. When a-c is passed through the coil the adjacent ends of the two small flat pieces of soft iron will always be magnetized in the same direction and consequently the movable vane will rotate, moving the spindle and the needle across the calibrated scale. This action is opposed by spiral springs which cause the pointer to return to zero when the current is not flowing through the coil. The scale on this type meter will be crowded at the high end of the scale.

Inclined-Coil Iron-Vane Meter

The Inclined-Coil Iron-Vane Meter is illustrated in Figure 7. In this meter there is only one coil and one vane. This one iron vane is mounted diagonally to the rotating spindle. When the pointer is at zero, the vane is almost at right angles to the axis of the coil. When current flows through the winding, the magnetic field set up about the fixed coil magnetizes the iron vane which is a long narrow oval. The magnetic field set up in this vane will attempt to align itself with the magnetic field set up by the coil and in so doing will cause the vane to rotate against the action of the spiral springs. Position A of Figure 7 shows the vane when no current is flowing through the coil, and position B shows how the vane lines up with the coil when acted upon by the magnetic lines of force.

The foregoing illustrates that meters designed either on the principle of the dynamometer or the iron vane may be used for reading alternating current or voltage. The only difference is that for a-c voltmeters the coils are made of fine wire and a large number of turns, and a series resistor is used; while a-c ammeters have coils wound with fewer turns of heavy wire which can carry the entire current of the load up to the limit of the meter. Of course, no series resistor is used in a-c ammeters.

Increasing Instrument Ranges

It is often necessary to use a low range instrument for measuring high current or voltage values. We have found that with d-c instruments, shunts and multipliers are widely used for this purpose. On first thought, one might conclude that shunts and multipliers could be used just as easily

and just as effectively with a-c meters. Such reasoning however is erroneous for the following reasons. In direct-current circuits, the current will divide inversely as the resistances of the two branches of the circuits, and any inductance such as that in the coils of the instrument play no part in the distribution of the flow of current. However, we have learned that alternating currents are affected by both resistance and inductance. The result is that the currents do not divide inversely as the resistances but rather inversely as the impedances; the impedances being a function of both the inductance and the resistance. Furthermore, the impedance of any circuit is determined by the frequency of the alternating current and in this case varies directly with it. Consequently, unless the ratio of inductance to resistance were the same in the shunt as in the moving coil, the instrument would be correct for any one frequency, and even then might be in considerable error if there is any irregularity in the sine wave voltage applied to the instrument. For these reasons shunts and multipliers are seldom used with a-c instruments.

In alternating-current instruments it is common practice to use specially designed transformers of various ratios to increase the range of ammeters and voltmeters. The transformers used with ammeters are called current transformers and those used with voltmeters are called voltage transformers or potential transformers. Thus, one ammeter and current transformer and one voltmeter and voltage transformer can be used to make up a wide range of instruments.

Electronics Instruments

The types of alternating-current instruments previously discussed are used chiefly for measurements in the 50 and 60 hertz power supply circuits. Certain limitations of these meters prevent their use in electronics circuits such as audio amplifiers, radio-frequency amplifiers, etc. For measurements in these circuits it is common place to use an adaptation of the permanent-magnet, moving-coil, D'Arsonval type instrument. These instruments employ means of changing the alternating current to direct current which will register on the D'Arsonval meter. This will be explained in detail in this assignment but before proceeding with this subject, it will be well to consider the alternating current values encountered in communication circuits. Very low frequencies of a few cycles per second are encountered in television and other circuits. The audio frequencies cover a band of from about 20 hertz to 20,000 hertz. Above this and extending up to billions of cycles per second come the many radio frequencies used in communication. Thus, measurements must be made of alternating currents and voltages ranging in frequency from a few cycles per second to millions of cycles per second. Also the range of currents which must be measured is very wide. For example, very small currents are adequate for carrying communication messages over telephone lines, whereas the current present in the antenna circuit of a large radio transmitter may be many amperes. For this reason instruments must be available for measuring alternating

current of a few microamperes to many amperes. What was said regarding electronics currents applies to voltages also. In electronics circuits voltages of a few microvolts to thousands of volts must be measured.

The power limitation in electronics circuits is one of the important factors seriously limiting measurements. The amount of power in an electronics circuit may be only a few microwatts (the output of a microphone for instance), or it may be a few milliwatts (as in a control circuit), or the power level may be many kilowatts (as the output of a dielectric heating unit).

Unless the frequency of the a-c to be measured is too high, large values of current, voltage and power are much easier to measure than are small values. Consider for a moment the measurement in a circuit in which the voltage is only a few volts, the current is only a few milliamperes, and the power is only a few milliwatts. The power required to operate an alternating-current instrument of the types considered previously in this assignment is greater than the useful power in the circuit being used to perform the desired control function. It is not uncommon to find that ten watts of power is required to operate an alternating-current voltmeter of the type used in the 60 hertz power circuit. For this reason such an instrument could not be used in the low-power electronics circuit just mentioned. Also, if radio frequencies are to be measured, instruments containing coils having a great deal of inductance cannot be used, since it is not possible to force the high frequency signal through these coils. For these and other reasons special instruments are used in alternating current and voltage measurements in electronics work. The copper oxide instrument, the hot-wire instrument, and the thermocouple instrument will be considered in this assignment.

The D'Arsonval instrument has one outstanding advantage when compared with most a-c instruments. In the D'Arsonval instrument, a strong permanent magnet provides a strong magnetic field. The energy that this instrument must take from the circuit being measured is just that small amount necessary to energize the moving coil. However, all of the magnetic field strength in the a-c instruments must be produced by energy taken from the circuit being measured. Thus we see it is advantageous to use a D'Arsonval instrument, in conjunction with some means of changing a-c into d-c, to read the a-c current and voltage in communication circuits.

Copper-Oxide Rectifiers

A rectifier is a device that will permit current flow in only one direction. You will study vacuum-tube rectifiers and semi-conductor rectifiers (selenium, silicon, and germanium) in the assignment dealing with power supplies. The copper-oxide rectifier is a rectifying unit which was employed for many years in a-c measuring devices.

A plate of copper coated with cuprous oxide (commonly called copper oxide) has an interesting property. Although an electric current will flow

quite easily from the copper to the copper-oxide coating there is an extremely high resistance to the flow of current from the copper oxide to the copper.

When an alternating voltage is applied to a copper-oxide rectifier unit, current will flow from the copper to the copper oxide during one half of the cycle. During the next half of the cycle practically no current will flow. Thus, we see that when an alternating voltage is applied to a copper-oxide rectifier, the current which flows is a pulsating direct current.

In Figure 8, we have connected a single copper-oxide rectifier in series with a D'Arsonval type d-c instrument. The schematic symbol for this rectifier is shown in Figure 8. Current will flow from the plate indicated by the long line to the plate indicated by the arrow. This device will work satisfactorily when used as a voltmeter as shown in Figure 8(A). During every other half cycle a small pulse of current will pass through the rectifier and the meter. The meter will deflect in proportion to the average value of this pulsating current.

In Figure 8(B), we see the same meter and copper-oxide rectifier connected in series. In this case, the instrument is to be used to measure a-c current and is to be connected in series with the circuit. If Figure 8(B) is analyzed carefully, one fault will be noticed. During every other half cycle current will pass through the rectifier and milliammeter. During the remaining half cycle the rectifier will completely halt the flow of current in the **entire** circuit! It is obvious then that an a-c current cannot be flowing in this circuit. For this reason, the copper-oxide rectifier and d-c milliammeter cannot be used in this type circuit as an a-c **current indicating device**.

Figure 9 shows a circuit which overcomes the difficulties encountered in the circuit shown in Figure 8(B). Four rectifier elements are used in order to permit current flow during each and every half cycle. Each of the rectifier elements in the arms of the bridge is a small copper-oxide rectifier disc. The four are usually combined into a single unit with the proper leads brought out. Across one portion of the bridge is connected a sensitive permanent-magnet D'Arsonval type instrument. The alternating current to be measured is passed in at the other pair of bridge terminals.

The combined action of the four elements is quite simple. During the half cycle that the **lower** a-c input terminal is negative, current will flow from the lower terminal through rectifier number 3, through the instrument **from left to right**, and up through rectifier number 2 to the upper input terminal. This path is shown by the dashed arrows. During the next half cycle, the **upper** a-c input terminal is negative. The current will flow from the upper terminal through rectifier number 1, through the instrument **from left to right**, and down through rectifier number 4 to the lower input terminal. This path is shown by heavy arrows. Notice that the current flows through the instrument in the same direction for both halves of the cycle. The alternating current has been rectified, or changed

into pulsating d-c, so that it can be measured by the d-c instrument. Current flow in the circuit being measured will not be interrupted, so this type meter may be used as a milliammeter or as a voltmeter.

Copper-oxide milliammeters will perform quite satisfactorily at frequencies below 5000 cycles per second. At higher frequencies, the rectifier elements will have capacitor action during the half cycles that they are not conducting. This capacitance effect will shunt some of the current around the instrument at high frequencies. As a result, the instrument will indicate lower than proper amounts of voltage or current at high frequencies. The graph in Figure 10 shows how the needle deflection decreases at high frequencies in a typical copper-oxide rectifier instrument.

In our study of d-c milliammeters, we learned that an efficient milliammeter should have a very low internal resistance. But the internal resistance of a copper-oxide milliammeter is fairly high. (A typical one having a resistance of almost one thousand ohms.) Furthermore this resistance is found to vary widely depending on the amount of current being measured. For these reasons, the copper-oxide milliammeter is recommended only for special purposes where the characteristics enumerated are of no disadvantage. The copper-oxide voltmeter however is a satisfactory general utility instrument for audio communication purposes. If a high value of resistance is connected between one terminal of the a-c input, and the bridge circuit of Figure 9, the device becomes an alternating current voltmeter. Because it contains a high value of series resistance its internal impedance is quite constant and is high, as it should be for a voltmeter. The copper-oxide voltmeter has a frequency error as explained for the ammeter and is shown in Figure 10. This limits its use for most purposes to measurements in the audio frequency range between 20 and 20,000 cycles per second. Most of the semi-conductor diodes have much less capacitance effect and consequently do not shunt as much high-frequency signal components around the meter as copper-oxide rectifiers. When higher frequency signals are to be measured, meters employing semi-conductor diodes may be employed. Due to the shunting effect of the higher frequencies by the capacitance effect of the rectifier discs, the copper-oxide meter is never used for the measurements of radio frequency voltages.

Hot-Wire Ammeter

One of the effects of an electric current is the heat produced when the current flows in a conductor having resistance. An instrument which was developed to make use of this effect is called the Hot-Wire Ammeter. Its construction is shown in Figure 11. The current to be measured is passed through the **hot wire** shown in Figure 11. Due to the heating effect of the current, this wire expands and thus increases in length. The slack so produced in the wire is taken up by the tension strand attached near its center, the tension being provided by the spring below. This tension strand is looped around the spindle of the pointer shaft between the current carrying

wire and the spring, thus turning the shaft and moving the pointer, the deflection depending on the magnitude of the current. The tension strand is electrically insulated from the current carrying wire.

This type of meter is sometimes used for measuring high frequency a-c current such as radio frequency currents in the medium range of radio frequencies. This is possible because the heating effect of a current is proportional to the current squared and is independent of the frequency of the current.

The main disadvantage of this instrument is its dependence upon surrounding thermal conditions. Variations in surrounding temperature introduce errors because they alter the length, not only of the current carrying wire, but of the base of the instrument, so the distance between the two "fixed" ends of the current carrying wire is also variable. These changes in length result in errors in reading the amount of current flowing. Furthermore, the instrument is slow in reacting and even slower in returning to the zero reading. The manufacture of this type of instrument is on the decline in this country.

Thermocouple Meters

Many instruments used to measure a-c currents and voltages in the radio-frequency range employ the D'Arsonval type movement in conjunction with a thermocouple. The action of a thermocouple is illustrated in Figure 12. The thermocouple consists essentially of two wires (A and B of Figure 12) of **unlike** metals fastened together at one end and separated at the other end. The point at which the two wires are fastened together is called the **thermocouple junction**. When heat, from any source, is applied at the thermocouple junction, a d-c voltage will exist between the two open ends of the unlike wires, as shown in Figure 12. If these two ends are connected to a sensitive D'Arsonval type instrument, a current will be forced through the instrument and its pointers will deflect. The amount of voltage which appears across the two open ends of the unlike wires is dependent upon the amount of heat applied to the junction, and to a certain extent upon the material used in the two wires A and B. Any two unlike materials will exhibit the thermocouple effect when joined together and the junction heated as illustrated in Figure 12. However, some materials will produce a much greater voltage than others for a given amount of heat at the junction. In most commercial instruments, one of these thermocouple wires is made of a platinum alloy and the other is made of constantan. To use the thermocouple effect to indicate the value of alternating current flowing in a circuit, the alternating current is passed through a heater wire which is then used to heat the junction of the thermocouple.

Three methods are shown in Figure 13 for heating the thermocouple junction. The arrangement shown in (A) of this figure is called the mutual type of thermocouple. The alternating current to be measured is passed

through the thermocouple itself rather than through a separate heater. The alternating current to be measured divides, part passing through the instrument and part through the thermocouple. The instrument will have a small amount of inductance and thus the current division will depend on the frequency of the current to be measured. This introduces a **shunting error**. Also, there is a bad **reversal error** with the mutual type. That is, the deflection of the instrument is not the same for the same value of current in different directions through the thermocouple. Therefore, this type of thermocouple is seldom used.

The **contact type** of thermocouple, shown in Figure 13(B), is a widely used type that is very satisfactory. In this arrangement, the current to be measured is passed through the **heater** which makes metallic contact with the thermocouple junction and readily transmits heat to it. With this thermocouple, no shunting error exists, and the reversal error is usually negligible.

The **separate heater type** of thermocouple, shown in Figure 13(C), is particularly well suited for measurement in radio-frequency circuits. It has been especially designed to reduce errors that thermocouples introduce in the radio-frequency circuits. Because of the importance of this in communication measurements, it will be discussed in the following separate section.

Thermocouples at Radio Frequencies

At frequencies of a few thousand cycles per second or below, measurements are usually relatively easy to make. Above ten thousand cycles per second, more attention must be paid to the grounding and shielding of circuits. When measurements are made at radio frequencies (from 20,000 hertz on up to billions of hertz), an inexperienced person may get almost any answer if his technique is faulty.

The contact type of thermocouple is generally used for audio and the lower radio frequencies. In this instrument, the heater may have only a few ohms resistance if it is to measure large currents, or it may be as high as 1000 ohms if it is to measure very small currents. When the alternating current to be measured is passed through the heater, power equal to I^2R is dissipated in the heater and this raises the temperature of the thermocouple junction. Since the amount of heat produced by the heater and therefore transmitted to the junction of the thermocouple is proportional to the square of the current flowing, the d-c current which will be forced through the D'Arsonval instrument will be proportional to the square of the a-c current flowing. For this reason, the calibrated scale on the thermocouple type meter is not a linear scale but will be crowded near the low end and spread out near the high end of the scale.

In sensitive thermocouples, that is one which will operate with small values of current, the thermocouple wires are very delicate, and they are usually mounted in an evacuated glass bulb. This protects them from

mechanical injury, prevents air from conducting heat away from the heater, and makes the thermocouple more sensitive.

If the thermocouple is casually examined, its electrical characteristics will appear to be those of a simple pure resistance, because only a heater resistor is connected in the circuit in which the measurements are desired. But if a very critical examination is made, the equivalent circuit of a thermocouple is found to appear as shown in Figure 14.

We have learned that any wire carrying current is surrounded by a magnetic field; therefore, any wire carrying current contains a certain amount of inductance. In Figure 14, L_1 and L_2 are the series inductances of the leads and the heater wires respectively. R_1 represents the resistance of the leads. We have also learned that any two conductors, separated by an insulating medium, form a capacitor. C_1 in Figure 14 is the stray capacitance existing between the leads. C_2 represents the capacitance between the heater and the thermocouple. C_3 is the capacitance between the thermocouple junction and the heater.

Because the reactances of these small inductances and capacitances will vary with the frequency, it is evident that a calibration made for one frequency will not hold at another frequency. Nevertheless, by using extreme care in the design of the thermocouple for radio frequencies, these stray effects can be kept at a minimum. The result of this careful design is that thermocouples having excellent characteristics are available. In well designed instruments the error is only about one per cent at 200 megahertz. The separate heater type of thermocouple is normally used for measuring these high radio frequencies.

In Figure 14, it will be noted that an insulating bead is placed between the heater and the thermocouple junction. This bead electrically insulates the thermocouple junction from the heater wire. However, the material chosen for the bead has good heat conducting properties so that the heat from the heater is readily conducted to the junction. By careful choice and construction of this bead, the separate heater type thermocouple has been made almost as sensitive as the contact type in which the heater and junction are in metallic contact.

To understand completely the advantages of the separate heater type of thermocouple, as compared to the other two types, requires a knowledge of balanced and unbalanced circuits which will be discussed later. For the present, let us say, that in radio-frequency measurements, the less the circuit is disturbed, the better. Inserting a contact type of thermocouple directly connects the thermocouple leads and the measuring instruments to the heater which is of course connected to the a-c circuit. Thus, a large amount of stray capacitance is connected to one side of the circuit, and this may disturb the original circuit conditions. Inserting a separate heater type of thermocouple does not disturb the circuit to such a great extent because the thermocouple, the leads, and the measuring instrument are not

in direct metallic contact with the heater. They are connected to it only by the small stray capacitance C_2 and C_3 in Figure 14.

Of course, inserting the heater in any circuit, irrespective of the frequency, disturbs the circuit. This must be tolerated, however, if a thermocouple is to be used. In fact, the effect may be entirely negligible. For instance, if an oscillator having an internal resistance of several hundred ohms is connected to a load of several hundred ohms, inserting a thermocouple with a heater of a few ohms will not cause appreciable error. About the only rule that can be stated is to examine the circuit before the thermocouple is inserted and estimate the error that will result. Usually a mental Ohm's Law analysis will suffice.

There may be certain carefully balanced radio-frequency circuits in which, if a thermocouple is inserted in one wire, a small resistance of the same value should be inserted in the other wire.

For measuring a-c voltages, and particularly high frequency r-f voltages, a thermocouple may be used with a series multiplier resistor.

It will be recalled that a given value of direct current and the **effective**, or root mean square ("rms"), value of alternating current, produce the same heating effect in a resistor. For this reason, the calibration of a thermocouple ammeter or milliammeter may be checked by passing direct current through the meter.

Summary of A-C Meters

In general, we have found that two effects of an a-c current have been used for instruments measuring the value of a-c current in a circuit. These two current effects are the magnetic effect produced by a current and the heating effect produced by a current. We have seen that in every case, in the meters employing the magnetic effect of the current to produce their deflection, the use of two magnetic fields is required. Each of these fields reverse with each alternation of the alternating current. In the dynamometer type meters and in the inclined-coil type meters, these two constantly reversing magnetic fields were produced by the current passing through two coils. In the spreading-vane type meter, these two constantly reversing magnetic fields were produced in the two vanes by the magnetic field of the coil. It was also pointed out that these meters are insensitive devices and require a considerable amount of power for their operation.

The hot-wire ammeter and the thermocouple ammeter each employ the heating effect of the a-c current for their operation. Thermocouple meters are used almost exclusively for the measurement of radio-frequency currents.

The copper-oxide rectifier type instrument operates on the principle of changing, or rectifying, the a-c into pulsating d-c. This pulsating d-c is then passed through a D'Arsonval type meter and indicates on the

calibrated scale of that meter. Copper-oxide rectifier instruments are used for measuring alternating current and voltages in the audio-frequency range from about 20 to 20,000 cycles per second.

Power in A-C Circuits

When we studied d-c circuits in a previous assignment, it was pointed out of power, measured in **watts**, is equal to the **product** of the **voltage** times the **current**. To state this as a mathematical equation, we could write $P = EI$. Any change in either voltage or current will cause a change of power and therefore when we speak of watts we mean the instantaneous power.

In a-c circuits, both the voltage and current are continually changing in value, and the current may or may not be in phase with the voltage. However, the **actual** power in watts will still be equal to the product of the **instantaneous** values of voltage and current.

Figure 15 shows the sine waves of voltage and current and also the graph of the power in an a-c circuit. Figure 15(A) shows the voltage and current and the power in an a-c circuit containing only a pure resistance. Notice that the voltage and the current are in phase. Figure 15(B) shows the voltage and the current and the power in an a-c circuit containing only a pure inductance. The current is lagging the voltage by 90 degrees. Figure 15(C) shows the voltage and the current and the power in an a-c circuit containing pure capacitance. In this case, the current is leading the voltage by 90 degrees. Let us examine the graph of the power in these three figures. Remember that power is found by multiplying the instantaneous value of voltage by the instantaneous value of current. In Figure 15(A), over the first half cycle of the a-c voltage and current, the value of the power will be found by multiplying a positive value of voltage by a positive value of current. The resultant power is, of course, positive as shown by the graph. Over the second half of the cycle, while the current and voltage are both negative, the power will still be a positive value. This is true because multiplying a negative value of current by a negative value of voltage will produce a positive value of power. We found in an algebra assignment that multiplying one negative quantity by another negative quantity would give an answer which was positive. With the pure resistance as shown, the power in the a-c circuit is all positive. This means that the power is being fed from the power source into the load resistance where it is dissipated in heat or used for some other useful purpose.

Now let us carefully examine Figure 15(B). In this figure, since the voltage and current are not in phase, we will have a condition during parts of the cycle when the voltage is positive and the current is negative. As an example, notice the first 90 degrees shown on the graph. The voltage is positive and the current is negative. When these two instantaneous values are multiplied together, the result is that the power is a negative value. This is shown on the graph.

During the next 90 degrees of this graph, the current and voltage are both positive, so the power over this portion of the cycle is positive. Continuing this same process, that is, multiplying the **instantaneous** value of current times the **instantaneous** value of voltage, we find that the power is negative over the portion of the cycle from 180 degrees to 270 degrees, and is again positive over the portion of the cycle from 270 degrees to 360 degrees. Notice also that the graph for the power shows an equal amount of power on the positive side of the axis and on the negative side of the axis. The positive power indicates power which is being sent from the source into the load. Whereas the negative portion of this graph indicates that **part of the power is being returned from the load into the source.**

The curves shown in Figure 15(B) are when a pure inductance is being used as the load for an a-c circuit. It will be recalled that in an inductance, the magnetic lines of force are built up about the inductance by the current, and as the current changes its direction on the next alternation, these magnetic lines of force which have been built up about the inductance collapse, thereby cutting the turns of the inductance and generating a counter-voltage. This counter-voltage forces a current through the source in the opposite direction. This is how the negative portion of the power graph occurs. Let us repeat this statement. During half of the a-c input cycle to the inductance, the inductance absorbs power from the source and stores this power in the form of magnetic lines of force. During the other half cycle of input, the magnetic lines of force collapse, returning the power from the inductance to the source. Thus we find that by connecting a pure inductance as the load on an a-c generator, the net result is that no power is used. As much power as is drawn by the load, is again returned to the source by the load.

In Figure 15(C), we find a similar condition. The voltage and current in this case are also 90 degrees out of phase, although the current is leading the voltage in this case. If the graph for the power in this figure is studied carefully, it will be discovered that in this case we are also using no power from the source. On one half of the input cycle the capacitance draws power from the source, storing it in the form of electrostatic lines of force. During the other half of the cycle the power is returned to the source from the capacitor. The net result is that no power is actually used or dissipated in the capacitance. From this we see that either a pure inductance or a pure capacitance will draw no power from the source, in spite of the fact that voltage is being applied to the components and current is flowing in the circuit.

Apparent Power, True Power and Power Factor

Suppose that a circuit contains some resistance and some inductance, and that the current is, therefore, not lagging the voltage by 90 degrees but some value between zero and 90 degrees. These conditions are shown in Figure 16. In this figure, the current is lagging the voltage by 45 degrees.

The power wave has also been plotted in this figure. It will be noted that for a circuit of resistance and inductance, where the phase angle is less than 90 degrees, a net power flows **into** the circuit as indicated by the fact that the negative portion of the power curve or graph is much smaller than the positive portion. Of course, the same reasoning would apply to a resistance and capacitance in series. By carefully analyzing Figure 15 and Figure 16, it should be apparent that the angle between the current and voltage determines the amount of power taken for a given amount of current and voltage. When the current and voltage are in phase, it can be seen that the maximum amount of power is drawn from the source; when they are 90 degrees out of phase, no net power is taken, and when they are out of phase by some angle less than 90 degrees, some net power is taken.

It is only that part of the curve above the base line, or that part which is positive, that does useful work such as heat a resistor or drive a motor. It can be seen that if we multiply volts times amperes our result would be equal to the total power both above and below the base line.

The true, or useful power, in an a-c circuit is the positive power only, and we will have to find a way to indicate the difference between it and the total power as found by multiplying the volts times the amperes. The value found when the voltage in an a-c circuit is multiplied by the amperage is called the **apparent power**, since it would seem that this would indicate the **power** in an a-c circuit. The true power is found by multiplying the voltage times the current times some decimal that is less than one. This decimal is determined by the phase angle of the voltage and the current in the a-c circuit and is given in the table below. This decimal is called the **power factor**.

Degrees	Power Factor	Degrees	Power Factor
0	1	45	.707
15	.97	60	.5
30	.866	75	.26
		90	.0

The answer obtained by multiplying the voltage times the current times the power factor will give the true power in an a-c circuit. Let us state this as a formula:

$$\text{Power} = EI \times \text{power factor.}$$

To illustrate the use of this new term, power factor, let us assume that an a-c circuit contains an inductance and a resistance; that the applied voltage is 110 volts; the current flowing in the circuit is 5 amperes; and the phase angle between the voltage and the current is 30 degrees. The **apparent** power would be found by multiplying the 110 volts times the 5 amperes and would be equal to 550. This is commonly called 550 volt-amperes, since we have multiplied volts times amperes, yet our result is not power as has been pointed out previously but is merely apparent power.

The power wave has also been plotted in this figure. It will be noted that for a circuit of resistance and inductance, where the phase angle is less than 90 degrees, a net power flows **into** the circuit as indicated by the fact that the negative portion of the power curve or graph is much smaller than the positive portion. Of course, the same reasoning would apply to a resistance and capacitance in series. By carefully analyzing Figure 15 and Figure 16, it should be apparent that the angle between the current and voltage determines the amount of power taken for a given amount of current and voltage. When the current and voltage are in phase, it can be seen that the maximum amount of power is drawn from the source; when they are 90 degrees out of phase, no net power is taken, and when they are out of phase by some angle less than 90 degrees, some net power is taken.

It is only that part of the curve above the base line, or that part which is positive, that does useful work such as heat a resistor or drive a motor. It can be seen that if we multiply volts times amperes our result would be equal to the total power both above and below the base line.

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$$\text{Power} = EI \times \text{power factor.}$$

To illustrate the use of this new term, power factor, let us assume that an a-c circuit contains an inductance and a resistance; that the applied voltage is 110 volts; the current flowing in the circuit is 5 amperes; and the phase angle between the voltage and the current is 30 degrees. The **apparent** power would be found by multiplying the 110 volts times the 5 amperes and would be equal to 550. This is commonly called 550 volt-amperes, since we have multiplied volts times amperes, yet our result is not power as has been pointed out previously but is merely apparent power.

To find the true power in the circuit, we will refer to our table to find the power factor for a phase angle of 30 degrees. Our table shows this to be .866. Let us then put the known values in the formula for true power and find the actual power used in this circuit.

$$P = EI \times \text{power factor}$$

$$P = 110 \times 5 \times .866$$

$$P = 476.3 \text{ watts}$$

In this a-c circuit, the **apparent power** is 550 volt-amperes, but the **true power** is 476.3 watts.

To further illustrate the process of finding the power in an a-c circuit, let us solve the following problems:

Problem 1. What is the true power in an a-c circuit if the voltage is 110 volts, the current is 10 amperes and the phase angle is 15° ?

$$P = E \times I \times \text{power factor}$$

$$= 110 \times 10 \times .97$$

$$P = 1067 \text{ watts}$$

Problem 2. What is the true power and the apparent power in an a-c circuit which has a voltage of 50 volts, a current of 2 amperes and the phase angle between the voltage and current is 45° ?

$$\begin{aligned} \text{Apparent power (volt-amperes)} &= E \times I \\ &= 50 \times 2 \\ &= 100 \end{aligned}$$

$$\text{True power} = \text{apparent power} \times \text{power factor}$$

$$\text{Power} = 100 \times .707$$

$$\text{Power} = 70.7 \text{ watts (true power)}$$

Wattmeters

From what has been said about alternating-current power, it can be seen that this power must be measured with a-c voltmeters and ammeters and calculations made involving the phase angle, or with an instrument designed specifically for this purpose. The instrument that measures power is the **wattmeter**. Figure 17 shows the moving parts of an alternating-current wattmeter. At this point, turn back and compare the movement with that of the indicating electro-dynamometer shown in Figure 4. Notice that the two constructions are identical. They both have two coils which are stationary and one moving coil. In the case of the dynamometer, all coils are connected in series, while in the wattmeter, the fixed coils act as the current carrying coils and the moving coil acts as the voltage coil. The voltage coil is connected across the line and the current carrying coils are connected in series with the line. A wattmeter may be used to measure power in either an a-c circuit or a d-c circuit. The only difference between

the wattmeter, when used for a-c instead of d-c, is that the scale is a little different and that the meter is now taking into account the power factor. The meter accounts for the power factor due to the inertia of the moving coil.

The two stationary coils F_1 and F_2 are wound with heavy wire so that they may carry almost twice the current that a load of unity power factor (a power factor of 1) would draw when the meter is reading full scale. This is very important and will be covered more fully later. The moving coil is wound with fine wire and has the usual series resistance with it to limit the current. Since the stationary coils are in series with the load, the field set up by them is proportional to the current drawn by the load at every instant. The field set up by the moving coil is proportional to the voltage of the supply at every instant. Therefore for any given position of the moving coil, the torque (or motion) is proportional to the product of the current and voltage at that instant of time. In a-c, both the voltage and current are rising and falling continually. Thus, the torque acting on the moving coil is constantly changing from instant to instant. If the moving coil had but a small amount of inertia, it would tend to follow these changes, which are taking place at twice the frequency of the current. This would cause the needle to vibrate and a reading would not be possible. Because of the relatively large amount of inertia in the moving system, the needle assumes a steady deflection corresponding to the average power, which is the desired reading. The power factor of the circuit is accounted for in the meter in the following manner.

If the power factor is unity (one), thus putting the current and voltage in phase, the instantaneous power will be used by the load. Thus the total power will be the average sum of all the instantaneous powers. If the power factor of the load is zero (purely capacitive or inductive), exactly one half of the time the power is flowing back to the source from which it came. This is the negative power which was shown in Figure 15. Therefore, the wattmeter will try to read up-scale one instant to indicate positive power, and the next instant will reverse itself and try to indicate negative power of an equal amount. This means the coil will attempt to turn first one way and then the other. Due to the inertia of the coil, as already mentioned, such a thing cannot happen. The result is that the needle remains at zero watts. This is the condition we found to be true in Figure 15.

Now let us see what happens when we have neither unity power factor nor zero power factor, but some other phase relation such as is obtained when resistance and capacity are connected in series across the line. Under these conditions, when the capacitor is being charged, that is when it is drawing positive power from the source, this current will be flowing through the series resistance and consequently power will be dissipated in this resistance. Now as the capacitor starts to discharge or to give its power back to the source, the current will again flow through the series resistor dissipating heat in the resistor. This means one important

thing. The amount of negative power which gets back to the source is less than that which was given out by the source. In other words, the load is dissipating a certain amount of power in this case. Since a deflection of the meter up scale is due to the positive power and the deflection of the meter down scale is due to the negative power, it is evident that in this case the positive power which is tending to move the pointer up-scale is larger than the negative power tending to move it downscale. Consequently, the coil will assume an up-scale position which is a compromise between these two forces. Thus, we see that the inertia of the moving coil causes the wattmeter to adjust itself for the power factor or phase angle of the voltage and current.

Considering the fact that a large current can flow through a wattmeter and still the indicator will not necessarily show a large deflection, one word of caution is worthwhile at this point. **It is always a good policy when using a wattmeter on loads that are suspected of having low power factors to connect an ammeter in the line also.** The ammeter will immediately indicate whether or not the current is near the maximum rating of the wattmeter. As was already mentioned, the wattmeter is usually designed to carry about twice as much current as would normally be expected of it when used in a load with a power factor of 1. There are times, however, when it is easy to exceed this limit and the meter will be damaged.

Watt-Hour Meter

Meters used to indicate the amount of power used over a period of time are called Watt-Hour Meters. Figure 18 is a diagram of an induction watt-hour meter. The first obvious difference between this movement and that of other power reading meters already discussed is that it has no moving coil. In this meter, there is a moving metal disc "D". In the figure, V is the voltage coil. It is wound of many turns of fine wire and is mounted on a laminated magnetic core. This coil and core are placed directly above the metal disc. Below the disc, wound with heavy wire and mounted on two iron cores, are the current coils, C_1 and C_2 . These two coils are connected in series but are so wound that when one coil is sending its flux upwards the other is sending it downwards. A fourth coil known as the compensating winding, CW, is placed on the same core as the voltage winding, above the disc. The leads from this compensating coil are fastened to the variable resistor, R. This resistor is adjusted to make the meter indicate correctly when the power factor is low. To adjust the compensation, the meter is set correctly for a power factor of 1 and then the power factor of the load is dropped to some lower value, such as .5. If the meter now reads incorrectly the resistance on the compensating winding is adjusted by either increasing or decreasing its value for the proper meter reading.

When the current and voltage coils are connected into the circuit, each of them sets up its own magnetic field. These changing magnetic fields from these coils cuts across the disc D, in Figure 18. This disc is a conductor

and as we have learned in previous assignments, when the changing magnetic fields cut the conductor, a current will be induced in that conductor. In this case, currents are induced into the metal disc. These currents are, of course, eddy currents, and these eddy currents in the disc set up magnetic fields of their own. These magnetic fields in turn have their own north and south poles which act in conjunction with the poles existing in the cores of the voltage and current coils. The result is an inter-action of magnetic fields which cause the metal disc to rotate. This metal disc does not rotate against retaining springs as in other types of meters, but is allowed to rotate on its pivot much as the armature in a motor rotates. The speed of the rotation of the disc is directly proportional to the power which is being drawn by the load. The disc is connected through a group of gears to some calibrated dials which register the number of kilowatt hours of energy which have been drawn by the load. This is the type of meter which the power companies use to measure the amount of electrical energy consumed by the individual subscriber.

Summary of A-C Power

The true power of an a-c circuit can be found by the formula, $\text{Power} = EI \times \text{power factor}$. The apparent power in an a-c circuit, that is, $P = EI$, is not the same as the true power due to the fact that if the circuit contains either inductance or capacitance, the current and voltage will not be in phase. The product of EI will indicate the amount of power drawn from the source but if an out of phase condition exists, part of this power will be returned to the source from the coil or capacitor. The decimal, called the power factor, by which apparent power must be multiplied to obtain true power, is determined by the phase angle of the current and voltage in the circuit. We shall find in a later mathematics assignment how to determine this power factor for any given phase angle. For the present, the values given in this assignment for each fifteen degree phase angle will be sufficient. Power is measured by a wattmeter which contains coils which produce a magnetic field proportional to the voltage and the current in the circuit. The wattmeter also takes into account the power factor of the circuit. The total amount of energy consumed over a period of time is measured by the watt-hour meter.

TEST QUESTIONS

Use a multiple-choice answer sheet for your answers to this assignment.

The questions on this test are of the multiple-choice type. In each case four answers will be given, one of which is the correct answer. To indicate your choice of the correct answer, **mark out** the letter opposite the question number on the answer sheet which corresponds to the correct answer. For example, if you feel that answer (A) is correct for Question No. 1, indicate your preference on the answer sheet as follows:

1. ~~(A)~~ (B) (C) (D)

Submit your answers to this assignment immediately after you finish them. This will give you the greatest possible benefit from our personal grading service.

1. What will the meter indicate if a 60 hertz a-c current is passed through a D'Arsonval type meter?
 - (A) The peak value of the a-c current.
 - (B) The rms value of the a-c current.
 - (C) One-half the value of the a-c current.
 - (D) Zero.

2. When copper-oxide rectifiers are used with D'Arsonval type meters to measure a-c, the current which flows through the meter itself is:
 - (A) a-c
 - (C) pulsating d-c
 - (B) pure d-c
 - (D) r-f

3. For what frequency readings are the dynamometer, the inclined coil, and the spreading vane meter used?
 - (A) Zero frequency or d-c.
 - (C) Audio frequencies
 - (B) Power line frequencies.
 - (D) Radio frequencies.

4. Which of the following meters is the most logical choice to use in measuring radio frequency current?
 - (A) The D'Arsonval meter without rectifiers.
 - (B) The copper-oxide rectifier type meter.
 - (C) The electro-dynamometer.
 - (D) The thermocouple meter.

5. If a pure capacitance is connected to the output of an a-c generator:
 - (A) there will be no true power used in the circuit.
 - (B) there will be no apparent power used in the circuit.
 - (C) the true power will be equal to the apparent power.
 - (D) the true power will be greater than the apparent power.

332006
 $\begin{array}{r} 1466 \\ 79200 \\ 79200 \\ \hline 105600 \\ 11431200 \end{array}$

6. In an a-c circuit, if the voltage is 220 volts, the current is 60 amperes, and the phase angle between the voltage and the current is 30 degrees, what is the **apparent** power?

- (A) 13,200 volt-amperes
- (B) 11,431.2 volt-amperes
- (C) 3.66 volt-amperes
- (D) 396,000 volt-amperes

In the example given in Question 6, what would be the true power?

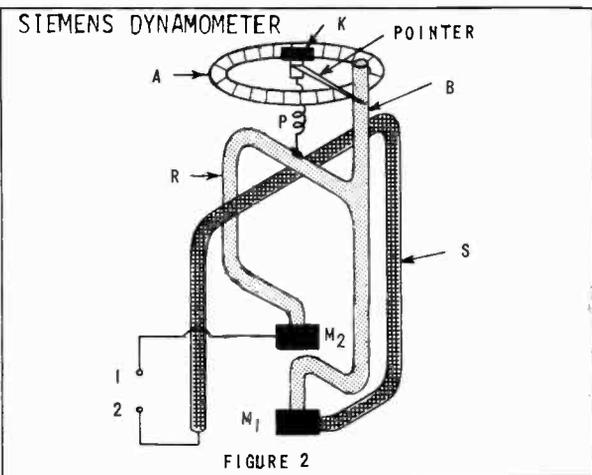
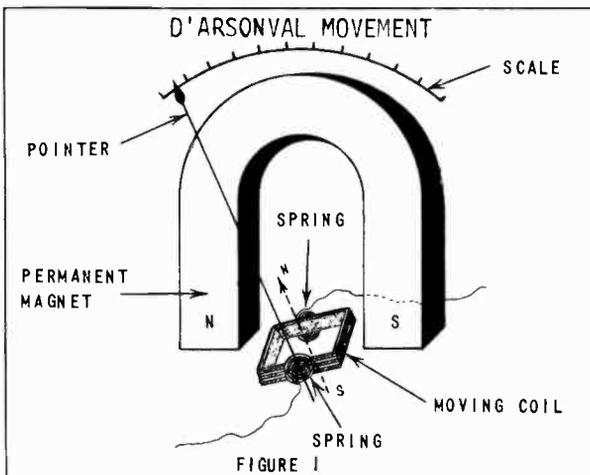
- (A) 13,200
- (B) 11,431.2 watts
- (C) 3.66 watts
- (D) 396,000 watts

- 8. Which meter will require the least power for its operation?
 - (A) The electro-dynamometer
 - (B) The D'Arsonval type meter
 - (C) The inclined coil meter
 - (D) The spreading vane meter
- 9. What happens when heat is applied to the junction of a thermocouple?
 - (A) A voltage is generated.
 - (B) The thermocouple will burn out.
 - (C) The thermocouple will heat a hot-wire type r-f ammeter.
 - (D) The thermocouple couples this heat to a copper-oxide rectifier type meter.

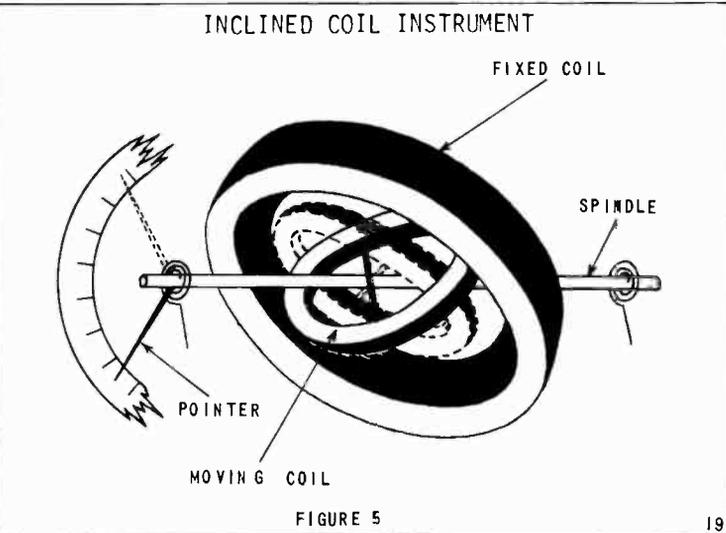
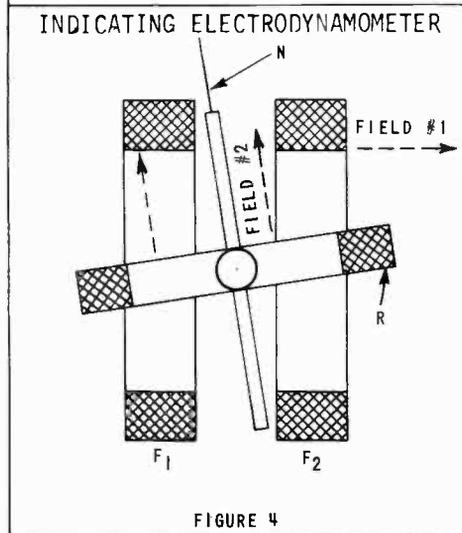
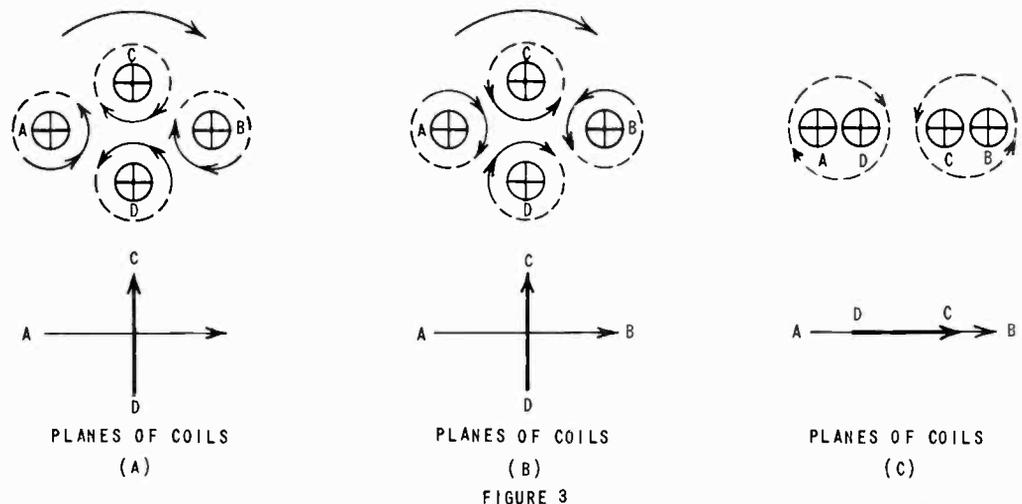
10. What is the formula for finding the **true power** in an a-c circuit?

- (A) $P = E \times I$
- (B) $P = \frac{E \times I}{pf}$
- (C) $P = \frac{E}{I} \times pf$
- (D) $P = E \times I \times pf$

COSINE'S
 $0^\circ - 1$ $60^\circ - .5$
 $15^\circ - .97$ $75^\circ - .26$
 $30^\circ - .866$ $90^\circ - .0$
 $45^\circ - .707$



PRINCIPLE OF DYNAMOMETER OPERATION



SPREADING-VANE METER

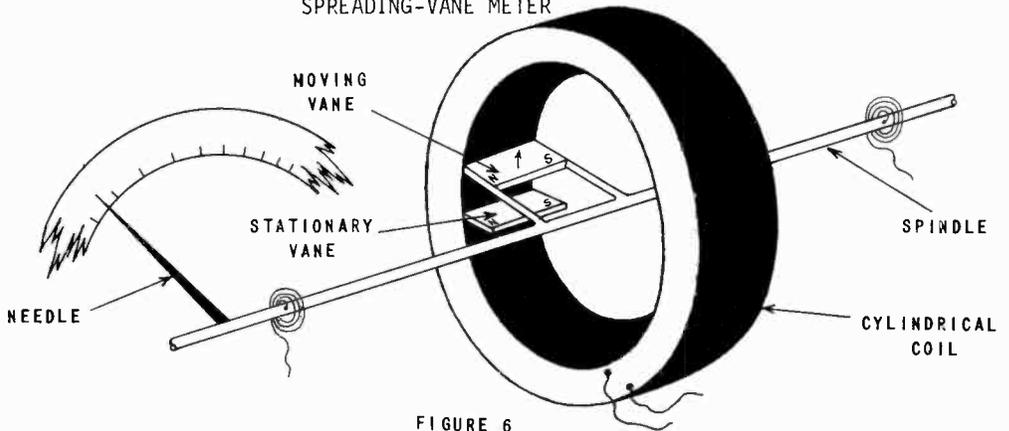


FIGURE 6

INCLINED-COIL IRON-VANE METER

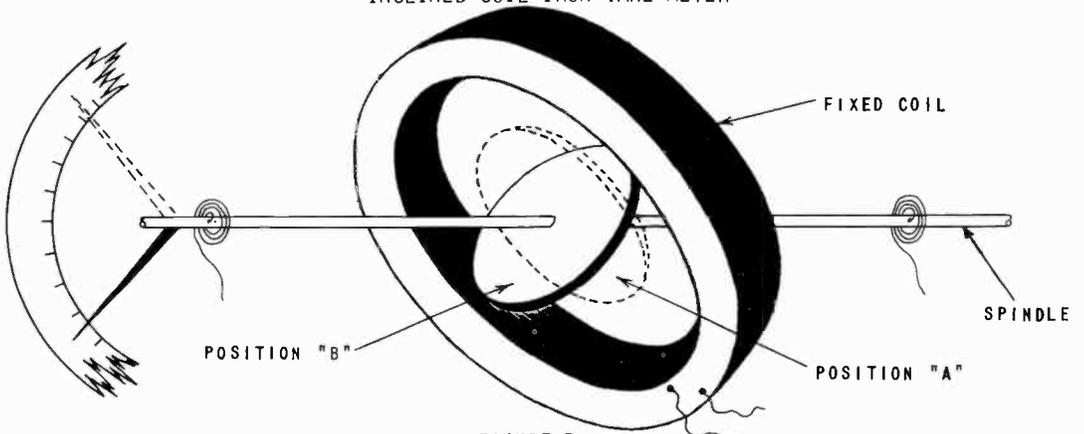
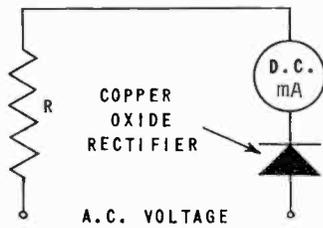


FIGURE 7

SIMPLE RECTIFIER CIRCUITS



(a)

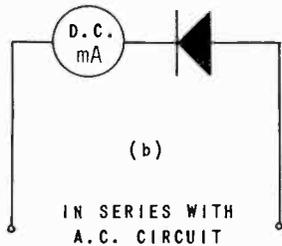


FIGURE 8

BRIDGE-TYPE RECTIFIER CIRCUIT

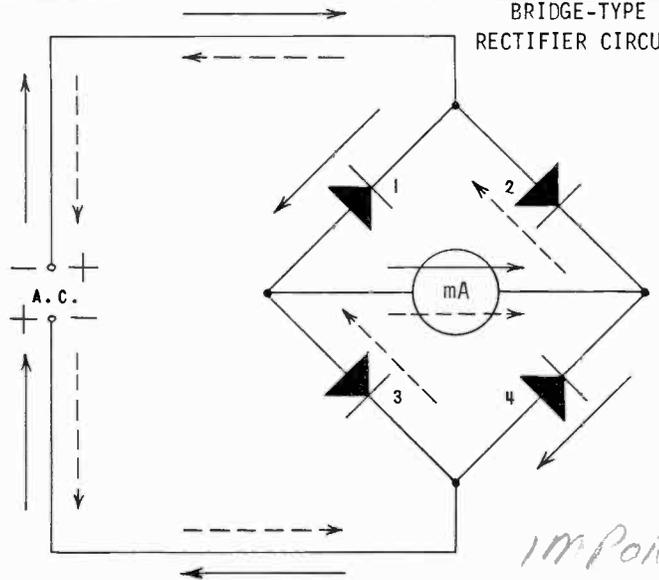


FIGURE 9

IMPORTANT

FREQUENCY ERROR OF COPPER-OXIDE VOLTMETER

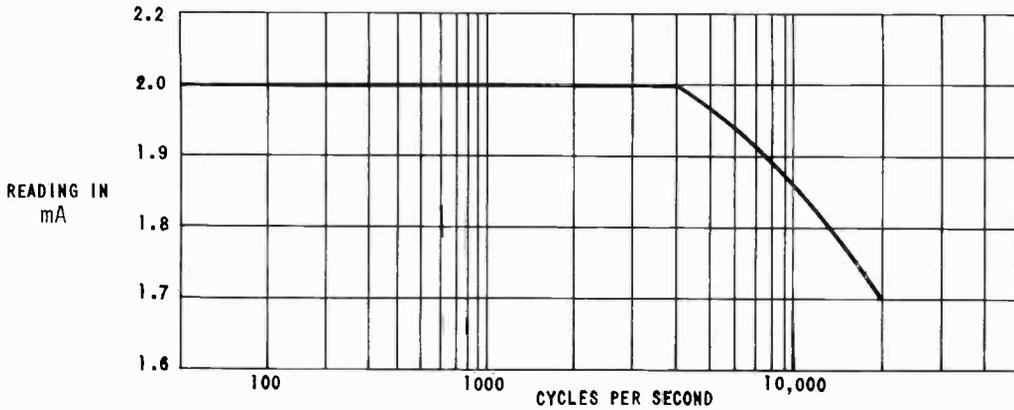


FIGURE 10

HOT-WIRE AMMETER

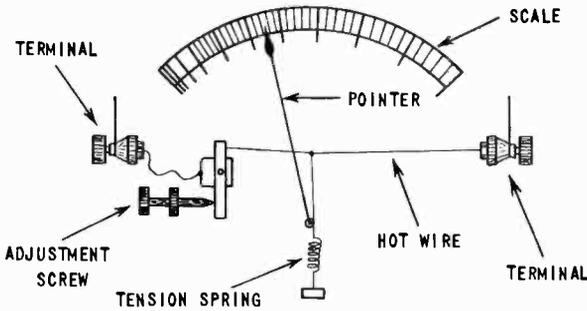


FIGURE 11

THERMOCOUPLE PRINCIPLE

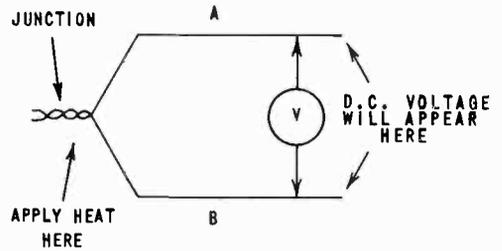


FIGURE 12

THERMOCOUPLE HEATING METHODS

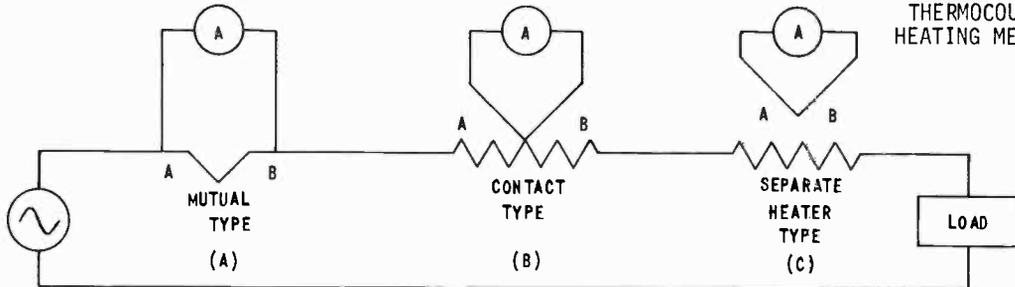


FIGURE 13

SEPARATE HEATER TYPE THERMOCOUPLE

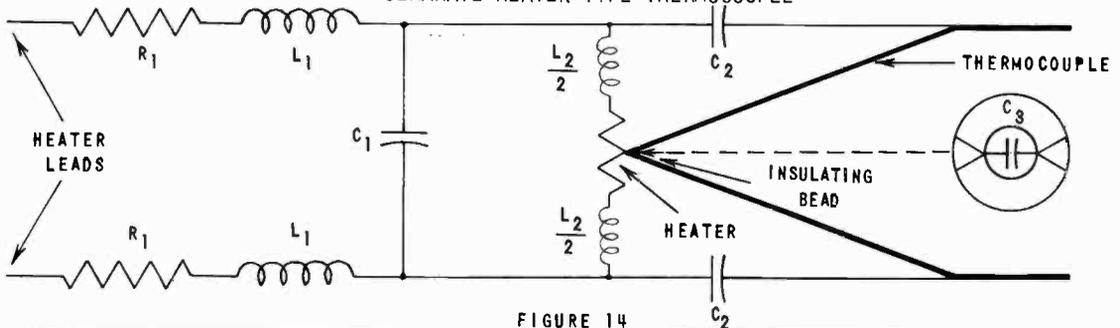


FIGURE 14

POWER VALUES IN A-C CIRCUITS

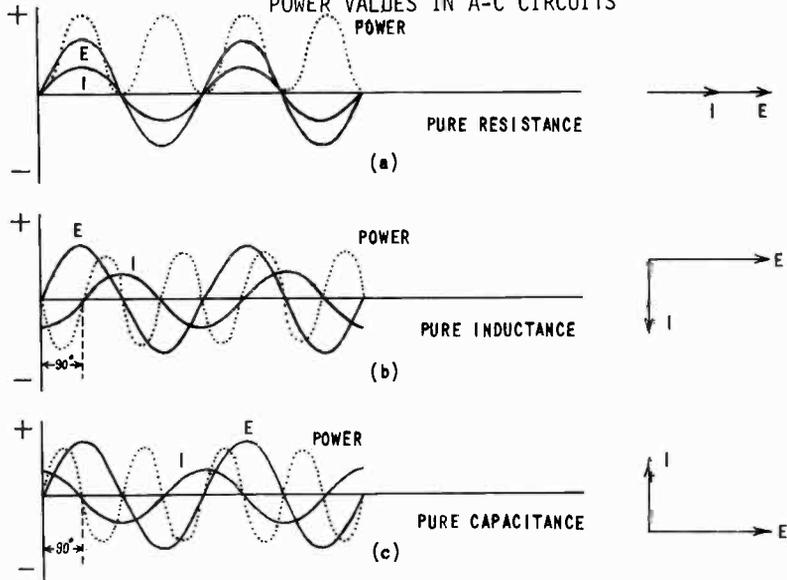


FIGURE 15

A-C CIRCUIT CONDITIONS WITH RESISTANCE AND INDUCTANCE

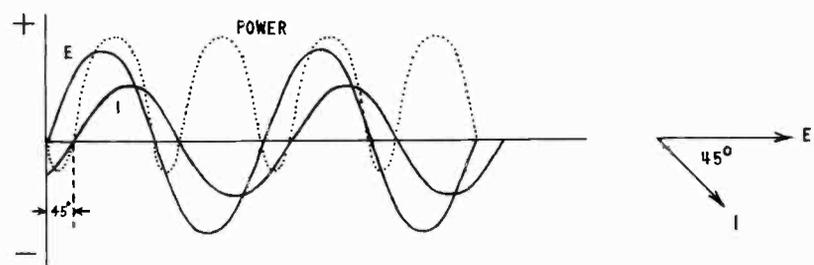


FIGURE 16

A-C WATTMETER CIRCUIT

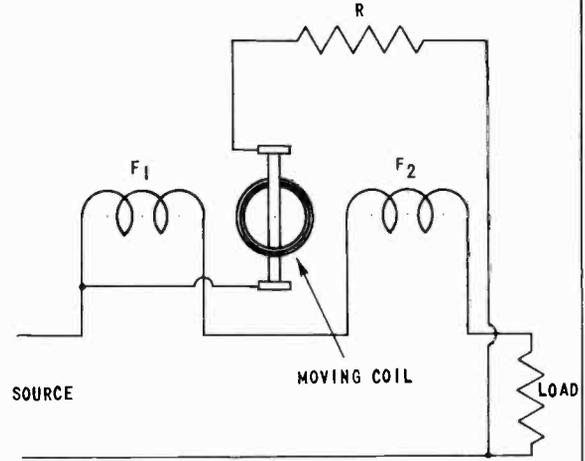


FIGURE 17

INDUCTION TYPE WATT-HOUR METER

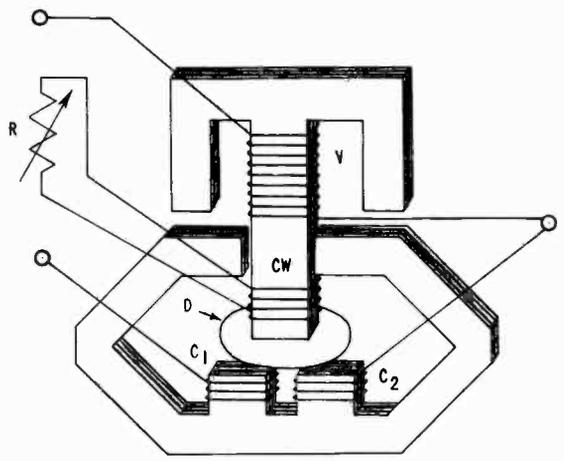


FIGURE 18