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Weston Technical Monograph

ELECTRICAL MEASURING INSTRUMENTS

BY.... JOHN H. MILLER

STANDARD WESTON THE WORLD OVER

A DISCUSSION OF ELECTRICAL MEASURING INSTRUMENTS

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The Discussion of Electrical Measuring Instruments in this monograph was written by John H. Miller for inclusion in the 1956 edition of the Encyclopaedia Britannica. It replaces the classical thesis written by C. V. Drysdale nearly fifty years ago and is reprinted here with the permission of Encyclopaedia Britannica, Inc., Chicago, U.S.A.

A broad cross section of the field is presented including many of the recent instruments incorporating the use of vacuum tubes as well as cathode ray tubes.

Mr. Miller received his degree in engineering from the University of Illinois, and served with the U.S. Signal Corps during the first World War. Associated with electrical measuring instruments for his entire career, he joined the Weston Electrical Instrument Corp. in 1931 as Assistant Chief Engineer. Successively Mr. Miller has carried the responsibilities of Chief Engineer, Vice President in Charge of Engineering, and Vice President and Consultant. He is a Fellow of the American Institute of Electrical Engineers and the Institute of Radio Engineers, a member of the Institution of Electrical Engineers (Great Britain), the American Society of Mechanical Engineers, and the Acoustical Society of America. He has been chairman of numerous groups developing standards covering electrical instruments and has authored various technical papers on the subject.

INSTRUMENTS, ELECTRICAL MEASURING. Electrical measuring instruments have aided in the growth of the electrical industry, including the field of electronics, because the very nature of most electrical phenomena is beyond the reach of man's physical senses. Of course lightning, an electric arc and the filament of an incandescent lamp are visible, but the physical senses give only a rough idea of the electrical magnitudes involved. Only by measurement of the invisible electrical quantities did it become possible to design and manufacture the vast array of electrical equipment in daily use.

Hans C. Oersted in 1819 first noted that if a conductor is stretched straight over a pivoted magnetic needle and parallel to it, the needle tends to turn at right angles to the conductor when current is flowing through it (fig. 1). If the current is reversed the needle turns in the opposite direction. The same reversal effect is produced by moving the conductor to the underside of the needle so that if the conductor is wound into a coil encircling the needle, all parts of it tend to deflect the needle in the same direction and the effect is enhanced. This was put into practical form as the first galvanometer by J. S. C. Schweigger in 1820.

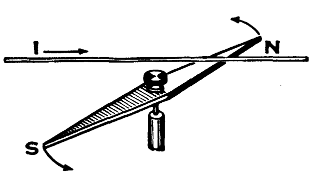

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FIG. 1.—OERSTED'S EXPERIMENT

GALVANOMETERS

Galvanometers per se should be differentiated from indicating instruments. A galvanometer is used to indicate the presence of an electric current; its measurement of the magnitude of that current is less important than its ability to show the presence of very minute currents. Indicating instruments, on the other hand, have somewhat less sensitivity to minute currents but are carefully designed and manufactured to give quantitative indication of the magnitudes involved whereby a true measurement of current, potential, etc., can be had.

The earliest instruments were essentially galvanometers, in which high sensitivity was desirable. Sensitivity of the Schweigger galvanometer was limited by the earth's magnetic field. Since the deflecting force or torque caused by the coil of the galvanometer is resisted by the controlling torque of the earth's magnetic field, it was obvious that reducing the effect of the latter would increase the instrument's sensitivity. Leopoldo Nobili in 1825, therefore, introduced the astatic needle system in which two nearly equal magnetic needles were mounted with opposite polarities on the same vertical stem, one being inside and the other outside the coil. The system was suspended by a silk fibre and provided with a light pointer.

In 1858 Lord Kelvin produced a highly sensitive reflecting type of galvanometer (fig. 2) employing an astatic system like Nobili's but with each of the needles inside a coil so that the deflectional torque was doubled while preserving the small control of the astatic system. The needle system was composed of a thin vertical aluminum wire across which two sets each of three or four short pieces of hardened watch spring were cemented; the two sets were magnetized in opposite directions by being placed between the poles of a powerful electromagnet. Midway between the magnet systems, a light concave mirror was cemented to the aluminum stem, and the whole system was suspended by a single fibre of cocoon silk from the upper bar of the frame.

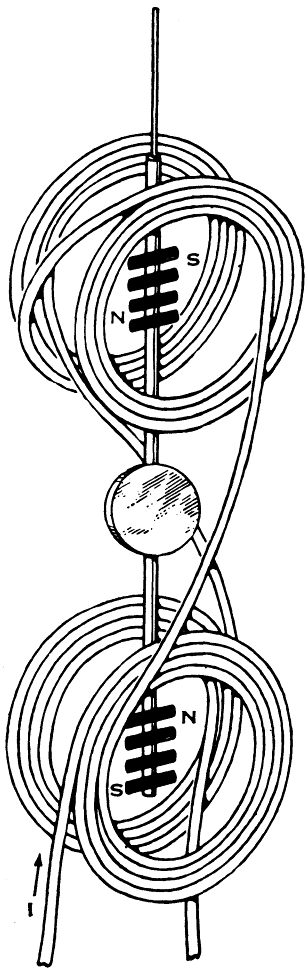

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FIG. 2.—KELVIN ASTATIC MIRROR GALVANOMETER

In successive years the moving-magnet galvanometer was improved, as by C. V. Boys in 1890, who used a quartz fibre for the suspension, and about 30 years later by A. V. Hill, who used a smaller system and cobalt steel for the magnets.

One of the greatest obstacles to general use of the moving-magnet galvanometer was its disturbance by stray variable magnetic fields, found frequently in electrical laboratories. It was found necessary to shield the system, preferably with concentric shells of highly permeable material such as soft iron or nickel iron alloy (78% nickel, 22% iron) known as permalloy or mumetal. By mid-20th century, moving-magnet galvanometers were being used only infrequently because of the difficulty of shielding although they still represented, basically, the most sensitive type of galvanometer. One manufacturer listed a reflecting galvanometer of this type having a sensitivity such that, at 1 m. distance, a motion of 5 mm. will be had with 10^{-9} amp. in a coil having a resistance of only 40 ohms, equivalent to 1.6×10^{-18} w. for 1 mm. deflection.

Tangent and Sine Galvanometers.—The tangent galvanometer as a refinement of the moving-magnet galvanometer was devised by C. S. M. Pouillet in 1837. It was probably the first instrument in general use for current measurement. In its simplest form it consisted of a pivoted magnetic needle rotating horizontally over a scale in degrees at the centre of a large vertical coil through which the current could be passed. The coil was positioned so that the magnetic needle was in the plane of the coil with no current passing. On making the circuit, a magnetic field was produced in the coil which combined with the earth's magnetic field; the needle aligned itself with the resultant magnetic field. And it can be shown that the current in the coil is a function of the tangent of the angular deflection, the coil constants and the value of the earth's field.

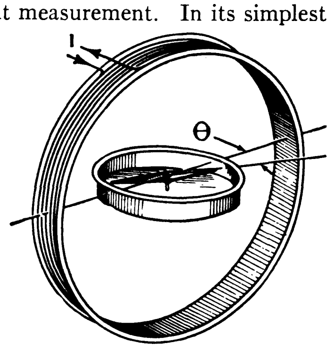

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FIG. 3.—TANGENT GALVANOMETER

Another method of using this assembly is to rotate the coil with the current passing through it until the coil is again in line with the pointer. The current is then a function of the sine of the angle through which the coil has turned.

Because the earth's field may vary as much as 10% from one location to another the tangent galvanometer is rarely used today.

Polarized Iron Vane Mechanism.—Since the controlling field is enormously increased through use of a permanent magnet, the moving magnet may be replaced with a soft iron piece magnetized by induction. By surrounding the moving magnetized iron with a coil having its field at right angles to that of the magnet, the simple polarized iron vane mechanism is produced (fig. 4). This mechanism suffers from the deficiencies of hysteresis in the iron and is neither accurate nor sensitive; it is extremely inexpensive, however. Reversal of the current through the main coil will reverse the direction of the instrument pointer so that it indicates polarity as well as current magnitude. The battery ammeter on the instrument panel of an automobile is an instrument of this type. It indicates the passage of current from the generator to the battery or, when deflecting in the reverse direction, the magnitude of current from the battery into lights, heaters, fans, etc.

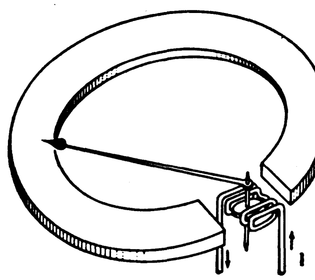

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FIG. 4.—POLARIZED IRON VANE MECHANISM

Moving-Coil Galvanometers.—The moving-coil galvanometer arose from the discovery by André Marie Ampère, in 1820, that a conductor carrying an electric current tended to move transversely across a magnetic field. The first application of this principle to galvanometers was by William Sturgeon in 1836, followed, in 1867, by the siphon recorder of Lord Kelvin; but this was used for recording cable signals. Arsène d'Arsonval in 1882 introduced the first reflecting moving-coil galvanometer. It consisted of a light rectangular coil of fine wire suspended by the thinnest possible wires between terminals (fig. 5) swinging between the poles of a vertical horseshoe magnet. In order to intensify the magnetic field, a soft iron cylinder was mounted inside the coil without touching it.

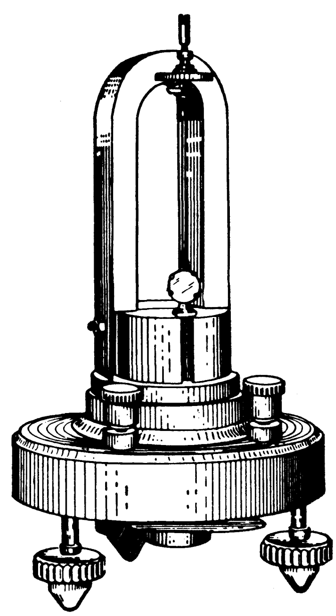

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FIG. 5.—PERMANENT-MAGNET MOVING-COIL GALVANOMETER

Because the moving-coil galvanometer can be used without regard to extraneous magnetic fields, it is the accepted galvanometer for most laboratory and research work. Galvanometer structures at mid-20th century included shaped pole pieces and soft iron core to concentrate the magnetic field into a radial path through which the coil turns. The coils themselves are made of small diameter to reduce the moment of inertia and the periodic time, and with various windings of low and of high resistance to match the circuits into which they may be placed. Suspensions are of bronze or gold alloy strip.

Typical sensitivities of galvanometers such as the one illustrated in fig. 6, and for a 500-ohm coil with a period of 20 sec., give a deflection of 3 mm. for 10^{-9} amp. on a scale at 1 m. distance. This amounts to 1 mm. deflection for 55×10^{-18} w. Coil resistances are offered from 12 to 500 ohms with periods of from 2 to 30 sec.

In selecting a D.C. galvanometer for a specific purpose, the periodic time and damping must be considered along with high sensitivity. Most galvanometers are listed not only with the sensitivity and periodic time stated but also with the external critical damping resistance. This is the value of resistance which, if connected across the galvanometer terminals, will cause it not to overshoot on any excursion. If a galvanometer is used in a circuit of considerably lower resistance, it may take several times the periodic time for the galvanometer to come to rest and thus may unduly extend the time for a group of observations. A galvanometer of somewhat smaller sensitivity but with a lower critical damping resistance will operate much more rapidly and may give entirely adequate readings. Conversely, a galvanometer used in a circuit having a resistance considerably higher than the critical value will oscillate around its final position and not come to rest rapidly. The galvanometer terminals, however, may be shunted by an additional resistance which, while it will reduce the over-all sensitivity of the apparatus, will bring the galvanometer rapidly to rest; here again, the sensitivity may be quite adequate and the readings can be obtained much more rapidly. For these reasons galvanometers are frequently selected for a specific use more on the basis of their critical damping resistance than on the basis of their inherent sensitivity; in most cases sensitivity is adequate, and promptness of response to the final reading is important.

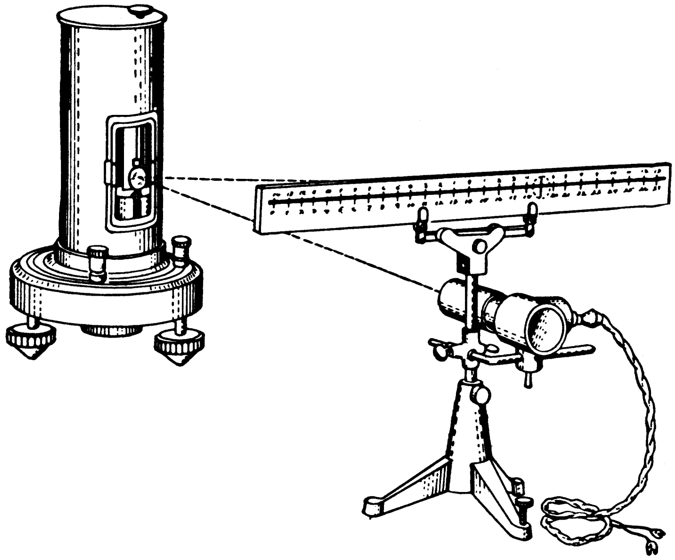

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FIG. 6.—PERMANENT-MAGNET MOVING-COIL GALVANOMETER

Ballistic Galvanometers.—All of the foregoing galvanometers and instruments are used for the detection or measurement of steady electric currents; they are designed preferably to be prompt in response to the currents and well damped to eliminate undue oscillations. However, in studying electrical phenomena it is also necessary to indicate and measure discrete pulses, charges or discharges, as from a condenser, an inductance or from a derived circuit when current changes in a main circuit. An instrument to measure such a single pulse may be slow in final response, may have no damping and usually has a low restoring force. It can be shown mathematically that when the pulse passes through the instrument before the moving system moves more than 10% of its maximum deflection, that maximum deflection is a measure of quantity of electricity, in coulombs or ampere-seconds, which has passed through the galvanometer. Essentially the instrument is similar to a ballistic pendulum, which when struck by a bullet, proceeds to deflect slowly in a normal swing, the extent of the swing being a measure of the total energy in the original impact or energy impulse.

Where the maximum throw in response to a pulse is the desired value, ballistic galvanometers can be of any of the types responding normally to steady currents. However, they are mostly of the permanent-magnet moving-coil type where the coil is frequently made short in length but rather wide to increase both sensitivity and periodic time.

If a coil of wire is connected to the ballistic instrument and the coil inserted in a magnetic field, the ballistic deflection will be proportional to the field strength. Knowing the area of the coil and the number of turns it contains, the constant of the instrument as a fluxmeter can be obtained. That is, for a given instrument there may be a constant such as "1 division deflection equals 10 gauss per turn per square centimetre." This constant may be calculated from the basic constants of the instrument, or, more commonly, the instrument may be calibrated by means of a standard coil in a standard magnetic field.

MOVING-COIL PERMANENT-MAGNET INSTRUMENTS

Moving-Coil Measuring Instruments.—Around 1884 Edward Weston, needing accurate electrical measuring instruments in his laboratory at Newark, N.J., took the moving-coil galvanometer as developed by D'Arsonval and, by adding pivoted sapphire bearings and spiral bronze control springs and making the magnetic system stable, produced the prototype of the moving-coil instrument.

The pivoted bearings allowed for the use of the instrument in any position; the suspended type had been limited to vertical operation. The spiral bronze control springs were used to secure compactness and at the same time serve as conductors to introduce the current into the moving coil; two of them were used. But Weston's greatest contribution was the stable magnetic system since, with established torque control, the deflection of the system on a given current was proportional to the flux density in the air gap through which the coil rotated.

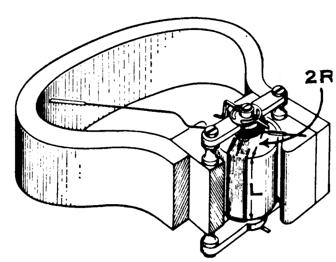

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FIG. 7.—PERMANENT-MAGNET MOVING-COIL MECHANISM

Weston was the first to show that a sufficiently long permanent magnet, driving a flux across a proportionately short air gap, could be relied on to maintain its strength indefinitely without deviation. For the tungsten magnet steel used at that period, the magnet length was made about 100 times the length of the air gap. In 1888 Weston produced the first commercial D.C. instrument of this type, shown pictorially in fig. 8. In this structure the torque developed by current flowing through the moving coil is given by

$$T = \frac{B2RLIN}{10} = \frac{BAIN}{10}$$

where T = torque in dyne centimetres; B = flux density, lines/sq.cm. in air gap; A = coil area in square centimetres; I = moving-coil current in amperes; and N = turns of wire in moving coil.

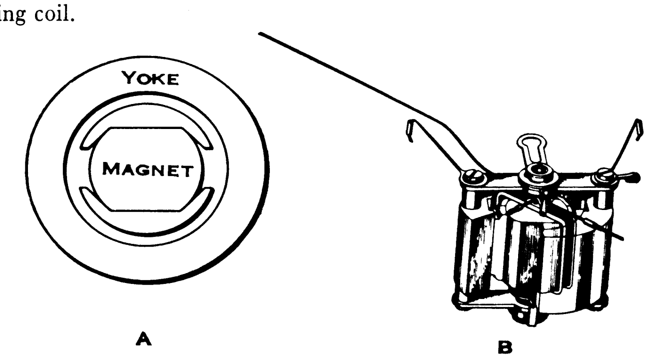

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FIG. 8.—CORE-MAGNET MOVING-COIL MECHANISM, (A) SCHEMATIC, (B) ASSEMBLED

Modifications were made later in the arrangement of the pole pieces, the shape of the moving coil, the shape of the magnet and in the housing. Such instruments are usually placed in hardwood or plastic boxes for laboratory use and in metal cases for switchboard use. Nevertheless, the design remained fundamentally the same. Another important modification was the use of magnetic materials having vastly higher strength and thereby allowing the magnet system to be materially shortened. By using the cobalt-nickel-aluminum-copper-iron alloy known as Alnico 5 the magnet can be made so short that it can be placed inside the moving coil to form the core of the instrument whereby the outer magnetic return path becomes merely a ring of soft iron (fig. 8). Such a structure is not only more compact but is also more immune to the effects of external magnetic fields, which, if strong, would affect the conventional structure of the older types.

The moving system of all moving-coil instruments must be made as strong and as light in weight as possible. Most such systems incorporate a frame or former of aluminum, flanged for strength and to retain the winding. Eddy currents generated in the frame because of its motion in the magnetic field damp the moving system and bring it to rest quickly. The winding, generally of several layers of enamelled wire, is coated with a suitable lacquer for permanence. To its ends are cemented brass pivot bases carrying the hardened steel pivots on which the coil turns, as well as the inner end of the control and current-carrying springs. In addition, the upper pivot base mounts the balance cross and pointer, the latter usually of aluminum tubing. Threaded balance weights, or their equivalent, are adjusted on the balance cross to balance the moving system in its sapphire cup bearings, much as the balance wheel in a watch is poised. Moving systems may weigh about a gram in the larger sizes; in small panel instruments the weight is frequently as low as 200 mg. Such low weight leads to friction-free operation in the jewelled bearings and long life in operation.

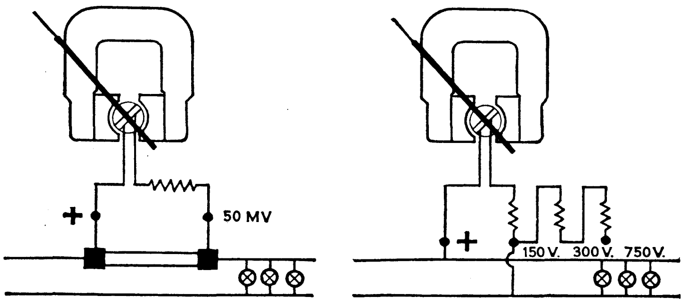

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FIG. 9.—CIRCUIT CONNECTIONS (A) FOR AN EXTERNAL SHUNT AMMETER AND (B) FOR A TRIPLE-RANGE VOLTMETER WITH ITS LOWEST RANGE CONNECTED TO A LINE

The structure will serve for direct measurement of currents in the moving coil varying from considerably less than 1 milliampere up to about 50 milliamperes, depending upon the number of turns in the moving-coil system, the flux density and the spring torque.

For higher currents it becomes necessary to shunt the excess current around the moving coil by a parallel resistance ("shunt") mounted internally or externally.

Since at high currents considerable power is dissipated in the shunt, which is costly and causes heating, the drop across the shunt is kept to a value as low as possible and still satisfactory for the instrument. For most work shunts are designed to have an IR drop of 50 mv at full current rating; the instrument is correspondingly designed to give full-scale deflection on 50 mv applied to its terminals, or, more exactly, to the shunt end of the connecting wires.

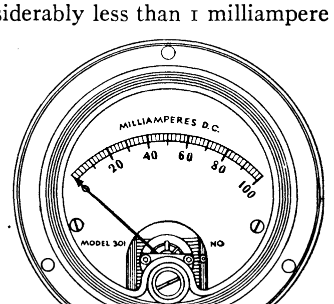

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FIG. 10.—MILLIAMMETER FOR FLUSH PANEL MOUNTING

For the measurement of potential with a moving-coil instrument, recourse is had to Ohm's law, which states that the current through a fixed resistance is proportional to the potential and is equal numerically to the potential in volts divided by the resistance in ohms. Thus, an instrument which deflects full scale on 0.1 amp. (10 milliamperes) can be made to read 150 v. full scale by adding sufficient series resistance to its circuit to make a total of 15,000 ohms. Since little heat is developed by this low current, the resistance for voltmeters is usually placed internally in the instrument; for voltages of 1,000 v. and higher, however, it is placed in a separate external ventilated and insulated housing as a protective measure.

In developing the design of moving-coil permanent-magnet instruments it is necessary to take into account the effect of variations in temperature. A change in temperature affects the magnetic system to change slightly the flux density in the air gap. Temperature changes affect the torque of the control springs and also cause a change in the resistance of the copper windings.

However, through the use of special alloy wires such as manganin, constantan, nichrome, etc., having little or no change in resistance with temperature, it is usually possible to develop electrical networks to mitigate the effects of temperature change. And by taking into account the fact that some of these effects oppose others, it is usually possible to largely eliminate the effect of temperature on the accuracy of the instrument over a moderate temperature span.

Ordinarily instruments of this class are expected to give normal accuracy from 15° C. to 30° C.; most makers will give a factor to be used for temperatures outside these limits.

Fig. 9 shows typical connections for an ammeter into a line measuring current in the load, and a triple-range voltmeter measuring the potential across that load.

The sensitivity of the permanent-magnet moving-coil D.C. mechanism is relatively great. Commercial panel mounting instruments of this type (fig. 10) having a flange diameter of $3\frac{1}{2}$ in. may give full-scale deflection on as little as 10 μw; *e.g.,* 100 μa and 1,000 ohms. This low power consumption permits use of the mechanism in conjunction with auxiliary elements to indicate other than D.C. quantities, even though such auxiliary elements are very inefficient themselves. Examples are reading of alternating current through converting elements, of speed through the use of small generators, of light through the use of photovoltaic cells, of temperature through the use of thermocouples and of radiant energy as in radium through the use of a Geiger-Müller counter or an ionization chamber.

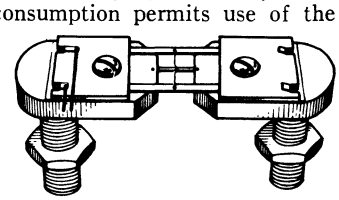

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FIG. 11.—THERMAL CONVERTING ELEMENT

Thermal Instruments.—The earliest hot wire meter was invented by Major Cardew, R.E., who about 1880 looped a long platinum-silver wire back and forth across pulleys, and thence to a small rotating drum carrying a pointer and terminating in an extensible spring. When current was placed through the wire it expanded, the drum rotated and the resulting pointer motion could be calibrated in terms of the heating current. Later types, particularly those of Johannes F. Hartmann and Karl Braun, used shorter wires with motion multiplying systems. However, all hot wire types absorbed unduly large amounts of energy and showed large errors with variations in ambient temperature, although they functioned well up to quite high frequencies.

In 1904 William D. B. Duddell took a suspended moving-coil galvanometer and terminated the coil at its lower end in a soldered bismuth-antimony thermojunction beneath which was placed a short heater wire carrying the high-frequency current to be measured. Such a junction of dissimilar metals, when heated, develops a small potential depending on the temperature rise in the junction, and the current in the moving coil and its resulting deflection are proportional to that temperature rise. Since the heat developed in the heater wire is proportional to the square of the current in it, the galvanometer deflection in terms of the heater current can be calibrated, the result having a general square law characteristic. However, these instruments suffered from errors caused by variations in ambient temperature, and good results were obtainable only in a laboratory and when handled with great care.

In 1917 W. N. Goodwin, Jr., of the Weston Electrical Instrument corporation in Newark, N.J., completed the development of the compensated thermocouple ammeter, the thermal converter element of which is shown (fig. 11). The heater itself is a short wire or tube of platinum alloy between heavy terminals. The thermocouple itself, of constantan and platinum or other noncorroding alloys, has its junction welded to the centre of the heater; the cold ends of the thermocouple wires are soldered to copper strips clamped to the heavy end terminals but electrically insulated therefrom with thin mica plates. Thus the temperature rise of the thermocouple junction over the cold ends and the resultant potential are strictly proportional to the temperature rise of the centre of the heated conductor over its heavy terminals. A sensitive moving-coil instrument is connected to the two copper strips and deflects as the square of the heater current.

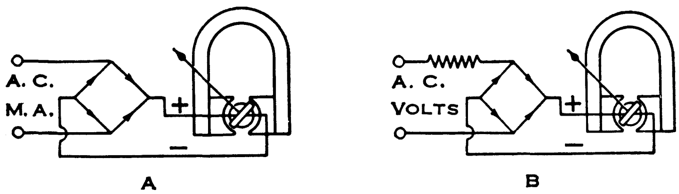

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FIG. 12.—RECTIFIER-TYPE METER CONNECTIONS: (A) MILLIAMMETER, (B) VOLTMETER

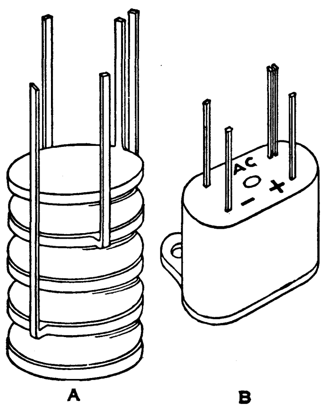

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FIG. 13.—INSTRUMENT RECTIFIER DISK GROUP (A) AND ASSEMBLY (B)

Such a structure disposes rather completely of variations caused by changes in ambient temperature, heating of the terminals and thermal gradients within the instrument. Having a drop of about 200 mv across the heater, such instruments are made in various ranges giving full-scale deflection on from $\frac{1}{2}$ to 30 amp.; for still higher currents the thermal converting element is made external to the instrument. The mechanisms show little error at high frequencies. The larger sizes, if supplied with tubular heating elements as disclosed by John H. Miller in 1936, have a frequency error of less than 2% up to 65 mc.

Rectifier Type Instruments.—With the advent of dry disk copper oxide rectifiers developed by Lars O. Grondahl in 1928, instrument engineers became intrigued with the possibility of utilizing such a rectifier ahead of a sensitive D.C. mechanism to secure an A.C. instrument of much higher sensitivity than any previously available. W. N. Goodwin, Jr., was probably the first to develop such an instrument, in 1929, by utilizing a full four-element rectifier bridge giving full wave rectification into the instrument. Fig. 12 shows the methods of connection as a milliammeter and as a voltmeter; fig. 13 shows the assembly of the stack of tiny 3/16-in. diameter disks and as they are assembled in a housing. Small disks are used primarily to get a high current density in the rectifying surface at the desired low currents; the high current density leads to high efficiency, low forward resistance and better response at the higher audio frequencies.

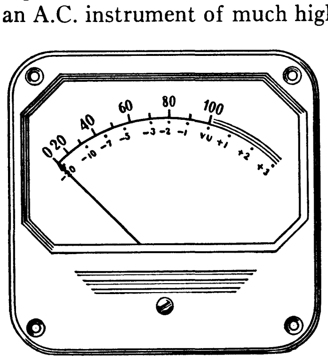

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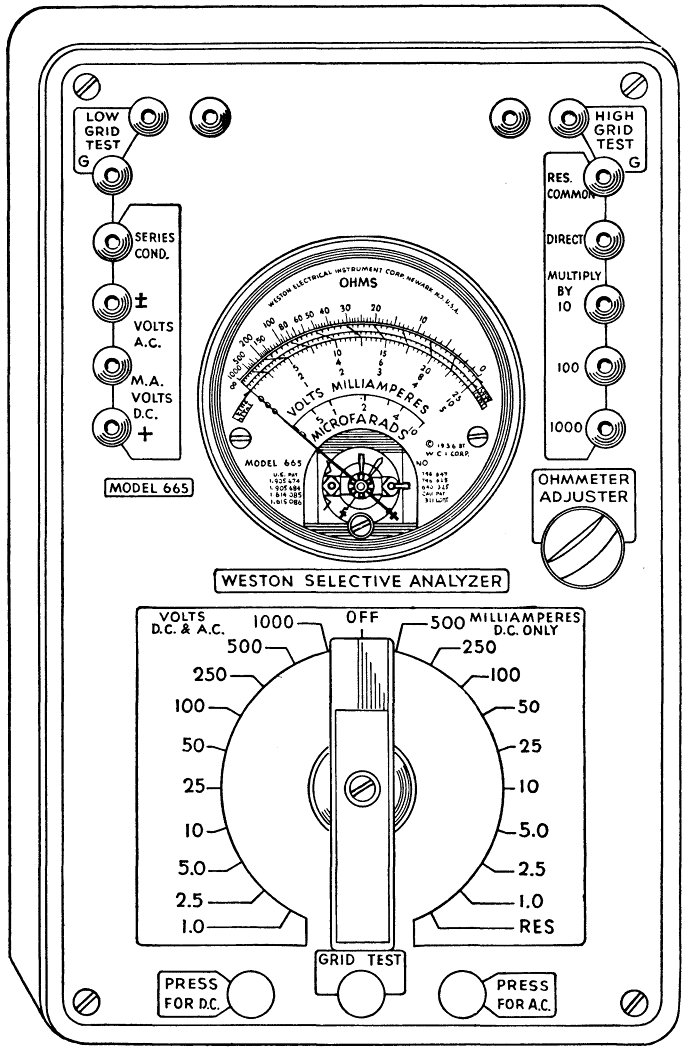
FIG. 14.—VU METER

Rectifier type instruments as a whole are most suitable for voice frequency currents even though they indicate an average value of the current or voltage instead of the more desirable root-mean-square function required in power engineering. They have high sensitivity and responsiveness. One type, the "vu" meter, became the standard for monitoring voice frequency at radio broadcast studios and switching points throughout North America and to some degree in Europe (fig. 14).

Since the D.C. mechanism is available by disconnecting the rectifier, this general type is also widely used in compact test sets where, by suitable switching, both A.C. and D.C. can be indicated on the same instrument. Such instruments (fig. 15) are widely used in electronic laboratories and also as portable instruments for servicing radio and television sets in the home.

Light Measuring Instruments.—In 1931 the dry disk photovoltaic cell was reduced to a practical and stable converter of luminous to electrical energy by A. H. Lamb and C. H. Bartlett. It consists of an iron disk coated with a thin layer of elemental selenium of high purity which has been crystallized on the disk over a critical temperature cycle. A thin translucent film of metal covers the front and serves as a current collector. When light



BY COURTESY OF WESTON ELECTRICAL INSTRUMENT CORP.
FIG. 15.—RADIO SERVICE TEST SET

impinges on the selenium through the translucent film, a voltage is developed which will drive a small current through a load circuit such as a D.C. instrument. Here again the high sensitivity of the permanent-magnet moving-coil mechanism allows for a practical assembly since on a 45-mm. diameter cell of this type the output into a load of 200 ohms is only 4 to 5 μa per foot-candle.

Illumination meters of various types are made on this basis; such a meter having ranges of 60, 120 and 600 foot-candles is shown in fig. 16. Improvements in the lighting of homes, schools and manufacturing establishments have been the result of the ability to measure light values and prescribe the optimum requirements.

Photographers were particularly interested in the development of simple light meters, since, in the process of taking the photograph the film sensitivity is known or is available, and the lens opening and the time of exposure can be set. The amount of illumination on the scene is always in question, however, and previously only the expert could correctly evaluate its intensity, adjust shutter and lens and invariably take a good picture.

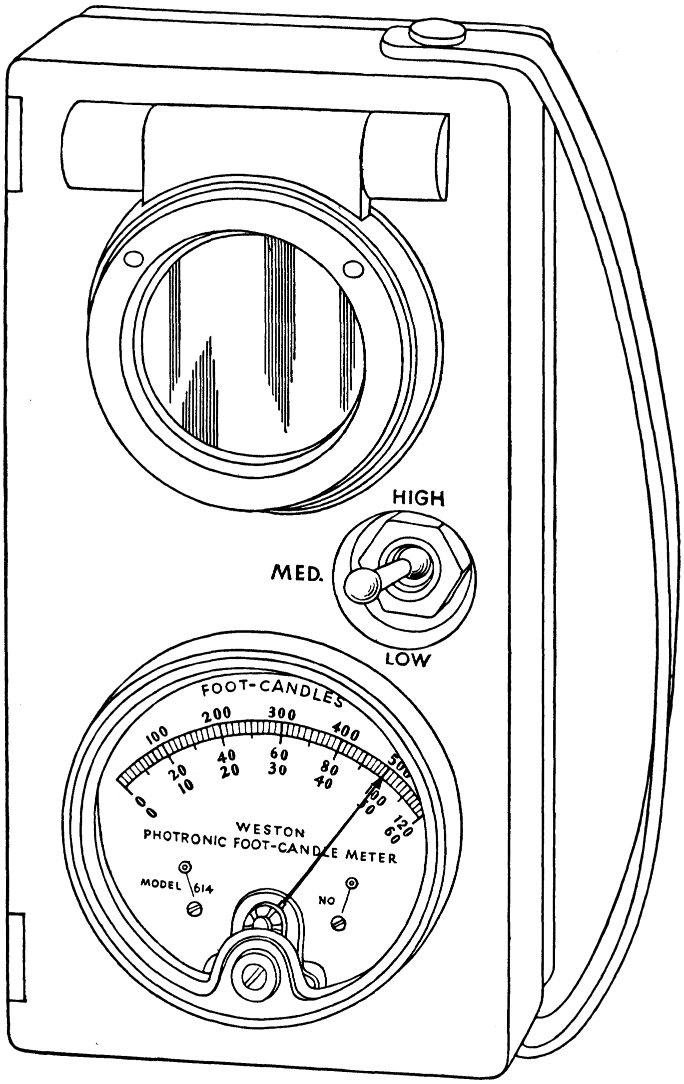


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FIG. 16.—ILLUMINATION METER

The photographic exposure meter (fig. 17) is simply a light meter as explained above but with the dry disk photocell baffled to restrict the angle of light entering from the scene being photographed to approximately that entering the lens. Because of the enormous range in light to be expected, a special magnet system is used in the associated instrument to give a broad logarithmic response. When the light value of the scene has been determined, it is set on the circular calculator mounted on the face of the instrument along with the speed of the film. The correct shutter speed for any usable lens opening is then directly indicated.

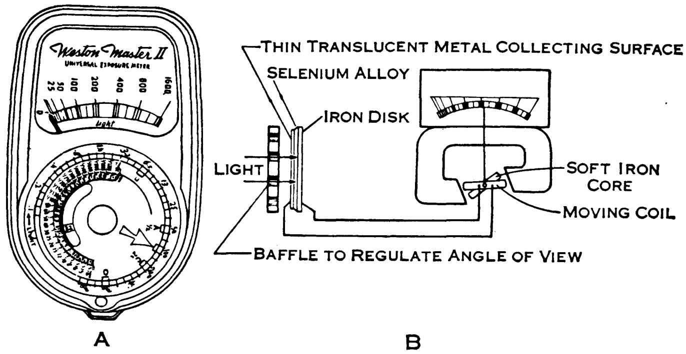
Exposure meters have found favour with both professional and amateur photographers since the saving in film which would have been spoiled by incorrect estimates of the light soon warrants the expense of the meter, not to mention the assurance of perfect exposures where the picture cannot be repeated. Commercial rating of films for such use has progressed rapidly to the end that measurement has taken much of the mystery from photographic procedures.

Temperature Measurements.—Mention has been made of the thermojunction in which two dissimilar metal wires are joined together and, when the junction is heated, a small voltage is generated. When connected to an indicating instrument, a small current will flow and deflect the pointer across the scale which can be calibrated in terms of temperature.

There are always two or more junctions in such a circuit, and the actual voltage generated is proportional to the temperature difference between the heated junction and the other or cold junction. The voltage is not strictly proportional to the temperature difference, but follows an empirical curve. Data for the value of the voltage produced at various temperatures with the cold junction at 0° C., for example, are available in publications of the national bureau of standards in Washington for the several combinations of metals or alloys commonly used. Similar data are also available from manufacturers of the wires, which must be of uniform analysis to follow the published data.

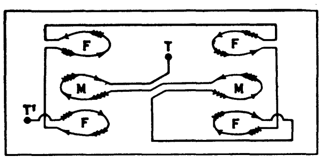
A common combination for temperatures up to 1,000° C. is iron and constantan, the latter an alloy of 60% copper and 40% nickel. In such a thermocouple, with the cold junction at 0° C., 58.22 mv will be generated if the hot junction is at 1,000° C.; if at 500° C., 27.58 mv will be available. For higher temperatures up to 1,400° C., nickel chromium alloys such as chromel and alumel are widely used; again with the cold junction at 0° C., for a hot junction temperature of 1,200° C., 48.89 mv are generated. Both of these thermocouples are known as base metal couples as opposed to thermocouples made from the nonoxidizing noble metals discussed below. Where base metal couples are used at the highest allowable temperatures they may require comparatively frequent replacement because of oxidation or other corrosive influences in the furnace atmosphere in which they are placed. They are relatively inexpensive, however, and replacement costs are only moderate. Alternatively, these couples may be placed in a metal or ceramic protective tube which will lengthen their life by protecting them from the surrounding atmosphere; but such protective tubes slow down the response of the thermocouple to changes in temperature.

For still higher temperatures up to 1,650° C., the most commonly used combination is of pure platinum against an alloy of 90% platinum and 10% rhodium. The output of this type of couple is relatively low; if the cold end is at 0° C. and the hot end at 1,400° C., 14.31 mv will be generated. This noble metal thermocouple is ordinarily not oxidized in most atmospheres; in virulent atmospheres such a couple is frequently protected by a porcelain, quartz or other ceramic protecting tube. While noble metal thermocouples are inherently expensive because of the cost of the metals involved, they do not wear out and when damaged or otherwise require replacement, the scrap value of the metal is usually completely recoverable.



BY COURTESY OF WESTON ELECTRICAL INSTRUMENT CORP.
FIG. 17.—EXPOSURE METER (A) AND SCHEMATIC DRAWING OF METER (B)

Various methods are used to assure maintenance of the cold junction at a specific temperature. In the laboratory the cold ends may be immersed in an insulated receptacle filled with melting ice, equivalent to 0° C. In industry, cold ends are frequently buried in the ground at sufficient depth to attain constant temperature, usually only a few feet below the ground. Another method of compensation for cold end temperature is to bring the cold junction back to the instrument and compensate the instrument for this effect. William H. Bristol in 1905 developed the cold end compensator for permanent-magnet moving-coil instruments. This consists of a spiral of bimetallic material mounted on the top bridge of the instrument to which is attached the outer abutment of the upper control spring. The motion of the bimetal spiral is so adjusted that as the temperature of the instrument itself changes, the motion of the spiral acting on the spring rotates the pointer so that it always indicates the ambient temperature and that of the cold junction of the thermocouple. Although not as accurate a method as using a controlled temperature for the cold end, the results are practical and the arrangement is widely used in industry.



BY PERMISSION OF KELVIN, BOTTOMLEY AND BAIRD

FIG. 18.—CONNECTIONS OF KELVIN AMPERE BALANCE

Other Applications.—There are many special uses of the highly sensitive permanent-magnet moving-coil D.C. mechanism. With networks it is possible to indicate values of circuit resistance directly, and voltage or current differences as well as sums can also be read. With auxiliary equipment, speed and speed differences can be read. Through the use of the vacuum tube amplifier and rectifier such devices as the vacuum tube voltmeter can be assembled; the input is connected to a vacuum tube grid with the indicating instrument in the output, and readings may be taken drawing practically no current.

Still another class of D.C. instrument, using a modified moving-coil mechanism, indicates the ratio of two currents, and may be used as a direct reading ohmmeter or as a voltage or current comparator. In the form of an ohmmeter, enclosed in the same case with a small hand-driven D.C. magneto generator, is the combination widely known as the Megger for measurement of high resistance.

ELECTRODYNAMOMETER INSTRUMENTS

The galvanometers and indicating instruments previously discussed function through the reaction between a fixed magnetic field and the field of a coil carrying the electric current to be indicated or measured. Since the fixed field is constant, torque to produce rotation of the mechanism is produced only with direct current; alternating current in the coil would produce only an oscillating torque around the zero position.

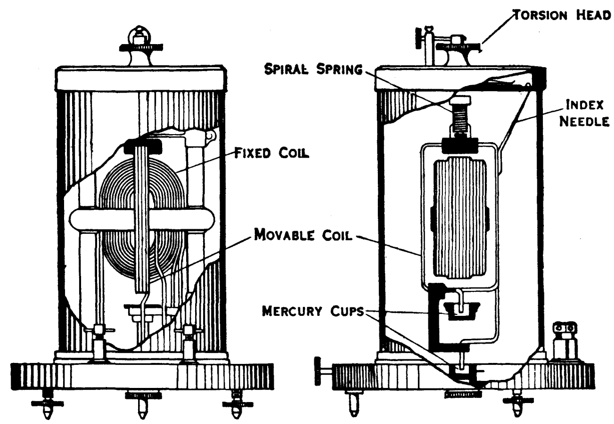
André Marie Ampère, in 1820, discovered that parallel conductors carrying currents attract each other if the currents are in the same direction or repel each other if they are in opposite directions. In 1843 Wilhelm E. Weber produced a simple form of electrodynamometer on this principle, but the first practical measuring instruments appeared in 1883, when Lord Kelvin and James P. Joule devised the standard current weigher or balance, and the Siemens brothers the dynamometer.

The principle of the Kelvin balance is shown in fig. 18. The instrument consists essentially of six horizontal coils, four of which are fixed (F) and two movable (M); the current to be measured traverses the whole of the coils in series. In order to allow the two movable coils to swing freely between the fixed ones, they are suspended by a large number of straight fine wires forming straight straps or ligaments. The current passes round the coils as shown by the arrows; on the right hand side the current in the centre moving coil is in the same direction as that in the upper and in the opposite direction to that in the lower of the fixed coils. The moving coil is therefore attracted to the upper and repelled from the lower coil and tends to move upward, while the left hand moving coil in which the current circulates in the opposite direction tends to move downward. The whole moving-coil system therefore cants upward at its right end and can be brought back to the level or zero position by a weight hung at that end. To simplify the measurement the moving coils are mounted in a light frame having a long bar and scale in front, along which a weight can slide as in a steelyard balance; this is operated by a silk cord passing through the ends of the cover and provided with a device for freeing the cord from the weight when the latter is in position.

The force upward on one coil system and down on the other is proportional to the product of the magnetic fields of the fixed- and the moving-coil systems; since the fields are proportional to the currents causing them, the force is proportional to the product of the current in the moving coils times the current in the fixed coils. If the coils are all in series as shown, the torque is proportional to the square of the electric current flowing.

If the current reverses, the torque does not reverse since, if both magnetic poles reverse, they still repel if alike and attract if of opposite polarity. As a result this type of instrument is useful for the measurement of alternating as well as direct current.

Another form of electrodynamometer consists of a movable coil suspended or pivoted inside a larger fixed coil. This form was studied by Maxwell, Gray, Weber, Clark and other prominent physicists prior to 1900, but the design most frequently referred to is that of Siemens (fig. 19). It consists essentially of two coils at right angles, the inner having a large number of turns and being fixed with its axis horizontal on a wooden frame, and the outer in the form of a loop encircling the fixed coil and suspended by a silk thread, with its two ends brought out at the bottom to dip into two mercury cups. On the top of the frame a circular scale is fixed, with a torsion head and pointer, a cylindrical spring encircling the suspension being mounted between the torsion head and the top of the coil. The current circulates around both coils in series and causes the swinging coil to turn, whereupon the torsion head is turned until the torsion of the spring brings the coil back to its zero position as indicated by a pointer fixed to the top of the coil. The current then $= K\sqrt{D}$, where K is the constant of the instrument and D the angle turned by the torsion head. In order to increase the range of the instrument, the fixed coil is generally made of two portions with different thicknesses and number of turns of wire, and either of these can be connected in series with the moving coil.



BY PERMISSION OF SIEMENS, LTD.

FIG. 19.—SIEMENS ELECTRODYNAMOMETER

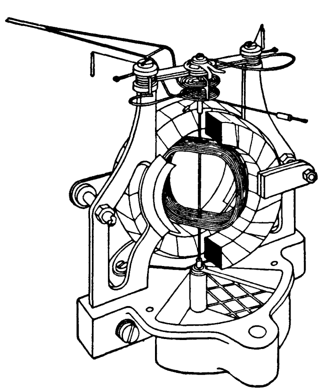
Both of the above instruments are of the standard type in which it is necessary always to bring the coils into the same position, in order that the theoretical square law shall be followed. But deflectional direct indicating instruments can be made by simply providing the moving coil with a pointer and control spring, in which case they are equivalent to permanent-magnet moving-coil instruments in which the magnet is replaced by the fixed coil. In 1890 the first instrument of this type was introduced by Edward Weston as a dynamometer voltmeter, the fixed and moving coils being circular, wound with fine wire and connected in series through the spiral springs which provided the control. A high noninductive resistance was connected in series with the combination and the instrument was graduated as a direct reading voltmeter. Additional ranges were provided by extra series resistances.

About 1910, after a period of study to determine optimum relations as to the size and conformation of both fixed and moving coils, electrodynamometer indicating instruments began to take their final form and the basic design approaches were so fundamentally sound that they were still being followed at mid-century. A typical structure is shown (fig. 20), and it will be noted that circular coils are used which are more stable as to shape than oval or flat sided coils. The ratios of the moving and fixed coil diameters along with the coil width are so selected that a very nearly pure square-law scale results when fixed and moving coils are connected in series, as in a voltmeter.

Electrodynamometer instruments are made as voltmeters, ammeters and wattmeters.

But the most important use of the electrodynamometer mechanisms is as a wattmeter for the measurement of power. Power expended in, or taken from, an electrical circuit, in watts, is equal to the product of the impressed potential in volts and the current in amperes. These can be individually measured by the direct current instruments previously discussed and the values multiplied together. But with alternating or pulsating currents this is not the case, and a special instrument is needed in which the torque is proportional to the product of the potential and current at each instant and indicates the mean value. Such an instrument is a true wattmeter and is essential for alternating-current power measurements. While wattmeters conforming to the above requirement can be electromagnetic, electrostatic or thermal, most indicating wattmeters are of the electrodynamometer type. As already stated, if two current-carrying coils are near each other, the force or deflecting torque between them is proportional to the product of the strengths of the two currents so that if one of the coils ties the current in the circuit by being connected in series with it and the other is wound with fine wire and connected across the circuit as in a voltmeter, the current in the second coil is proportional to the potential if its resistance is constant and the force or torque between the coils is proportional to the product of a potential and the current; *i.e.,* to the power in the circuit at each instant. Proceeding with this theory, if the shunt coil swings inside the series coil and is provided with a pointer and control spring, the deflection is proportional to the average power as the inertia of the moving coil system prevents it from following the rapid variations of the alternating currents.

The principle of the electrodynamometer wattmeter was first put forward by William E. Ayrton and J. Perry in 1881, and was adopted by Lord Kelvin in his watt balance, and by Siemens in 1884, the moving coils of the Kelvin balance or Siemens' dynamometer being made of fine wire and in series with noninductive resistances.

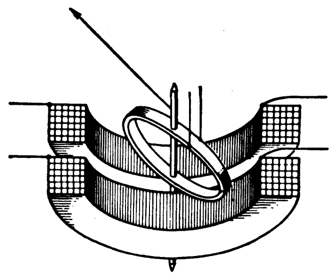


BY COURTESY OF WESTON ELECTRICAL INSTRUMENT CORP.
FIG. 20.—INDICATING ELECTRODYNAMOMETER MECHANISM

Deflectional direct-reading dynamometer wattmeters have been designed by many manufacturers, a typical mechanism being the same as shown for the voltmeter (fig. 21). In a typical wattmeter as made by the Weston Electrical Instrument corporation after designs by W. N. Goodwin, Jr., and B. P. Romaine, the field coils are each wound with 16 turns of no. 12 (0.081 in. diam.) copper wire and connected in series. These coils are nominally rated at 5 amp., producing a total of 160-amp. turns for full-scale deflection. The moving coil is wound with fine wire and takes approximately 25 ma. to secure full-scale deflection (86°) when used with springs having a total torque constant of 170 dyne-centimetres per radian. The total loss in the field coils at 5 amp. is approximately 0.8 w.; in the potential system at 115 v., approximately 2.9 w.

For a given watt value such as full scale on a wattmeter, as the power factor is reduced, the current leads or lags the potential and increases in amount. In the referenced wattmeter the fixed-coil resistance is quite low so that although rated at 5 amp., current as high as 10 amp. can be carried without difficulty; the loss in the coils will rise from 0.75 w. to 3.0 w. The instrument will thus give full-scale deflection on its scale value of watts at 50% power factor. Special types of instruments with extra heavy wire in the field coils and somewhat subnormal torque are also made to give full-scale deflection on as low as 20% power factor.

Polyphase Wattmeters.—Where polyphase distribution is used the measurement of potential and current between and in the several lines can be taken successively with single instruments, or a group of instruments can be mounted on a panel to give the whole picture. A. Blondel showed in 1893 that the total power in any polyphase system supplied through *n* conductors can be measured as the sum of the indication of *n*-1 wattmeters so connected as to have the current coil of a wattmeter in every wire but one, and with the potential coils connected from the same wire as the current coil over to the odd conductor. While theoretically correct, in practice it is found that some of the instruments may read reversed because of phase differences of more than 90°; in this case the current coil connections alone are reversed and the positive readings obtained must be considered as negative and subtracted from the sum of the others.



BY COURTESY OF WESTON ELECTRICAL INSTRUMENT CORP.
FIG. 21.—SECTIONAL VIEW OF ELECTRODYNAMOMETER COIL SYSTEM

In a three-phase, three-wire system commonly used for power distribution, the sum of the readings of two wattmeters so connected will thus give the total power. One wattmeter of the pair reverses when the power factor drops below 50%, however, and frequently raises difficulty in establishing correctly the sign of that power and the total value. To resolve the difficulty, two complete wattmeter systems may be superimposed, with the two moving coils on the same staff. The torques and the consequent deflections add algebraically even when the torque of one reverses, and the actual deflection is thus always a correct measure of the total power under all conditions.

ABSOLUTE MEASUREMENTS

The electrodynamic type of structure, where the reaction between two coils carrying current is measured as a force is also used in the absolute measurement of current. The standards laboratories of various countries (the national bureau of standards in the United States, the national physical laboratory in Great Britain, etc.) conduct absolute measurements, from which secondary standards in turn can be calibrated. The majority of electrical measuring instruments are actually comparison devices, requiring initial calibration against other and more accurate standards. The basic standards of the national laboratory, then, must be predicated on a definition and such fundamental standards as those of length, mass and time which are presumably always available.

Such definitions are usually involved mathematically, but the definition for current can be resolved by stating that 1 amp. flowing in a circuit consisting of two infinitely long parallel conductors causes a force of .02 dynes per centimetre length between them when they are 1 cm. apart and when the surrounding space is devoid of all matter; *i.e.,* in a vacuum. Of course, in the practical sense infinitely long parallel wires would be impossible to arrange and the force would be extremely small. Accordingly, in the standard current balance for determining the ampere there is a highly accurate form of the Kelvin balance.

The current balance used at the national bureau of standards in Washington is of the type developed by Lord Rayleigh and Mrs.

Henry Sidgwick and described in the *Philosophical Transactions,* 175, 411 (1884). Structurally only one set of coils is used, two fixed coils and one coil between them, the moving coil being suspended from one arm of a highly accurate balance; the weight of the moving coil is properly counterweighted in the pan on the opposite side of the balance beam with no current flowing. When current flows a force is measured, either upward or downward, by adding weights to the appropriate side.

Considering the basic definition above, it is necessary to integrate the effect of the current in all parts of the fixed-coil system on the current in the moving-coil system, which calls for mathematical analysis of a high order. To attain high accuracy, measurements of such items as effective coil diameter, wire size, coil spacing and the like must be made with the utmost accuracy. However, when all of this work has been accomplished and measurements are made, it is usually possible to duplicate readings to within a few parts per 1,000,000. Harvey L. Curtis of the bureau of standards reported in 1935 that agreement was reached between several countries to approximately ten parts per 1,000,000.

Another classical definition of the ampere in terms of its electrochemical equivalent was adopted by the Chicago Electrical congress in 1893 and confirmed at the London Electrical conference in 1908. In it, the ampere was defined as "the unvarying electric current which, when passed through a solution of nitrate of silver in water, in accordance with specifications attached, deposits silver at the rate of 0.00111800 of a gramme per second." But it was only with great difficulty that the specifications could be followed strictly. The measurement of the time of the deposit was difficult to make to the required accuracy, and less than a year after the London conference Rosa and Vinal discovered that the specifications were somewhat indefinite since the weight of the deposit was sometimes modified by the filter paper used in accord with the specifications. The device itself is known as the silver voltameter. Its use was practically abandoned in later years since greater accuracy could be attained with the current balance, which is fundamentally a truly absolute method.

To develop an absolute system of units, the absolute volt and the absolute ohm must also be developed. But these are connected by the simple Ohm's law equation $E=IR$. Accordingly, only two of these factors are needed to obtain the third. With the ampere determined, either the volt or the ohm can be considered. To develop the volt, absolutely, is extremely difficult since this would require a measurement of the electric repulsion or attraction between two vanes charged to the potential to be determined. Electrostatic forces are low, and although special types of equipment have been used for this purpose, it has been deemed easier to develop an absolute standard of the ohm.

The ohm, the unit of resistance, was defined in 1893 by the Chicago Electrical congress as the resistance of a mercury column at the temperature of melting ice, a cross section of 1 sq.mm. and a length of 106.3 cm. At the London Electrical conference in 1908 it was concluded that the length of the mercury column was not known to a great degree of accuracy and to make the international ohm more definite, the conference arbitrarily added two zeros to the figure adopted at Chicago, making the length 106.300 cm. Difficulties arose in making an insulating tube of this exact cross section and length, filling it with mercury and obtaining proper terminal equipment.

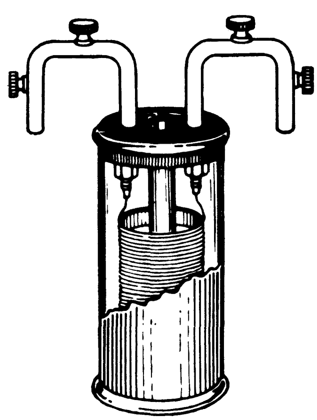
Parallel with this work, studies were made on the possibility of an absolute measurement of the ohm so that a measurement could be made in terms of length and time by several different methods. Probably the best of these methods is that originally due to L. Lorenz in 1873. Essentially it consists of a metal disk rotated steadily in the magnetic field of a coaxial cylindrical coil through which a current is passed. The arrangement is therefore equivalent to a Faraday disk in which the magnet is replaced by the current-carrying coil, and an electromotive force is induced between the centre and edge of the disk. If M is the coefficient of mutual inductance between the coil and disk (the magnetic flux through the disk for unit current in the coil), i the current in the coil, and n the number of revolutions per second of the disk, any radius of the disk cuts across the whole flux Mi in each revolution or Mni lines of force or Maxwells per second. This is, by definition, the e.m.f., E between the centre and edge of the disk. The current passing through the coil is also led through the resistance R to be tested, producing a potential Ri, and the ends of this resistance are connected through a galvanometer G to two contacts at the centre and edge of the disk. On varying the speed of the disk a speed can be found for which the galvanometer remains at zero, indicating no current in which case $V=E$, or $Ri=Mni$, so that $R=Mn$. The mutual inductance M is a constant of the apparatus which can be calculated from the dimensions and number of turns of the coil and the diameter of the disk, so that when balance is obtained the resistance R can be determined by multiplying this constant by the speed, which is easily measured with accuracy.

Thus the absolute measurements of the ampere and the ohm are established. But these measurements are so involved that the next problem is the practical maintenance of standards in the national laboratories; this is accomplished through the use of the standard cell and a standard ohm made from wire which can be maintained within a few parts per 1,000,000 over many years.

The Standard Ohm.—Considering the standard ohm first, the method of standardization is that of the Lorenz method discussed above. The actual physical standard is in the form shown in fig. 22. In this so-called national bureau of standards form, a metal cylinder contains a second silk-insulated brass cylinder on which carefully annealed manganin wire is wound and varnished in position. After adjustment of the resistance of the wire its ends are silver soldered to the heavy terminals which, in turn, are arranged to be set in cups of mercury in the comparison apparatus. After extended baking to ensure dryness the assembly is placed in moisture-free oil and the case is sealed. A thermometer is used for taking the exact temperature at the time of the comparison.

The bureau of standards has a number of such units, some of slightly modified construction, which have been checked with a modified Lorenz apparatus over a number of years and which have been found to vary less than ten parts per 1,000,000 over considerable periods of time. Units having a nominal value of 1 ohm are considered most important as standards, but similar standard resistors are made for use by other laboratories having resistance values varying as widely as from 0.0004 ohms to as high as 1,000,000 ohms. The extremely low values of resistance are quite bulky and are intended to carry high currents; they may also carry rotating vanes to keep the oil in circulation and maintain constant temperature. In the high values leakage becomes a problem. Best accuracy is attained in the vicinity of 1 to 1,000 ohms.

The Standard Cell.—Since a standard ampere cannot be maintained, a standard voltage is obviously desirable if it can be attained. As early as 1836 the use of the Daniell cell was proposed, having electrodes of zinc and copper in zinc sulphate and producing a potential of 1.08 v. But this cell was not permanent, new cells were required every few weeks, and the accuracy of reproduction was only about 1%. In 1872 the Clark cell was proposed, and many were used. In it the electrodes are zinc amalgam and mercury in a saturated solution of zinc sulphate. However, the Clark cells lasted only a few years and had a relatively large temperature coefficient of potential. In 1891 the Carhart-Clark cell was brought out with essentially the same electrodes but modified to have a lower temperature coefficient although the life was equally short.



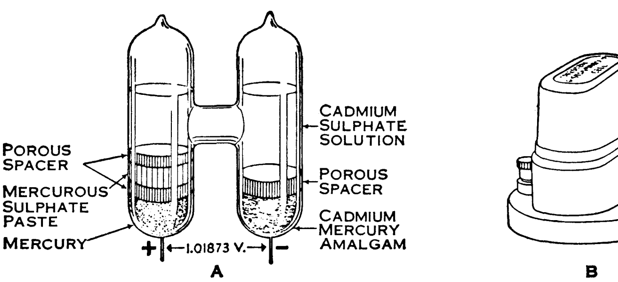
BY COURTESY OF WESTON ELECTRICAL INSTRUMENT CORP.

FIG. 22.—STANDARD RESISTOR, NATIONAL BUREAU OF STANDARDS TYPE

In 1892 Edward Weston developed the standard cell, with electrodes of cadmium amalgam and mercury in a cadmium sulphate solution. This combination had a low temperature coefficient and a long life.

Fig. 23A shows the general arrangement of the Weston standard cell. It is somewhat similar to the Clark cell but with cadmium replacing zinc both in the amalgam and in the electrolyte. The positive electrode is mercury held in position with a porous spacer on top of which is placed a paste of mercurous sulphate, also retained in position by a porous spacer. The negative electrode is an amalgam of approximately 10% cadmium in mercury, likewise retained in position with a porous spacer. The electrolyte is a cadmium sulphate solution. Platinum wires are sealed through the glass envelope. The upper limbs of the cell may or may not be hermetically sealed.

The Weston cell is made in two forms. The normal cell is made with a saturated solution of cadmium sulphate with an excess of cadmium sulphate crystals placed above the porous spacer in both limbs. Assembled with materials of a high degree of purity, such a cell has an open circuit potential of 1.01863 absolute volts at 20° C. Cells so made are checked against the potential drop through a standard ohm of a suitable current, measured by a current balance; the current is so adjusted that the drop through the resistor balances the potential of the normal cell as determined by a highly sensitive galvanometer. Thus, through the use of the standard ohm and the current balance, the potential of the normal cell can be checked. Experience over a period of years indicated that the normal cell has a high degree of stability and is an easily maintained potential standard. It is so used in the various national laboratories, which assemble their own cells to rigid specifications as to purity of all chemical components. The temperature must be maintained exactly since the voltage of this combination shows a variance of about 40 μv per degree centigrade at 20° C.



BY COURTESY OF WESTON ELECTRICAL INSTRUMENT CORP.

FIG. 23.—WESTON STANDARD CELL (A) AND CELL CASING (B)

The other form, the Weston standard cell, has the same electrodes but the solution is made saturated at 4° C., above which point the solution becomes unsaturated. In this unsaturated cell the temperature coefficient is much smaller and for practical purposes may be disregarded.

Enclosed in their glass envelopes, standard cells are perhaps in the category of delicate instruments. Nevertheless, they are shipped to the national standardizing laboratories by the hundreds for certification with only moderate protection and with practically no losses. On the other hand if such a cell is shaken or moved it should be allowed to attain equilibrium for several hours before being used for accurate work. Cells should preferably not be exposed to sudden and large temperature changes and should not be exposed to heat in excess of 40° C. Further, standard cells are not intended to supply any considerable amount of current. Ordinarily used in potential opposition to another e.m.f., current is usually allowed to flow only momentarily to give a galvanometer reading.

Fifty microamperes is a good top value for the current which may be taken without damage; 100 μa may be taken momentarily. Standard cells have a resistance of from 100 to 500 ohms depending on their size and other details of manufacture and thus in any event cannot supply any appreciable current. To hold the current to less than 100 μa, a resistance of 10,000 ohms may be connected in the circuit at all times except for a final balance in which the utmost sensitivity is required.

Absolute v. International Units.—The international values of the ampere, volt, ohm and other quantities stem from discussions at the Chicago Electrical congress in 1893 and the London Electrical conference in 1908. In most countries these values were legally adopted prior to 1910. For some years thereafter, reproducible standards such as the mercury ohm, the silver voltameter and the like could be maintained more accurately than absolute measurements (those obtained from dimensions, time and resulting forces) could be made. However, advances in scientific research in the field of absolute measurements improved as to precision to the point where, in the period 1930–40 it seemed desirable to shift to the absolute methods and resulting values.

On Jan. 1, 1948, the new absolute values became legal in the United States instead of the older international values. The changes were small and negligible in most engineering work but are listed below for reference. The listing allows for the conversion of values determined in international units as with apparatus so calibrated into the absolute units.

Conversion Table for Electrical Quantities
International Units to Absolute Units

1	int. ohm	=	1.000495 abs. ohms
1	int. volt	=	1.000330 abs. volts
1	int. ampere	=	0.999835 abs. ampere
1	int. coulomb	=	0.999835 abs. coulomb
1	int. henry	=	1.000495 abs. henrys
1	int. farad	=	0.999505 abs. farad
1	int. watt	=	1.000165 abs. watts
1	int. joule	=	1.000165 abs. joules

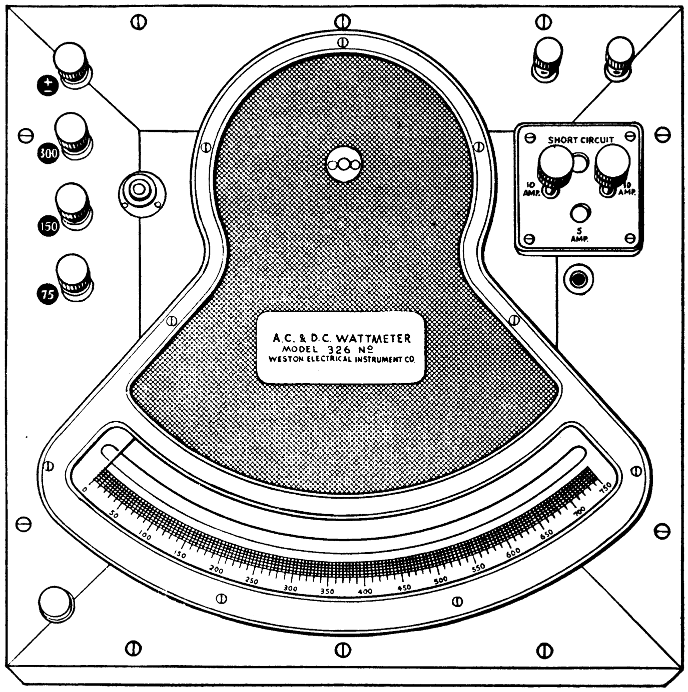
Where refined measuring apparatus is sensitive to .1% or better, it should be stated whether international or absolute values are used. If made prior to 1948 and not otherwise marked, international values may be assumed. Likewise, if made after Jan. 1, 1948, most reputable makers will have calibrated in terms of the absolute units and will have so stated on the apparatus or the accompanying certificate.

It is to be noted that there is no standard A.C. ampere, volt or watt. The A.C. ampere may be defined in several ways, but basically it is that current which will accomplish the same result as a D.C. ampere in the same time. It will also, in a noninductive resistance, produce heat at the same rate. Since heat and power are a function of the current squared, and the torque or deflection of an electrodynamometer instrument is also as the square of the current, we have in the electrodynamometer a transfer instrument of great value.

Thus, for A.C. current standardization, a high-grade electrodynamometer ammeter is calibrated on D.C. against a standard cell and a standard resistor. That calibration will then hold for A.C. provided that the instrument is known to be within the desired accuracy limits as regards such possible A.C. errors as those resulting from eddy currents, phase shifts in parallel circuits, capacity between turns and the like. These special A.C. effects are usually determinable from special tests on the instrument; in the more accurate types such effects are kept very small by correct design.

The electrodynamometer wattmeter is of great importance in the United States, Great Britain and other countries because practically all electrical energy which is sold is based on the calibration of energy meters or watt-hour meters, which, in turn, are calibrated against the electrodynamometer wattmeter. Even slight errors become of fantastic proportions when the entire billings for electric power are considered.

Most electric utilities maintain in their meter laboratory a group of electrodynamometer wattmeter standards against which the energy meters on their system are ultimately referred. Those wattmeters are periodically checked against D.C. using the procedure outlined above. The best of such instruments are guaranteed by their makers to be accurate to within .1% of full-scale deflection and they are frequently certified by the bureau of standards to this degree of accuracy where legal requirements make official standardization important. In an instrument of this type (fig. 24) every precaution is taken to obtain the best transfer accuracy. Frequently mounted on a stone pier or with some other arrangement to eliminate parasitic vibration, the instruments are carefully levelled and rarely moved; connections are frequently made at a distance to avoid moving the instrument in any way, and



BY COURTESY OF WESTON ELECTRICAL INSTRUMENT CORP.
FIG. 24.—PRECISION ELECTRODYNAMOMETER WATTMETER FOR USE IN LABORATORIES

records are kept of the performance of the instrument at the time of its periodic checks on D.C. to determine its drift, if any. Experience has proved the reliability of the electrodynamometer transfer instrument, which is universally used as the basic standard of alternating current power. Similarly, an electrodynamometer voltmeter may be calibrated on D.C. and, with cognizance of the extent of the A.C. errors, used as a standard for A.C. voltage.

The same procedure holds for wattmeters. An electrodynamometer wattmeter may be calibrated on direct current in terms of the product of the D.C. current through the field coils and the potential applied to the moving-coil system through its series resistance. In many instances the current and voltage may be derived from entirely independent sources; as far as the instrument itself is concerned, the product of the two quantities is indicated and the scale may be calibrated in that product, or, effectively, watts in such an instrument may then be used in an A.C. system, again with full cognizance of such special A.C. errors as might exist but which are either compensated for or taken into account. The instrument then becomes a perfectly valid standard for A.C. power.

At low power factor, where the alternating current may lag the voltage, for example, the electrodynamometer wattmeter still reads true power since, as explained in the discussion on the instrument, it actually averages the instantaneous power applied to the system.

MOVING IRON VANE INSTRUMENTS

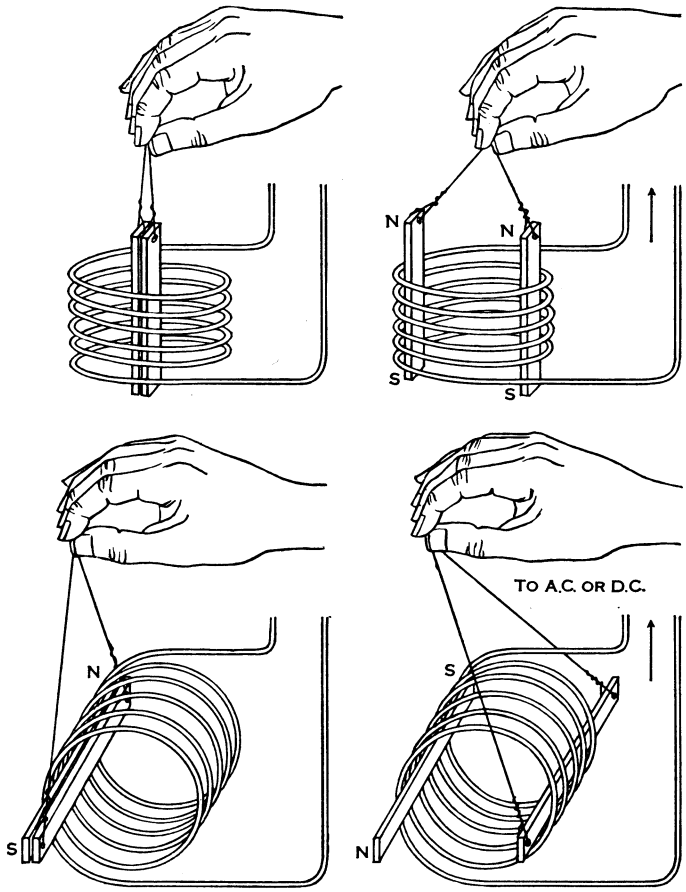
While instruments of the electrodynamometer type represent the ideal for A.C. measurements at power frequencies, they tend to be expensive because of the dual coil system required. A much simpler type of mechanism is obtained through the use of a single actuating coil and one or more iron pieces. The first instruments of this type were introduced by William E. Ayrton and J. Perry in 1884. The principle is simply that if a current is passed through a coil, a piece of soft iron will be sucked into it, and if a suitably shaped piece of soft iron is pivoted and provided with a pointer, a useful form of ammeter can be made.

A later development by the Nalder brothers in Great Britain and Edward Weston in the U.S.A. is illustrated in fig. 25; two iron pieces are used. If two similar adjacent iron vanes are similarly magnetized by the coil they will be repelled as they will be magnetized with like poles adjacent. The magnetization may be due to A.C. or D.C. If one is fixed and the other attached to a pivoted arm provided with a pointer, a deflection is produced and may be controlled by the conventional spring. This construction has some advantages over the suction type as the two pieces of iron lie close together when the current is small and are farther apart for large currents. For a given distance apart the force between the iron pieces is proportional to the square of the current so that it is very small for small currents; but this is partially compensated by their greater proximity. The torque is consequently much more nearly proportional to the current, and the instrument has a larger useful range than does the suction type.

One of the preferred forms is the so-called book type shown in fig. 26, sometimes also called a radial vane mechanism. This requires good design and better magnetic vanes but is moderately sensitive, requiring something less than a watt in the actuating coil for satisfactory over-all performance. An aluminum damping vane operates in a closed chamber to bring the pointer to rest quickly.

While responsive to direct current, hysteresis or magnetic lag in the vanes causes errors on D.C. With moving-coil permanent-magnet instruments available at low cost, the moving vane instrument is rarely used except in the case of inexpensive indicators—for example, those used on an automobile to indicate charging or discharging of the automobile battery.

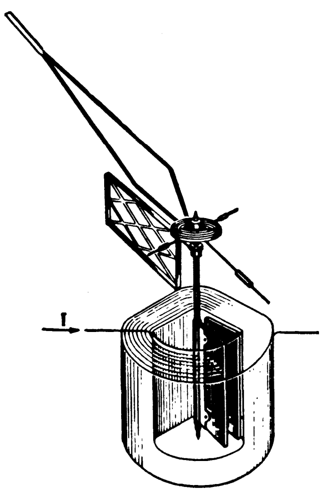
For alternating current the magnetic lag causes no difficulty, and iron vane mechanisms are widely used in A.C. switchboard instru-



BY COURTESY OF WESTON ELECTRICAL INSTRUMENT CORP.
FIG. 25.—THEORY OF THE REPULSION IRON VANE MECHANISM

ments; in laboratory types accuracies as good as within $\frac{1}{2}\%$ of full-scale value are offered by several markers.

Approximately 200 amp. turns are required in the actuating coil for the large size instruments with a 90° scale length of 5 in. The required coil, 1 in. high, may be wound with the needed turns of appropriate wire for any desired range; *i.e.*, 40 turns for a 5-amp. meter, 200 turns for 1 amp. For a high range—200 amp.—a single turn casting is used. Conversely, for a voltmeter, 4,000 turns will give a full-scale sensitivity of 50 ma. and when placed in series with a suitable resistance results in a voltmeter. Voltmeters so constructed should be compensated against temperature by proportioning the copper of the coil and the alloy wire of the series resistance to compensate for the temperature coefficient of the spring, as explained previously. Heating of the instrument from the energy dissipation in the resistance may require some ventilation of the resistor compartment, particularly in multiple-range voltmeters; such self-heating errors are sometimes called working errors or errors resulting from sustained operation.



BY COURTESY OF WESTON ELECTRICAL INSTRUMENT CORP.
FIG. 26.—RADIAL VANE MOVING IRON MECHANISM

INSTRUMENT TRANSFORMERS

In general, A.C. instruments take a great deal more power than do D.C. instruments by a factor of several thousand; instead of microwatts in the mechanism, from 1/10 to 2 or 3 w. are used in most A.C. instruments for full-scale deflection. Shunting to high currents or adding series resistance for high voltages would require the dissipation of large amounts of power making the apparatus large and bulky. And yet very high A.C. voltages and currents must be measured, efficiently and accurately. Fortunately the instrument transformer is available for such measurements and has been improved until its errors are practically negligible.

In the case of the potential transformer, the primary of many turns is connected across the high-voltage circuit; to the secondary of fewer turns is connected a voltmeter usually of 150-v. rating. The value of the high voltage is then the instrument reading times the ratio of the primary to secondary turns. In a current transformer the primary of a few turns is connected in series with the load; the secondary has a greater number of turns and to it is connected an ammeter, usually with a 5-amp. rating. The primary current is then the reading of ammeter times the ratio of the secondary turns to the primary turns.

Such transformers, suitably designed with adequate iron core material and copper conductors, are quite accurate, inexpensive, and serve to broaden enormously the A.C. values that can be measured with relatively simple instruments.

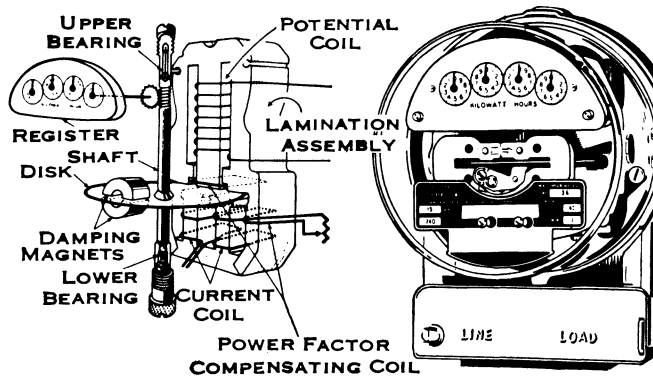
Watt-hour Meters.—Variously called integrating wattmeters, energy meters, electric supply meters or simply house meters, these instruments essentially indicate the time integral of electric power in the circuit to which they are connected. They are of great importance to the electrical industry since it is through their indications that the entire income of electrical utilities is billed.

Historically, the first effort to charge for electric power on the basis of metering was made by Thomas A. Edison, who in 1879 invented and built an electrolytic ampere-hour meter for his direct-current distribution system. It contained zinc electrodes in a zinc sulphate solution; the passage of current through it caused the zinc from one electrode to be electroplated over to the opposite electrode. Periodically this electrode was removed, weighed, and the increase in weight since the previous record was a measure of the current-time product, or quantity of electricity used. Billings were made on this basis; the resulting value was not proportional to energy except as a constant voltage was assumed. In practice it was necessary to interchange electrodes from time to time, further complicating the weighing and the keeping of proper records.

In 1882 Ayrton and Perry suggested a motor meter amounting essentially to an electrodynamometer except that the moving coil was replaced by a group of coils connected to a commutator. It rotated freely, and with armature connections made by a pair of brushes, the rotation was continuous when power was applied. The field coils were of heavy wire connected in series with the line; the rotating element, wound of fine wire, was connected through its brushes and a series resistance across the mains. The connections were identical to those of an indicating wattmeter, and the rotational torque developed was proportional to the watts in the circuit. Accordingly, to obtain rotational speed also proportional to watts, a damping or energy absorbing means was required to produce a damping torque also proportional to speed, and this was rather simply provided by a copper or aluminum disk on the rotating shaft, revolving between the poles of a heavy permanent magnet. Since the speed is proportional to watts or power, the watt-hours or energy which have passed through the meter in any period of time can be determined by counting the revolutions in that time. Elihu Thomson further refined the design and developed it into the type of watt-hour meter still used at mid-20th century for direct-current circuits.

While this type of meter can also be used for alternating current, the induction type for use on A.C. only is quite as accurate and, being much simpler and less expensive, is used almost exclusively for A.C. circuits. Induction instruments are in a sense dynamometer instruments in which current is led into the moving system by induction or transformer action instead of by conduction through springs, and they can therefore only be used for alternating currents. Galileo Ferraris is credited with initiating the use of induction instruments in 1885, although they were apparently developed independently by William Stanley in the United States a few years later.

The principle of operation of the induction wattmeter may best be understood by considering two laminated electromagnets A and B fixed close together and acting on a single circular disk. The alternating magnetism of A induces currents in the disk, part of which pass through the gap of magnet B so that the disk behaves as a moving coil carrying current derived from A and traversing the magnetic field at B, thus producing a torque. But reciprocally, the currents induced in the disk by magnet B traverse the field of A; and if the two magnetic fields vary in the same phase, there will be no resultant torque, as there is no reason why it should move from A to B rather than from B to A. But if the



BY COURTESY OF SANGAMO ELECTRIC CO.
FIG. 27.—SINGLE PHASE WATT-HOUR METER: (A) SCHEMATIC, (B) ASSEMBLED

magnetic field in B lags behind the phase of A, there is a resultant torque from A to B which is proportional to the product of the two currents producing the flux multiplied by the sine of the angle of phase difference between the fields.

To produce a torque in a rotating disk proportional to power or watts, one of the electromagnets referred to above is wound with heavy wire and connected in series with the line. The flux in this electromagnet will be in phase with the current. On the other hand the other electromagnet is wound with fine wire and is connected across the lines as with any wattmeter potential system. Considerable magnetic leakage is allowed in this potential system magnet whereby the inductance of the coil predominates and the current flow lags behind the voltage producing it nearly 90°. Through the use of an additional shading coil the flux from the potential magnet through the disk is made to lag a full 90°. Since the sine of 90° is unity, full torque will be developed, if the current in the series coils is in phase with the voltage.

Just as in the rotating-coil type, an aluminum damping disk is used between the poles of a permanent magnet to secure a damping torque also proportional to speed; in the practical instrument the same disk of aluminum is used both to secure the main torque from the electromagnets and the damping torque whereby a compact mechanism is assured. Rotating on a sapphire step bearing friction is kept to a minimum and with modern designs (fig. 27) the rotational speed is closely proportional to the power in the circuit at which the meter is connected and with errors which can be maintained to much less than 1% of the established rating of the meter.

Linked to the rotating shaft is a gear train terminating in a set of counting dials which indicate the total number of revolutions. Instead of using an odd constant to determine watt-hours, the gear ratios are so arranged that the several dials indicate watt-hours directly or through the use of a simple decimal constant. To determine energy or watt-hours passing in a circuit in a period of time such as a month, it is merely necessary to record the reading of the dials at the beginning and the end of the elapsed time. This is the procedure used in billing for electric current.

Fig. 27 shows the single phase variety for measuring the energy used by the ordinary household. Polyphase types having two elements for three-wire distribution or three elements for four-wire distribution are commonly used where polyphase power in large blocks must be metered. For very heavy currents the series coils are connected to the line through current transformers previously described; where metering is to be accomplished at high voltages potential transformers are also used.

RECORDING INSTRUMENTS

The electrical instruments previously being discussed all indicate the present value of the quantity being measured, or as near thereto as is possible in consideration of the natural period of the moving system. But frequently it is necessary to record the manner in which quantity fluctuates or remains constant over some period of time.

Instruments which make a record on paper of the magnitude of an electrical quantity with time are available in considerable variety. They draw the graph in rectangular or polar co-ordinates. Since the process of drawing a curve on paper takes much more power than merely positioning a pointer, the problem of designing recording instruments, sometimes called graphic or curve drawing instruments, becomes somewhat involved.

Recording instruments may be divided into two general classes: direct writing types and servo types. In the direct writing type the moving system, similar to that in an indicating instrument although usually larger, carries directly a pen arm which traverses the paper chart. The torque requirement is from 100 to 1,000 times that of an indicating instrument, and the required power is in milliwatts instead of microwatts. In the servo type a motor, taking energy from a separate source, actuates the pen arm; a balance arrangement is then required to turn the motor on, off, or reverse it to maintain the pen arm in a position corresponding to the present value of the quantity being measured. In both types a clock mechanism is required, electric or spring wound, to advance the chart paper if of strip form, or to rotate it if the chart is circular.

A typical direct writing recorder (fig. 28) is available with various mechanisms to record volts, amperes, watts, etc., on direct or alternating current. The chart is 6 in. wide over-all, with a $4\frac{1}{2}$-in. wide record. Paper speeds of $\frac{3}{4}$, $1\frac{1}{2}$, 3, 6 or 12 in. per hour and $\frac{3}{4}$, $1\frac{1}{2}$, 3, and 6 in. per minute are available, the rapid movements being for rapidly varying phenomena, the slower speeds for daily, weekly or monthly records.

In the servomotor type of recorder the input quantity does not directly drive the recording pen but rather operates through a more or less complex amplifying arrangement whereby auxiliary power actually drives the pen to a position representative of the input quantity. Although there are numerous varieties the potentiometer recorder is representative of this class and serves to describe the general approach to the problem.

Large numbers of potentiometer recorders are used in industry, mostly for making temperature records of heat treating furnaces, petroleum stills, chemical processing and the like, using a thermocouple. The temperature responsive thermocouple produces less than 50 mv, far too little to actuate a direct writing recorder especially through relatively long connecting wires as from a petroleum fractionating column to a central laboratory. The potentiometer recorder, however, being a null device and taking no appreciable current, operates satisfactorily in such a situation.

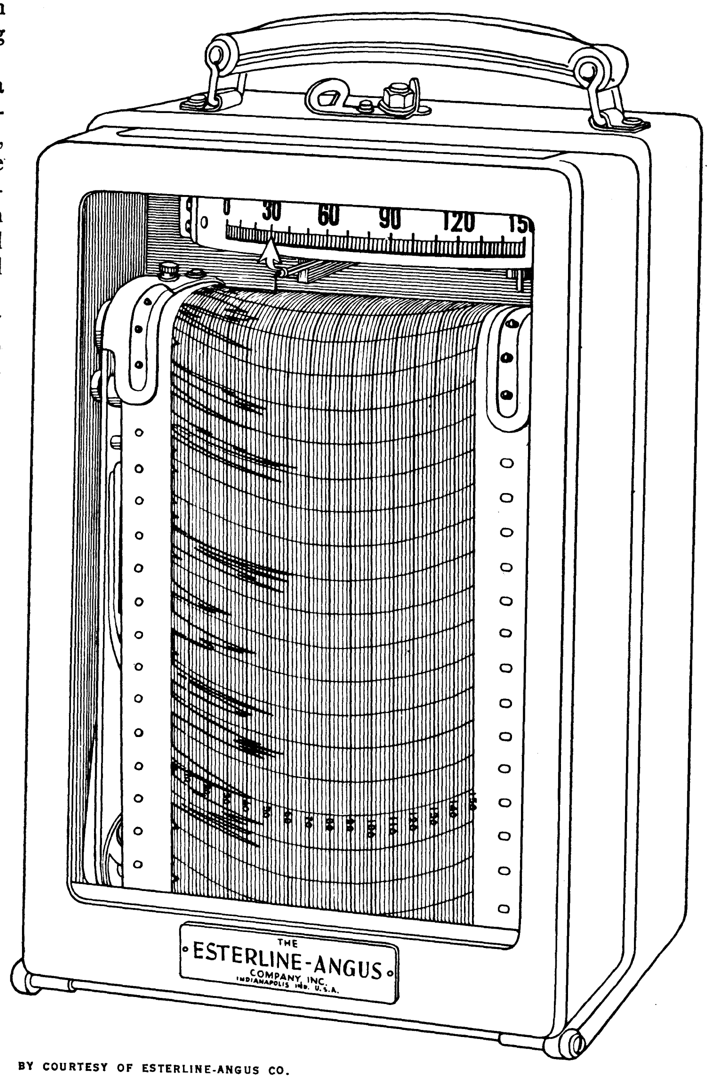


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FIG. 28.—DIRECT WRITING RECORDER

Essentially the instrument is a recording millivoltmeter, with scale and chart markings in temperature—degrees centigrade or Fahrenheit, as required. The full-scale adjustment is to that millivolt value matching the thermocouple output for the full-scale temperature. Such a recorder for 2,000° F. is shown in fig. 29.

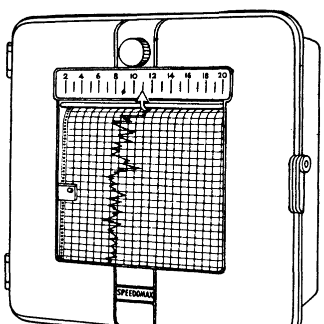
The basic principle of the potentiometer recorder is shown in fig. 30. The diagram is similar to that of the laboratory type potentiometer described under laboratory instruments above. The slide wire carries a current of 1 ma for instance. Assuming the use of an iron-constantan thermocouple for a full-scale value of 800° C., the corresponding generated potential is 49 mv with the cold end junction at 0° C. The slide wire is then made exactly 49 ohms whereby the potential drop for a current of 1 ma is also equal to 49 mv. The resistance, R, plus the slide wire must be such as to balance the standard cell voltage for standardization purposes; with the standard cell voltage taken as 1.019 v., 1,019 ohms are needed in the total circuit, or 970 ohms will be the value of resistance R. The adjustable resistance or rheostat has a value of 600 ohms to match the total dry cell voltage of approximately 1.5 v.

With the switch from the amplifier in the "standardize" position, and the amplifier actuated by a separate power source, any deviation from 1 ma in the slide wire will cause the voltage across the slide wire and R to deviate from the 1.019-v. value of the standard cell. The difference voltage will then be applied to the amplifier which, in turn, will put power into the pen motor to drive it down scale or up scale. The rheostat is then adjusted until the pen motor remains stationary which means a balance has been had and the slide wire current is standardized.

The amplifier is then switched to the "temperature" position. The difference between the millivolts of the thermocouple and that picked up by the contact on the slide wire will drive the pen motor through the amplifier until the contact position on the slide wire balances the millivolts of the thermocouple. Any change in the thermocouple output will again be reflected by a difference voltage which will again drive the pen motor to bring the contact on the slide wire to a new balance. Such rebalancing is continuous as long as the thermocouple temperature changes. In essence the position of the slide wire contact and the pen fluctuates as that of the thermocouple output and its temperature. As the chart is advanced a graph is drawn to tell the story.

In such instruments the chart paper is normally from 10 to 12 in. wide with a slightly narrower record. The moving contact and pen on the slide wire also carry an index on a bold scale as shown in the cut so that readings may also be taken at any time. The record itself is usually made in ink and the pen has a relatively large reservoir to take care of long records.

Such recording potentiometers differ widely in the type of amplifier used to pick up the error signal and cause it to operate the pen motor. The earliest such amplifying arrangements used a pointer type galvanometer with a series of cams and contacts amounting essentially to a mechanical amplifying system. About 1930 the amplifying power of vacuum tubes came to be used although necessarily through auxiliary equipment. One rather common type of amplifier changes the D.C. error signal to an A.C. voltage by passing it through a vibrating set of reversing switches operated synchronously from the A.C. line. Such an A.C. signal is readily amplified through a vacuum-tube system, and can be used to give a phased output which will drive the pen motor in one direction or the other. Since the sensitivity of the recorder depends upon the sensitivity of the amplifier, major efforts were spent in the development of greater sensitivity and stability in the amplifier.



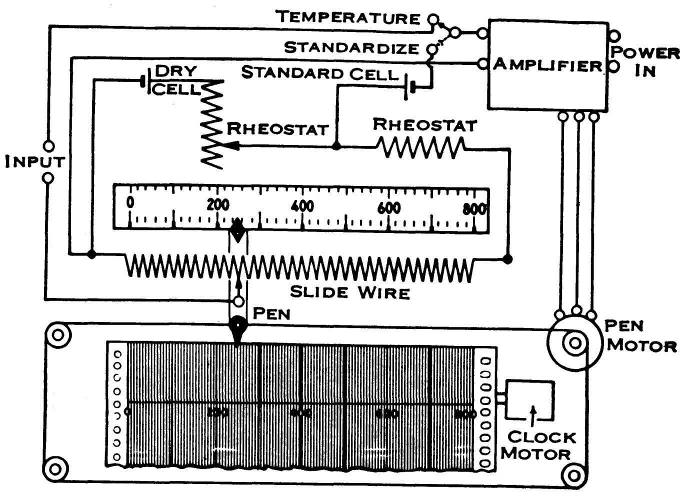
BY COURTESY OF LEEDS AND NORTHRUP CO.

FIG. 29.—POTENTIOMETER RECORDER; USED WITH A THERMOCOUPLE FOR TEMPERATURE MEASUREMENTS

Widely varying chart speeds are offered along with calibration for most any range and type of thermocouple. Automatic compensation for cold end junction temperature is usually incorporated in the network. An automatic periodic standardization of the current from the dry cell against the potential of the standard cell is also included in many designs.

This highly sensitive D.C. recorder can be used to make a record of many derived functions such as A.C. current through a thermocouple converter or speed through the use of a small magneto generator. All of the auxiliaries used with indicating instruments can also be used with recording devices of this type. In other circuit variations, the ratio between two currents or potentials can be recorded. Still another variation uses the motor to drive a large indicating pointer perhaps a foot long on a large bold scale either alone or in addition to driving a pen across the chart. Such a bold indication is frequently desired in a boiler room, for example, for indicating furnace temperature.

Finally the movement of the pen motor may cause switches to close when the pen arm has reached a certain point on the slide wire to give automatic control of processing. For example a



BY COURTESY OF WESTON ELECTRICAL INSTRUMENT CORP.

FIG. 30.—SCHEMATIC DIAGRAM OF POTENTIOMETER RECORDER

hardening furnace may be controlled within close temperature limits by varying the fuel flow through the operation of valves which are turned on or off by the position of the pen arm. Thus the potentiometer-recorder-controller may take charge of an entire process, leaving the human element entirely in a supervisory capacity.

LABORATORY INSTRUMENTS

The indicating and recording instruments which have been discussed up to this point are rapid and direct reading in their indications. But at the same time their basic accuracy is only moderate; *i.e.*, from .1% for the best types to 2% for small panel types, this percentage figure being the maximum error in terms of full-scale value.

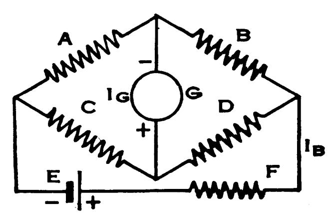


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FIG. 31.—SCHEMATIC DIAGRAM OF WHEATSTONE BRIDGE

To obtain higher accuracies an entirely different approach is necessary, usually requiring manipulation of a series of dials to balance a network until a null indication is had on a galvanometer. Essentially one compares the resistor in question with a standard resistor, or the potential in question with the voltage output of a standard cell. When a balance has been reached, the wanted value may be read from the position of the several dials. Accuracies of 1/50% are common with such apparatus; ultimate accuracies of a few parts per million are obtained with specially built apparatus such as found in the various national laboratories.

In 1843 Sir Charles Wheatstone called attention to the bridge arrangement developed by S. Hunter Christie (*Phil. Trans.* [1833]). It was an arrangement of conductors (fig. 31) whereby under certain conditions of proportionality between the resistance elements, no current would flow in the galvanometer circuit. Because the galvanometer was bridged across the centre points of the resistor pairs, the network became known as a bridge; because Wheatstone brought it into general use it took his name and since that time has been universally called the Wheatstone bridge.

With the terminology in the figure, when the galvanometer is balanced, *i.e.*, shows no current, then

$$\frac{A}{B}=\frac{C}{D} \text{ or, } C=D\frac{A}{B}.$$

Resistance C is usually made the unknown; resistances A and B are frequently made so-called ratio arms. In the final arrangement as made for laboratories (fig. 32) these ratio arms have such values as 1, 10, 100 or 1,000 ohms. Arm D is then made a series of decade resistors or, if of the plug type, arranged so that any resistance value can be had.

The bridge circuit is a powerful analytical tool, and is used in many different ways. Sensitivity of a high order is attained with moderate voltage applied. However, it is frequently desirable to know the galvanometer current for any condition of bridge unbalance to the end that adequate sensitivity be had for any application.

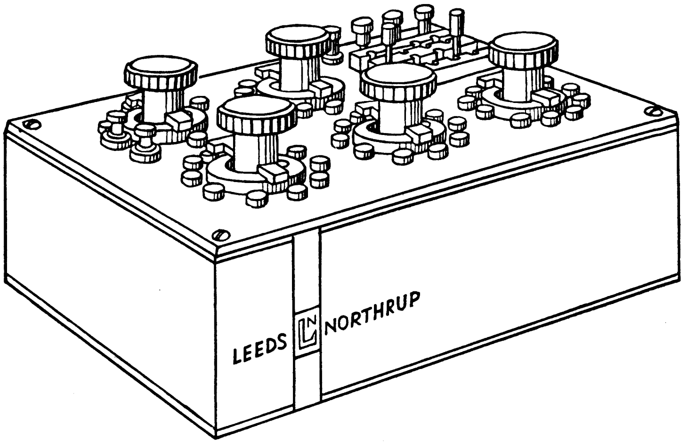

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FIG. 32.—WHEATSTONE BRIDGE USED IN LABORATORY WORK

With the same terminology, the general equation for the current in the galvanometer is:

$$I_G = \frac{E(BC-AD)}{GF(A+B+C+D)+G(A+B)(C+D)+F(A+C)(B+D)+AB(C+D)+CD(A+B)}.$$

If the resistance in series with the battery is zero or negligible, the equation for the galvanometer current reduces to the following:

$$I_G = \frac{E(BC-AD)}{G(A+B)(C+D)+AB(C+D)+CD(A+B)}.$$

Using the above equations, a solution can be obtained for the galvanometer current in any bridge arrangement. If values are used for the minimum unbalance to be indicated, the galvanometer current can be obtained for any given applied voltage E. A galvanometer may then be selected with sufficient sensitivity to show that current with, *e.g.*, at least 1 mm. deflection. While the deflection is proportional to the applied voltage, it is usually necessary to limit it to about 6 v. with most commercial bridges to avoid overheating of the resistance coils. On the other hand, special bridge assemblies for high resistances may sometimes be operated at 1,000 v. or more.

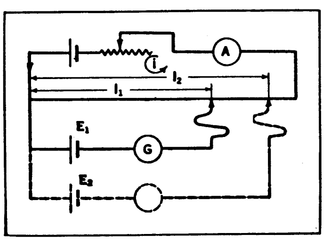

FIG. 33.—POTENTIOMETER

It should be stressed that the Wheatstone bridge is a method, not merely a specific assembly and as a method is widely applicable in resistance measurement. Modifications of the basic bridge have been developed from time to time for somewhat specialized uses. For example, the Kelvin double bridge is useful for the measurement of extremely low values of resistance where four terminal standard resistors are used, thus wiping out the resistance of the connections themselves. The Carey-Foster bridge is used for obtaining the utmost in accuracy in the medium resistance range; this is the type of bridge used at the various national laboratories for the comparison of the basic standards of resistance. Somewhat further afield, there is the Hoopes conductivity bridge for the specific measurement of the resistance of copper wire.

The bridge may also be used on alternating current with a suitable A.C. galvanometer. When inductances and capacities must be considered, however, the bridge equations become quite complex. Special variations of the basic bridge circuit have been developed over the years by James C. Maxwell, A. Anderson, E. C. Rimington, A. Campbell, D. Owen, H. Schering, Max Wien and others.

Potentiometers.—The potentiometer is essentially another assemblage of resistance networks arranged for the comparison of potentials although it is equally applicable for the measurement of currents of any value when a few suitable resistance standards are available. Its fundamental principle is derived from a method devised by J. C. Poggendorff for comparing the e.m.f.'s of two cells; it consists in employing a long uniform wire through which a steady current is kept flowing and in which consequently there is a uniform fall of potential from one end to the other (fig. 33). If r is the resistance of the wire per unit length and i the current flowing through it, the fall of potential per unit length is ri, so that the potential difference between any two points on the wire is $V=ril$ where l is the distance between them. If, then, a cell having a known e.m.f. E_1 is connected in series with a galvanometer to two contacts on the wire, and one of them is moved until the galvanometer is at zero, indicating that no current is flowing, then $E_1=V=ril_1$.

On substituting another cell of unknown e.m.f., E_2, and moving the contact until balance is again obtained, $E_2=ril_2$, so that if the current in the wire has kept constant during the whole process,

$$\frac{E_2}{E_1} = \frac{l_2}{l_1} \text{ or } E_2 = \frac{l_2}{l_1} E_1.$$

The method is analogous to weighing by a steelyard with sliding weight.

If the wire is made of a definite resistance, *e.g.*, 2 ohms for a length of a metre, and is traversed by a current of .05 amp., then the total potential difference for 100 cm. is 0.1 v. or 0.0001 v. per millimetre. Further, if at one end of this wire any number of resistances each of 2 ohms are connected in series, each of them will have a potential drop of 0.1 v., which can be added to that of any section of the wire, as additional weights to a steelyard. This is the basis of the first accurate form of potentiometer devised by J. A. Fleming in 1885 and practically developed by R. E. Crompton.

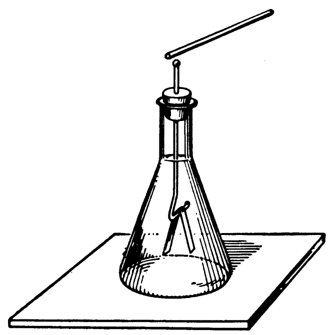

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FIG. 34.—GOLD-LEAF ELECTROSCOPE

Electrostatic Instruments.—One of the first electrical phenomena noted by man, well known to the ancient Greeks, was the attraction of light materials, such as pith balls or straw, by amber which had been electrified by rubbing. William Gilbert (1544–1603) devised the first electroscope which consisted simply of a light pivoted metallic needle, either end of which was attracted on the approach of an electrified body. The next step was to utilize the repulsion of two similarly electrified bodies. For this purpose Benjamin Franklin employed two linen threads hanging close together, and Charles François du Fay, John Canton, William Henley and Tiberius Cavallo built double straw or pith ball electroscopes.

The Cavallo electroscope (*c.* 1770) was the prototype of the modern repulsion electroscopes, having a glass bell jar with a metal stem sealed into its neck; at the bottom of the stem two pith balls were suspended by fine silver wires and two metal strips were cemented on the inner surface of the bell jar and connected to ground. In 1787, Abraham Bennet substituted gold leaves for the pith balls, forming the ordinary electroscope inside of a glass jar (fig. 34).

After the advent of current electricity, electroscopes were little used except for teaching purposes in connection with electrostatics.

However, the discovery of radioactive materials and their power of discharging a charged body by ionization led Pierre and Marie Curie to employ the rate of discharge of an electroscope as the best means of detecting the intensity of radioactive bodies. Their electroscope consisted of a small brass case carrying a block of sulphur at its top from which a metal strip was suspended carrying a gold leaf. A charged condenser was connected to the gold leaf assembly and a knob was connected to it protruding through one side of the case. After charging the condenser until the gold leaf diverged from the suspended strip, the leaf should maintain its position for some time with satisfactory insulation. On inserting a small amount of radioactive material between the plates of the condenser, however, the ionization of the air between the plates would cause the charge to leak away. The rate of fall of the gold leaf would then be a measure of the radioactivity of the material.

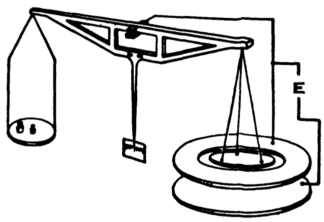

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FIG. 35.—ATTRACTED DISK ELECTROMETER

The advent of more modern measuring devices for radioactivity such as the Geiger-Müller counter with its associated vacuum tube circuitry, largely eliminated the use of the electroscope for such measurements except in the case where an extremely simple device is required.

The electrometer is a more refined type of electroscope. The first instrument of this sort was built on the attraction disk principle which seems to have been originated in 1746 by Daniel Gralath of Danzig. Probably the earliest practical forms were those of A. Volta and Sir William Snow-Harris, in which a flat horizontal disk was suspended from the arm of a balance just over a similar fixed insulated plate. When the latter was electrified or when a potential was established between the fixed and moving plates, the suspended plate was attracted downward, and balance could be restored by adding weights on a scale pan at the opposite end of the balance arm. Fig. 35 shows one form of this electrometer in which a guard ring is placed around the attracted disk and connected to it to prevent any nonuniformity in the electric lines of force. Snow-Harris found that the weight required to restore balance was proportional to the square of the charge or voltage between the disks. This arrangement permits weighing a potential in a manner similar to that used in the current balance previously described. The forces are so low, however, that high accuracy becomes difficult, and the instrument is rarely used as a primary measure of potential.

The vacuum tube voltmeter practically replaced electrostatic indicating instruments because it is so much more rapid in action, can be used to indicate much lower voltages and is generally more flexible.

Vacuum Tube Equipment.—The making of electrical measurements was broadened enormously with the introduction of vacuum tubes. As amplifiers, they can be placed between the measuring element and the source and will amplify the source potential so that, without drawing appreciable energy from the source, ample energy is available for the measuring system. The latter may be of conventional form or even a direct writing recorder needing a watt or two to function properly. Vacuum tube voltmeters are in this category, having input impedances in the region of millions of ohms, and still indicating on a conventional permanent-magnet moving-coil instrument. Since the vacuum tube also rectifies, a vacuum tube voltmeter can be arranged to measure alternating current, although it usually measures a peak value rather than the root-mean-square or power value. In this instance the arrangement is relatively insensitive to frequency variation, and can be used up to a megacycle. With care in design, reduction of stray capacity and with low loss components, readings up into tens or even hundreds of megacycles per second are possible.

Large numbers of special measuring sets are used at radio frequencies.

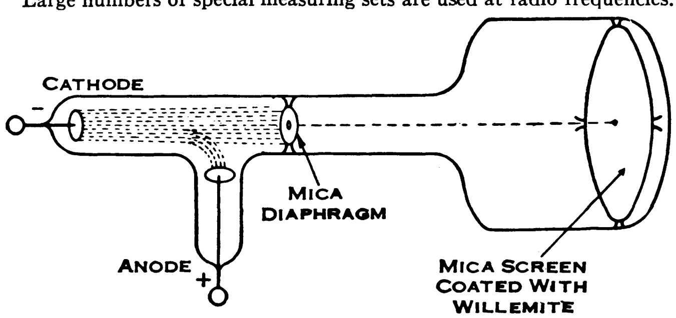

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FIG. 36.—ORIGINAL BRAUN TUBE

Bridges of various types are available for measuring resistance, capacity and inductance. Measuring sets are available for wave-length or frequency measurement, for finding the harmonic content of a wave, for determining the percentage modulation of one wave by another of lower frequency as required in broadcasting; and for analysis of the reactance-resistance ratio of an inductor or capacitor at any frequency to determine its quality factor or "Q." Most such equipment falls back on the basic measuring instruments previously discussed for the actual measurement, although headphones are sometimes used to determine a null point for balance measurements at audio frequencies.

Oscilloscopes.—The classical oscilloscope for power frequencies consisted of a simple permanent-magnet moving-coil system on which was mounted a tiny mirror. A beam of light was reflected by the mirror onto a screen with a rotating mirror interposed at right angles to give a time base. Such a combination was also used as an oscillograph with a rotating film on a drum replacing the rotating mirror for permanent records. In this general arrangement the moving coil was reduced to a single loop of wire, tautly stretched in a strong magnetic field. The mirror was cemented to the center of the loop. Using fine bronze wire under a tension of half its ultimate strength, the resulting natural frequency of the system was raised to several hundred cycles per second. Power frequency phenomena at 60 cycles per second was then presented with good accuracy. Oscillograph records taken with apparatus of this type have been used to analyze the effect of short circuits and other faults in long-distance high-voltage transmission lines. From the records of instantaneous voltage and current during such faults, lightning arresters and other protective equipment have been designed and installed, reducing line outages to a marked degree.

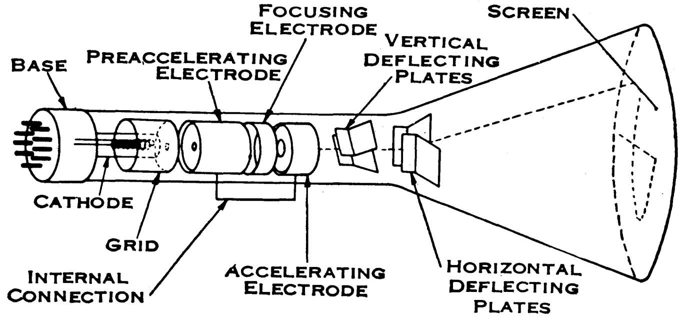

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FIG. 37.—SCHEMATIC ARRANGEMENT OF A MODERN CATHODE-RAY TUBE

The cathode-ray oscilloscope largely replaced the moving coil type after about 1930. Sir William Crookes investigated the phenomena known as cathode rays, which are rays produced in an evacuated glass envelope with a high voltage electric current passed between sealed-in electrodes; in 1879 he concluded that cathode rays were actually a beam of moving particles. Sir Joseph John Thomson in 1897 measured the velocity of these negative particles and found the ratio of the charge to the mass of the particles, which is one of the fundamental constants of nature. The tube with which he made this measurement was further improved by Karl Ferdinand Braun, also in 1897, and his tube is shown in fig. 36.

When a high potential is connected between the cathode and the anode of the figure with polarity shown, a stream of electrons is produced at the cathode which is projected perpendicularly into the evacuated space. The anode is at one side and does not interfere with this stream of charged particles. They impinge on the diaphragm, and a small stream limited by the aperture progresses down the axis of the tube until it strikes the fluorescent screen, producing a spot of light. This screen is of a material such as willemite, (zinc sulphide), held in place by a thin lacquer. Since the stream of negatively charged electrons is effectively an electric current, it is acted upon both by electrostatic or magnetic fields. Such fields can then be applied to the stream, from internal or external electrodes or magnets, and the beam and spot of light will move according to the kind and magnitude of those fields.

The modern refinement of the Braun tube is in the replacement of the cold cathode with a more modern electron source, usually a hot cathode of the coated type as in a conventional vacuum tube. Surrounding the cathode are a series of electrodes to which are applied graded potentials for acceleration and focusing of the electron stream, and a baffle containing a fine aperture for allowing only a narrow beam of electrons to emerge. The combination of electrodes and high potentials results in a very narrow beam which may, in fact, be so highly concentrated where it impinges on the screen that the energy concentration will cause the fluorescent material to be destroyed by heat. This fact in turn has led to the development of new phosphors which are more resistant to this electron bombardment and which give more light than the original materials. Further, for different purposes materials are used having various decay times, that is, the trace may be retained for a period of several seconds or even minutes or may decay in a small fraction of a second. While a willemite screen gives a green light, phosphors fluorescing in all colors have been developed including the brilliant white used in similar tubes for television. Because of its high efficiency, however, a modified willemite screen giving a green or blue trace is usually used in a laboratory oscilloscope. Indeed, the investigation of phosphors and the development of the many possible varieties in use today has been one of the larger projects in the over-all development of the cathode-ray oscilloscope.

The sketch shows a modern cathode-ray or oscilloscope tube (fig. 37) with the several elements customarily found in a tube arranged for electrostatic deflection. The cathode, it will be noted, is heated by a suitable internal spiral filament. The face of this cathode is coated with the usual layer of high emission material much as the cathode in a vacuum tube. Immediately surrounding the cathode is a grid cup with a small aperture in its centre by which the electron stream can be controlled in magnitude through varying the potential of the grid.

The electron stream next passes through a preaccelerating electrode maintained at a high potential to accelerate the stream. A focusing electrode is next in the path connected to a lower potential and causing the stream to become concentrated into a beam. A final accelerating electrode is next in line to further increase the velocity. The beam then passes through a pair of horizontally disposed plates, whose variation in potential with respect to the cathode will cause the beam to rise and fall. Similarly a pair of plates vertically disposed cause horizontal deflection so that with these two pairs of plates the stream can be caused to move in rectangular co-ordinates by varying the respective potentials.

For clarity the connections to these electrodes are not shown; in the complete structure they are supported on rods which carry connections back to the insulating base where the several connections are made to the pin terminals.

The sketch shows probably the simplest version of the cathode-ray oscilloscope tube. Many types of more complicated structures have been developed including additional electrodes for special purposes including multiple arrangements whereby several electron guns are disposed within the same tube so that in these more complicated arrangements several traces may simultaneously be placed on the same screen. Other versions dispense with the electrostatic deflecting plates; deflection is then obtained from external magnetic fields produced by coils suitably disposed and carrying currents to be analyzed.

A typical oscilloscope as used in the electrical laboratory is shown (fig. 38). Within the case is a power supply arranged for connection to the A.C. mains and which develops the several D.C. voltages required. Additionally, two vacuum-tube amplifiers are made available with their own power supplies to the end that a 1-in. deflection of the beam on the face of the tube may be obtained with an input of as little as 0.7.

Since in most instances it is desirable to obtain a picture of the variation of a potential with time, the oscilloscope assembly also contains a sweep circuit which generates a saw-tooth voltage which can be applied to the horizontal deflection plates, effectively causing the beam to sweep horizontally from left to right at any selected rate up to 30,000 cycles per second in the type shown. The unknown voltage may then be applied to the vertical deflecting plates through the associated amplifier and a picture of the variation of the voltage with time be obtained.

As a typical example a simple 60-cycle voltage applied to the oscilloscope and swept across the scale at 20 cycles, thus presenting 3 complete cycles of the wave is shown in fig. 39. A transparent screen with linear co-ordinates is superimposed on the picture in this instance to enable quantitative reading of the results whereby peak values can be obtained; actually it is necessary to calibrate the deflection of the beam and the position of the trace but this is readily accomplished by applying known potentials and comparing the resulting trace with the trace of the unknown potential.

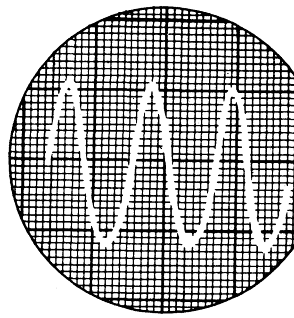

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FIG. 39.—OSCILLOGRAM OF A 60-CYCLE WAVE

In general the oscilloscope has expanded measuring technique through its ability to place on a screen a visual picture of the variation of electrical voltages with time. And through the use of translating elements which give an electrical voltage in terms of other phenomena, visual renderings of the tone of a violin, the flutter of an aeroplane wing, the abnormal beat of the human heart may be obtained, all in addition to the presentation of the many types of pure electrical phenomena around us.

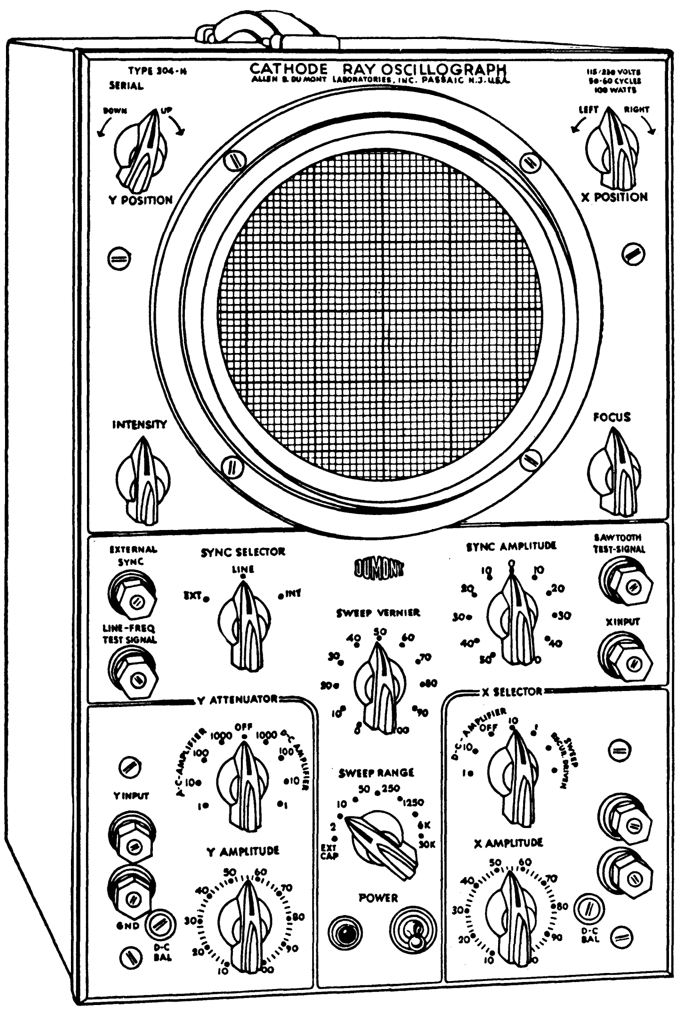

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FIG. 38.—CATHODE-RAY OSCILLOGRAPH

BIBLIOGRAPHY.—The books listed below, while merely a portion of those available, represent a reasonable small library on the subject. To the student of electrical measuring instruments the more important disclosures are made in technical papers presented before the national technical societies such as the American Institute of Electrical Engineers, the Institute of Radio Engineers (U.S.A.) and the Institution of Electrical Engineers (Great Britain), and contained in their monthly publications available in most libraries.

Mention should also be made of specifications on electrical measuring instruments, usually available from the national standards organizations of various countries. In the United States reference is made to the "American Standard for Electrical Indicating Instruments," C 39.1-1955, available from the American Standards Association, New York city; standards on instrument transformers, watt-hour meters, recording instruments, etc., are also available or in process as of 1955. In England analogous standards are available from the British Standards Institution, London.

Scientific studies of electrical measuring apparatus are made from time to time by the National Bureau of Standards in Washington, D.C., and reported in the *Journal of Research* of that bureau. Much of the same applies to papers on the part of the National Physical Laboratory at Teddington, Middlesex. Reprints of such papers, usually available from those institutions, are classics in their special fields.

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