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S. W. STRATTON, Director

No. 20

ELECTRICAL MEASURING INSTRUMENTS

[2d Edition]
Issued May 28, 1915

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This Circular supersedes the first edition of Circular No. 20, issued October 1, 1909. Sections 2 to 5, inclusive, in the first edition dealt with regulations, instructions, and fees for electrical tests made by this Bureau. These matters are now the subject of a separate publication, namely, Circular No. 6 of the Bureau of Standards.

S. W. Stratton,
Director.

ELECTRICAL MEASURING INSTRUMENTS

CONTENTS

I. INTRODUCTION

The object of this circular is to present briefly the fundamental principles underlying the construction and operation of commercial electrical measuring instruments, together with such information concerning the advantages and limitations of the various types of instruments as will assist the user in the determination of the general type best suited to a given purpose.

The question of sources of error has been treated in some detail, with a threefold purpose: First, to suggest how some errors may be avoided; second, how corrections may be made for known sources of error; and third, to furnish suggestions which will assist those who have to specify instrument performance or to select instruments.

In view of the increasing number of central stations, public-service commissions, and colleges which are equipping testing rooms for the maintenance of electrical standards and the precision checking of electrical instruments, some space has been given to a discussion of the apparatus which seems best suited for use in such laboratories.

While it is not the purpose of this circular to treat in detail the design of electrical instruments, some points of design of more than ordinary interest and importance to the user are briefly discussed.

Electrical measuring instruments may be classified as indicating, integrating, and recording. Indicating instruments either give directly the value of an electrical quantity at the time of observation, or may be so balanced or manipulated as to give such a value. Integrating electrical instruments take account of time, as well as of the electrical quantity. For example, a watthour[1] meter gives a reading proportional to the product of the average power and the time, or, in other words, to the energy that has passed through it. Recording instruments, properly so called, draw a curve or other graphic record showing the variation of an electrical quantity with time.

Electrical instruments may be otherwise classified, according to construction and method of use, into switchboard, portable, and semiportable or laboratory types. They may also be divided into the three following classes, namely, those capable of service on direct current only, those which may be used on direct current and on alternating current, and those which operate on alternating current only.

While the word "instrument" is a general term which may properly include indicating, integrating and recording devices, there is a tendency[2] to restrict its use to indicating devices and to recording (graphic or curve drawing) devices. Integrating devices are then denoted by the word "meter."

II. INDICATING ELECTRICAL INSTRUMENTS

1. INSTRUMENTS OPERATING ON DIRECT CURRENT ONLY

(*a*) Principle of Operation.—Many types of instruments have been devised for the measurement of direct current and voltage, but the pivoted moving-coil, permanent-magnet, direct-reading instrument has found the widest application. It consists of a light coil free to turn in the field of a fixed permanent magnet. The latter is usually provided with soft-iron pole pieces and a cylindrical iron core in order to give a uniform radial field in which the coil moves. The motion of the coil is opposed by a counter force, usually that of two flat spiral springs which also

[1] The watthour meter has been variously designated by the terms "recording wattmeter," "integrating wattmeter," or "wattmeter." These terms are all open to objection, the last named being especially so. In recent years the use of the term "watthour meter" has been standardized.

[2] Haraden, Gen. Elec. Rev., 12, p. 474; 1909.

serve to carry the current to and from the coil. Since the deflecting torque is proportional to the product of the (constant) field strength and the current in the coil, and the counter torque of the springs is approximately proportional to the angle through which the coil has turned from the initial position, it follows that the deflection will be approximately proportional to the current strength; that is, the scale will be uniform. The scale may be marked to read the values of current strength corresponding to various deflections. The coil is wound on a thin metal frame, usually of aluminum, and the eddy currents set up in this frame by its motion in the magnetic field tend to bring it to rest. By proper design the motion of the moving system may be made aperiodic (dead beat). It is to be noted that this instrument always measures the strength of current in its moving coil; that is, it acts as an ammeter. To apply it to other measurements, some known relation must exist between the current in the coil and the quantity to be determined.

(*b*) Direct-Current Ammeters.—Since the spiral springs will carry only a small current (a fraction of an ampere), the use of the simple instrument just described is limited to the measurement of relatively small currents. When larger currents are to be measured, use is made of a shunt, that is, a low resistance connected in parallel with the instrument.

Self-contained ammeters have the shunt mounted within the instrument and are used only for moderate currents. For larger currents a separate shunt may be inserted in the circuit with no extra expense for heavy conductors; small conductors then connect the shunt and the instrument. The above statements apply both to switchboard and to portable ammeters. As the latter are usually required to give more accurate results than the former, the use of a separate shunt is, in this case, of further advantage, in that the heat developed in the shunt does not change the temperature of the instrument, and the magnetic field, due to the main current, may be prevented from altering the magnetic field in which the coil moves.

(*c*) Direct-Current Voltmeters.—Instead of connecting a shunt across the terminals of the instrument, a relatively high resistance may be connected in series with the moving coil, this resistance being adjusted until a certain voltage, say 150 volts, produces the current necessary for full-scale deflection. The instrument thus becomes a voltmeter, and its scale may be marked to read the voltage at its terminals. A multiple-range voltmeter has one or more taps brought out from intermediate points on the series resistance. When voltages higher than the maximum must

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be measured, external resistance boxes, called multipliers, are used. Thus, a voltmeter for 0 to 150 volts, whose resistance is 15 000 ohms, will require an additional 15 000 ohms in the multiplier in order to measure up to 300 volts.

(*d*) Some Details of Design.—In principle, the ammeter and voltmeter of this type differ only in method of use. In practice, however, some differences of design are necessary. Since a voltmeter should draw as little current as possible from the circuit to which it is connected, the moving coil of the voltmeter is wound with a relatively large number of turns of fine wire, so that the ampere-turns required for full-scale deflection may be had with a small current and the resistance of the voltmeter may be large. The moving-coil ammeter must give full-scale deflection with a relatively small voltage [3] at its terminals. This requirement is met by winding the moving coil with relatively coarse wire, or with several wires in parallel, so that the necessary ampere-turns may be had when a relatively low voltage is applied to the coil. To assist in reducing this voltage, it is also customary to use a smaller number of ampere-turns than in voltmeters, thereby decreasing the torque and making it necessary to use springs weaker than those used in voltmeters of similar design.

Since the resistance of a millivoltmeter is low, the resistance of the springs may be appreciable compared with the coil resistance. It is, therefore, usual to make the springs of special alloy having high conductivity. The elastic properties of some of these special alloys are inferior to those of the phosphor bronze commonly used for voltmeter springs. The springs used in millivoltmeters are usually of the minimum strength consistent with good performance as regards frictional errors.

In order to reduce the temperature error of shunted ammeters it is necessary to wind the moving coil to give full-scale deflection with a voltage applied to its terminals, which is only a fraction [4] of the full-load drop on the shunt.

2. INSTRUMENTS OPERATING ON DIRECT AND ON ALTERNATING CURRENTS

Instruments for use on direct and on alternating currents may be divided into four types, namely, moving-iron, electrodynamometer, electrothermal, and electrostatic.

[3] The power lost in an ammeter shunt is equal to EI, where E is the voltage at its terminals and I is the current to be measured. To keep down this loss, as well as the weight, size, and cost of the shunt, E must be kept low.

[4] For a further discussion of this matter, see p. 31.

(*a*) Moving-Iron Instruments, General.—Of these four types, the moving-iron [5] type has found the widest commercial application. Ammeters of this type may be divided into two main classes: First, movable-core (plunger) instruments, in which an iron core is drawn into a coil when the current flows through the coil; second, those instruments in which a movable iron piece and one or more fixed iron pieces are located within the coil, the usual construction being that in which the movable iron is repelled by the fixed iron. Early instruments of the moving-iron type were constructed with heavy iron cores (sometimes solid rods; in other cases heavy bundles of wires or strips) the length of which was comparable with the length of the solenoid into which they were drawn. The theory of such instruments is now better understood, and it is now known that these instruments were unsuitable for accurate measurements. The quantity of iron should be small, and the length of the path of the magnetic lines in the iron should be small compared with the length of the path in air.

The iron should have low hysteresis, high permeability, and high specific resistance. These qualities are possessed in marked degree by the silicon-steel sheets now used for the best transformers. In addition, the design should be such that the iron is not used near magnetic saturation, as a moving-iron ammeter with nearly saturated core tends to give readings proportional to the average value of an alternating current instead of the effective (square root of mean square) value which is almost always desired.

In the so-called inclined-coil instrument several pieces of sheet iron are carried on a pivoted shaft within the coil. When current flows through the coil, the plates turn so as to be more nearly parallel to the axis of the coil. This is virtually a variation of the movable-core (plunger) instrument just described.

(*b*) Moving-Iron Ammeters.—Properly designed and well made moving-iron ammeters, such as are now available, are only slightly affected by large changes of frequency, wave form,[6] and temperature. On direct current the readings depend slightly on the direction of the current through the

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[5] Often designated by the terms "soft-iron" and "electromagnetic." The latter term is not used in the same sense by all writers; for example, one writer classes permanent-magnet moving-coil and also induction instruments under this head. The term "soft-iron" is also somewhat ambiguous; for example, an induction instrument contains a large amount of soft iron.

[6] An article by Benischke in the Elektrotechnische Zeitschrift (vol. 22, p. 301, 1901) has been frequently quoted as showing that moving-iron ammeters and voltmeters, though practically independent of frequency, are seriously affected by such departures from the sine wave form as are met in practice. While his results were doubtless correct for the old and badly designed instruments he tested, the best modern instruments show only a few tenths of 1 per cent change for as large variations in wave form as would be found in good practice.

coil and upon the value and direction of the current in the preceding readings. The error due to this cause may, in a good instrument, be under 1 per cent of the full-scale reading.

(*c*) Moving-Iron Voltmeters.—These voltmeters have in general a higher time constant (ratio of inductance to resistance) than voltmeters of the same range made on the electrodynamometer principle. They are thus more affected by change of frequency, but in general this effect is small over the commercial range of frequencies used for lighting and power. In special cases, such as the use on 500 cycles of a moving-iron voltmeter calibrated at 60 cycles, the correction can be calculated if the inductance and resistance of the voltmeter, as well as the frequency, are known. If a well-made moving-iron voltmeter is correct at some definite frequency (say, 60 cycles), the ordinary variations of frequency of commercial circuits will have no appreciable effect on the reading.

(*d*) Electrodynamometer Instruments, General.—This type of instrument is of great importance, especially from the laboratory point of view. The operation of these instruments depends upon the force exerted by one current-carrying circuit upon another, or by a portion of one circuit upon another portion of the same circuit. Instruments of this type usually contain one or more fixed coils within which is arranged a moving coil or system of coils, with provision for passing current through them. If the two sets of coils are connected in series and a current is passed through them, the torque exerted upon the moving system, for a given relative position of the coil systems, is proportional to the square of the current strength and is not dependent upon the direction of the current. When provided with a spring or other suitable counter-force such an apparatus constitutes an ammeter which is equally correct on direct current and on alternating or pulsating current of any frequency [7] or wave form.

The importance of this type of instrument is due partly to its inherent accuracy on these various kinds of current and partly to its adaptability, as it may be made up as an ammeter, voltmeter, wattmeter, power-factor meter, or phase meter. Several other special applications of the principle are also used.

[7] This assumes that no change takes place in the distribution of the current over the cross section of the wire. With thick wires and high frequencies the current will be unequally distributed over the cross section, and the reading of the instrument for a given current will vary somewhat with the frequency. It is also assumed that there are no masses of metal near the coils, as the eddy currents induced in such masses would produce magnetic fields, which would combine with the field due to the fixed coils and would thus introduce errors in the indications of the instrument. With fine wire coils used at high frequencies the displacement (capacity) currents between layers also introduce an error.

Since the fundamental electrical standards involve direct current, and a large number of electrical instruments which are used on alternating current can not be tested with direct current, there is a need for "transfer instruments" which can be checked on direct current and which have errors that are negligible, or else small and determinable, on alternating current. The electrodynamometer type is especially valuable for this purpose, and transfer instruments of this type are used at the Bureau of Standards. The electrostatic type is also used to some extent abroad. In special cases this type has some advantages, but for commercial lighting and power frequencies the electrodynamometer instrument has the advantage of more rapid and convenient working and of being less affected by vibration.

(*e*) Electrodynamometer Ammeters.—In an electrodynamometer ammeter, having the fixed coil and the moving coil in series, and using spiral springs to carry the current into and out of the moving coil, the carrying capacity of the springs limits the current to a small value, usually much less than 1 ampere. In the Siemens electrodynamometer, the earliest instrument of this type, the current is taken into and out of the moving coil by mercury cups, into which dip the ends of the moving coil. In the Kelvin balance, the axis about which the moving coil turns is horizontal, and ligaments of fine wire are used as supports and conductors. Both of these instruments have done good service in the laboratory, but they are slow and inconvenient to use and require that the current to be measured be quite steady. The readings of Kelvin balances change appreciably due to heating at or near rated load, and the larger sizes have frequency errors which are greater the larger the ampere capacity.

A modification of the Kelvin balance is made in this country by pivoting the moving system and using the counter-torque of a large spiral spring instead of gravity.

By connecting the fixed coil and the pivoted moving coil in parallel the electrodynamometer ammeter [8] may be made portable and easy to operate. The moving coil carries only a small fraction of the current. It is essential that the percentage of the current which passes through the moving coil should be constant (within negligible limits) on all the frequencies for which the instrument is to be used and at all working temperatures. This requires that the time constants of the two coils should be

[8] Such instruments are made by several foreign makers; at this writing, April, 1915, electrodynamometer ammeters of a new design are being put on the market by an American maker.

equal and their temperature coefficients also equal. Both these objects are attained more or less completely by adding noninductive resistance of low temperature coefficient to each coil, thus reducing both the time constant and the temperature coefficient of each circuit. If these temperature coefficients are made equal, the division of the current between the two coils will depend only upon any temperature difference that may exist between them. A well-made ammeter of this type may be checked on direct current (using the mean of reversed readings) and used as a transfer instrument in the checking of alternating-current ammeters. Such transfer instruments may be much more rapidly operated than Kelvin balances; they are less expensive, and the accuracy of the results will probably be at least equally good.

(*f*) Electrodynamometer Voltmeters.—This voltmeter has both its fixed coil and its moving coil wound with moderately fine wire. These coils are connected in series with each other and with a noninductive resistance of low temperature coefficient. This resistance reduces the time constant to a small value, so that well-made instruments of this type, for the usual commercial voltages, may be calibrated on direct current and used on alternating-current circuits with a practically negligible error. Good voltmeters of this type are thus suitable transfer instruments for use in checking working voltmeters.

(*g*) Electrodynamometer Wattmeters.—The electrodynamometer wattmeter is an instrument of great commercial importance. It is used to measure power in alternating-current circuits, and is the most suitable instrument [9] for testing alternating-current watthour meters.

The wattmeter has a fixed coil wound with relatively coarse wire and brought out to two terminals by means of which it may be connected in series with the portion of the circuit in which the power consumption is to be measured. The magnetic field set up by the fixed coil will be proportional to the current strength. The moving coil is of fine wire and has a large noninductive resistance in series with it; this constitutes the voltage circuit, and is connected across the line. The torque exerted upon the moving coil at any instant is proportional to the product of the currents in the two coils, and the instrument measures the power in the circuit. While the power taken by an noninductive load, such as incandescent lamps, may be found even with alternating current by multiplying the current by the voltage, it

[9] This does not refer to the testing of small alternating-current service meters in position, for which the use of a good portable watthour meter (so-called rotating standard) is probably the most convenient method. Portable watthour meters, however, should be checked very frequently, and for this purpose the wattmeter is useful.

becomes necessary to use a wattmeter when alternating-current power is to be measured in circuits where the power factor is below unity and is not known.

Before the advent of well-designed and accurate portable wattmeters, use was made of the three-voltmeter method and the three-ammeter method for measuring power. Although still presented in some textbooks, and of some value for teaching principles, these latter methods are not of commercial importance to-day. In some exceptional cases of laboratory work they may prove useful.

(*h*) Electrothermal Instruments, General.—Instruments of this type depend upon the heating of a conductor by the passage of a current through it. In most commercial instruments on this principle the expansion of a heated wire is used to operate a pointer.

(*i*) Hot-Wire Voltmeters.—In one of the earliest of hot-wire voltmeters (the Cardew) a fine platinum-silver wire was used, of such a length that it could be connected across a 110-volt circuit without any series resistance. The necessity of accommodating such a length of wire caused the instrument to be bulky; it has now almost disappeared from use. The more modern instruments of the hot-wire type have a working wire 15 or 20 cm (6 or 8 inches) in length. This wire is of small diameter in a voltmeter and has a considerable amount of added resistance in series.

(*j*) Hot-Wire Ammeters.—In the hot-wire ammeter the working wire is of larger diameter; in all but low-range unshunted ammeters the wire is electrically divided by silver tap-off strips into several sections which are connected in parallel, to reduce the required drop in the shunt. Above say 5 amperes, shunts are used, except for high-frequency work.

(*k*) High-Frequency Ammeters.[10]—For very high frequencies, such as are used in radiotelegraphy, shunted hot-wire ammeters are by no means reliable, as for such frequencies the effective resistance of the shunt is much greater than for direct (or low-frequency) current, and the time constants of shunt and instrument, which ought to be equal for independence of frequency, may be very different. Ammeters which are free from this objection have been placed on the market in the last few years. In the hot-strip ammeter [11] a number of thin alloy strips are arranged in a symmetrical manner so as to avoid change of current distribution with change of frequency. The expansion of one of these strips is used to operate the pointer.

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[10] See paper on this subject by Dellinger, Bulletin of the Bureau of Standards, **10**, p. 91, 1913; Scientific Paper No. 206.

[11] Hartmann-Kempf, Elektrotechnische Zs., **32**, p. 1134, 1911; also Jahrbuch der drahtlosen Telegraphie, **5**, p. 517; 1912.

(*l*) Hot-Wire Wattmeters.—A hot-wire wattmeter, made to some extent abroad, is used to measure the power taken by a load, either inductive or noninductive. This wattmeter has two working wires joined in series and connected in parallel with a current shunt which is inserted in one line of the two-wire circuit in which the power is to be measured. The point of junction of the two hot wires is connected through a series resistance to the other line wire. The difference of expansion of the two wires is proportional to the power in the circuit, and actuates the pointer.

In a modification of this hot-wire wattmeter a switch is provided by means of which the connections may be altered so as to give in succession the watts, volts, and amperes of the load.

The hot-wire "wattmeter" used in radiotelegraphy is an unshunted hot-wire ammeter whose scale is not marked in amperes, but in terms of the power absorbed by the instrument itself. A more logical name for this instrument is desirable; the expression "current-square meter" has been suggested.

(*m*) Thermocouple Ammeters.—Another class of electrothermal instruments depends upon thermal electromotive forces. As an illustration may be mentioned the Duddell thermoammeter, in which the heat produced by the passage of the current through a suitable heating coil acts upon a thermojunction in a loop of wire which constitutes the moving coil of a permanent-magnet direct-current instrument. The use of thermojunctions arranged to be heated by the current to be measured, the thermocurrent operating a galvanometer, is a method which is employed in various forms in laboratory work.

(*n*) Advantages and Defects of Hot-Wire Instruments.—The hot-wire instrument is not used in this country to any extent in lighting and power plants. Its defects are relatively large consumption of power, uncertainty of zero, errors due to change of surrounding temperature, and to heating when left in circuit. As the working wire must be run at a fairly high temperature to give proper sensitivity, it is easily damaged by sudden overloads, which would do little or no damage to other forms except the possible bending of a pointer. The good features of the hot-wire instrument, which cause it to be still used for certain classes of work, are its relative independence of frequency, wave form, and stray magnetic fields; the fact that it may be checked with direct current, and that shunts may be used with the ammeter for alternating current of the usual lighting and power frequencies. For use in the laboratory with unusual frequencies or wave forms, and where facilities are at hand for checking with direct current, the hot-wire instrument has some marked advantages.

(*o*) USE OF PLATINUM-IRIDIUM IN HOT-WIRE INSTRUMENTS.[12]—A recent improvement in hot-wire instruments consists in the substitution of platinum-iridium alloy for the platinum-silver which had previously been generally used. The actual expansion of a given length of platinum-iridium wire per degree rise of temperature is less than that of a platinum-silver wire of equal length. However, the platinum-iridium wire may be run at a much higher temperature, giving a greater expansion of the wire as used. The platinum-iridium wire is also much stronger, and can be used in finer sizes, thus reducing the current required by voltmeters, and making them much less sluggish in following changes of voltage.

(*p*) ELECTROSTATIC INSTRUMENTS.—Instruments of the electrostatic type depend upon the attraction of oppositely charged bodies and the repulsion of similarly charged ones. As these forces are relatively small, such instruments can not well be made as ammeters, and in fact it is difficult to construct satisfactory voltmeters on this principle for the ordinary 110-volt range. The great advantage of this type of voltmeter is that it takes no current, when used on direct-current circuits, and an extremely small current when used on alternating-current circuits. It is not affected by frequency changes, wave form, or stray magnetic field. It has the defect of small ratio of torque to weight of moving parts, so that frictional errors are hard to avoid. For this reason, low-range instruments of this type are usually made with a suspension strip or wire in place of pivot and jewel bearings.

While these instruments are used abroad to some extent, in this country they find little use except in the laboratory. The electrostatic ground detector operates on the same general principle as the electrostatic voltmeter. Wattmeters may be constructed on the electrostatic principle,[13] but they are too delicate for any but laboratory use. Such wattmeters are of value in some special applications; for example, in determining the power losses in insulating materials under electrical stress.

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[12] Hartmann-Kempf, Elektrotechnische Zs., **31**, p. 269; 1910.

[13] Electrostatic Method for the Measurement of Power, by Patterson, Rayner, and Kinnes, J. Inst. Elec. Eng., **51**, p. 294; 1913.

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3. INSTRUMENTS OPERATING ON ALTERNATING CURRENT ONLY.

(*a*) Induction Instruments.—These instruments have a fixed core of laminated iron wound with one or more coils of wire, and a moving element, usually a metal disk or cup, which is pivoted to move in the air gap of the iron core. They are called induction instruments because they depend upon the interaction of the induced currents in the cup or disk with the inducing field.

The general principle of induction instruments may be understood by considering the induction wattmeter or the induction watthour meter. An iron core is wound with a large number of turns of fine wire, and to this winding the voltage of the circuit is applied. The metal disk or cup forming the moving element passes through an air gap in the core. Eddy currents are set up in the moving element by the flux from this voltage coil. The load current passes through a coarse winding on another arm of the iron core or on a separate core. The eddy currents produced in the disk by the voltage flux react with the magnetic field of the current coil producing a torque which tends to drive the disk continuously in one direction.

In an induction indicating instrument this rotation may be opposed by gravity or by a spiral spring. The latter is usually employed, as it permits a rotation of about 300°, thus giving a great length of scale for a given diameter of the instrument.

In an early form of induction ammeter the fixed laminated electromagnet is wound with a single coil. A single turn of copper strip, called a "shading coil," surrounds about half of the polar projection of the iron core. The induced currents in this strip retard the phase of the magnetic flux in the part of the core inclosed by the strip, and the resultant flux in the core as a whole shifts across the pole face. This shifting flux induces currents in the disk, or cup, and the action between the shifting magnetic field and the induced currents tends to set the cup or disk in rotation.

A simple induction ammeter made as just outlined would be very unsatisfactory, as its readings would vary greatly with change of frequency and of temperature. Variation with frequency may be compensated for to some extent by connecting a noninductive resistance in parallel with the magnetizing coil. As the frequency increases, a larger proportion of the current will flow through the noninductive resistance, thus preventing the increase of reading which would otherwise result. By making the noninductive resistance of copper, a certain amount of compensation for temperature is secured. An increase of temperature increases the resistance of the noninductive branch, thus causing more current to flow through the magnetizing coil, and tending to offset the effect of the increased resistance of the moving element, which acts to decrease the torque.

Induction instruments of the rotary-field class are similar to induction motors, except that the moving element contains no magnetic material. The moving element is usually in the form of a cup, and an iron core is ordinarily supported within the cup. The laminated iron stator contains two sets of windings, the currents in them differing in phase. This phase difference may be produced in the ammeter by making the time constants of the two circuits different, as by adding noninductive resistance to one circuit; the circuits are then connected in parallel. In the "series-transformer" induction ammeter,[14] which is probably the most advanced form of induction ammeter, the current to be measured flows through a single circuit wound on the two cores of a laminated electromagnet. This winding corresponds to the primary winding of a current transformer. A secondary winding under the main winding has a current induced in it which will be approximately proportional to the main current, over a considerable range of frequency and temperature. The electromagnet has polar extensions between which a metal cup is pivoted to turn, and these polar projections are wound with coils through which the secondary current is passed. The phase relations of the primary and secondary currents and the location of the magnetizing coils included in the secondary circuit are such as to give a rotary field in the air gap, thus exerting a torque on the moving element, as in an induction motor. As the temperature increases, the torque would decrease (if the flux remained constant), due to the increase of resistance of the moving element. However, as the secondary winding is of copper, its resistance will also increase, thus causing the flux to increase in the same proportion and maintaining the torque unchanged.

The induction voltmeter is essentially a low-range induction ammeter with a suitable noninductive resistance in series, and with a scale marked to read the voltage at the terminals.

The advantages claimed for the induction instrument for switchboard work where the frequency and wave form do not vary greatly are as fol-

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[14] MacGahan, Electric J., **4**, p. 113, 1907; Proc. Am. Inst. Elec. Eng., **31**, p. 1203, 1912.

lows: Simplicity and ruggedness of the moving element, high ratio of torque to weight of moving element, relative independence of stray magnetic fields, and great length of scale for a given area occupied by the instrument. If properly designed to reduce the frequency errors to a negligible value, the induction ammeter is suitable for portable work for the reasons just given. The induction ammeter may be adjusted to read correctly on two frequencies, such as 25 and 60 cycles. The error at frequencies between these values is stated to be less than 1 per cent. The induction wattmeter is limited to a single frequency. The induction voltmeter may be arranged for use on two frequencies, a switch (or its equivalent) being used to alter the impedance of the voltmeter so as to make it read correctly on the frequency in use.

III. INTEGRATING ELECTRICAL INSTRUMENTS (METERS)

1. AMPEREHOUR METERS

Amperehour meters measure the product of the average current in amperes by the time in hours. They are of two general types: First, those depending on electrolysis; second, those of the motor type. The Edison chemical meter, which has gone out of use, contained plates of zinc in a solution of zinc sulphate. A small fraction of the current to be measured passed through this cell and transferred zinc from one plate to another. The loss of weight gave a measure of the amperehours which had passed through the meter. Another chemical meter which is used to some extent depends on the decomposition of water by the passage of the current. A third form, which was developed in England, depends on the electrolysis of a solution containing a salt of mercury. The passage of a current transfers mercury electrolytically from a mercury anode to an iridium cathode, from which the mercury falls into a tube. The height of the column of mercury is shown by a graduated scale alongside the tube. The scale is usually marked in kilowatthours on the assumption of a stated supply voltage.

Amperehour meters of the motor type may be classified as commutator meters and mercury motor meters. Commutator amperehour meters have an armature free from iron arranged to rotate between the poles of a strong permanent magnet. The winding of the armature is such that the meter develops full speed with about 1 to 2 volts at the brushes and with a small armature current. The armature is connected to the terminals of a shunt which carries the greater part of the current to be measured.

Mercury amperehour meters have a chamber within which a copper disk (or, in some designs, a cup) is submerged in mercury and arranged to rotate. The current enters the mercury at one side of the chamber and flows through the disk. A permanent magnet produces a magnetic field through the disk, and the disk is caused to rotate by the interaction of the current in the disk with the magnetic field. Like the other forms just described, this amperehour meter operates only on direct current.

The principal application of the amperehour meter as such is in connection with storage batteries. By arranging the connections to the meter shunt so that the speed of the meter on discharge exceeds the speed on charge (for a given current) by a definite percentage depending on the amperehour efficiency of the battery, the meter will aid in determining the state of charge of the battery.

Abroad, the amperehour meter is largely used as a substitute for the watthour meter in the sale of electric current, especially in England.[15] It is customary to mark the dials to read kilowatthours at some stated voltage. The chief advantages of the amperehour meter for this purpose are its lower first cost and the absence of voltage (potential) circuits which consume energy continually and are liable to burn out or develop open circuits.

2. DIRECT-CURRENT WATTHOUR METERS, THOMSON TYPE

Integrating meters as now used in this country are practically all of the motor type and are watthour meters; that is, they measure electrical energy. They may be classified as direct-current meters and alternating-current meters. The Thomson watthour meter (the so-called "recording wattmeter") is the earliest example of American direct-current motor meter, and most other direct-current watthour meters differ from it only in details of design and construction. This meter contains a small commutator motor free from iron. The line current passes through the fixed field windings, and the armature, which is wound with fine wire, is connected through a series resistance across the line. On the shaft of the motor is a disk of copper or aluminum which rotates between the poles of several permanent magnets. The upper end of the armature shaft has a worm which engages with the first gear wheel of the register. The best meters of this general type, as now made, have much lighter moving elements, higher

[15] For a description of the principal foreign amperehour meters, see Electrical Instruments and Meters in Europe, by H. B. Brooks, issued by the Bureau of Foreign and Domestic Commerce, Washington, D. C.

torque, and smaller losses in the voltage circuit than the original Thomson meter. It is important that the loss in the voltage circuit be small, as the total loss in a large installation is appreciable and is going on as long as the voltage is on the lines. Heating due to losses in the meter is also objectionable because it tends to affect the accuracy of the meter.

3. DIRECT-CURRENT WATTHOUR METERS, MERCURY TYPE

The driving element of this type of meter consists of a copper disk submerged in mercury. The line current enters the mercury chamber, flows diametrically across the disk and out at the other side. A laminated electromagnet, wound with fine wire and connected across the line, provides a magnetic field which passes up through the copper disk and down through it on the other side of the axis of rotation. A ring of laminated iron above the disk is used to reduce the reluctance of the magnetic circuit. The interaction of the current in the disk with the magnetic field causes the disk to rotate. The upper end of the shaft carries an aluminum disk which rotates between the poles of drag magnets and provides the retarding torque.

A three-wire mercury motor meter has recently been developed. It consists of two motor elements, one above the other, with a common shaft. Special arrangements are provided to prevent the escape of mercury from the upper element.

The mercury motor meter has several advantages. It dispenses with the commutator, which is one of the most troublesome features of the usual direct-current meter. It has a very low drop of potential in the current circuit, which adapts it for use with shunts. It is only slightly affected by stray magnetic fields. The weight of the moving element is carried by flotation. It has the disadvantages of small torque and of being limited to ranges of 10 amperes and above.

4. ALTERNATING-CURRENT WATTHOUR METERS

(*a*) Use of Commutator Meters on Alternating-Current Circuits.—The Thomson watthour meter and other meters designed on the same principle for direct-current service may be used on alternating-current circuits with an error which is occasioned partly by the inductance of the armature circuit and partly by eddy currents. This error is smaller, the lower the frequency and the nearer the power factor of the load is to unity. To avoid this error such meters have sometimes been "lagged" by connecting a noninductive resistance in parallel with the current coil of the meter.

(*b*) INDUCTION WATTHOUR METERS.—There is little occasion, however, for the use of commutator meters on alternating currents, as the induction watthour meter is much to be preferred, having no moving wire, no contacts, a much lighter moving system, better ratio of torque to weight, and better performance. The losses in the induction meter are much smaller, and in most designs the effect of stray magnetic fields is much smaller than in the direct-current meter.

The induction watthour meter depends on the same general principle as the induction wattmeter, as briefly described on page 16. The moving element is extremely simple, consisting usually of an aluminum disk mounted on a vertical spindle; the spindle is supported by a jewel bearing, and has a worm which engages with a worm wheel on the register. The disk serves a double purpose—the driving torque is due to the interaction of currents induced in the disk with the magnetic fields inducing them, and the retarding torque is due to eddy currents set up in the disk by one or more permanent magnets between whose jaws the disk revolves. The induction watthour meter must be adjusted to operate at some one definite frequency.

(*c*) EFFECT OF WAVE FORM.—Induction meters are affected to some extent by variations in the wave form in the circuits on which they are used. This was of consequence in the earlier years of alternating-current distribution, when generators were designed for maximum weight efficiency (or other desiderata) with more or less complete ignorance or disregard of the wave form. The present tendency is to design generators to give a reasonably good approximation to a sine wave.

5. PORTABLE WATTHOUR METERS

In order to facilitate the testing of electric meters on the premises of consumers, portable watthour meters have been devised. These are sometimes called "rotating standards"; they are substantially the same in construction as the service meters, but usually have arrangements for varying the current range by having a separate coil for each range, or a stranded coil whose sections may be grouped in various ways, or by a combination of these methods. The style of mounting is such as to adapt them for portable use, and the dials are such as to enable a close reading to be made for very short runs. These meters are constructed on the induction principle for alternating current. This gives a satisfactory instrument for commercial work on a definite frequency. Direct-current meters, on account of the use of commutator and brushes and the much higher drop in the field coils, are not so satisfactory as the former. In either case the portable watthour meter should be considered as a secondary instrument, liable to change in use, and it should be frequently checked by reliable standard instruments.

The annual reports of the Committee on Meters of the National Electric Light Association contain much valuable information on watthour meters. The Electrical Meterman's Handbook, prepared by this committee,[16] contains a large amount of information on American watthour meters as well as the auxiliary apparatus required for testing meters.

IV. RECORDING ELECTRICAL INSTRUMENTS

1. GENERAL DISCUSSION

Recording (also called graphic or curve-drawing) electrical instruments make a graphic record of the varying values of current, voltage, power, or other electrical quantities in the circuit to which they are connected. Almost any of the types of indicating instruments previously referred to may be utilized in the design of a recording instrument, but in general the permanent-magnet moving-coil type is used for direct-current work, and the moving-iron, electrodynamometer, and induction types for alternating-current work. Recording instruments are useful for giving a check on the operation of plants, for determining the power required by motor-driven machinery, determining voltage regulation, and similar purposes. They may be broadly classified as direct-acting and as relay instruments.

2. DIRECT-ACTING RECORDING INSTRUMENTS

A direct-acting recording instrument is essentially an indicating instrument having a pen, pencil, or stylus attached to its pointer to draw a record on a paper chart which is moved under the pointer by clockwork or its equivalent. The friction of the marking device would interfere seriously with the motion of the pointer of an ordinary indicating instrument, and the design of a recording instrument must take this into account. This is usually done by modifying the operating system so as to get a large value of torque. In some recording instruments a large torque is made unnecessary by allowing the moving system to swing freely except at certain regular intervals when a bar is depressed, forcing a stylus against the paper and making a dot. By arranging the apparatus so as to make these dots fre-

[16] Published by the National Electric Light Association, 33 West Thirty-ninth Street, New York, N. Y.

quently, an approximation to a continuous curve is made. This form of instrument may also be regarded as a relay instrument, since a force other than that due to the operating system assists in making the record. Another method which is used for avoiding friction consists in causing the discharge from a spark coil to jump from the end of the pointer through the paper to the drum on which the paper is carried, thus piercing the paper.

3. RECORDING INSTRUMENTS ON THE RELAY PRINCIPLE

In a recording instrument on the relay principle the operating system is relieved of the work of making the record directly, and merely operates relay contacts which bring into action auxiliary devices, such as solenoids, which operate the pen. One of the chief advantages of this type is that the operating system (measuring system) of the instrument has very little work to do, and hence may be designed to take a relatively small amount of power as compared with a direct-acting recording instrument of the same type. This feature is sometimes important when the recording instrument must be operated from instrument transformers whose output is limited, or which already have other instruments connected, and have but little margin of output available for operating the recording instrument. Another advantage of the relay type instrument is that a slight displacement of the pen from the true reading results in full torque being applied to restore the true reading, whereas in the direct-acting type the restoring torque is only proportional to the amount of the displacement. The relay type is necessarily more complicated and more expensive than direct-acting instruments.

In a recent recording instrument, which may be classed as a relay instrument, there are no electrical relay contacts, but the position of a galvanometer pointer mechanically relays the work of making the record to a small auxiliary motor running at constant speed. This motor also moves the paper.

V. INSTRUMENT TRANSFORMERS

1. GENERAL DISCUSSION

Instrument transformers are of two classes, current transformers and voltage transformers. Current transformers are used to reduce large alternating currents to smaller values which can be measured conveniently, and similarly, voltage transformers reduce high voltages to values which can be measured on an ordinary voltmeter. Their use makes it possible to

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exclude high voltages from the instruments, thus insuring greater safety to the operator; the instruments can be wound with standard current and voltage windings, usually for 5 amperes, 110 volts, and the instruments may be placed in any convenient location, connection to the transformers being made with small wires.

2. VOLTAGE TRANSFORMERS

A voltage transformer [17] is essentially a lighting or power transformer of small capacity used to step down the line voltage for the operation of instruments. The rated output of the transformer is generally made considerably less than the output which could be safely carried without overheating; this limitation of the output is for the purpose of limiting the variation of the ratio of transformation [18] with change of output. To minimize the error in the ratio, voltage transformers may be wound so that the ratio is correct for an average secondary load; it will then be slightly low at no load and slightly high at rated load. The error is thus zero at the average load, and the maximum error in the ratio is less than if the winding had been designed to give correct ratio at either no load or full load.

(*a*) Phase Angle of Voltage Transformers.—In an ideal voltage transformer, having no losses, the secondary induced electromotive force would be exactly in opposition to the primary voltage. In an actual transformer, however, the iron and copper losses and magnetic leakage cause the no-load secondary voltage to lead opposition to the primary applied voltage by a small angle. This small angle is called the "phase angle" of the transformer; it amounts to only a small fraction of a degree in good transformers, and its effect is negligible, for most practical purposes, if the secondary current is small. The effect of adding a noninductive load to the secondary is to decrease this angle of lead; as the load is increased, the secondary terminal voltage usually passes through the position of opposition to the primary and lags behind opposition.

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[17] The term "potential transformer" has been in use since the beginning of the alternating-current art. However, as the word "potential" when used in this sense is incorrect unless assumed to be a contraction of "potential-difference," and is used in other senses in scientific work, it has been suggested that the expression "voltage transformer" be used instead, as it is not ambiguous. The term "pressure transformer" is an objectionable one, as are also the words "pressure" and "tension" when used in the sense of electromotive force or difference of potential.

[18] The ratio of transformation of a voltage transformer is the quotient of the voltage applied to the primary terminals divided by the voltage available at the secondary terminals. The ratio of transformation is a variable quantity, and while it is nearly equal to the quotient of primary turns divided by secondary turns (in properly designed voltage transformers) it should be distinguished from the ratio of turns.

Voltage transformers usually operate on circuits of approximately constant voltage and frequency, and their design and construction present no special problems not found in lighting and power transformers for the same voltages.

3. CURRENT TRANSFORMERS

(*a*) General Discussion.—Alternating-current ammeters are not well adapted for operation from shunts, as a rule, and the windings of shunted instruments are necessarily at the same potential as the shunts. For these reasons, and others of perhaps less importance, the current transformer [19] is widely used.

While the current transformer does not differ in principle from ordinary lighting or power transformers, it is rather sharply limited as to design if good results are to be secured. The magnetic induction must be kept low, the core must be of good material (such as silicon steel), and the magnetic circuit should be short and have interlaced joints, if joints are present. The number of ampere-turns of each winding should not be less than 300, as a rule. This value [20] refers to the rated maximum current.

(*b*) Ratio of Transformation.—The ratio of transformation of a current transformer is the quotient of the primary current divided by the secondary current; this ratio, in a good transformer which is not overloaded, is nearly equal to the quotient of the number of secondary turns divided by the number of primary turns. The ratio of transformation depends on the secondary current, and in nearly all cases the ratio becomes greater as the secondary current decreases. The ratio is also dependent on the impedance of the secondary circuit, including the secondary winding itself, the secondary instruments, and the connecting wires. In general, an increase in the impedance of the apparatus connected to the secondary will increase the values of the ratio for all values of secondary current and also increase the rate of change of the ratio with changing secondary current. The impedance of the secondary circuit should therefore be reduced to the minimum.

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[19] All transformers which have closed secondary circuits transform both the voltage and the current. The terms "current transformer" and "voltage transformer" refer merely to the use to which the transformers are put. In the voltage transformer the thing of importance is the voltage; the primary voltage may be very great while the currents are small. In the current transformer the reverse is true; the voltages are small and are not recorded or used while the currents are important and the primary current may be very large. The current transformer is sometimes called a "series transformer."

[20] This figure is given by Edgcumbe, Industrial Electrical Measuring Instruments, p. 140. It is too small for any but special cases, such as the operation of one ammeter. For the better types of current transformer used with wattmeters or watthour meters, the number of ampere-turns should be not less than 800 to 1,000, as a rule.

(*c*) Phase Angle of Current Transformer.—In an ideal current transformer whose core had infinite permeability and no core loss, and in which there was no leakage flux, the secondary current would be exactly in opposition to the primary current and the ratio of transformation would equal the ratio of turns. The effect of the magnetizing current and the core loss is to cause the secondary current to be slightly in advance [21] of opposition to the primary current. The amount of this advance is called the "phase angle"; it is dependent on the resistance and reactance of the secondary circuit, and usually decreases as the secondary current increases. If the secondary circuit is noninductive, the magnetizing current produces the phase angle, and the core loss causes the ratio of transformation to depart from the ratio of the number of turns. This statement is correct to within small quantities of the second order. With a secondary circuit having reactance but no resistance, the magnetizing current would affect the ratio and the core loss would produce the phase angle. For such secondary loads as are usually found in practice the magnetizing current and the core loss each affect both ratio and phase angle.

The phase angle of a current transformer is of no consequence when the secondary circuit contains only ammeters or other apparatus, such as trip coils, which depend only on the current strength. If wattmeters, watthour meters, or power factor meters are to be operated, it is important to have the phase angle small. This might be accomplished by having a sufficiently large reactance in the secondary circuit, but this would have the undesirable effect of causing the ratio of transformation to increase considerably as the secondary current decreased. It is therefore better, in general, to keep the secondary resistance and reactance low, thus obtaining a good ratio performance, and to keep the phase angle as small as possible by good design and good materials in the transformer. In measuring single-phase power or energy accurately with a wattmeter or a watthour meter in connection with current or voltage transformers, the observed value must be corrected for the instrument error, then multiplied by the ratio of the voltage transformer and by the ratio of the current transformer. These ratios must be known for each transformer as a result of tests, and are most conveniently taken from curves showing values of ratio for various secondary conditions. If the load to be measured has nearly unity power factor, phase angles may be neglected unless in extreme cases of current transformers whose design

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[21] This applies to the case of secondary connected loads having moderate reactance. When the secondary connected load has a large reactance, as in the case of oil-switch trip coils and relay coils, the secondary current may lag behind opposition to the primary current, at least for some values of the secondary current.

entirely unfits them for power or energy measurements. As an extreme case may be mentioned a current transformer tested by this Bureau. The transformer was of the "hole type," having an opening to enable it to be slid over a bus bar carrying 100 amperes maximum. The ampere turns at full load were thus very low, being only 100 as against the minimum of 300 referred to on page 25. The phase angle was excessive, ranging from 18° at 0.5 ampere secondary current to 5° at 5 amperes. The ratio varied 7 per cent over the same range of secondary current. This transformer was intended by the maker for the operation of a relay only, in which case the phase angle is not objectionable. If the power factor of the load is appreciably below unity, it is necessary to take into account not only the ratios but also the phase angles of the instrument transformers. A discussion of this matter, with illustrative examples and tables, is given by L. T. Robinson in Transactions of the American Institute of Electrical Engineers, volume 28, page 1005, 1909. This article also discusses the matter of phase angle corrections to measurements in polyphase circuits with the help of current and voltage transformers.[22]

(*d*) SECONDARY CIRCUIT TO BE KEPT CLOSED.—The secondary circuit of a current transformer should never be opened while current is flowing through the primary, not only on account of the rise of voltage at the secondary terminals, which may become dangerously high, but also because both the ratio and the phase angle will be changed. With current flowing in the primary and the secondary circuit open, the magnetic flux in the core rises to an abnormally high value, and the heating due to the greatly increased iron loss may damage the insulation. The magnetic condition of the core is also altered, so that on a return to normal condition of the secondary circuit the magnetizing current and the core loss are greater than normal, thus changing the ratio and the phase angle.[23] The same abnormal condition of the core will occur if a direct current of sufficient strength flows through either of the windings.

(*e*) EFFECT OF DIRECT-CURRENT FLOW.—A case was reported to the Bureau in which the accuracy of a current transformer used in connection with an important watthour meter was appreciably affected by the flow of direct current through the secondary winding. The secondary circuit was connected at two places to two independent station grounds. One of these grounds became defective, and direct current which normally

[22] See also N. E. L. A. Meter Code, 1912, p. 125; Meterman's Handbook, p. 296; American Handbook for Electrical Engineers, p. 1819.

[23] Agnew and Fitch, Bulletin of the Bureau of Standards, 6, p. 297, 1910; Scientific Paper No. 130.

would have flowed to earth through this ground passed along the secondary wiring, through the secondary coil of the transformer, and to earth by way of the second ground.

In case the secondary circuit is accidentally opened, or if the core becomes magnetized by the flow of direct current through either winding, the core may be brought back to its normal condition (demagnetized) by passing at least half the rated primary current through the primary winding with a resistance of 10 ohms or more connected to the secondary, in series with the secondary instruments. This resistance should then be gradually reduced to zero by steps of 1 ohm or less.

The phase angle of an instrument transformer depends on the frequency, the secondary current, and the secondary impedance.

VI. PERFORMANCE OF ELECTRICAL INSTRUMENTS

1. ACCURACY, SENSITIVITY, AND RELIABILITY

The distinction between accuracy and sensitivity should be carefully noted. For example, a particular indicating instrument may be sensitive, so that a change in the quantity under measurement of, say, 0.1 per cent will give a perceptible change in the position of the pointer. However, there may be defects in the design or construction of the instrument such that an error of 1 per cent may enter into the result without the possibility of detection except by the simultaneous use of a second instrument which is able to give results correct to, say, 0.1 per cent under the given conditions. The first instrument is *sensitive* to 0.1 per cent, but *accurate* to only 1 per cent. Consider a third instrument which is sensitive to 0.2 per cent but is accurate under the given conditions of use to 0.5 per cent. It thus has double the accuracy of the first instrument though only half as sensitive, and for most purposes it would be preferable to the first instrument.

The reliability of an electrical instrument is an important property which is difficult to determine except through extended experience. It is to be distinguished from permanency, though the two are closely related. To secure reliability requires that the materials used be suitable, that the operating principle be a suitable one for the purpose, the design such as tends to rigidity, strength, and permanence of adjustments; that the materials used be suitable, and that no materials be employed which may occasion damage[24] to any part; and,

[24] The use of soft rubber tubing, for example, is liable to cause corrosion of springs and connecting wires. Similar results have been occasioned by hard rubber. Superior substitutes for these materials are now available and are coming into extensive use.

further, that the materials be properly worked and assembled. For example, even the best magnet steel will give poor results if the heat treatment is not suitable. These conditions show upon what complex conditions the reliability of electrical instruments depends, and hence to what a large extent the experience, facilities, and shop system of the maker affect the reliability of the product.

The accuracy, sensitivity, and reliability of electrical instruments are determined by their design and the materials and care used in their construction. No instruments made are "absolutely accurate" or entirely independent of their surroundings, and a knowledge of the magnitude of the errors likely to occur, the origin of these errors, and the means used to make the errors negligible or as small as possible, is of value in enabling one to choose between different types of instruments which may be used for a given work, and in obtaining the best results from an instrument under working conditions.

2. EFFECTS OF CHANGE OF ROOM TEMPERATURE

(*a*) GENERAL DISCUSSION.—A change of temperature of 1° C produces various effects on the parts of an instrument. These effects differ widely in magnitude. For example, the linear expansion of the metal parts will be of the order of 10 to 20 parts in a million, and the change of resistance of manganin and some other alloys will be of the same order. Both the foregoing may be neglected in all ordinary cases. The change of the elastic force of a spring will be several parts in ten thousand, and the change of resistance of a copper coil will be about 4 parts in a thousand.

(*b*) TEMPERATURE COEFFICIENTS OF DIRECT-CURRENT VOLTMETERS.—The effect of an increase of temperature of 1° C is to weaken a phosphor-bronze spring about 0.04 per cent, and hence if no other part of an instrument was affected by the temperature change, the reading of the instrument would be increased by this percentage. In an instrument of the permanent-magnet moving-coil type, the strength of the magnetic field in the air gap will usually decrease by about 0.02 per cent [25] for a rise of temperature of 1° C. This decrease in the field strength tends to reduce the reading of the instrument, and hence the reading will in general be increased by only 0.02 per cent by a rise of room temperature of 1° C. This figure applies to a permanent-magnet moving-coil instrument used as a milliammeter with

[25] This is an average of the values found by Sanford and Fearing for the magnetic fields of six instruments from three makers. The individual values ranged from −0.01 to −0.03 per cent.

the whole current to be measured flowing through the moving coil. If the instrument is to be used, in connection with some added resistance, as a voltmeter, the effect of temperature change on the resistance of the instrument circuit must also be considered. It is evident that if the resistance of the voltmeter can be made to increase by about 0.02 per cent [26] per degree C, the current taken by the voltmeter (when a definite voltage is applied to its circuit) will decrease 0.02 per cent for a rise of 1° C, thus offsetting the resultant temperature coefficient of the magnet and springs, and making the instrument compensated for room temperature changes. For example, the moving coil may have 60 ohms resistance, and be of copper wire whose temperature coefficient is approximately 0.4 per cent per degree C. If to this coil be added a series resistance of manganin, constantan, or other suitable alloy of negligible temperature coefficient, so as to make a total of 1200 ohms, the resistance of the instrument will increase 0.02 per cent per degree C rise of temperature, and the voltmeter will be compensated for ordinary changes of room temperature.

(*c*) Temperature Coefficients of Direct-Current Ammeters.—On account of the necessity, for commercial reasons, of keeping down the size, weight, and cost of switchboard ammeter shunts, as well as the power lost in them, shunted ammeters are designed to give full-scale deflection for very low voltages, usually from 50 to 75 millivolts. As the shunts are usually made of resistance alloy of low temperature coefficient, while a considerable part of the instrument circuit consists of copper, the proportion of the total current which passes through the instrument will change appreciably with changing room temperature. The resulting temperature errors range from less than one-tenth per cent to about four-tenths per cent per degree C, so that in extreme cases errors of 5 per cent or more may be caused by room temperature changes. This is ordinarily not a matter of importance, as switchboard ammeters serve mainly as indicators to guide in the operation of a plant, to prevent overloading of generators, motors, or feeders. Such ammeters, however, should not be used where accuracy is required,[27] as, for example, in making efficiency tests or in checking watthour meters, unless suitable correction is made for the effect of room temperature. It is, however, preferable to use instruments having smaller corrections, as it is

[26] This is an average value, and to compute the percentage of manganin (or similar alloy) for accurate temperature compensation for a given instrument would require the determination of its temperature coefficient as a milliammeter.

[27] F. P. Cox, Transactions American Institute of Electrical Engineers, **24**, p. 181, and E. B. Rosa, discussion, p. 223; 1905.

not always possible to determine temperatures accurately at the points where they need to be known.

(*d*) TEMPERATURE COMPENSATION OF DIRECT-CURRENT AMMETERS.—Portable shunted ammeters for direct current should be compensated for temperature. The simplest method of doing this is to proceed as outlined above for the compensation of a voltmeter, namely, to add enough series resistance of low temperature coefficient to make the instrument (considered as a millivoltmeter) independent of temperature. The shunts should be of manganin, or other alloy having similar properties. In order to secure a close approach to compensation for temperature in this way, it is usually necessary to increase the full-load drop across the shunt to, say, 150 or 200 millivolts. This method of temperature compensation is the one ordinarily used by American makers.

Another method [28] is used to some extent abroad. A small amount of resistance of low temperature coefficient is added to the moving-coil circuit and the whole is shunted with a coil of copper or other material of high temperature coefficient. To this branched circuit is then added a certain amount of resistance wire of low temperature coefficient. When the proper relations exist between the resistances and temperature coefficients of the various parts the instrument will be compensated for temperature as a millivoltmeter. This plan has the advantage over the method of plain series resistance, in that the temperature compensation may be secured with a considerably lower voltage for full-scale deflection, and hence the shunts are smaller and less expensive. The method has the disadvantages of being more complicated and of requiring greater care in construction, and the instrument so compensated as a millivoltmeter may have an appreciable temperature coefficient if used as a milliammeter.

(*e*) TEMPERATURE COEFFICIENTS OF MOVING-IRON INSTRUMENTS.—In the moving-iron ammeter, with spring control, an increase of temperature affects the magnetic conditions in the iron in such a way as to decrease the operating torque by about the same percentage that it reduces the spring strength. These ammeters thus are very nearly independent of room temperature changes.[29] The temperature coefficient of a moving-iron voltmeter thus depends mainly upon the ratio of the resistance of the copper coil to the total resistance of the instrument. For example,

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[28] Hallo and Land, Elektrische und Magnetische Messungen und Messinstrumente, p. 259.

[29] This statement is based on the experience of this Bureau with several instruments of each of two prominent American makes. It is not certain that it applies to all types and grades of moving-iron ammeter.

if the copper coil has a resistance of 150 ohms, and the series resistance of alloy of low temperature coefficient (such as constantan) makes up a total of 1,500 ohms, the voltmeter will read lower by one-tenth of 0.4 per cent, or 0.04 per cent, for an increase of temperature of 1° C.

(*f*) TEMPERATURE COEFFICIENTS OF ELECTRODYNAMOMETER INSTRUMENTS.—In an electrodynamometer ammeter, with the fixed coil and the moving coil in series, the only appreciable effect of temperature on the reading is that caused by change in the strength of the controlling springs. An increase of temperature of 1° C will reduce the strength of the springs by 0.04 per cent. For any given relative position of the coils, the operating torque varies as the square of the current; the scale, however, is marked to read the first power of the current. Such an instrument will therefore read 0.02 per cent higher on a given current for each degree C of temperature elevation. Hence, if a milliammeter of this type, of suitable range, be supplied with a series resistance of low temperature coefficient, such that the total resistance is twenty times the resistance of the copper windings, the temperature coefficient of resistance of the circuit will be 0.02 per cent per degree C and will offset the effect of temperature changes on the strength of the springs. The instrument will be compensated for temperature as a voltmeter.

A similar condition, namely, total resistance equal to approximately ten times the copper resistance, applies to the potential circuit of an electrodynamometer wattmeter, if the readings of the wattmeter are to be independent of temperature changes. The torque of a wattmeter is proportional to the first power of the quantity it measures, for any given relative position of its coils.

(*g*) TEMPERATURE COEFFICIENTS OF INDUCTION INSTRUMENTS.—In the induction ammeter of the shifting-field type the use of a noninductive copper coil in parallel with the magnetizing coil has already been referred to (p. 16) as giving approximate correction for both frequency and temperature changes. The rotary-field induction ammeter is also designed to be independent of temperature, as are also induction voltmeters. A low temperature coefficient is more difficult to obtain in the case of induction wattmeters. For this purpose it is necessary to use a special alloy instead of aluminum for the moving element, thus decreasing the ratio of torque to weight. (See p. 47.)

(*h*) TEMPERATURE COEFFICIENTS OF HOT-WIRE INSTRUMENTS.—In the hot-wire instrument a change of room temperature changes the length of the working wire, and also changes the distance between the supports of the ends of the wire. Hence, if the base plate carrying these supports be made of material having the same temperature coefficient of expansion as the working wire, this source of temperature error in the instrument will be removed. The instrument thus constructed may, however, still have a temperature coefficient caused by changes in the rate at which energy is lost from the wires by radiation and convection with changing room temperature. In the hot-wire ammeter an appreciable amount of heat also escapes by conduction to the end supports and to the flexible strips used to divide the wire electrically into several sections.

(*i*) Temperature Coefficients of Electrostatic Instruments.—Room temperature effects in electrostatic instruments resemble those in the electrodynamometer ammeter with fixed coil and moving coil in series. The operating torque for a given voltage will be practically independent of temperature. If the moving element is hung on a phosphor-bronze strip, the torque of this strip (for a given angle of twist) will be 0.04 per cent less for each degree C rise. Hence, such a voltmeter, if correct at a given room temperature, will read 0.02 per cent too high for each degree C rise.

(*j*) Temperature Coefficients of Watthour Meters.—In the direct-current watthour meter of the Thomson type the retarding torque is due to the eddy currents set up in the copper or aluminum disk. An increase of temperature of 1° C increases the resistance of the disk 0.4 per cent, and if this effect were not compensated, the speed of the meter on a given load would be increased by this percentage. Compensation is secured by using wire of high temperature coefficient for the series resistance in the armature circuit, so that the armature current decreases as the temperature increases. Some foreign makers use constantan wire for the series resistance, thus producing a meter whose readings vary greatly with room temperature. This state of things is due to the absence of proper performance specifications for meters in the given localities.

In the induction watthour meter both the driving torque and the retarding torque are occasioned by eddy currents in the disk, and as both are weakened alike by an increase of resistance of the disk, the speed of the meter is independent of the temperature of the disk. In stating the torque of such meters, the temperature at which the torque was determined (or the temperature to which the observed value was reduced) should be given.

In both the above cases there are other factors which affect the temperature coefficient of the meter; for example, the change in the permanent magnets. These other factors are minor ones in comparison with those discussed above.

3. EFFECTS OF SELF-HEATING OF INSTRUMENTS

(*a*) General Discussion.—In the preceding discussion of effects of room temperature it has been assumed that temperatures within the instrument were the same throughout. If no source of heat existed in the instrument this would be very nearly the case. Most instruments, however, contain sources of heat, usually coils of wire through which currents flow. Unequal heating is therefore possible, and an error may result which will depend upon the value of the current or voltage under measurement and upon the length of time that the instrument is kept in circuit.

In direct-current millivoltmeters and in voltmeters of moderate range (say, not over 300 volts) the amount of power converted into heat is relatively small. In alternating-current voltmeters and the voltage circuits of wattmeters the resistance for a given voltage is much lower, and the amount of heat liberated per second is much greater. As a large part of this heating occurs in the dead resistance in series with the working element, this heat-producing resistance should be partitioned off from the working system and properly ventilated.[30]

(*b*) Self-Heating of Shunted Direct-Current Ammeters.—In direct-current ammeters with external shunts there is practically no self-heating within the instrument. The heating of the shunt may be considerable at full load.[31] While the alloys used in shunts are commonly such as have very small temperature coefficients, there is another important property which must not be overlooked, namely, the thermal electromotive force of the alloy against the brass or copper used for the shunt blocks. The alloy constantan has some properties that make it desirable for shunts, from the standpoint of ease of manufacture, but it has a very large thermal electromotive force which makes it objectionable. Constantan is known also by various trade names, such as Ia Ia, advance, eureka, and others. For the construction of coils of high resistance, such as voltmeter multipliers, constantan has some advantages over manganin.

A considerable part of the heat produced in switchboard ammeter shunts is carried away by conduction to the bus bars, from which it escapes by

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[30] Neglect of this precaution usually results in an instrument which can not be left in circuit for any appreciable time without introducing an appreciable error due to internal heating.

[31] See paper by Fitch and Huber, Bulletin of the Bureau of Standards, 7, p. 412; Scientific Paper No. 163.

radiation and convection. Even if the opportunity for escape of heat is the same at each end of the shunt, there will still be a difference of temperature. This is caused by the flow of current through a circuit made up of dissimilar metals, and is known as the Peltier effect. It causes a thermal electromotive force in such a direction as to increase the reading of the ammeter. In cases of unequal heating of the two ends of the shunt, caused by bad contacts or by difference in size of bus bars, the resultant thermal electromotive force may either increase or decrease the reading of the ammeter.

Thermal electromotive force may be detected by allowing the current to flow until the shunt has reached its maximum temperature elevation, and then breaking the main circuit, when the index will fail to return to zero if appreciable thermal electromotive force is present. This effect may be distinguished from zero shift (due to spring fatigue) by disconnecting one lead from the instrument, when the position of the index will change by an amount proportional to the thermal electromotive force.

(*c*) Use of Copper Bar as Ammeter Shunt.—The use of portions of copper bus bar as ammeter shunts is not now recommended on acount of the large temperature errors due to heating of the bus bar by the current. In special cases, where a length of bus bar is available which gives a drop at full load of several times that required by the instrument, a fine insulated copper wire can be laid along the bar in intimate heat contact with it, and used as a series resistance in the millivoltmeter circuit. The heating of this wire will tend to compensate for the increased drop on the shunt as the latter heats up. This method is limited by the necessity of avoiding joints in the part of the bus bar used as a shunt and by the uncertainty as to the distribution of current between the separate bars of a laminated bus.

(*d*) Self-Heating of Portable Direct-Current Ammeters.—Portable direct-current ammeters have been made with internal copper shunts, in order to reduce the loss of power in the instrument. As both shunt and moving coil are of copper, changes of room temperature will not alter the relative distribution of current between moving coil and shunt. As the temperature coefficient of the unshunted instrument as a milliammeter is quite small, such a shunted instrument would be a very good one were it not for self-heating of the shunt and the resulting differences of temperature within the instrument. In the smaller sizes (say, up to 15 amperes) such instruments give a good performance, but as the ampere capacity increases the performance becomes poorer, until in capacities of 300 to 500 amperes the indications change very rapidly after closing the circuit, and the instruments are not suitable for any but rough work.

(*e*) USE OF MANGANIN FOR AMMETER SHUNTS.—For precision ammeter shunts, manganin is usually regarded as the most satisfactory material that is supported by a long service record. Manganin is an alloy of about 84 per cent copper, 12 per cent manganese, and 4 per cent nickel. Its specific resistance is about 25 times that of copper, and its temperature coefficient and thermoelectric power against copper are both very small. Two other alloys with properties similar to those of manganin have been in use for a shorter time and seem to give promise of good permanence; one is an American product which bears the trade name of therlo, and the other a German alloy known as Kulmiz alloy, or Achenrain resistance material.

(*f*) SELF-HEATING OF MOVING-IRON INSTRUMENTS.—In the moving-iron ammeter the conditions are favorable for a small error due to the effect of internal heating, since the power lost in the instrument (if the latter is well designed) is small, and the iron and the spring are usually near each other, and hence their temperatures will not differ greatly under any circumstances. In the moving-iron voltmeter the conditions are slightly less favorable, as the heating of the copper coil increases the resistance of the circuit.

(*g*) SELF-HEATING OF HOT-WIRE INSTRUMENTS.—The matter of internal heating in the hot-wire instrument is unique, in that the operation of the instrument depends on internal heating. However, some questions arise in this connection. For example, the base plate carrying the supports for the hot wire will be heated by the hot wire, and this heating will be very slow, on account of the heat capacity of the base plate. If a hot-wire instrument is to be kept in circuit continuously, it ought to be tested only after having been in circuit long enough to reach a steady state.

No energy losses occur in the electrostatic instrument, and hence it is free from errors due to internal heating.

(*h*) SELF-HEATING OF THOMSON DIRECT-CURRENT WATTHOUR METERS.—An interesting example of the effect of self-heating on accuracy is that afforded by the Thomson type of direct-current watthour meter. The accuracy curve for such meters rises between 10 per cent load and about half load, then droops for all loads above half load. This effect, which was long thought to be due to the counter electromotive force of the armature, has been shown [32] to be due largely to the increased resistance of the armature when the latter is heated by the series coils.

[32] Fitch and Huber, Comparative Study of American Direct-Current Watthour Meters, Bulletin of the Bureau of Standards, **10**, p. 188, 1913; Scientific Paper No. 207.

4. EFFECTS OF STRAY MAGNETIC AND ELECTROSTATIC FIELDS

(*a*) General Discussion.—The effect of stray magnetic field upon the indications of an instrument depends on the nature of the field and the operating principle of the instrument. A magnetic field of constant direction and magnitude, such as is produced by a direct current in a conductor, or by an electromagnet excited by direct current, will in general affect the indications of the following types of instrument: Permanent-magnet moving-coil; moving-iron; and electrodynamometer. It has been shown [33] that such a stray field changes merely the strength of the magnetic field in the air gap of a permanent-magnet moving-coil instrument, but not the distribution of this latter field. The error due to the stray field will therefore be a constant percentage of the indication of the instrument, so long as the disturbing stray field is constant in amount and direction. It is usually recommended that when portable instruments must be used in places subject to strong stray fields the mean of two readings be taken, the instrument being turned 180° about the axis of rotation of the moving element for the second reading. In the case of permanent-magnet moving-coil instruments, another method consists in placing the instrument with its magnetic field at right angles to the direction of the stray field, the latter being determined by the use of a compass. In this position the effect of the stray field will be small, and changes in the *magnitude* of the stray field are not important. It is, of course, better to avoid exposing instruments to stray fields as far as possible. In the case of moving-iron and electrodynamometer ammeters and voltmeters it is better to leave the instrument in one position and take the mean of two readings, the current through the instrument being reversed for the second reading. However, these latter instruments should in general not be used for direct-current work, if permanent-magnet moving-coil instruments are available.

Stray fields due to direct currents have no effect (or a very small effect) on instruments of the hot-wire, electrostatic, and induction types.

If the stray field is due to an alternating current, no perceptible effect will be observed on the reading of a permanent-magnet moving-coil instrument, unless the stray field is strong enough to demagnetize the permanent magnet to some extent. This will cause the instrument to read low until it is repaired. An extreme case of this kind is given [34] in which a direct-

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[33] Heinrich and Bercovitz, Handbuch der Elektrotechnik, 2, pt. 5, pp. 9–11.

[34] E. P. Peck, Electrical World, 51, p. 1220; 1908.

current voltmeter was connected to a 600-volt circuit and placed within 18 inches of heavy bus bars. After a severe short circuit, which caused very heavy alternating currents to flow for an instant through these bars, the voltmeter read 350 volts when the applied voltage was 600.

MacGahan, in Proceedings of the National Electric Light Association for 1913, page 602, shows an instrument of the permanent-magnet moving-coil type having a single air gap which is stated to be practically unaffected by strong stray fields due to the current in a vertical conductor. The arrangement is such that the stray field passes through the magnet at right angles to the permanent flux.

It is doubtful whether any general rule can be given for determining the error due to stray magnetic field in the use of portable moving-iron instruments. Some makers surround the operating system with a magnetic shield of laminated soft iron as a protection against stray fields. This affords considerable protection, but adds appreciably to the weight of the instrument, and sometimes gives trouble when the instruments are used on direct current, on account of magnetic polarity which may develop in the iron shield.

Moving-iron instruments of the switchboard type are partially shielded from stray magnetic fields by the iron cases in which they are usually mounted. However, they should be placed so as to avoid stray fields as far as possible.

Electrodynamometer ammeters, voltmeters, and wattmeters, as usually made, are appreciably affected by stray magnetic fields. Such instruments are usually tested with direct current, and in order to eliminate the error caused by the earth's field, which may amount to 1 or 2 per cent of the maximum scale reading, it is necessary to take the mean of two readings, the direction of the current through the instrument being reversed for the second reading. It is usually possible to find a position of the moving coil such that the earth's field produces no effect on the reading; that is, for the given position of the instrument and the given scale reading, the moving coil incloses the maximum possible number of lines of force due to the earth. When such an instrument is used on alternating currents, stray fields such as the earth's, which do not change in direction, have no effect on the reading, but errors may be caused by the stray fields set up by large alternating currents whose frequency is the same (or nearly the same) as that of the currents in the instrument. To avoid this, all leads to the instrument and near the instrument should be run as noninductively as possible, by avoiding loops. The use of a magnetic shield of laminated iron surrounding the movement is becoming more general. In testing such instruments with direct current, the mean of reversed readings should be taken in order to eliminate any effect caused by magnetic polarity in the shield.

Hot-wire and electrostatic instruments are practically unaffected by stray alternating fields, though a slight error from this cause is theoretically possible.

(*b*) Astatic Instruments.—The preceding discussion applies to simple instruments of the various types. To avoid the effects of stray fields, astatic instruments are made by combining two operating systems, or their equivalent. For example, two permanent-magnet moving-coil systems are used, with the moving elements coupled to add their torques and with the two magnets arranged to have opposite polarities. Another astatic arrangement consists of two moving-iron systems coupled to operate a single index, the polarities of the two solenoids being opposite. Both the above are used in foreign recording instruments. An astatic electrodynamometer instrument contains two moving coils rigidly connected, with their polarities opposite, so that with direct current flowing in them, for example, the force due to the earth's field acting on one coil is balanced by the force on the other coil. This construction is not used as much as it deserves to be, probably on account of increased mechanical difficulties of construction. In another form of astatic instrument, applicable only to direct current, the deflecting torque and the controlling torque are both caused by the same magnetic field. This field is produced by an electromagnet supplied from a separate source or by means of a permanent magnet.

A word of caution is necessary concerning astatic instruments. They are much less affected by stray fields than the ordinary types, but they are strictly astatic only for fields which are uniform over the space occupied by the coils, or for nonuniform fields which may happen to produce the same torque on each coil. The field about a bus bar carrying a current is not uniform, but decreases in intensity as the distance from the bar increases. If an astatic instrument is placed near the bar, one coil of the astatic system may be so much closer to the bar than the other as to give an appreciably greater force on the nearer coil, and hence a residual error will be caused by the stray field. In using astatic instruments the same precautions should be taken as for simple instruments, if the maximum accuracy of which they are capable is desired.

(*c*) Errors Due to Electrostatic Action.—Stray electrostatic fields can produce no effect on an instrument wholly inclosed in a metal (conducting) cover. Electrostatic effects are therefore limited, as a rule, to those due to fields set up within the instrument. Rubbing the cover glass over the index will often cause the index to move from its proper position, due to the action of an electric charge produced on the glass. One remedy for this consists in breathing on the glass, the moisture causing the induced charge to disappear. Another electrostatic effect may be noticed when testing wattmeters by the method of separate sources of current and voltage. When the potential of the fixed coil is different from that of the moving coil, an electrostatic force is exerted between the two which may cause appreciable errors in the indications. The remedy is to arrange the circuits so that the fixed coil and the moving coil may be joined at one point. This requires care to avoid trouble, due to a possible contact betwen the circuits at some other point.

This connection between the coils may well be made through a direct-current voltmeter whose maximum reading is not less than the voltage used in testing the wattmeter. The index of this voltmeter should remain at zero; if a deflection occurs, leakages or contacts are present in the test circuits.

Instruments having a wooden baseboard and metal covers are liable to error from electrostatic forces between the index and the metal case. During a test of a direct-current voltmeter at 750 volts, variations of 4 or 5 divisions in the reading were observed when the observer touched the metal case.

Induction instruments have nearly closed magnetic circuits and strong working fields. They are consequently much less affected by stray alternating fields than unshielded instruments of the moving-iron and electrodynamometer types, and are not affected by direct-current fields.

5. EFFECTS OF IMPERFECT ELASTICITY OF SPRINGS

(*a*) General Discussion.—The quality of the springs used in an electrical instrument has an important bearing on the accuracy of the results obtained. At one time springs were looked upon with suspicion, and "gravity-controlled" instruments were often preferred. These are still made by foreign makers, most of whom also supply instruments with spring control. Gravity-controlled instruments are somewhat cheaper in first cost. While present-day springs should not be looked upon as free from the possibility of change with time, those used by the best makers give very good results, and may be considered to be no more liable to change than other parts of the instruments.

(*b*) Zero Shift.—If the index of an instrument stands at zero with no current flowing, after an interval of, say, several days of rest, and the circuit be closed so as to give full-scale deflection for a few minutes, then on breaking the circuit the index will usually return to zero, within the limit of reading. If full-scale deflection be maintained for an hour, the index will probably not return exactly to zero on breaking the circuit. If the deflection be maintained for several hours, the discrepancy will be still greater. This zero shift is due to elastic fatigue or viscosity; it is only temporary, and gradually disappears. The amount of this zero shift varies not only with the procedure of use, as just outlined, but also varies in different classes of instruments and in different individuals of the same class. In first-class voltmeters it should not be more than just noticeable (say, 0.1 division). In millivoltmeters it is usually greater, although occasionally a millivoltmeter will show very good performance in this respect.[35] The effect of zero shift upon the accuracy of the results (if the shift be not allowed for) is greater when an instrument is used for a small deflection soon after it has sustained a large deflection for a considerable time.

The amount of zero shift depends also on the design of the spring; this matter is referred to later. (See p. 48.)

Another form of zero shift is caused by the gradual change of form of springs with time. This has been observed in a number of instruments using a single spiral spring, and the change observed was evidently a gradual uncoiling of the spring. In moving-coil instruments it is customary to use two spiral springs wound in opposite directions. In this case the tendency of one spring to unwind would offset a similar tendency in the other spring.

The zero shift, due to thermoelectric effects, is considered on page 34.

(*c*) Hooke's Law.—It has often been assumed that the torque of a spiral spring is exactly proportional to the angle of twist; in other words, that the spring obeys Hooke's law. Hence, in testing such instruments as the Siemens dynamometer, the "constant" of the instrument was determined for one value of current and assumed to hold for any other value, or

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[35] The reason for the poorer spring performance of millivoltmeters, as a class, lies in the necessity of using springs which approach pure copper in electrical conductivity; such springs tend toward the greater elastic viscosity of pure copper. For voltmeters this limitation as to conductivity does not exist, and the springs may be made of any alloy which is non-magnetic and has the best mechanical and elastic properties. Phosphor bronze of good quality is usually considered to be a very satisfactory material.

the constant was taken as the mean of several determinations with different currents. This assumption has been shown to be incorrect and to lead to errors of 1 per cent or more.[36] In ordinary direct-reading instruments, with properly calibrated scales, such an error does not appear. However, if by accident the spring should be thrown out of its original shape, the scale will no longer be correct, even though by shifting the spring holder the index be brought back to zero. If the spring is considerably distorted, the instrument should be sent to the maker for repairs.

(*d*) ZERO ADJUSTMENT.—It is becoming more general to provide zero-adjusting devices for indicating instruments, and such devices are very good if properly used. They may be used to correct for small variations of the springs, but should not be used to bring to zero a pointer that has been bent, as such an adjustment brings the moving part into an initial position different from that which it occupied when the original calibration was made. In instruments which do not have a uniform scale this may introduce appreciable errors throughout the scale.

6. EFFECTS OF FRICTION AND LACK OF BALANCE

(*a*) FRICTION OF PIVOTS.—In a properly designed and well made instrument the friction of pivots should not affect the readings appreciably, unless the instrument is old or has been roughly handled. Good performance as regards friction requires not only good workmanship in the pivots and jewels but also good design. (See p. 47.) In general, it is preferable to have the axis of rotation vertical in pivoted instruments, as the friction will be smaller and more uniform than with a horizontal axis. This principle may be departed from in switchboard instruments, which need not be read with great refinement, but the vertical axis is to be used for precision instruments.

Friction at points other than the pivots often makes the readings so irregular as to call attention to the trouble and to make the instrument useless until the difficulty is removed. In some cases, however, friction of this kind may affect the readings only at certain times, and usually at certain parts of the scale, and the trouble may be difficult to discover. Such friction is sometimes caused by fine fibers loosening from the substance of the paper scale and projecting out till they touch the index. Similar trouble may be caused by small particles of foreign matter getting into the air gap of a direct-

[36] Wm. Bradshaw, Electric Journal, **3**, p. 395; 1906.

current instrument or into the air-damping box of an alternating-current instrument.

(*b*) Lack of Balance of Moving System.—If the moving system of a spring-controlled instrument is not properly balanced, the indications of the instrument will vary with change of level of the instrument. Errors due to this cause may be considerable. To investigate a portable instrument in this respect, it should be tipped say 10° from the horizontal; a switchboard instrument should be held with the axis of rotation of the moving system approximately horizontal, and should be slowly turned through 360° about this axis. The instrument should be disconnected from the circuit while this is done. Millivoltmeters, wattmeters, and alternating-current instruments, most of which usually have a smaller ratio [37] of torque to weight than the direct-current voltmeter, usually show somewhat more deviation than the latter. If a portable instrument shows considerable variation of zero reading, when examined as above, care should be taken to have it on a level support when in use as well as when it is being tested. At a convenient opportunity the moving system should be balanced; this should preferably be done by the maker.

7. EFFECTS OF SOME CONSTRUCTIONAL DETAILS ON ACCURACY

(*a*) Instrument Scales.—At one time instrument scales were engraved or printed, on the assumption of a particular law for the given type; generally the individual instruments were then adjusted by trial to make them fit the scale as closely as possible. Such a method does not give good results, in general, and it is now the usual practice to make an individual scale for each instrument. It is not necessary, of course, to determine every scale division by test, especially in direct-current instruments with nearly uniform scales. It is usually considered sufficient to determine 10 or 15 points of the scale of a direct-current instrument by actual test. The intermediate points are filled in, sometimes by hand, preferably by a mechanical method. The accuracy claimed for the scales of high-grade portable direct-current instruments is usually one-tenth [38] of a scale division (1/1500 to 1/1000 of a right angle). This refers to the error at any point on the scale, assuming that the resistance adjustments of the instrument are such as to reduce the error of the indications to a minimum. The remaining errors may then be charged to inexactness of graduation of the scale.

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[37] See discussion of this ratio on p. 47.

[38] To attain such an accuracy requires great care and good facilities.

Alternating-current instruments with nonuniform scales require the determination of a larger number of points of the scale by test, if an accurate scale is required.

(*b*) Resistance Adjustment.—Errors due to inexact adjustment of the resistances of an instrument affect all the readings of the scale by the same percentage, and may be removed by making an exact adjustment of resistance. Multiple-range instruments may have errors of resistance adjustment which are negligible on some ranges and appreciable on others. Multiple-range voltmeters may be checked in this respect by measurements of resistance, using a Wheatstone bridge. This method is not applicable to multiple-range ammeters, as the sensitivity and accuracy of the Wheatstone bridge are not adequate when such low resistances as those of ammeter shunts are to be measured.

(*c*) Temperature Compensation.—An instrument may be nominally compensated for temperature, but the compensation may not be good enough for some classes of work. This defect will not appear in the use of the instrument at a uniform room temperature, but may introduce an error too great to be tolerated when instruments are unavoidably used in extremes of temperature. An illustration is the use of an ammeter to measure the current taken by the incandescent lamp in a portable photometer or illuminometer. Here an error of 1 per cent in the current will make, say, 5 per cent error in the measurement of the candlepower, and as the instrument may be used outdoors, extreme temperatures may be unavoidable. For work of this kind where accuracy is essential, the temperature coefficient of the instrument should be determined.

8. PERMANENCE OF CALIBRATION

Permanent magnets, as now made by careful makers, show a very good constancy under normal conditions; that is, when the magnetic circuit is properly designed [39] and the instrument is not roughly handled or abused by exposure to strong magnetic fields, extremes of temperature, or severe overloads.[40]

In the above discussion of changes in magnets and springs it has been assumed that the windings of the instrument did not change with

[39] See discussion of this subject on p. 48.

[40] In several cases which have been noted, a change of several per cent in the indications of permanent-magnet moving-coil instruments could only be explained by the fact that through improper connections a current many times greater than normal had been momentarily passed through the moving coil, thus permanently affecting the strength of the magnet.

time. This is usually the case, but it is preferable to check the values of resistances of instruments at intervals of, say, six months or a year, depending on the conditions of use.

9. CONDITIONS AND MANNER OF USE

The result of a measurement with indicating instruments always involves the personal element, over which the instrument maker has no control. A few suggestions will now be given in regard to the care and use of instruments.

(*a*) Care in Handling.—Electrical instruments are essentially delicate; their operating forces are small, and their accuracy depends upon great refinement of construction, especially in such parts as pivots and jewel bearings. They should therefore be handled carefully, and not exposed to unnecessary vibration, moisture, or extremes of temperature. Portable instruments should be placed on a level support, and not too near each other, as they may affect each other's readings by 1 per cent or more if placed near together. If cover glasses must be wiped clean before taking readings, the observer should breathe on the glass to dispel any static charge which might be present.

Good contacts are essential to accurate measurements. This is especially true in the use of millivoltmeters with separate shunts. There are four contacts in the connections between shunt and instrument, and the resistance of the instrument is only a few ohms; a corroded or dirty terminal or binding-post surface may introduce errors of several per cent.[41]

(*b*) Power Losses in Instruments.—When measurements of small electrical quantities are made, for example, the iron loss in a small transformer, it becomes important to avoid (or correct for) errors due to the power required to operate the instruments. For example, the ordinary electrodynamometer wattmeter can be connected to measure a load, either with the voltage circuit in parallel with the load, in which case the reading includes the power required by the voltage circuit of the wattmeter, or with the voltage circuit connected on the source side of the wattmeter, in which case the reading includes the power required by the current circuit of the wattmeter. Similar conditions arise in many cases where several instruments are used in a given measurement.[42]

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[41] Such terminals and binding posts should be nickel plated, and the maker's instructions might well lay more stress on the matter of clean surfaces and firm connections.

[42] Jansky, Electrical Meters, 1st edition, pp. 118 and 357; Taylor, Electric Journal, 2, p. 476, 1905.

Compensated wattmeters have an auxiliary series winding; when properly constructed they avoid the necessity for correction for instrument losses.

Errors due to variations of frequency, when such variations are relatively large, are best avoided by using types of instrument which are inherently but little affected by frequency changes. The same is true of wave-form variation, which is, to a certain extent, analogous to variation of frequency. Fortunately, the tendency of design of modern alternators is toward the sine wave form, and the frequency in at least the larger modern plants is usually closely controlled.

The error of reading depends upon the construction of the instrument, the skill of the observer, and the steadiness of the quantity under measurement. Precision indicating instruments are generally provided with an index having a flattened end, and a mirror beneath the pointer to avoid error due to parallax. With a well-made instrument of this sort it is possible for a skilled observer to make a reading to about 0.1 mm, or 0.1 division on a uniformly divided scale of the usual length. This refers to the condition of steady current; on commercial circuits, where fluctuations occur, the precision of reading is not so good.

VII. NOTES ON THE DESIGN OF ELECTRICAL INSTRUMENTS

1. CONFLICTING REQUIREMENTS OF DESIGN

In all electrical design some compromises must be made. If the attempt is made to design a transformer of given output having very low copper losses, it will be found impossible to keep the iron losses as low as could be done in a better balanced design. If an incandescent lamp is designed to operate at an unduly high temperature, the life will be short.

Most electrical instruments have the disadvantage of small operating forces, and thus not only require very good workmanship, but more care in handling than many other measuring devices. If the design is modified so as to increase the operating forces, the power lost in the instrument may be increased, thus increasing the correction which must be made on this account. Another drawback is the increased heating, which tends to introduce errors.

2. EFFECT OF SERVICE CONDITIONS ON DESIGN

The nature of the service has an important bearing on design. In many kinds of switchboard instruments it is preferable to design for reliability and ruggedness, even at the expense of reducing the accuracy, in order that the instruments may not be damaged by handling, by vibration, or by occasional momentary short circuits. Standard instruments for laboratory use must be designed to give the required degree of accuracy. They may be more delicate than portable instruments and may require greater care in handling.

3. RATIO OF TORQUE TO WEIGHT OF MOVING ELEMENT

Even with the most careful workmanship in pivots and jewels, friction can not be entirely eliminated. The springs should therefore be strong enough to cause the coil to take up its proper position within the minimum error of reading. According to one writer [43] the torque for full-scale deflection, expressed in centimeter-grams, should not be less than one-sixth of the weight of the coil in grams. Other writers [44] give a considerably lower minimum value, namely, one-twentieth. In both these cases a deflection of approximately 90° is assumed, this being the usual full-scale deflection for most direct-current instruments. In this country it is perhaps more usual to express the torque of electrical instruments and meters in millimeter-grams; this gives a number for the ratio of torque to weight which is ten times as large as when the centimeter-gram is used. Using the millimeter-gram, the rule given by Janus becomes "torque must not be less than five-thirds of the weight in grams," and the rule given by Heinrich and Bercovitz becomes "torque must not be less than half the weight in grams." It is desirable to keep the ratio of torque to weight as high as possible, without unduly sacrificing other qualities. It should be noted that an instrument of very high torque may be a poor instrument if the high torque is obtained by using an excessively heavy moving element.

It is desirable to have a high ratio of torque to weight in watthour meters, as this tends toward good performance at light load. In American direct-current meters of the Thomson type, as now made, this ratio [45] (using the millimeter-gram and gram) will average a little over unity; in American induction watthour meters this ratio is more favorable, being about two to four times as great as for direct-current watthour meters.

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[43] Janus, Elektrotechnische Zs., 28, p. 560; 1905.

[44] Heinrich and Bercovitz, Handbuch der Elektrotechnik, 2, pt. 5, p. 14.

[45] Fitch and Huber, Study of American Direct-Current Watthour Meters, Bulletin of the Bureau of Standards, **10**, p. 171; 1913, Scientific Paper No. 207.

4. PERMANENCY FACTOR OF THE MAGNETIC CIRCUIT.

A general principle applying to permanent magnets used in instruments and meters is that the magnetic circuit should be as nearly closed as possible. The following empirical relation was first given numerically by Hookham [46] in 1888. He stated that if A equal the area of cross section of the air space, L the distance between the pole pieces, a the cross section of the magnet, l the length of the magnet (mean length of the lines of force in the permanent magnet), then $A \div L$ should equal about 70 times $a \div l$. This ratio of $A \div L$ to $a \div l$ may be called the permanency factor of the magnetic circuit. Heinrich and Bercovitz [47] restate Hookham's formula, but say that the permanency factor should not be less than 100. In the usual bipolar construction of permanent-magnet moving-coil instruments, L is equal to the sum of the lengths of the two air gaps, or in general, it is the total length of air gap.

The Hookham permanency factor of a magnet is a purely geometrical relation and does not take into account other matters which affect the permanency, such as composition of steel, heat treatment, aging treatment, and the flux density in the finished magnet. It is, however, a useful guide in design.

5. DESIGN OF SPIRAL SPRINGS.

The zero performance of a spring depends not only on the material and method of treatment, but on its dimensions and the angle through which it is twisted in use. Formulas for spring design [48] are given by Janus and by Edgcumbe.

6. MECHANICAL DETAILS

The mechanical construction should be such as to assure the permanent relation to one another of the various parts of the instrument. The moving parts should be inclosed in a dust-tight case, and for special uses the case may have to be water-tight.

The use of hard rubber in electrical instruments has the drawback of causing corrosion of springs and fine wires. Soft-rubber tubing should be avoided, as fine connecting wires covered with it are corroded by the free sulphur, sometimes resulting in open circuits. It is preferable to use treated cotton sleeving.

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[46] On Permanent Magnets, by George Hookham, Philosophical Magazine, fifth series, **27**, p. 186; 1889.

[47] Handbuch der Elektrotechnik, **2**, pt. 5, p. 29.

[48] Janus, Elektrotechnische Zs., **26**, p. 560; 1905. Edgcumbe, Industrial Electrical Measuring Instruments, p. 16. The latter states that for phosphor-bronze springs which are to be deflected 90° the length of the spring must be at least 1500 times its thickness.

(*a*) SWITCHBOARD SHUNTS.—The limitations as to space and cost imposed on switchboard ammeter shunts apparently make it impractical to design them with the precautions which are needed for precision work, especially in shunts for large currents. In the latter, changes [49] of several per cent in the effective resistance of the shunt may sometimes be caused by changes in the method of attaching the copper bars to the shunt. Shunts for precision purposes should have the terminal blocks longer, so as to make the lines of current flow more nearly parallel at the junction of the terminal block and the resistance metal, near which junction the potential terminals should be located. The same result may be attained by constricting the section of the terminal block considerably between the current terminal and the potential terminal.[50]

VIII. TESTING OF ELECTRICAL MEASURING INSTRUMENTS

1. NECESSITY FOR TESTING OF INSTRUMENTS

Since electrical instruments which are carried about and used at times under unfavorable conditions are liable to change, means should always be provided for their periodical testing. It is important to check switchboard instruments, not only when they are received from the maker, but also regularly after they are mounted. This periodical checking should be done without dismounting the instruments from the positions in which they are used, in order that their errors under working conditions may be determined. The portable instruments used in such checking should be placed so as to be as little exposed to stray field as possible. This condition may be shown to exist by turning the portable instrument through 180° and noting that the reading is not appreciably changed by the change of position. It has been shown [51] that the removal and replacement of the pole pieces of a direct-current instrument—in fact, even the tightening of the screws that hold the pole pieces—may affect the distribution of the magnetic flux so that a scale which fitted the instrument before the operation will now show appreciable errors. It is clear from this that any mechanical change, adjustment, or accident to an instrument should be followed by a test.

Fundamental electrical standards, with a few exceptions, are for direct current. The most accurate method of measuring direct current and

[49] Rosa, Trans. Am. Inst. Elec. Engineers, **24**, p. 223; 1905.

[50] For a discussion of the design of shunts, see Wenner, Bulletin of the Bureau of Standards, **8**, p. 571, 1913; Scientific Paper No. 181.

[51] Heinrich and Bercovitz, Handbuch der Elektrotechnik, **2**, pt. 5, p. 3.

voltage is by means of a potentiometer and suitable accessories, and no laboratory for the precision checking of electrical instruments should be considered complete without a potentiometer equipment.

Carefully calibrated deflection instruments are extensively used where the requirements are less exacting. A complete potentiometer installation is expensive and for many small laboratories its cost may be prohibitive. Whatever type of deflection instrument is used, it is good practice to have a reserve instrument to check the working standard in place from time to time, unless it is possible to have the instruments tested in a near-by laboratory to which they can be carefully transported by messenger. Deflection instruments arranged to be checked at one point by reference to a standard cell are made by foreign makers. They have one of the advantages of the potentiometer—namely, that of referring the results to a standard cell, which gives the possibility of using several cells to check one another.

2. POTENTIOMETERS AND THEIR ACCESSORIES

(*a*) Primary and Secondary Standards.—Primary standards, properly so called, are not suitable for general use, but are maintained in a few well-equipped laboratories.[52] The instruments used to check service instruments may properly be called secondary standards; they should be checked by a national standardizing bureau, or by such college or other laboratories as are prepared to do this work. The secondary standards to be provided by a central station, public-service commission, or other user of instruments, will depend upon the number and kind of service instruments to be tested, and on the nature of the electrical supply concerned.

(*b*) Principle of the Potentiometer.—The potentiometer is an arrangement of resistance coils through which a constant current is maintained by a storage cell. While the arrangement of coils may be rather complicated, in principle it is equivalent to a long wire of uniform resistance per unit length, with two contacts, one or both of which are movable. If these contacts are separated, the difference of potential between them will depend on the length of the wire included between them, on the resistance per unit length, and on the current in the wire. By properly choosing the latter two, the difference of potential between the two contacts may be made an even value, say, 1 millivolt per centimeter of wire. The current

[52] Primary standards for the United States are maintained by the Bureau of Standards at Washington; those for Germany, by the Physikalisch-Technische Reichsanstalt at Berlin; for England, by the National Physical Laboratory at Teddington; those for France at the Laboratoire Centrale d'Electricite at Paris.

through the wire is adjusted to the standard value by setting the two contacts apart by an amount equal to the certified voltage of a standard cell; this cell is connected, through a key and a galvanometer, in opposition to the voltage between the two contacts. The current is then regulated until, on closing the key, the galvanometer shows no deflection. The standard cell may then be removed, and an unknown voltage put in its place and measured by moving the sliding contacts until the galvanometer again shows no deflection; the value of the unknown voltage may then be read off from the length of wire between the contacts.

The potentiometer thus measures voltage in terms of the electromotive force of a standard cell, which is simply a cell made of pure chemicals of such nature as will give a constant difference of potential between its terminals. While a measurement made with a voltmeter depends on the permanency of the magnet and springs, which can not be checked by the user, the potentiometer has the great advantage that the user can have several standard cells, and may readily substitute one for another as a check, and may compare the values of standard cells. It is recommended that three cells be used; if two of these agree but fail to check with a third, the two may be used while the third is sent to a standardizing laboratory for test. A further advantage of the potentiometer is that its accuracy depends only on the *relative* resistances of its coils, and these relative resistances may be checked by the user.

(*c*) STANDARD CELLS.—The most convenient standard cell for general laboratory use is unquestionably the Weston portable [53] cell of the unsaturated type, as supplied by the Weston Electrical Instrument Co. These cells should be guarded from extremes of temperature, and so far as possible no current should be allowed to flow through them.

(*d*) VOLT BOXES.—The fundamental range of many potentiometers is 0 to 1.5 volts; the latter value came into use because it was a round figure slightly in excess of the value of the Clark cell; it has doubtless been continued because 150-division instruments are much used, and it is convenient to have the potentiometer range agree numerically with that of the instruments to be tested. It is often convenient to have the fundamental range of the potentiometer slightly greater than 1.5 volts. For measuring volt-

[53] The Weston "normal" cell with *saturated* solution and excess of crystals is used by national laboratories because of its reproducibility. On account of its variation in electromotive force with temperature, it is not so well adapted for general use as the unsaturated cell. The Clark cell was formerly much used, but it has an objectionably large temperature coefficient, and also a time lag of electromotive force behind the temperature. There is little reason for using it at this time.

ages in excess of the range of the potentiometer an adjunct called a "volt box" is almost universally used. This is simply a resistance box in which a high resistance is connected to the line whose voltage is to be measured, while the potentiometer is connected across a definite fraction of the resistance, usually one-tenth, one-hundredth, etc. Ordinary resistance boxes of known value may be used as volt boxes for low voltages, but for the usual direct-current lighting and power voltages this practice is not advisable. Volt boxes designed for the purpose should be used; they should have a sufficient number of coils to keep the dielectric stress per coil down to a safe value, and the coils, terminals, and other parts should be properly spaced and insulated for the maximum voltage.

(*e*) MEASUREMENT OF CURRENT.—A direct current which is to be measured by the potentiometer is passed through a suitable resistance standard. The potentiometer is connected to the potential terminals of the resistance standard and measures the fall of potential across these terminals. This fall of potential, in volts, divided by the resistance of the standard in ohms, gives the value of the current in amperes. Resistance standards for this purpose are usually made of manganin, and may be air-cooled or oil-cooled. The latter method of cooling is used for the most precise laboratory work, as it not only reduces the rise of temperature of the standard under load, but also makes it possible to determine the temperature of the resistance material more accurately. For commercial work, and for some classes of laboratory work, the air-cooled (Crompton) form of resistance standard gives sufficient accuracy, when properly designed, and avoids the disagreeable features attending the use of oil. Resistance standards for measuring very large currents may require oil immersion, not for the sake of high accuracy, but to reduce their dimensions and cost.

For small currents the resistance standard is usually made to give 1 to 1.5 volts drop at full load. This brings the full-load reading well up in the range of the potentiometer. For large currents it is advisable to use a lower full-load drop, but the reduction of the drop should not be carried too far, or both the sensitivity and the accuracy will be impaired. It has sometimes been stated that the drop on the resistance standard, in precise measurements, can be reduced to very small values, the only limit being the sensitivity of the galvanometer. This is not the case, for even manganin resistance standards show slight thermal electromotive forces, and such electromotive forces often exist in the potentiometer contacts, in the junctions of connecting leads, and in the galvanometer. The resultant of all these electromotive forces introduces an error which is proportionately greater the lower the drop on the shunt. While it is true that such sources of error may be practically eliminated even with very low shunt drops, this procedure requires the introduction of reversing switches and the multiplication of the readings necessary to be taken. For this reason it is advisable to have a full-load drop of at least 0.1 volt, in which case the thermal electromotive forces may generally be neglected.

It is convenient to have two resistance standards of each denomination, one for regular use and one which is used only to check the other at intervals. If the standards are for immersion in oil, the reserve standard should be immersed only at the times when comparisons of the two are made, as the oil may become contaminated and attack the manganin, thus affecting the value of the standards in the course of time. In case of disagreement, one of the standards may be sent to a standardizing laboratory for test. If the working standard is accidentally overloaded, it should be compared with the reserve standard before it is again used. This comparison may conveniently be made by connecting the two standards in series, passing a steady direct current through them, and measuring with a potentiometer the drop across the potential terminals of each. A quick-throw switch may be used with advantage to shift the potentiometer from the one to the other. A Wheatstone bridge is not suitable for comparing resistance standards of the values ordinarily used for current measurements.

(*f*) Storage Battery Equipment.—To supply the current [54] for such work as the testing of ammeters, it is convenient to have, say, four storage cells with switches for connecting them in parallel for the maximum current, in parallel series for medium, and in series for smaller currents and for charging. A voltmeter should be provided, with a switch to connect it to each cell or to the discharge circuit. This assists in determining the condition of the individual cells. There should be an ammeter in the discharge circuit, and preferably one in series with each cell. The scale of these latter ammeters should have the zero so located that the maximum discharge current may be read to the right and the maximum charging current to the left. As the accuracy required of these ammeters is not great, they may be small and inexpensive. Such a set of cells is also useful for supplying direct current to the series coils of wattmeters and watthour meters.

[54] The current through the potentiometer should be furnished by a storage cell used only for that purpose. This cell should be placed near the potentiometer, and should be well insulated. Such a mistake, for example, as using current from an end cell of a central-station battery for this purpose is liable to produce serious inaccuracies in the measurements, as well as to burn out parts of the apparatus.

For the voltage circuits of such instruments, and for direct-current voltmeters, it is desirable to have sets of smaller cells of 10 to 40 amperehours capacity, the number of cells depending on the maximum voltage to be supplied, and the amperehour capacity depending on how large a current will be drawn at one time, and what degree of steadiness of the voltage is required.

(*g*) The Deflection Potentiometer.—The kind of potentiometer to be used will depend on the nature of the work to be done. Where the most refined precision is required, and accurate measurements must be made of very small electromotive forces, such as those of thermocouples, the potentiometer should be of the usual four-dial or five-dial form, or equivalent, and be used with a reflecting galvanometer. With this type of potentiometer it is difficult or impossible to make measurements on commercial circuits, and the equipment of storage cells just referred to can not be dispensed with. If the testing requires an accuracy not higher than one twenty-fifth of 1 per cent, and is limited to the testing of commercial electrical instruments, some advantages may be secured by using a deflection potentiometer. This potentiometer measures the larger part of the unknown current or voltage by the null principle, thus securing accuracy and reliability; the small margin of the result is read by the deflection of a pivoted moving-coil galvanometer, thus securing quickness of reading. These potentiometers, as designed at the Bureau of Standards, may be used on commercial circuits, as the changes in current or voltage are quickly followed by the galvanometer, which is designed to be just aperiodic, and takes up a new position without oscillation. Deflection potentiometers are semiportable, and when necessary may be carried about and used wherever required, as they require no special setting up and adjustment, as is necessary with reflecting galvanometers. If the circuit is fairly steady, one observer can read in succession the instrument under test and the deflection potentiometer. If the circuit is very unsteady, two observers may be required. The deflection potentiometer [55] was designed at this Bureau for its own use, and also with reference to the needs of instrument makers, central stations, and public-service commissions.

3. ALTERNATING- TO DIRECT-CURRENT TRANSFER INSTRUMENTS

All the preceding measurements can be referred, through standard resistances and standard cells, to the international electrical units. For

[55] H. B. Brooks, Bulletin of the Bureau of Standards, 8, p. 395, 1912; Scientific Paper 172.

the testing of alternating-current instruments it is necessary to provide, in addition to the potentiometer and its accessories, suitable transfer instruments; that is, instruments which can be calibrated on direct current and used without error (or with small and determinable error) on alternating current. Electrostatic and hot-wire instruments can be used for this purpose, and a recently introduced type employing the electromotive force of a thermojunction heated by the passage of the alternating current shows promise. The most suitable instruments for the purpose are, however, of the electrodynamometer type, and for convenience of working they should usually be of the pivoted form, as suspension instruments, while indispensable for some purposes, are usually too troublesome and slow for commercial work. A portable electrodynamometer voltmeter of good construction, with suitable multipliers, is a convenient transfer instrument for use in checking voltmeters of the moving-iron and the induction types. The inductance of the transfer voltmeter will not usually cause an appreciable error at any frequency used for lighting or power. If tests are to be made at higher frequencies, say 500 cycles, it is necessary to know the inductance of the voltmeter and to apply a correction for it if it is important to obtain the highest accuracy possible with the method.

For alternating voltages in excess of about 750 volts it is preferable to extend the range of the transfer voltmeter by using a voltage (potential) transformer instead of a multiplier. The ratio of such a transformer is varied by changing the secondary connected load, and hence it is advisable to have curves for the transformer showing its ratio from no load to full load for the frequencies to be used.

For the measurement of alternating-current power, well-made electrodynamometer wattmeters should be used. In the best instruments of this type the inductance of the potential circuit will introduce no error of any practical consequence except at very low power factors. The effect of mutual inductance in good wattmeters is inappreciable at all ordinary frequencies. The effect of eddy currents in badly designed wattmeters is usually more serious than that of inductance in the potential circuit

When the power of large currents is to be measured, it may be necessary or convenient to use a current transformer to extend the current range of the transfer instruments. At or near unity power factor, it is necessary to know only the ratio of transformation for the given secondary load and the frequency. With power factors appreciably below unity, it is also necessary to take into account the phase angle. (See p. 26.)

For the measurement of alternating currents of moderate value, say not over 200 amperes, electrodynamometer ammeters are made which may be used as transfer instruments. For heavier currents, a 5-ampere ammeter of this type may be used in connection with a good current transformer of known ratio. In many cases it may be preferable to use a 5-ampere ammeter only, all higher ranges being measured with the help of current transformers, each of which may have several primary current ranges. It is not necessary to know the phase angle of the current transformers for this service. However, in using a current transformer for any purpose requiring accuracy, it should be remembered that the ratio and the phase angle vary not only with the secondary current and the frequency, but they also depend on the resistance and reactance of the instruments and connections in the secondary circuit.

To supply large currents for testing alternating-current ammeters, wattmeters, and watthour meters, transformers should be provided giving low secondary voltages, such as 2 and 4 or 4 and 8 volts, depending on the length and size of the current leads, the drop in each instrument and the number of instruments to be in circuit at once. The precision electrodynamometer ammeters require several volts (the amount varying with the range) to pass full-load current through them. It is advisable to have the secondary voltage high enough to give a little margin over the anticipated requirements.

It is convenient to have indicating instruments of low cost and moderate accuracy in the test circuits, partly as a means of roughly checking results, and also to avoid overloading apparatus and circuits. Good moving-iron instruments are very useful for this purpose, as they give results correct to within a few per cent on direct current and the error certainly should not exceed 1 per cent on alternating current. They are of moderate cost, so that a good assortment may be provided without making a large outlay.

4. MEASUREMENT OF RESISTANCE AND FREQUENCY

A Wheatstone bridge should be provided, and should be kept set up with battery and galvanometer ready for use. Measurements should be made of the resistance of voltmeters, potential circuits of wattmeters, multipliers, volt boxes, etc., at the time these are received from the makers. These values should be recorded, and the resistance measurements should be repeated at intervals. Often a defective contact in a key or a loose wire connection will be detected by a bridge measurement before the trouble becomes great enough to be apparent in service.

Defective contacts sometimes occur in the secondary windings of current transformers, particularly at the binding posts. As such defective contacts may seriously affect the performance of the transformer, a measurement of the resistance of the secondary winding should always be made before testing the transformer. It should be noted that this test should be made only with a Wheatstone bridge, or other device which requires only a very small current through the secondary winding. If the measurement of resistance were made by passing a direct current of several amperes through the secondary winding, the iron core would be magnetized, and the ratio and phase angle would be affected.

The Wheatstone bridge is not suited for very low resistance measurements, such as those of ammeter shunts. These may be determined by using a potentiometer, as described on page 53. If there is a considerable amount of low resistance measurement to be done, the use of a Kelvin double bridge is more convenient, as the current need not be kept as constant as for the potentiometer method for comparing resistances.

For the measurement of frequency, instruments of the vibrating-reed type are very useful. They are free from errors due to variation of voltage and wave form, which affect the indications of most other types of frequency meter, and are thus well suited to the laboratory, where it may be necessary to vary the wave form.

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