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IEEE Standard Test Code for Resistance Measurement

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Foreword

(This Foreword is not a part of IEEE Std 118-1978, Standard Test Code for Resistance Measurement.)

The Working Group to revise IEEE Std 118, Standard Test Code for Resistance Measurement, was organized by William J. Johnson, then chairman of the Power System Instrumentation and Measurements Committee. The group met initially on March 25, 1971. It was decided that the existing standard required almost completely rewriting and this was undertaken. The general outline of the original Master Test Code was followed but much new material was added to supplement the existing information and to include new techniques which have come into general use since the previous version was written.

At the time it approved this standard the Working Group had the following membership:

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IEEE Standard Test Code for Resistance Measurement

1. General

1.1 Purpose

The purpose of this code is to present methods of measuring electrical resistance which are commonly used to determine the characteristics of electric machinery and equipment. The choice of method in any given case depends on the degree of accuracy required and the nature of the circuit to be measured. A guide for selecting the appropriate method is given in Table 1.

1.2 Scope

The methods presented here are limited to those using direct current or commercial power frequencies of 60 Hz or below and to those measurements required to determine the performance characteristics of electric machinery and equipment. Although methods of measuring insulation and ground resistance are given in this code, more complete discussions may be found in [5], [7], [11].[1]

1.3 Units

The measurement of electrical resistance is based upon the system of electrical units maintained by the countries adherent to the International Convention of the Meter. These countries cooperate officially through the International General Conference of Weights and Measures. Under this General Conference, the International Committee of Weights and Measures, aided by the advisory committees, including the Advisory Committee on Electricity, has charge of the International Bureau of Weights and Measures, Sevres, France.

The National Bureau of Standards (NBS), Department of Commerce, Washington, DC, is responsible for establishing and maintaining standards for the legalized electrical units and is the final authority in the United States for their values. In other countries, legal authority is granted to national standardizing agencies.

The unit of resistance, the ohm, is intended to be the closest practical approximation to the International System (SI) unit of resistance. A more complete discussion of SI units may be found in ANSI/IEEE Std 268-1976, Standard Metric Practice. The value of the unit of resistance was adopted in 1948 by international agreement and has been maintained since then with negligible fluctuation by a group of standard resistors. This unit is usually designated as the legal ohm,

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[1] Numbers in brackets correspond to those of the references listed at the end of this standard, in Section 6.

the absolute ohm, or simply the ohm. Before 1948, the unit was designated as the international ohm and was 495 parts per million larger than the present unit.

Knowledge of the amount by which the legal unit differs from the defined SI unit depends upon the results of absolute measurements; on the basis of measurements made at NBS and other national standardizing laboratories, it may be concluded that the two units are unlikely to differ by more than one part per million.

Table 1—Applications of Resistance Measuring Methods

Resistance to be Measured	Accuracy Required Note (5)	Bridge Methods Note (2)	Direct Reading Methods	Alternative Methods
Low Resistance (see 2.1) (less than approximately 5 Ω	Greater than 0.1%	Kelvin (4.5.3), current comparator (4.5.6)	Note generally applicable	Note (4)
	0.1%–1%	Kelvin (4.5.3)	dual-slope in tegration meter (4.4.3) ratio device, crossed coil (4.4.1)	Note (4)
	less than 1 %	any bridge-type circuit	direct-reading ohmmeter (4.7.4) ratio device, crossed coil (4.4.1)	ammeter (4.3)
Intermediate value resistance (see 2.3) (between approximately 5 Ω and 10 Ω)	Greater than 0.01%	Wheatstone (4.5.1) ratio (4.5.2) comparators (4.6.1) current comparator (4.5.6)	Not generally applicable	
	0.01%–1%	Wheatstone (4.5.1) ratio (4.5.2)	dual-slope in gration tion meter (4.4.3)	Operational amplifier (4.4.2), ohmmeter, constant-current type (4.7.3)
	less than 1%	any bridge-type circuit	direct-reading ahmmeter (4.4.3)	voltmeter/ammeter (4.1), volt- meter (4.2), ratio device, crossed coil (4.4.1), note (3)
High Resistance (see 2.2) (above approx- imately 10 Ω M)	Greater than 0.1%	Modified Wheatstone (4.5.4) ratio (4.5.2) comparators (4.6.1) current comparator (4.5.6)	Not generally applicable	
	01.%–1%	modified Wheatstone (4.5.4) ratio (4.5.2)	operational amplifier (4.4.2)	Voltmeter/ ammeter,modified (4.1.1)
	less than 1%	Wheatstone (4.5.1)	radio device, crossed coil (4.4.1)	direct deflection (4.6.2) loss of charge (4.8.1) voltmeter/ammeter (4.1 and 4.1.1)

NOTES:
1 — Numbers in parentheses refer to section numbers in the text.

2 — Limit and deviation techniques may be applicable in all cases (see 4.5.5).

3 — Almost any of the measuring circuits described can be adapted for use in this category.

4 — Other bridge, ratio, and comparator circuits may be used.

5 — This column indicates long-term accuracy, including stability and temperature effects.

2. General Measurement Problems and Techniques

2.1 Low-Value Resistance Measurements

In low-value resistance measurements, contact resistances may seriously limit accuracy; however, their effects can be reduced considerably by using resistor with four terminals. A resistor of this type is shown in Fig 1. The four-terminal resistance is the resistance between the internal junctions J_1 and J_2 and is defined as

$$R_x = E_{cd}/I_{ab} \tag{1}$$

where I_{ab} is the current into terminal A and out of terminal B and E_{cd} is the potential between terminals C and D (and therefore between junctions J_1 and J_2).

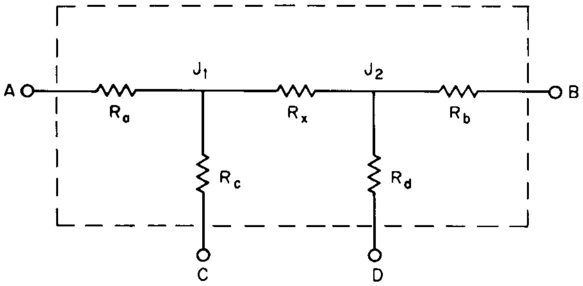


Figure 1—Four Terminal Representation of a Resistor

A very useful property of a four-terminal resistor, derivable from the reciprocity theorem, is that the four-terminal resistance is unchanged if the two potential terminals are used as current terminals while the two current terminals are used as potential terminals. In other words,

$$E_{cd}/I_{ab} = E_{ab}/I_{cd} = R_x \tag{2}$$

This statement assumes that the self-heating effects, if significant, remain the same when the current and potential terminals are reversed. Since this assumption is not always valid when high currents are used and significant heating occurs in the terminal resistances R_a, R_b, R_c, and R_d, the precise position of these terminals may be critical.

Based on the above definition of four-terminal resistance, the terminals on such a resistor are often referred to as current terminals and potential terminals. However, it is not necessary to measure a four-terminal resistor as implied in the definition (that is, with zero current at two of the terminals), and many four-terminal resistance measuring instruments operate with current in all four leads.

Some four-terminal resistance measuring instruments and techniques measure R(x) almost independently of the values of terminal resistances R_a, R_b, R_c, and R_d, the resistance of the leads connected to the terminals, and the contact resistance between the leads and the terminals. Other measuring instruments and techniques only reduce the effect of these resistances by putting them in series with resistances in the measuring circuit whose values are higher than R(x) or by connecting them in other less sensitive parts of the measuring circuit.

The advantages of a four-terminal resistance measurement can be realized when measuring two-terminal resistors by connecting two leads to each end of the resistor to convert it into a four-terminal resistor, as shown in Fig 2. The effect of the four contact resistances and lead resistances can then be effectively eliminated or reduced. It is important to note that the resistance measured with be the resistance between the contacts at each end that are closest to the resistor.

The value of resistance below which it is desirable to use the four-terminal technique depends somewhat on the accuracy required and the quality of the contact surface. The value often chosen is 5 Ω.

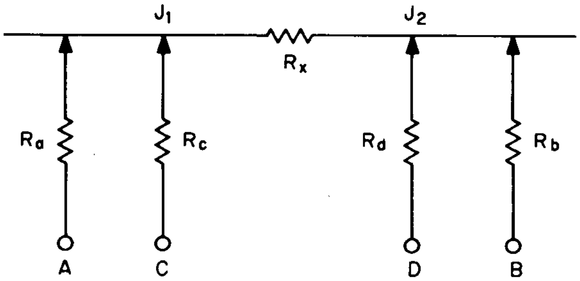


Figure 2—Four Terminal Connections to a Two Terminal Resistor

2.2 High-Value Resistance Measurements

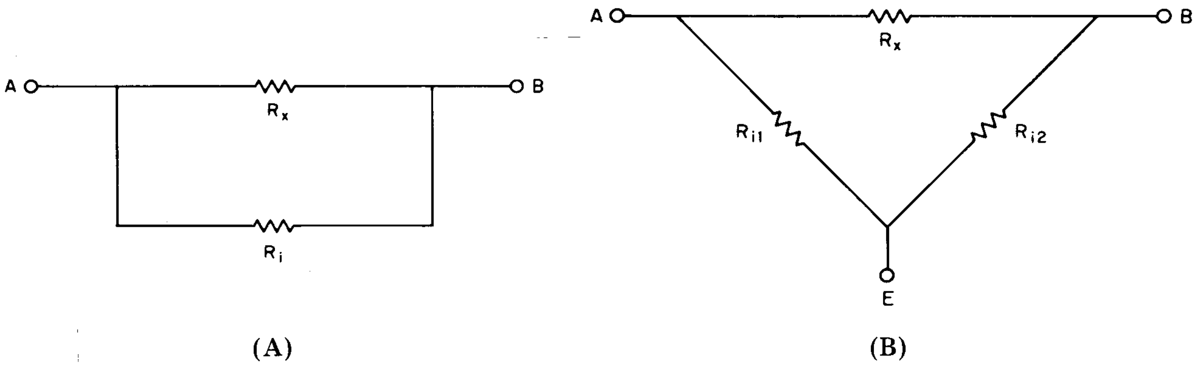
In high-value resistance measurements, insulation resistances may seriously limit accuracy. The equivalent circuit of an undesirable insulation is shown in Fig 3(A), where the resistance to be measured (R_x) is shunted by the resistance of an insulator (R_i). This would result, for instance, if both supports or test clips for a resistor were mounted on the same piece of insulation.

The equivalent circuit of a more desirable situation is shown in Fig 3(B). This circuit would result, for instance, if the supports or test clips at each end of the resistor to be measured were mounted on individual insulators that separated by a conductor to E. It would then be possible to measure R_x with the effects of the insulation resistances (R_{i1}) and R_{i2}) reduced or eliminated.

The effects of insulation resistances may be controlled by means of a three-terminal resistance measurement. This is done in the measuring circuit by connecting the insulation resistances (R_{il}) and R_{i2}) where they will not affect the result at all, or where they will shunt resistors that are lower in value than R_x, or by reducing the voltage across one of the insulation resistances to zero so that all of the current in one of the measurement terminals passes through the resistor being measured. (See also 4.5.4.)

Some standard resistors of higher value are of three-terminal construction (see also 3.7), with measurement terminals mounted on separate insulators and an additional terminal connected to the case.

To avoid problems with test connections in a three-terminal measurement, two separately shielded leads should be used for connections to the measurement themselves.



(A) (B)

Figure 3—(A) -- Equivalent Circuit for a Resistor Shunted by Insulation Leakage. (B) -- Equivalent Circuit Showing Method of Reducing the Effect of Insulation Leakage.

2.3 Intermediate-Value Resistance Measurements

In intermediate-value resistance measurements of moderate accuracy, usually no serious limitations on accuracy result from either contact resistances or insulation resistances. On the other hand, in resistance measurements of the highest accuracy, both contact resistances and insulation resistances can limit the accuracy.

Contact and insulation resistance problems can be handled simultaneously by combining the features of four-terminal and three-terminal measurements in the same measurement. The equivalent circuit of a resistor whose measurement could be limited by both of these factors is shown in Fig 4. The effects of the contact and insulation resistances are controlled as described in 2.1 and 2.2.

A measurement that controls the effects of contact and insulation resistances simultaneously can be referred to as a five-terminal measurement. Some standard resistors are of five-terminal construction. (See Section 3.)

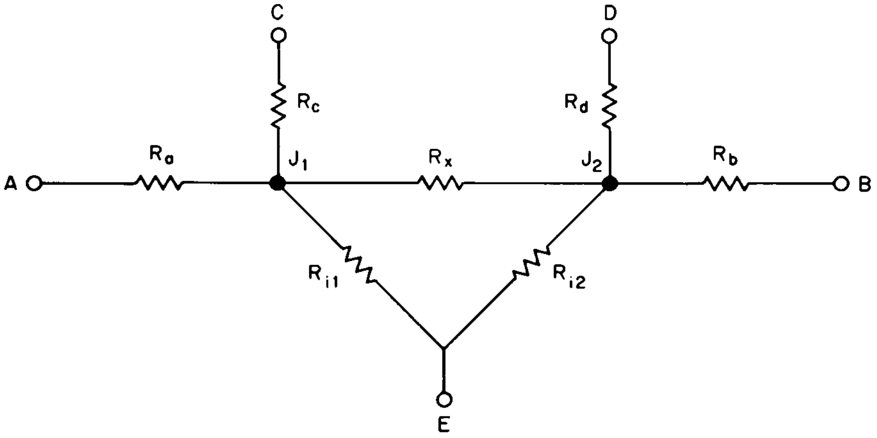


Figure 4—Equivalent Circuit of a Resistor Incorporating Techniques of Fig 1 and Fig 3(B)

2.4 High-Current Resistance Measurements

When measuring resistors at high currents, contact resistance effects, discussed in 2.1, and self-heating effects, discussed in 2.7, usually must be taken into account. An additional source of uncertainty in the effective resistance of a high-current resistor of the four-terminal type can arise from nonuniform distribution of current resulting from the placement of leads at different locations at the current terminals or nonuniform potential on the potential terminals. These effects can be minimized by increasing the length-to-width ratio of the conductors between the terminals and the four-terminal junctions. (See also 3.4.)

2.5 High-Voltage Resistance Measurements

When measuring resistors at high voltage, insulation effects, discussed in 2.2, and self-heating effects, discussed in 2.7, usually must be taken into account. In addition, some high-voltage resistors have a voltage coefficient, that is, their value is affected by voltage in addition to self-heating. In measurements where regions of high electrical stress exist, care must be taken to minimize the effects of partial discharges (corona). (See also 3.6.)

2.6 Environmental Effects

The value of most resistors is affected by environmental parameters such as temperature, humidity, atmospheric pressure, and chemical and biological corrosion. When measurements of the highest precision are undertaken, all of these factors must be taken into account. In most practical situations, however, temperature is the principal concern. Most pure metals have a temperature coefficient of approximately 0.4 percent per degree Celsius. Several precision resistor alloys have temperature coefficients below 0.0005 percent per degree Celsius over a range of at least 50 degrees.

2.7 Self-Heating Effects

It is usually essential that the resistance under test not be changed in value to a significant extent by the current which is necessarily used in the measurement. This requirement sometimes limits the permissible current and hence the sensitivity of the measurement. When measuring the resistance of a copper (or aluminum) winding, the error from this cause is proportional to the square of the measuring current. For small windings, the current should not exceed 15 percent of the rated current of the winding. If the winding is so massive that the resistance measurement can be completed before the full temperature rise that would result from continued application of the measuring current is reached, the error will be less and currents of up to 25 percent (or in extreme cases, 50 percent) of rated current may be used. It is important that the temperature of the winding at the time of the resistance measurement be known definitely, whether the resistance measurement is desired for calculating efficiency (after being corrected to an appropriate reference temperature) or as a basis for measuring temperature rise. Any heating by previous operation or by unduly prolonged measuring currents should be avoided [19], [20].

2.8 Interconnected Resistances

When a resistor, low enough in value to have its measurement seriously affected by contact resistances, is part of an interconnected network of resistors that can shunt it (that is, a closed loop of resistors), it is still possible to measure its value precisely using six-terminal techniques.

A practical situation involving this problem is the measurement of a winding resistance in a delta-connected transformer when it is difficult or undesirable to disconnect the measured winding from the others. The equivalent circuit is shown in Fig 5, where R_x is the resistance to be measured, R_a, R_b, R_c, R_d, R_f, and R_g are terminal resistances, and R_y and R_z are resistances with values usually comparable to R_x.

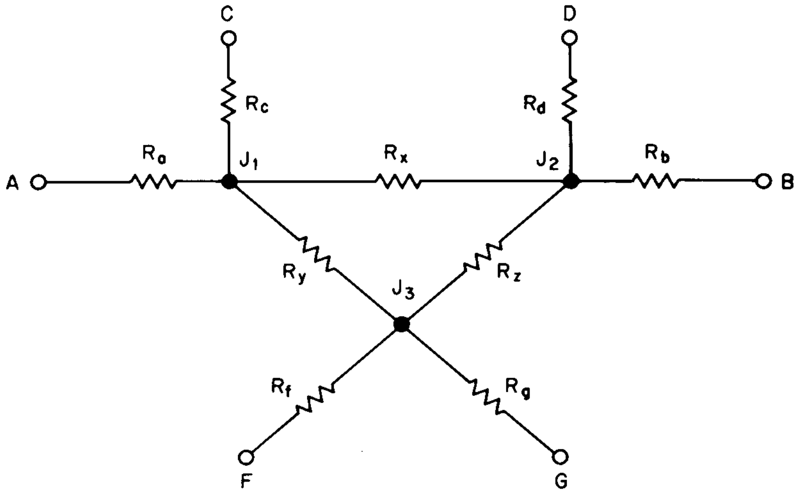


Figure 5—A Six Terminal Resistor Measurement

The value of R_x can be measured as follows:

$$R_x = E_{cd}/I_b \qquad \text{if} \qquad E_{gd} = 0 \tag{3}$$

where I_b is the current out of terminal B, E_{cd} is the potential between terminals C and D (and between J_1 and J_2), and E_{gd} is the potential between terminals G and D (and between J_3 and J_2). E_{gd} is brought to zero by adjusting the current out of terminal F. The current into terminal A is the sum of the currents out of terminals B and F. (See also 4.1.1 and Fig 11.) A six-terminal technique can also be used on three-terminal networks by applying the methods described in 2.1.

2.9 Substitution Methods

If a known resistance (R_s) is available which has about the same value as the unknown resistance (R_x), each should be connected in succession to the measuring apparatus and measured. Most of the systematic errors in the measuring apparatus will be the same in both measurements and will disappear when R_x is expressed as the product of R_s and a factor derived from the two readings; thus

$$R_x = R_s \times (\text{ratio of measured value of} R_x : R_s) \tag{4}$$

In resistance measurements for determining temperature rise, this principle comes into use almost automatically. In such cases, by proceeding so that all leads, contacts, etc, are changed as little as possible while the test specimen heats up, temperature rise measurements of a very high accuracy are possible.

If several known resistors are available, a large number of dial settings of the measuring circuit can be calibrated by measuring groups of these resistors in series and parallel combinations.

2.10 Measurement of Resistance in the Presence of Inductance

WARNING: When making measurements on highly inductive windings, hazardous voltage may be induced. Each individual situation must be carefully evaluated to avoid danger to personnel.

When the circuit being measured has such a high inductance that its time constant (*L/R*) is also very large, considerable inconvenience is caused by the delay in reaching steady conditions. In measuring the resistance of a heated winding which is cooling rapidly, any such delay may impair the measurement.

The inductive effect may be reduced by the following methods:

1) Use a higher voltage supply with a high resistance in series to reduce the time constant (*L/R*)
2) Apply a higher voltage initially, then decrease it as the current increases, either manually or by automatic current regulation
3) With iron-cored inductors when circumstances permit, sufficient voltage may be applied in an auxiliary winding to saturate the magnetic material
4) When measuring resistances where more than one winding is present, an idle winding may be used effectively (see Fig 6).

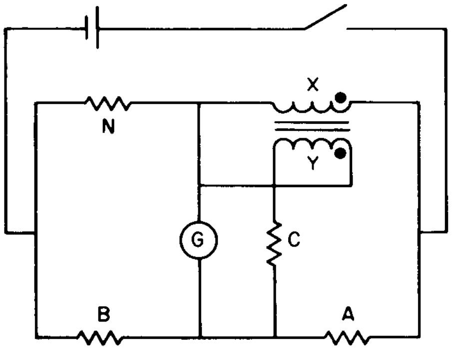


Figure 6—Use of an Idle Winding When Measuring Resistance in the Presence of Inductance

If the total resistance ($R_c + R_y$) in the compensating circuit is adjusted to satisfy the relation

$$R_c + R_y = R_a + R_x \frac{N_y}{N_x} \tag{5}$$

where N_x and N_y are the numbers of turns of windings X and Y, respectively, the current induced by the changing core flux, which is common to X and Y, will not circulate in the galvanometer. The bridge may be balanced by the adjustment of R_n (or R_b) without waiting for the current to become constant. An alternate circuit (shown in Fig 7) may be used if the number of turns of the idle winding is equal to or greater than that of the winding whose resistance is being measured. The voltage divider should be adjusted to provide unity voltage gain between winding X and the galvanometer; that is, its ratio should be set to N_x/N_y.

This technique is most often used with the Wheatstone bridge (see 4.5.1), but similar compensating circuits may be applied to other types of bridges.

WARNING: Damage to instrumentation or injury or paranel may result from the induced electromotive force if the circuit is opened while large currents are present.

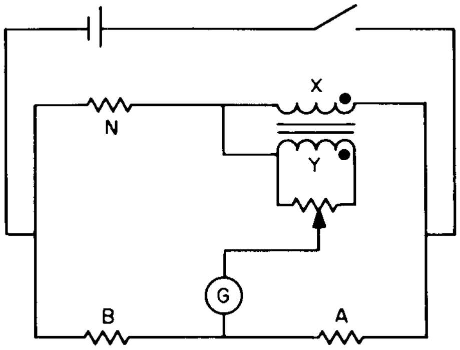


Figure 7—Alternate Circuit to Fig 6

2.11 Measurement of Resistance in the Presence of Capacitance

When the resistance being measured is high and has an appreciable shunt capacitance (either discrete or distributed), the charging current of the capacitance will cause a considerable delay in reaching a steady voltage. This delay can be reduced by using a supply whose internal resistance is low. If a resistance (R_x) shunted by a capacitance (C) is being supplied from a source whose effective internal resistance is R_i, the time constant (T_c) of the circuit is derived from the following equation:

$$T_c = \frac{R_x R_1 C}{R_x + R_1} \approx C R_i \quad \text{when} \quad R_x \gg R_i \tag{6}$$

When a constant supply voltage, the current must be allowed to decay for a period equal to 2.3 T_c for an accuracy of 10 percent, 4.6 T_c for an accuracy of 1 percent, and 6.9 T_c for an accuracy of 0.1 percent, etc. If the dielectric shows marked absorption, even longer periods will be required. If the voltage applied to the resistor varies by P percent during one time constant, the error in the measured resistance will be P percent.

> WARNING: Damage to instrumentation or injury to personnel may occur as a result of voltage that may be developed from charges still absorbed in the dielectric of a capacitor that has been apparently discharged.

2.12 Stray Effects

Most resistance measuring circuits contain undesirable currents that result from pickup of external noise and hum, internal signal sources that are not pure direct current or pure alternating current, spurious electromotive forces such as those due to thermoelectric effects, and current or voltage offsets of the detectors. The accuracy of the measurement will be limited by the response of the detectors to these undesirable signals. In alternating-current measurements, this problem is usually solved by using a detector tuned to respond only to the desirable signal frequency. In direct-current measurement, this problem is solved by using detectors with adequate alternating-current rejection (that is, those that do not indicate a significant direct-current signal due to an alternating-current input) and by use of the false-zero procedure.

The false-zero procedure refers to taking as the zero point of the measuring apparatus its indication when the spurious effects are present but when the power supply is disconnected. This false zero is then used as the null point. In bridge measurements a doubling of sensitivity may also be achieved by defining the balance point as that for which the detector indication does not change with reversal of the polarity of the power supply.

2.13 Measurement of Resistance with Alternating Currents

The measurement of resistance by means of alternating currents is attractive because it permits the use of very stable former ratio techniques and eliminates the effect of thermal electromotive forces. However, the resistance to alternating current may differ from the resistance to direct current for the following reasons:

1) Shunt or Series Reactance — Inductance in series and capacitance in shunt with a resistance, either discrete or distributed, will alter the impedance (or the effective resistance, or both) to alternating current
2) Skin Effect — Magnetic fields produced by the current within the conductor, which increases the impedance at the conductor's center, force the current to concentrate near the outside surface or skin. The effective cross-sectional area of the conductor is therefore reduced. Skin effect is most noticeable in conductors of large cross section. This effect increases with frequency and, in conductors of ferromagnetic material, is a function of the relative permeability

3) Proximity Effect — The magnetic field produced by currents in other conductors which are in close proximity will influence the current distribution in the resistance being measured and cause an increase in its effective value similar to that due to skin effect
4) Stray Coupling—Eddy Currents — Coupled losses may result from currents induced in nearby conducting material
5) Stray Coupling—Hysteresis — Hysteresis losses may result from magnetic fields induced in nearby ferromagnetic material
6) Dielectric Losses — Dielectric losses may occur in shunt capacitances.

The resistive equivalent of these effects added to the direct-current resistance is known as the alternating-current resistance. However, it is often possible to assume from the design of the resistor that these effects are negligible and hence that the alternating-current resistance is the same as the direct-current resistance.

3. Standard Resistors

3.1 Standardization of Apparatus

Before using an instrument, the user should have some assurance of its ability to give results to the accuracy or precision required. If the instrument is to be used for measurements at a limited number of points, it may be possible to use a substitution method (see 2.9) to calibrate the instrument. In the general case, where the instrument will be used to measure either a wide range of values, or values for which no standard is available, a complete calibration of the instrument may be required. Some instruments are designed for self-calibration, that is, they can be calibrated using little or no additional apparatus. The calibration of other apparatus may be so involved that it may be desirable to send it back to the manufacturer or to a commercial testing laboratory for calibration.

3.2 Reference-Standard Resistors

These standards (also called precision resistors, standard resistors, or shunts) are resistors demonstrating a high degree of stability and are intended for use as reference standards in accurate dc resistance measurements. These resistors are constructed from alloys having low temperature coefficients of resistance. They may be of the two-, three-, four-, or five-terminal design, depending upon the resistance value and the precision. Although the standard may be of any required value, values are predominantly decimal multiples or submultiples of 1 Ω. These standards may be intercompared with the National Standards (of resistance) on a periodic basis. (Specifications for Reference-Standard Electrical Resistors are given in [6].)

3.3 Working-Standard Resistors

These may be similar in construction to reference-standards, differing only in their application, or they may be adapted by construction or dimension to some specific measuring procedure. Thus, in the routine testing of copper wire and cable, working standards of copper of the same temperature coefficient as the test specimens are frequently used so that the measured value of the resistance of the specimen is automatically corrected to a standard temperature, provided the standard and the test specimen are at the same temperature when the specimen is tested and that the working standard was at the standard temperature when it was compared with the reference-standard.

Working standards may also be resistance boxes which consist of a number of resistors enclosed in a container and so arranged that numerous combinations of resistors can be connected between the terminals of the box by suitable manipulation of dial switches, links, or plug contacts. Some specific types of working standards are described in 3.4 through 3.7.

3.4 Heavy-Current Standard Resistors

For use in measurements involving large currents, the standard resistor must be provided with effective cooling, usually by increasing its surface area and by circulating oil, air, or water as a cooling medium. If the resistance is a definite function of the temperature of the cooling medium only (that is, if any heat developed by current through the resistor is carried off by the coolant without materially affecting the temperature of the resistance alloy), the standard resistor is “thermally self-contained” and, if previously tested over a particular current range, is suitable for measurements of high accuracy in this range. Standard resistors with short, thick current terminals, such as the usual forms of switchboard shunt, are not thermally self-contained. The resistance may depend to an appreciable extent upon the heat developed at the current terminal contacts or conducted inward or outward by the current leads. For precise work with such standard resistors, the temperature of the resistance alloy must be measured both when the shunt is tested initially and when it is used.

A common source of uncertainty in the effective resistance of heavy-current shunts of the four-terminal type is nonuniform distribution of current when connections are made at different locations on the current terminals. In extreme cases, errors of 1 percent may occur. These effects are minimized by locating the potential taps on the axis of symmetry and by providing resistance between the current contact surface and the potential tap. (See also 2.4.)

3.5 Nonreactive Resistors

For alternating-current measurements, it is essential that the inductive and capacitive reactance and skin effect of the standard resistors used are either negligible or so small and definite that corrections for their effects can be applied. In wire-wound standard resistors, inductive reactance predominates in resistors of less than 1 Ω, while capacitive reactance predominates in resistors of over 100 Ω. In the intermediate range, time constants as low as 10^{-8} s can be obtained.

In low-resistance standard resistors of the four-terminal type, the net inductance may often be made very small by arranging the potential leads so that the mutual inductance between them and the current circuit offsets the self-inductance of the current circuit between tap points. For use in precise alternating-current measurements, the standard should either have such a geometrical configuration that its inductance is computable or its inductance should be determined experimentally by comparison with a standard resistor of known inductance.

In wire-wound resistors of higher value, used with alternating voltages, serious errors may arise from the shunting effect of capacitance. Above 50 000 Ω it is usually necessary to subdivide the resistor and to provide shields for the component sections. If the shields are connected to points on a parallel guard circuit which have approximately the same potentials as the portions of the resistor which they shield, the capacitive currents to ground occur only in the guard circuit and their effect on the shielded resistor is greatly reduced.

3.6 High-Voltage Resistors

Resistors used in high-voltage circuits must be capable of dissipating a large amount of heat or be of very high resistance. These resistors are usually subdivided to reduce self-heating, and the component sections are shielded as described in 3.5 so that any partial discharges (corona) produce currents in the guard circuit only. If the shields are shaped with rounded edges of proper design, corona may be avoided. On direct-current circuits, such rounded shields may be tied to the working circuit. (A high-voltage standard resistor is described in [8].) (See also 2.5.)

3.7 High-Resistance Standard Resistors

Wire-wound resistors with values of 100 MΩ or more that have a high degree of stability and low temperature coefficients have been made, but they are very bulky and expensive. For some uses, resistors of 1 MΩ or larger are made by putting a semiconducting material on an insulating form which is then hermetically sealed. These resistors may have relatively poor stability, high temperature coefficients of resistance, and large and nonlinear voltage coefficients; and despite being hermetically sealed, they may still be affected by humidity due to surface conduction on the container. Whenever high accuracy is required, the standard should be calibrated as soon as possible before or after use. (See also 2.2.)

3.8 Combinations of Standard Resistors

To reduce the number of reference-standard resistors required, some means of accurately comparing resistors of different nominal values is necessary. One method of doing this is by using series and parallel combinations of standard resistors (commonly known as transfer standards), a common type having n (n=10 usually) nominally equal resistors connected in series and arranged so that they can be connected in parallel.

With *n* nominally equal resistors having the value

$$M_1 = M(1+m_1), M_2 = M(1+m_2), \ldots,\\ M_n = M(1+m_n) \qquad (7A)$$

(where *M* is the mean value of the *n* resistors and m_i is the departure of the *i*th resistor from the mean of the group), the total resistance of the group connected in series *S* will be

$$S = nM \qquad (7B)$$

If *P* is equal to the resistance of the group, connected in parallel,

$$\frac{1}{P} = \frac{1}{M} \sum_{i=1}^{n} \frac{1}{1+m_i} = \frac{n}{M}\left(1 + \frac{1}{n}\sum_{i=1}^{n} m i^2\right) \qquad (8A)$$

by neglecting terms of third and higher order, since by the definition of m_i,

$$\sum_{i=1}^{n} m_i = 0 \qquad (8B)$$

Then,

$$S = n^2 P\left(1 + \frac{1}{n}\sum_{i=1}^{n} m_i^2\right) \qquad (9)$$

Since there is no problem in matching resistors to 0.1 percent or better, the

$$(1/n)\sum_{i=1}^{n} m_i^2$$

error term can be reduced to less than 1 part per million if the effects of leakage are made negligible and the resistance of the conductors used in making the series and parallel connections can be neglected or accounted for. For resistors having a nominal value of 10 kΩ or more, there is no problem in meeting these requirements using two-terminal resistors; but for 10 Ω resistors, the resistance of the connecting conductor would make it very difficult to get a part per million or better accuracy using two-terminal resistors. Hamon described a method of connecting four-terminal resistors in parallel such that the parallel resistance would satisfy equation 9. (See [9].)

Since the square root of 10 is not an integer, this method cannot be used to make to 10-to-1 jump in resistance value; however, each of the 10 resistors can be measured against a reference resistor having the same nominal value, and then a standard of either 10 times or 1/10 the value of the reference resistor can be measured against the transfer standard connected in either mode.

4. Instrumentation

4.1 Voltmeter-Ammeter (Drop of Potential) Method

The basic circuits and operations for this method are shown in Figs 8 and 9.

The following equation is used for measuring with the circuit shown in Fig 8:

$$R_x = \frac{V}{I - V/R_v} \tag{10}$$

where V is the voltmeter reading, I is the ammeter reading, and R_v is the internal resistance of the voltmeter.

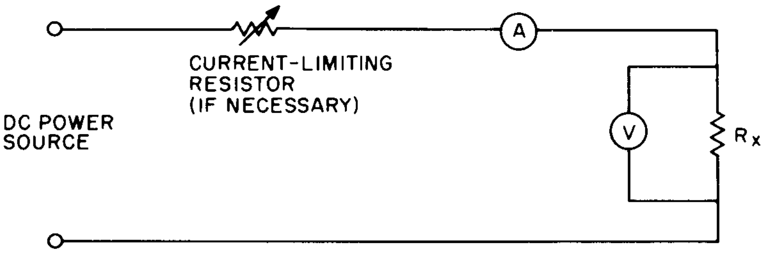


Figure 8—Voltmeter-Ammeter Measurement--Low Value Resistors

The equation used for measuring with the circuit shown in Fig 9 is as follows:

$$R_x = \frac{V - IR_a}{I} \tag{11}$$

where the nomenclature is the same as that used in equation 10, and where R_a is the ammeter resistance.

Fig 8 shows the circuit preferred for low-value resistors, while the circuit shown in Fig 9 is preferable for high-value resistors. Either circuit may be used for intermediate-value resistors. Depending upon the desired accuracy, the correction terms (due to R_v and R_a) may frequently be neglected. For low-value resistors, R_x may be a four-terminal device and the voltmeter may be a millivoltmeter used with calibrated leads. For high-value resistors, the ammeter may be a microammeter or a more sensitive instrument, such as an electronic electrometer. In such cases, it is necessary to employ guarding and to bypass the leakage current around the current meter, as shown in Fig 10.

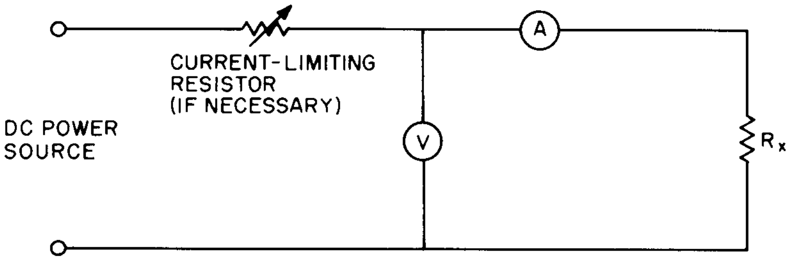


Figure 9—Voltmeter-Ammeter Measurement–Medium Value Resistors

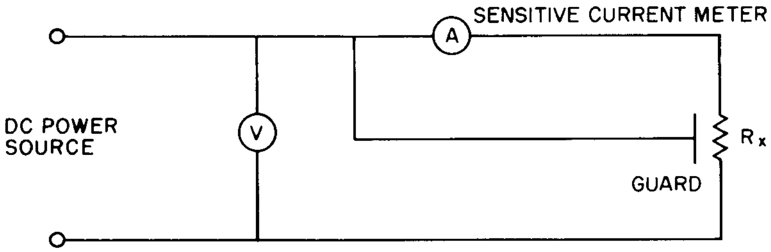


Figure 10—Voltmeter-Ammeter Measurement-High Value Resistors

4.1.1 Modified Voltmeter-Ammeter Method for Measuring Six-Terminal Resistors

The circuit for this method is shown in Fig 11. (See also 2.8.) Rheostat R_1 is adjusted until the galvanometer (G) indicates a null. R_2 is adjusted to obtain the desired current in the unknown resistor (R_x). For these conditions,

$$R_x = V_{cd}/I_b \tag{12}$$

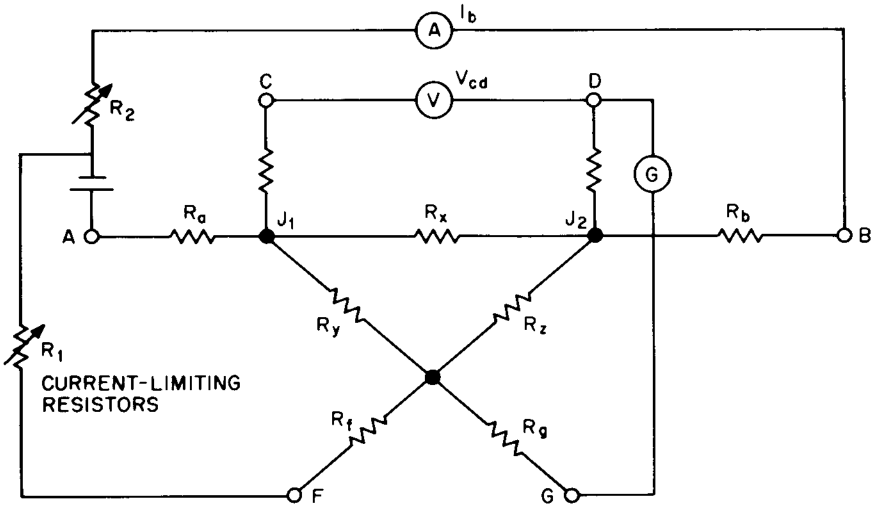


Figure 11—Modified Voltmeter-Ammeter Method (Six Terminal Resistor)

4.2 Voltmeter Method

The circuit used in this method is shown in Fig 12. The voltmeter method permits both voltage and current to be measured by one instrument. Two readings are taken: with the switch (S) in position one, the supply voltage (V_1) is measured; with the switch in position two, V_2 is read. R_x is given by the following equation:

$$R_x = \frac{V_1 - V_2}{V_2} R_v \tag{13}$$

where R_v is the internal resistance of the voltmeter.

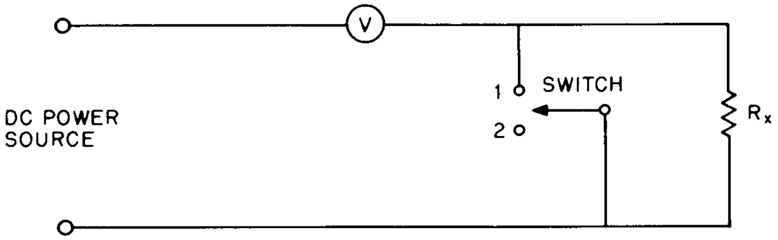


Figure 12—Voltmeter Method of Resistance Measurement

4.3 Ammeter Method

For low-value resistors the ammeter method is more suitable than the voltmeter method. The basic circuit is given in Fig 13. An ammeter reading (I) is taken with the switch open. The switch (S) is then closed and a reading (I_2) is taken. For large values of the limiting resistor (giving essentially a constant current source), R_x is given by the following equation:

$$R_x = \frac{I_2 R_a}{I_1 - I_2} \tag{14}$$

where R_a is the resistance of the ammeter.

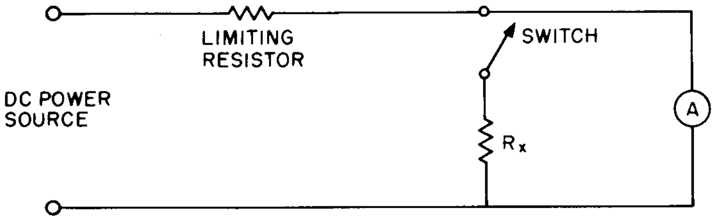


Figure 13—Ammeter Method of Resistance Measurement

4.4 Ratio Devices

4.4.1 Crossed-Coil Type

Several meter movements are available which indicate the ratio of two currents. Most incorporate two moving coils arranged so that the meter deflection is proportional to the ratio of the voltage and current applied to an unknown resistance. Such devices may be powered by internal or external sources, and they can be calibrated to indicate the unknown resistance directly. The basic circuit is shown in Fig 14.

While such instruments give readings which are, within wide limits, independent of the source voltage, constant voltage sources are frequently provided to avoid charging-current effects when the resistance of electric cables or other capacitive specimens is measured. Instruments of this type are available for measuring wide ranges of resistance and can be built with provisions for guarding and for measuring four-terminal resistors.

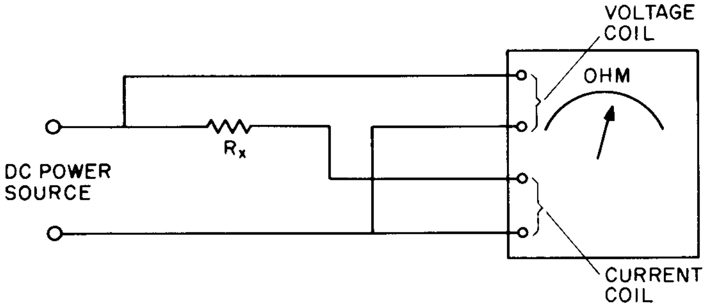


Figure 14—Crossed-Coil Type Ratio Ohmmeter

4.4.2 Operational Amplifier Type

Resistance can be measured by means of an operational amplifier and a direct-current voltmeter. Extensive literature exists describing operational amplifier techniques in detail. Fig 15 shows a typical circuit.

$$V_{out} = \frac{R_x}{R_s} \times V_{in} \text{ and } R_x = V_{out}\frac{R_s}{V_{in}} \tag{15}$$

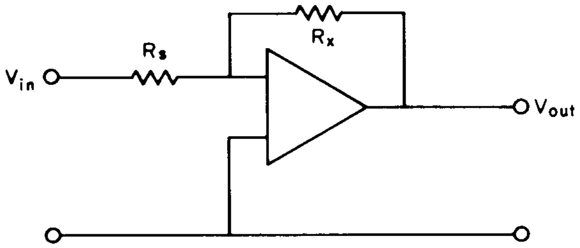


Figure 15—Operational Amplifier Resistance Measurement

4.4.3 Dual-Slope, Integration-Type Digital Ratio Meter

In this method, illustrated in Fig 16A, a constant current source, derived from a voltage reference (V_{ref}), produces a current (I) in the unknown resistor (R_x). (This circuit was originated and patented by Gilbert [21].) The resulting voltage generated across R_x charges the capacitor of an integrating circuit [see Fig 16B] in a known time (T_1) determined by a stable oscillator producing N_1 clock pulses. At the end of this period, the counter which has been counting the pulses is returned to zero. The reference voltage is then reversed across the input of the integrating circuit, causing the capacitor to discharge.

When the capacitor is fully discharged (output voltage zero) in time T_2, the counter is stopped and shows count N_2.

R_x is then derived by the following equation:

$$R_x = \frac{V_{ref}}{I} \times \frac{N_2}{N_1} = KN_2 \tag{16}$$

The resulting value of R_x is independent of the clock rate and the time constant (RC) of the integrating circuit. It depends primarily upon V_{ref} and the value of the resistor used to generate the constant current (I). Range changing is done by varying the current either manually or automatically.

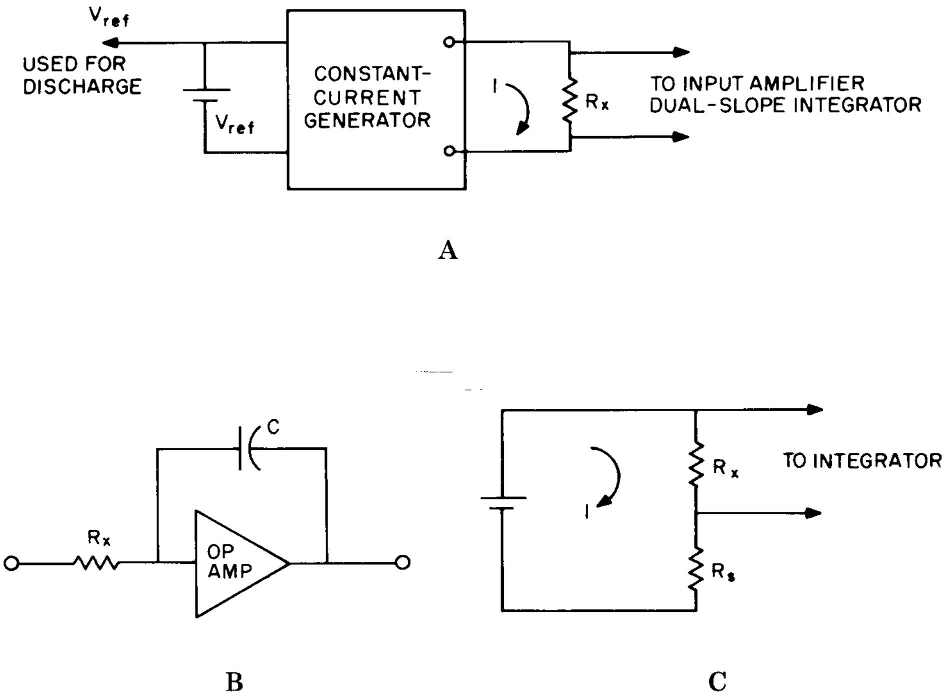


Figure 16—A — Dual Slope, Integration-Type Digital Ratio Ohmmeter. B — Capacitor Integrating Circuit-Dual Slope Integrator. C — Alternative Integration Method

Another method consists in first charging the capacitor by means of the IR_x drop in the unknown resistor, as shown in Fig 16C. This again occurs in time T_1 and count N_1. The capacitor is discharged by the drop IR_s in the standard resistor in time T_2 and count N_2. For this condition,

$$R_x = \frac{R_s N_2}{N_1} = KN_2 \tag{17}$$

Thus the measurement depends upon only the standard resistor (R_s). Range changing is clone manually or automatically by changing R_s. This method requires either an isolated power supply or isolated inputs for both IR_x and IR_s.

4.5 Bridges

Under most circumstances, a bridge circuit is the most accurate method of measuring resistance. The following subsections describe some of the bridge circuits most commonly used for resistance measurement.

4.5.1 Basic Wheatstone Bridge

The circuit of a Wheatstone bridge, shown in Fig 17, consists of four resistance arms, a source of current (usually a battery), and a detector. The measurement of the unknown R_x is made in terms of the three known resistances. Adjustment of the three resistances is made for zero current in the detector at balance; therefore, this is a "null balance" method of resistance measurement.

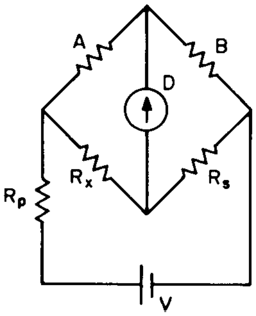


Figure 17—Wheatstone Bridge

When the bridge is balanced, as indicated by a null reading of the detector D, the unknown resistance is given by the following equation:

$$R_x = \frac{R_A}{R_B} = R_s \tag{18}$$

where R_A and R_B are the values of the ratio resistors, while R_s is the value of the standard resistor. These resistors may be adjustable either continuously or in steps. A protective resistor R_p is used to protect the bridge elements.

4.5.2 Julie Ratio-Type Bridge

In order to make use of high-precision voltage dividers, the circuit shown in Fig 18 is used. For this circuit, at balance,

$$R_x = K\frac{R_d(1 + R_A/R_B)}{1 + (R_d + R_{det})/C} + \frac{(R_{det}R_A/R_B) - R_d}{1 + (R_d + R_{det})/C} \tag{19}$$

where R_d is the total resistance of the divider and K is the divider setting. This circuit can be adjusted so that R_x is proportional to the divider setting k as follows. The resistance of D is adjusted to set the zero offset to zero. Resistor C is adjusted so that, with R_x replaced by a standard resistor, a range factor M is set in terms of the standard, and

$$R_x = kM \tag{20}$$

This circuit is patented and is described in [15].

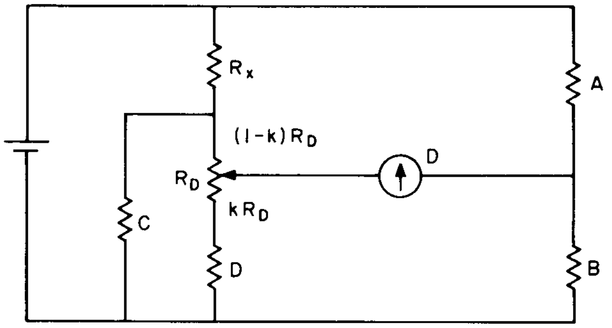


Figure 18—Julie Ratio-Type Bridge

4.5.3 Kelvin Bridge

When four-terminal resistors of low value (generally below 5 Ω) are to be measured, the Kelvin bridge (shown in Fig 19) is frequently used. The bridge is similar to the Wheatstone bridge; however, the circuit contains an additional set of ratio arms (a and b). This arrangement permits four-terminal measurement of resistance elements, essentially eliminating the effects of lead and contact resistance errors in the measurement of low resistance (see 2.1). When the bridge is balanced, as indicated by a null reading of the detector D, the unknown resistance is given in the following equation:

$$R_x = R_s\frac{R_A}{R_B} + \left[\frac{R_bR_y}{R_a + R_b + R_y}\right]\left[\frac{R_A}{R_B} - \frac{R_a}{R_b}\right] \tag{21}$$

where R_a and R_b are the resistance values of the ratio arms a and b and R_y is the value of the yoke Y. If R_A/R_B is exactly equal to R_a/R_b, equation 21 becomes

$$R_x = R_s\frac{R_A}{R_B} \tag{22}$$

equation 21 is useful, because it shows the necessity to keep the resistance of the yoke (R_y) as small as possible in order to minimize the error caused by lead and contact resistances to the unknown and standard in case of discrepancies between the ratios R_A/R_B and R_a/R_b. For the highest accuracy, care must be taken to ensure that the connection resistances are balanced, because R_y is not negligible. For a detailed study of the procedures required for the highest accuracy, see [16], [17], and [18].

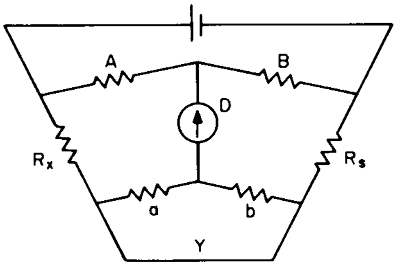


Figure 19—Kelvin Bridge

4.5.4 High-Resistance Bridges

The open-circuit voltage for an almost balanced Wheatstone bridge (see Fig 20) is given by the following equation:

$$V_{oc} = \frac{V\Delta R_xR_s}{(R_s + R_x)^2} \tag{23}$$

where V is the voltage applied to the bridge and ΔR_x is the error in measuring R_x. When R_x becomes high, Equation 23 becomes

$$V_{oc} = \frac{V\Delta R_xR_s}{R_x^2} \tag{24}$$

The bridge is then very insensitive. This situation may be improved by increasing V and using a very sensitive electronic detector. If practical, it is helpful to increase the value of R_s, in which case the simplification of equation 23 is not correct.

Since high-value resistors have leakage resistances comparable to their own values, guarding must be employed as shown in Fig 20. The leakage resistor (M) shunts the relatively low-valued ratio arm (A), while the leakage resistor (N) shunts the detector (D). Other specialized bridge circuits are occasionally used for high-resistance measurements.

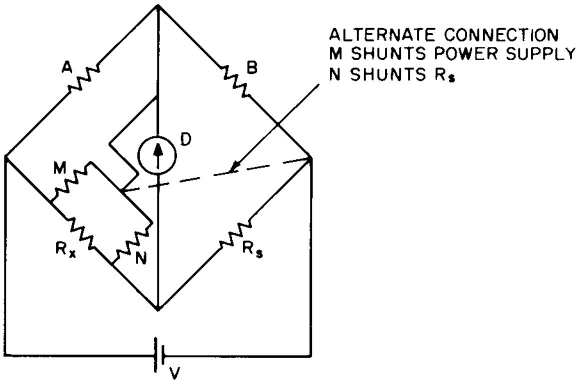


Figure 20—High Resistance Bridge (Modified Wheatstone)

4.5.5 Limit and Deviation Bridges

For production purposes, devices are used which permit sorting of resistors into groups with specified deviations from a mean. The simplest method of doing this is by using equation 23 and calibrating the detector reading in terms of deviation from null point. However, this method depends upon the bridge voltage (V).

By modifying the resistance of the ratio arms (A and B) and adding switches, the ratio R_A/R_B can be readily changed so that one can determine whether R_x is within production limits. Bridges can be built with auxiliary adjustments that are direct reading in deviations of parts per million or percentage deviation from the setting of the standard resistor.

4.5.6 Kusters and MacMartin Current Comparator

This device is used primarily in a standards laboratory for high-accuracy resistance measurement. As shown in Fig 21, it operates on the principle of balancing the ratio of two direct currents until the voltage drops, as indicated by a galvanometer (G), are equal across the unknown and know resistance standard. Measurement is accomplished by means of transformer ratio arms. When the ampere-turns imposed on the magnetic core by the two windings are equal and opposite, the flux in the core is zero. At zero flux condition, as indicated by the detector (D), the unknown resistance is given by

$$R_x = \frac{N_x}{N_s} R_s \tag{25}$$

Fig 21 shows this circuit in its simplest form. High-precision bridges of this type often have additional complications, including more complex magnetic circuits. This circuit is described in [13] and [14]; some features of the circuit are patented by the authors of these papers.

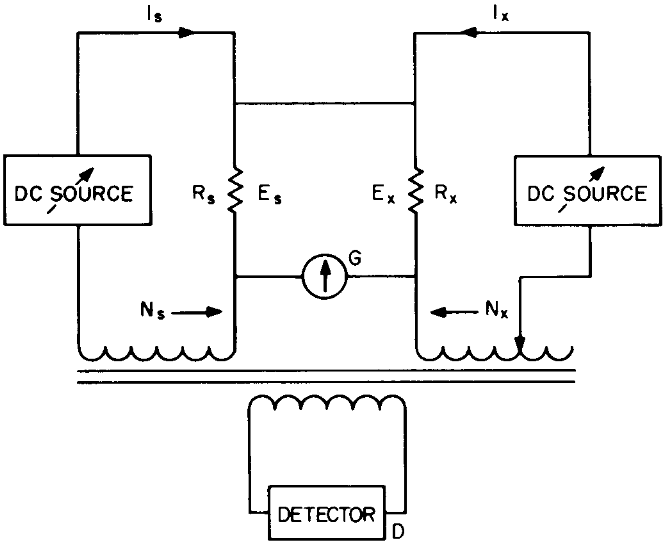


Figure 21—Kusters and MacMartin Current Comparator

4.6 Comparators

For many purposes, unknown resistors are compared to standard resistors by a comparison circuit.

4.6.1 Direct-Comparison Method Using a Standard Resistor and Potentiometer

In this method, the unknown resistor, the standard resistor, and a current source are connected in series, as shown in Fig 22, and a potentiometer is used to measure the voltage drop across each resistor.

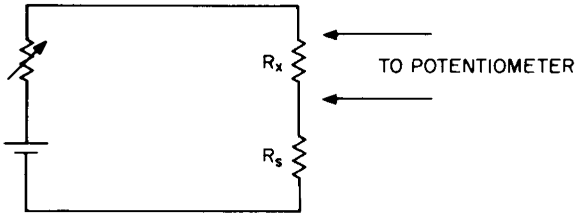


Figure 22—Potentiometer Measurement

The unknown resistance (R_x) is given by the following equation:

$$R_x = (V_x/V_s)R_s \tag{26}$$

where V_x is the voltage measured across R_x and V_s is the voltage measured across R_s. It is essential that the current remain constant during the two measurements.

4.6.2 Direct-Deflection Method

A modification of the direct-comparison method has been used to measure high-voltage resistors. The basic circuit is shown in Fig 23. For this circuit,

$$R_x = \frac{M_s D_s}{M_x D_x} R_s \qquad (27)$$

where M is the multiplying value of the shunt for each setting and D is the detector reading for each setting. The galvanometer and shunt combination can be replaced by an electronic electrometer.

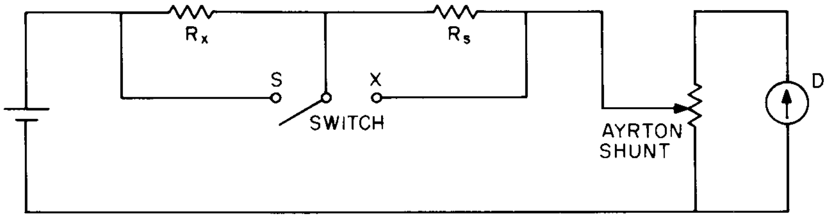


Figure 23—Direct Deflection Method

4.7 Ohmmeters

Ohmmeters are self-contained devices which show resistance readings directly in ohms. The basic calibration equations are as follows.

4.7.1 Simple Ohmmeter

In this instrument, the voltmeter is powered by self-contained batteries. The basic circuit is shown in Fig 24. The initial reading (V_1) is brought to full scale by short-circuiting R_x and adjusting R. The unknown resistor is then inserted in series with the battery-meter combination. Instead of reading V_2, the scale is directly calibrated in ohms, so that

$$R_x = \frac{1-m}{m} R_v \qquad (28)$$

where m is the fraction of the meter scale indicated and R_v is the resistance of the voltmeter. R_v is assumed to be much greater than R_x.

The midscale reading is the resistance of the voltmeter. The ohmmeter ranges are changed by changing the meter resistances and battery voltages. Various circuit modifications are used to offset the effects of battery aging.

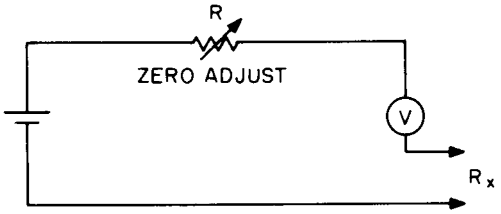


Figure 24—Simple Ohmmeter

4.7.2 Modified Comparison Method

The simple ohmmeter has two disadvantages: its scale is nonlinear and the meter reads from right to left. The circuit shown in Fig 25 circumvents the latter problem. In this case,

$$R_x = \frac{m}{1 - m} R_s \tag{29}$$

where m is the fraction of the meter scale read.

The voltmeter impedance (V) should be very high compared with the value of R_x and in practice may be an electronic type selected for high input impedance. The electronic voltmeter will read full scale when R_x is infinite (that is, disconnected). Ranges are changed by changing the value of R_s.

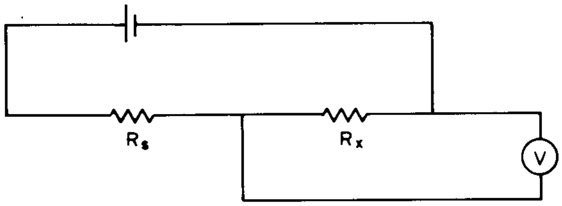


Figure 25—Modified Comparison Type Ohmmeter

4.7.3 Constant-Current Source

A modification of Fig 25 uses a constant-current source, as shown in Fig 26. As in the previous circuit (see Fig 25), the voltmeter should be of much higher impedance than the value of R_x to be measured. For this case,

$$R_x = V/I = KV \tag{30}$$

where K is a constant.

Such an instrument has linear scales. Ranges are changed by changing the output of the constant-current source. Voltmeters using electronic circuits or null-balance potentiometric methods are particularly suitable and may be adapted to direct digital reading.

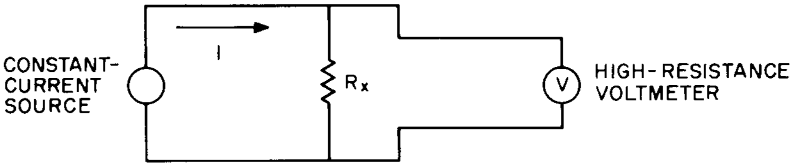


Figure 26—Constant-Current Source Ohmmeter

4.7.4 Ammeter

This method is suitable for measuring low-value resistors. The basic circuit is shown in Fig 27. With R_x disconnected, R is adjusted so that the meter reads full scale. The reading is then taken with R_x connected. The value of R_x is given by the following equation:

$$R_x = \frac{mR_a}{1-m} \tag{31}$$

where R_a is the ammeter resistance and m is the fraction of the meter scale indicated. Ranges are changed by changing the full-scale current and the ammeter resistance.

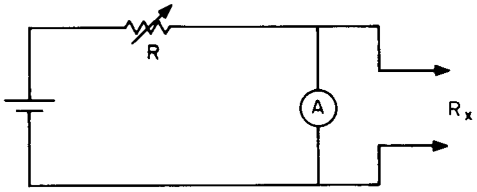


Figure 27—Ammeter Type Low Resistance Ohmmeter

4.8 Other Methods

4.8.1 Loss-of-Charge Method

In this method, used for very high value resistors, a capacitor is first charged. It is then discharged through the unknown high-value resistor. After a measured period of time, the charge remaining on the capacitor is measured by a ballistic galvanometer or charge meter. The basic circuit is shown in Fig 28. The charge remaining on the capacitor (C) is given by the following equation:

$$Q = Q_0 \exp(-t/R_x C) \tag{32}$$

where Q_0 is the initial charge and C is the capacitance value.

Taking the log of equation 32,

$$\log Q = \log Q_0 - \frac{0.4343t}{R_x C} \tag{33}$$

Thus, if log Q is plotted against t, the negative slope equals 0.4343 $R_x C$, and R_x can be found.

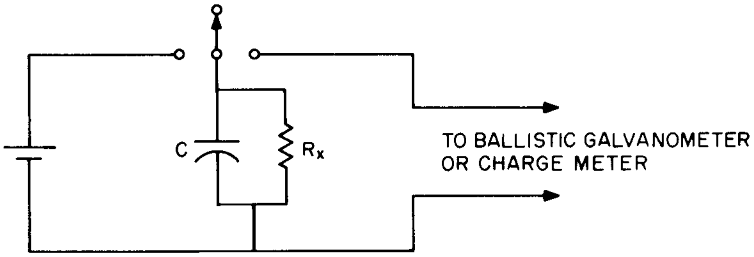


Figure 28—Loss-of-Charge Method Ohmmeter

5. Applications

5.1 Preferred Circuits and Measuring Techniques

Table 1 indicates the preferred circuits and measuring techniques to be used for various measurements.

5.2 Temperature Measurement by Change in Resistance

A commonly used method for determining the average temperature of a winding is to measure the resistance of the winding at the unknown temperature and to compare this value with the resistance at a known temperature. The average temperature of the winding may be calculated by the equation:

$$t - t_1 = (R_t / R_1 - 1) t_1 + C \tag{34}$$

where t is the unknown temperature in degrees Celsius, t_1 is the known temperature in degrees Celsius, R_t is the measured resistance at t, R_1 is the known resistance at t_1, and C is the zero-resistance temperature constant More extensive information about this method is contained in [12].

The constants C = 234.5 for copper and C = 224.1 for aluminum have been deduced perimentally for commercial grades of conductors of annealed copper and aluminum of fairly high purity. The experimentally determined linear relationship between resistance and temperature over a considerable range, the deduced temperatures for zero resistance [—234.5°C (copper) and —224.1°C (aluminum)] and the proportionality of corresponding sides of similar triangles permit the relationship to be expressed as

$$\frac{t + C}{t_1 + C} = \frac{R}{R_1} \tag{35}$$

from which equation 34 was derived. Temperatures computed by equation 34 are recognized as valid for commercial purposes.

When measuring the resistance of any winding that is highly inductive or of low resistance, or both, readings should be delayed until the measuring current has reached a steady state. The inductive effect and low resistance of the winding may cause the time constant (L/R) to become quite large, and the measuring current may increase for several minutes or even hours before the steady-state value is reached. Premature readings may result in gross errors in the calculated temperature rise, although errors in the measured resistance may be small.

Methods have been devised to decrease the delay in resistance measurements for temperature tests to prevent cooling of the apparatus under test. See [12] for additional information on this subject.

5.3 Computation of Resistance for a Required Temperature

Measurements of resistance are usually made at ambient temperatures. For various reasons, such as loss calculations for efficiencies, the value of resistance required must be the value at a specified temperature. To convert the measured resistance value to the required value, the relationship described in 5.2 may be rearranged so that

$$R_t = R_1 \frac{t + C}{t_1 + C} \tag{36}$$

where R_t is the resistance at a specified temperature, R_1 is the measured resistance at t_1, t is the specified temperature in degrees Celsius, t_1 is the temperature in degrees Celsius of measured resistance, and C is the zero-resistance temperature constant.

5.4 Measurement of Insulation Resistance

The resistance of the insulation between, and in contact with, two metallic bodies or electrodes is defined as the ratio of the direct voltage applied to the electrodes to the total current between them. The insulation may be a specimen of a specific material or an assembly of materials constituting an insulation system.

The current measured is dependent upon both the volume and surface resistance of the material or system, unless a third electrode is provided to permit a three-terminal measurement using guarding techniques.

The volume resistance results from that portion of the current that is distributed throughout the volume of the material or system, whereas the surface resistance results from that portion of the current which is primarily in a thin layer of moisture or other conducting material that may be deposited on its surface.

The current that results from the application of a direct voltage to an insulating material or system is principally ionic in nature, as compared to the free-electron charge carried in metals. Semiconductors are intermediate in their ability to conduct electricity. An arbitrary distinction between the realm of semiconductors and that of insulating materials, in terms of resistivity, is usually considered to be 10^{10} Ω.cm.

Insulation-resistance measurements can be greatly influenced by several factors, which must be taken into consideration and reported as test conditions:

1) The insulation resistance may be voltage sensitive, depending upon the voltage stresses that may exist during the test
2) The degree of conditioning before making the test determines the dryness and cleanliness of the specimen
3) The temperature of the specimen material or insulation system and its relationship to the dew-point temperature of the test environment directly affect the measurement
4) The resistance of insulating materials and systems is usually time dependent
5) Depending upon moisture content, the resistance of insulating materials and systems may be affected by the polarity of the applied voltage and by any field nonuniformity that may exist as a result of electrode configuration.

For more complete information on making resistance measurements on insulating materials, see [10], and for insulation systems, see [11].

5.4.1 Methods

The methods to be used for measuring the resistance or resistivity of relatively small specimens of insulating materials may be somewhat different from those used in the case of insulation systems, particularly in regard to sensitivity. A table of suggested methods or apparatus in terms of conditions of use is given in [10].

For insulation systems, where the accuracy requirements may not be so stringent, megohm bridges and ohmmeters of lower sensitivity are commonly used.

5.4.2 Testing Techniques

Insulation-resistance measurements customarily fall in the range of 10^6 to 10^{15} Ω, and such measurements are greatly influenced by the factors noted in 5.4. The techniques referred to must be closely followed and precautions carefully observed if meaningful results are to be obtained. Furthermore, and particularly in the case of certain insulation systems, considerable geometric capacitance may be inherent in the system; and if such systems are tested at relatively high voltages, the matter of safety becomes a primary concern.

It is recommended tha relevant documents, such as [10] and [11], be carefully reviewed before making insulation-resistance measurements.

5.5 Measurement of Ground Resistance

Resistance measurement of a ground connection presents a number of problems not encountered in most other resistance measurements. The conduction of electricity in the soil is electrolytic, and the continued passage of direct current produces chemical action and polarization potential differences which may seriously interfere with the measurement. It is therefore almost essential that the measurement be made using alternating current (or periodically reversed direct current). Inductive and capacitive effects, however, are usually negligible.

The distribution of a current in the vicinity of a ground electrode is such that the equipotentials are roughly hemispherical surfaces centered on the electrode. Most of the drop in voltage occurs in the region fairly close to the electrode. Assuming that the soil is of uniform resistivity, approximate calculations indicate that, for driven rods, 90 percent of the resistance is localized within a radius equal to twice the depth of the rod and that 99 percent is localized within a radius 20 times the depth of the rod. For plates buried at a considerable depth, 90 percent of the resistance is localized within a radius of 6 or 7 times the greatest dimension of the plate. The measuring procedure should be such that at least 90 percent of the resistance is located inside the auxiliary potential electrode used in the measurement.

Still another complication may arise from stray currents, either alternating or direct, which may be present in the earth and even in the electrode under measurement at the time of test. A convenient way of mitigating their effects is to utilize in the measurement a frequency not likely to be present in the stray current.

It is recommended that relevant documents, such as [5], be carefully reviewed before making ground-resistance measurements.

5.5.1 Measurement by Reference Ground

To measure the resistance of a ground, it is essential that a measuring current be passed from the electrode under test into the ground; hence, a second ground connection must be provided to carry the measuring current. This second connection can be a distant, metallic waterpipe system which, because of its large extent, may be of very low resistance, or it can be formed by connecting in parallel a large number of other driven grounds separated rather widely from each other and also from the test ground. In these cases, it is sufficient to measure the total resistance of the two grounds in series and, neglecting the resistance of the second or reference ground, ascribe the measured resistance entirely to the ground under test. The measurement of the total resistance of the two grounds may be made by the drop-of-potential method (see 4.1) or by a Wheatstone bridge (see 4.5.1), using alternating current to avoid polarization effects in the ground. As most sources of alternating current are themselves grounded at some point, an insulating transformer must be used to isolate the measuring circuit. Errors from the presence of stray currents of the same frequency as that used in the measurement may be reduced by reversing the connections at the secondary terminal of the isolating transformer and taking the mean of the two sets of data thus obtained.

5.5.2 Three-Measurement Method

When no reference ground connection of negligible resistance is available, it is necessary to provide both an auxiliary current ground to conduct the measuring current and a third or potential ground. The potential ground serves to separate the resistance of the ground under test from that of the auxiliary ground connection. The theoretically simplest procedure would be to drive two auxiliary grounds at a sufficient distance from the test ground and from each other that the regions in which their resistance is localized do not overlap. Then if R_{ab}, R_{bc}, and R_{ca} are the total resistances measured successively between the pairs of electrodes indicated by the subscripts, the resistance of the test ground (R_a) is given by

$$R_a = (R_{ab} + R_{ca} - R_{bc})/2 \qquad (37)$$

This procedure is practical only if all three grounds are of nearly the same resistance. If, as is usually the case, the two auxiliary grounds are of materially higher resistance than the test ground, R_a will be the difference of two nearly equal quantities, and errors in the individual readings will be greatly magnified in the final result. Stray currents and their changes between successive readings may be another serious source of error.

5.5.3 Ratio Ohmmeter

A commonly used method of measuring ground resistance is shown in Fig 29. Current from the direct-current generator is periodically reversed by the current-reversing switch and will exist in the earth between the ground under test (X) and the auxiliary electrode (C). The drop of potential between X and the other auxiliary electrode (P) is rectified by the potential-reversing switch, which is operated in synchronism with the current-reversing switch. The coils of the ratio ohmmeter carry current proportional to the voltage (X—P) and the current through X, respectively, so that the scale of the instrument can be calibrated to read directly the resistance (R_x) of the test ground. The distance d_1 must be large enough to span the region in which the desired fraction of R_x is localized. Similarly, d_2 must be large enough that the potential gradient around C has a negligible effect at P. Excessive resistance at C will reduce the sensitivity of the measurement, and a less definite balance will be obtained. The resistance (R_p) at P must be negligible compared with that of the series resistor. This method is only slightly affected by stray currents if the frequency of the reversals remains different from that of the stray current.

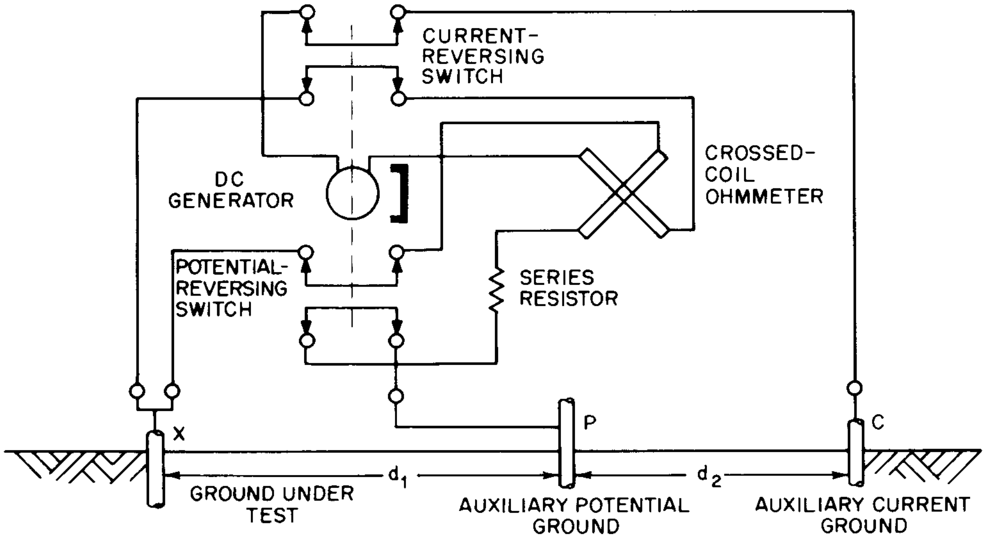


Figure 29—Crossed-Coil Ratio-Type Ground Resistance Measurement

5.5.4 Double-Balance Bridge Method

A convenient bridge method for measuring ground resistance is shown in Fig 30. In this method, currents from the alternating-current source occur in two parallel circuits. The lower circuit includes the fixed resistance R_A and the resistance of the ground under test (R_x) and of the auxiliary current ground (R_c). The upper circuit includes the fixed resistance R_s and an adjustable slide rheostat on which two sliders (S_a and S_b) make contact. With the detector switch closed to the left, slider S_a is adjusted until the detector shows a balance. The currents in the two branch circuits are then inversely proportional to the resistances R_A and R_B. The switch is then closed to the right and slider S_b is adjusted until the detector again shows a balance. The potential drop between X and P is then equal to the drop in the portion R_b of the slide rheostat, and the resistance of the ground under test is then given by

$$R_x = R_b R_A / R_B \tag{38}$$

The scale over which S*b* moves can thus be calibrated to read R_x directly.

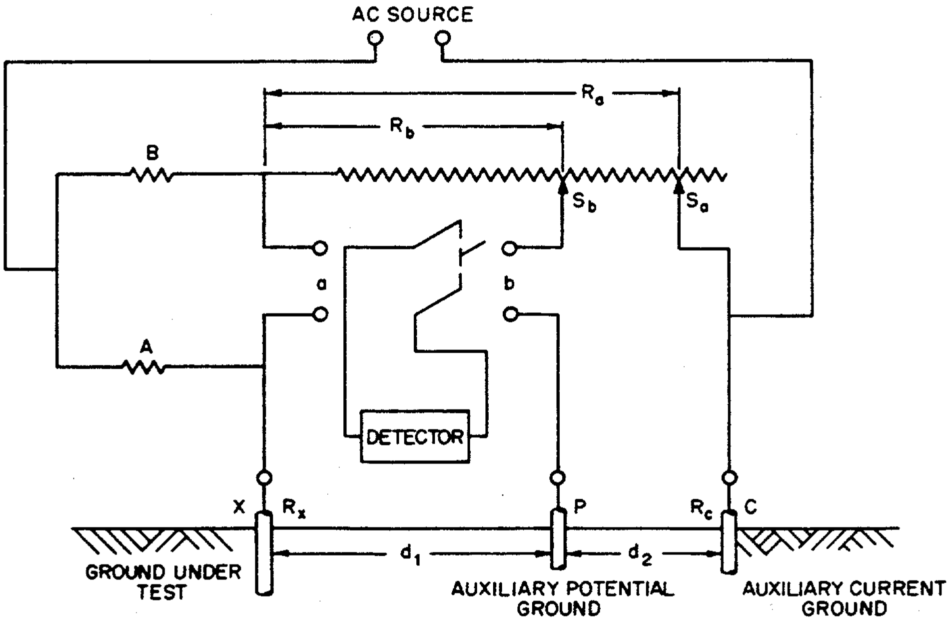


Figure 30—Double Balance Bridge for Ground Resistance Measurement

The alternating-current source may be an electronic or electromechanical oscillator, and the detector may have an audible output. The tone of the oscillator can usually be recognized and balanced out, even in the presence of considerable background noise caused by stray alternating currents. Resistance at P merely reduces the sensitivity of the detector. Excessive resistance at C may limit the range of resistance which can be measured. The locations of electrodes P and C are determined by the same considerations as in the crossed-coil ohmmeter method.

5.5.5 Single-Balance (Transformer) Method

Fig 31 shows a circuit in which a single balance is sufficient to give a measurement of the ground resistance (R_x) of the ground (x) if auxiliary potential ground (P) is at a sufficient distance from X so as not to influence R_x. (See [5]).

The current transformer maintains a fixed ratio (N) of the secondary current (I_2) to the primary current (I_1). Hence, at balance,

$$R_x = R_2 N \tag{39}$$

Various devices may be incorporated into this circuit to minimize the disturbing effects of stray ground currents. A transformer coupling in the detector circuit eliminates errors from direct currents in the ground. A tuned bypass circuit or a detector excited separately and in synchronism with the alternating-current ground current minimizes the effect of the phase angle of the transformer. An alternative is to use a direct-current detector with synchronous rectification suitably phased with the alternating-current source.

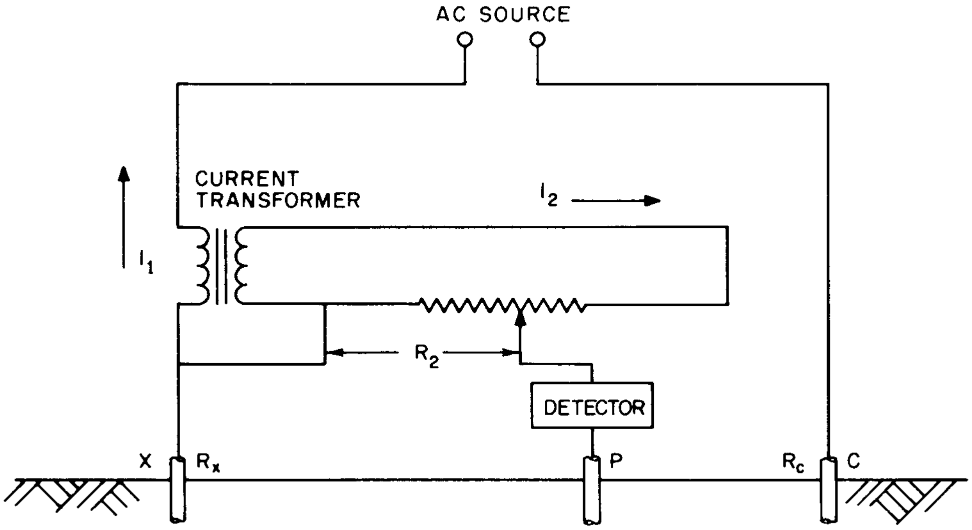


Figure 31—Single Balance (Transformer) Ground Resistance Measurement

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