

# WITHDRAWN

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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].<sup>1</sup>

#### 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,

<sup>1</sup>Numbers in brackets correspond to those of the references listed at the end of this standard, in Section 6.

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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<br>Note (5) | Bridge Methods<br>Note (2)                                                               | Direct Reading<br>Methods                                                | Alternative Methods                                                                      |
|---------------------------------------------------------------------------------------------|-------------------------------|------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
| Low Resistance (see 2.1) (less than approximately 5 $\Omega$ )                              | 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 $\Omega$ and 10 $\Omega$ ) | 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 approximately 10 $\Omega$ 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

$$R_x = E_{cd}/I_{ab} \quad (1)$$

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  $J_2$ ).

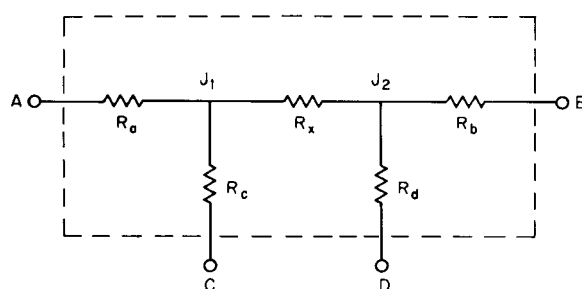


**Figure 1—Four Terminal Representation of a Resistor**

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,

$$E_{cd}/I_{ab} = E_{ab}/I_{cd} = R_x \quad (2)$$

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 will be the resistance between the contacts at each end that are closest to the resistor.

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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  $5\ \Omega$ .

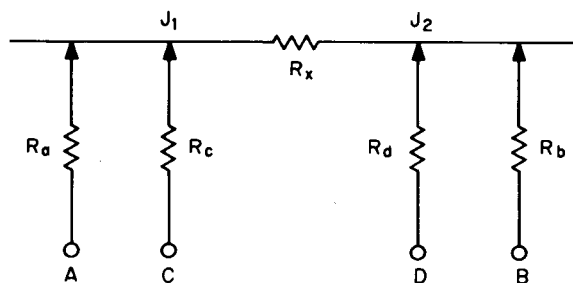


Figure 2—Four Terminal Connections to a Two Terminal Resistor

## 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 ( $R_{i1}$ ) 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.

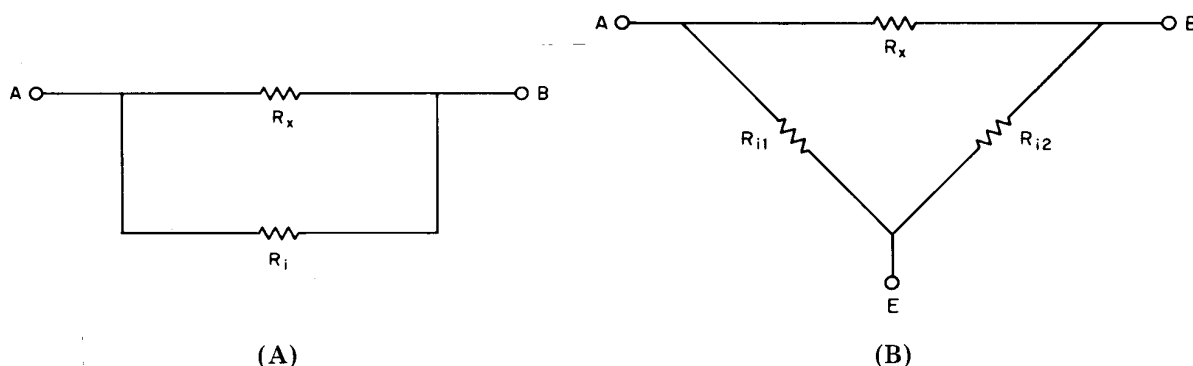


Figure 3—(A) -- Equivalent Circuit for a Resistor Shunted by Insulation Leakage. (B) -- Equivalent Circuit Showing Method of Reducing the Effect of Insulation Leakage.

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## 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.)

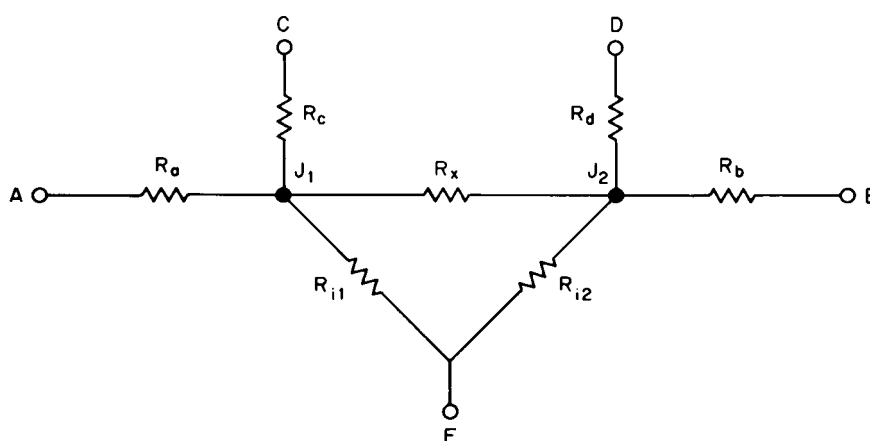


Figure 4—Equivalent Circuit of a Resistor Incorporating Techniques of Fig 1 and Fig 3(B)

## 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

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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  $R_x$ .

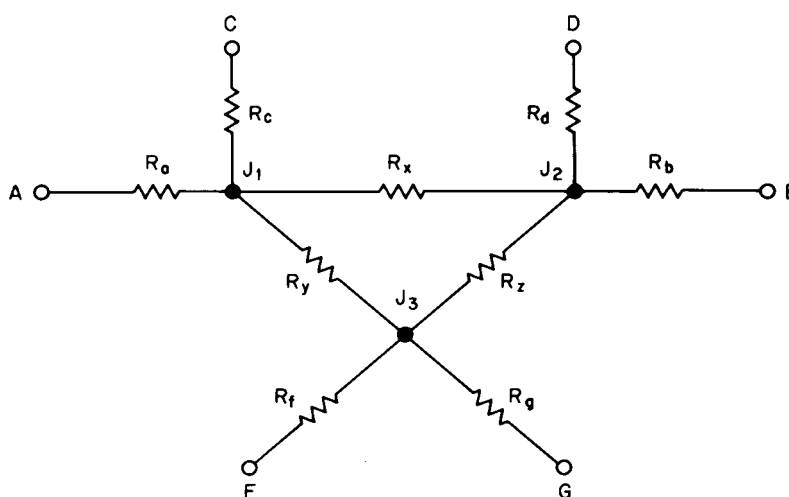


Figure 5—A Six Terminal Resistor Measurement

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The value of  $R_x$  can be measured as follows:

$$R_x = E_{cd}/I_b \quad \text{if} \quad E_{gd} = 0 \quad (3)$$

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

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

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).