IEC 62812

Edition 1.0 2019-05

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Low resistance measurements – Methods and guidance

Mesures de faibles résistances – Méthodes et recommandations

IEC 62812:2019-05(en-fr)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 31.040.01 ISBN 978-2-8322-6870-4

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FOREWORD

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The text of this International Standard is based on the following documents:

FDIS	Report on voting
40/2665/FDIS	40/2671/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

The contents of the corrigendum of March 2020 have been included in this copy.

LOW RESISTANCE MEASUREMENTS – METHODS AND GUIDANCE

1 Scope

Resistance measurements are typically compromised by a variety of phenomena, for example serial resistance in the measurement path, self-heating or non-ohmic properties. Whether the effect of such phenomena on a resistance measurement is acceptable or not depends on the magnitude of each effect in comparison to the resistance and to the required accuracy. Hence, the risk of erroneous resistance measurements increases with decreasing resistance and with a tightening of the permissible tolerance.

This document specifies methods of measurement and associated test conditions that eliminate or reduce the influence of adverse phenomena in order to improve the attainable accuracy of low-resistance measurements.

The methods described in this document are applicable for the individual measurements of the resistance of individual resistors, and also for resistance measurements as part of a test sequence. They are applied if prescribed by a relevant component specification, or if agreed between a customer and a manufacturer.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60068-1, *Environmental testing – Part 1: General and guidance*

IEC 60115-1:2008, *Fixed resistors for use in electronic equipment – Part 1: Generic specification*

IEC 60294, *Measurement of the dimensions of a cylindrical component with axial terminations*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60115-1 and the following apply.

A list of used letter symbols and abbreviated terms is provided in Annex A.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
electromotive force
e.m.f.
difference in potential that gives rise to an electric current

3.2
thermoelectric e.m.f.
E_T
potential difference occurring at the junctions of dissimilar conductors when a temperature difference exists between the junctions

3.3
low resistance
resistance for which the predictable error when measured with a conventional two-wire sensing method is significant in comparison to the required precision or to the stated tolerance

3.4
four-wire sensing
Kelvin sensing
four-terminal sensing
four-point sensing
electrical impedance measuring technique using separate pairs of wires for carrying the measuring current and for sensing the potential difference in order to eliminate the impedance contribution of wiring and contact resistances

3.5
two-wire sensing
conventional electrical impedance measuring technique using one pair of wires for carrying the measuring current and for sensing the potential difference on the same wires

4 Resistance measurement phenomena

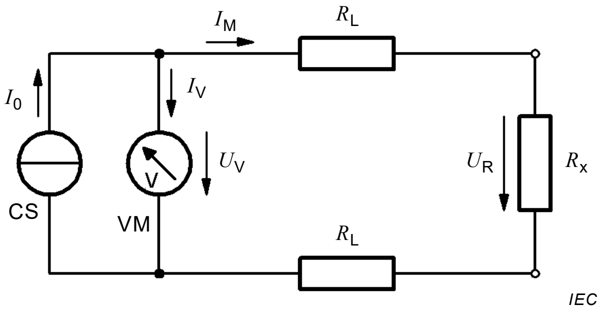
4.1 General

The measurement of a low resistance usually relies on the measurement of a low voltage, which requires a number of precautions against typical detrimental phenomena such as offset voltages, radio frequency interference, electromagnetic interference, electrical noise, or non-ohmic contacts. However, these phenomena are not discussed here as they are not specifically related to the measurement of resistance.

The voltage to be measured increases with an increase of the measuring current, which may also result in effects which are adverse to the measurement. Such phenomena are discussed in Clause 4.

4.2 Lead and contact resistance

A conventional method for measuring a resistance is to use a constant current source with a known (or measured) output current and a voltmeter for measuring the voltage across the unknown resistor, while the connection is built with a single pair of test leads, as shown in Figure 1.



Key

CS	current source
VM	voltmeter, measuring voltage U_V
R_L	lead resistance, including contact resistance to the specimen
R_x	resistance to be measured
I_0	supply current from current source
I_V	current passing through the voltmeter
I_M	current passing through the unknown resistor

Figure 1 – Resistance measurement using two-wire sensing

In this circuit, the source current I_0 splits up into the current I_M passing through the path with the unknown resistor and the current I_V passing through the voltmeter, where I_V depends on the measured voltage U_V and the voltmeter's impedance R_V.

$$I_0 = I_M + I_V \tag{1}$$

$$I_V = \frac{U_V}{R_V} \tag{2}$$

The voltmeter measures the following voltage drop of current I_M along both lead and contact resistances R_L, plus along the unknown resistor R_x:

$$U_V = I_M \cdot \left(2R_L + R_x\right) \tag{3}$$

This leads to the apparent result of the resistance measurement, R', based on the measured voltage U_V and the known sourced current I_0:

$$R' = \frac{U_V}{I_0} = \frac{I_M}{I_M + I_V} \cdot (2R_L + R_x) = \frac{2R_L + R_x}{1 + \frac{2R_L + R_x}{R_V}} \tag{4}$$

With $I_V \to 0$, which is the case if $R_V >> (2R_L + R_x)$, the apparent result tends towards:

$$R' = \frac{U_V}{I_0} = \frac{I_M}{I_M + 0} \cdot (2R_L + R_x) = 2R_L + R_x \tag{5}$$

This final apparent result still bears the error ΔR of

$$\Delta R = R' - R_\mathrm{x} = 2R_\mathrm{L} \tag{6}$$

This error will only be negligible if $(2R_\mathrm{L}) << R_\mathrm{x}$, where the negligibility depends on the required accuracy for the measurement of R_x.

EXAMPLE 1 A 1 m copper wire with a cross section of 0,5 mm² has a resistance of 35 mΩ. Using a pair of these wires for two-wire sensing for measuring a 100 mΩ resistor results in an unacceptable error of 70 %. The current passing through the voltmeter due to its limited impedance is not likely to gain any significance on the error figure.

EXAMPLE 2 Using the same circuit for measuring a 10 Ω resistor results in 0,7 % error, while first assuming the current through the voltmeter to be zero. This 0,7 % error may be acceptable if the relative tolerance of the resistance is given as ±10 %, but not if it is only ±1 %.

Using a voltmeter in this circuit with an impedance of 1 MΩ results in only a −0,001 % additional error, which is not significant compared to the error caused by the lead wires. If the voltmeter, however, has an impedance of only 10 kΩ, the additional error is −0,1 % and thus may no longer be negligible.

EXAMPLE 3 For a resistor of 1 kΩ, measured as above, even the seemingly small error of only 0,007 % renders the described circuit useless, if it is a high precision type with, for example, a relative tolerance of ±0,01 %.

Using a voltmeter in this circuit with an impedance of 1 MΩ results in the additional error of −0,1 %. Comparing the absolute error contributions, this influence is even larger than the error caused by the lead wires.

4.3 Self-heating

The measuring current I_M passing through the unknown resistor with its resistance R_x causes dissipation of the power P_R

$$P_\mathrm{R} = I_\mathrm{M}^2 \cdot R_\mathrm{x} \tag{7}$$

The dissipation P_R produces a temperature rise on the unknown resistor, which depends on the ability of the test assembly or fixture to dissipate heat to the environment, expressed as the thermal resistance R_th. The steady-state temperature rise $\Delta\vartheta_{\mathrm{R}\infty}$ on the unknown resistor is

$$\Delta\vartheta_{\mathrm{R}\infty} = R_\mathrm{th} \cdot P_\mathrm{R} \tag{8}$$

which adds to the ambient temperature next to the specimen, ϑ_amb, and thereby leads to the steady-state temperature $\vartheta_{\mathrm{R}\infty}$ on the unknown resistor of

$$\vartheta_{\mathrm{R}\infty} = \vartheta_\mathrm{amb} + \Delta\vartheta_{\mathrm{R}\infty} = \vartheta_\mathrm{amb} + R_\mathrm{th} \cdot P_\mathrm{R} \tag{9}$$

NOTE The heat conduction out of the unknown resistor is considered to be a linear system for the purpose of this specification. This is based on the general observation that radiation and convection from the body of most low-power resistors only have a minor share in the total heat dissipation. A more complex consideration can be suitable for large resistors where radiation and convection from the body's surface prevail over conduction through the terminals or lead wires.

The temporal rise of the temperature $\vartheta_\mathrm{R}(t)$ on the unknown resistor before reaching the steady state is determined by the thermal time constant τ_th of the unknown resistor in its test assembly or fixture:

$$\vartheta_\mathrm{x}(t) = \vartheta_\mathrm{amb} + \Delta\vartheta_{\mathrm{R}\infty} \cdot (1 - e^{-t/\tau_\mathrm{th}}) \tag{10}$$

Knowledge of the thermal time constant τ_th is necessary for measurements aiming at the steady state and for determination of the timing of switched measurements alike.

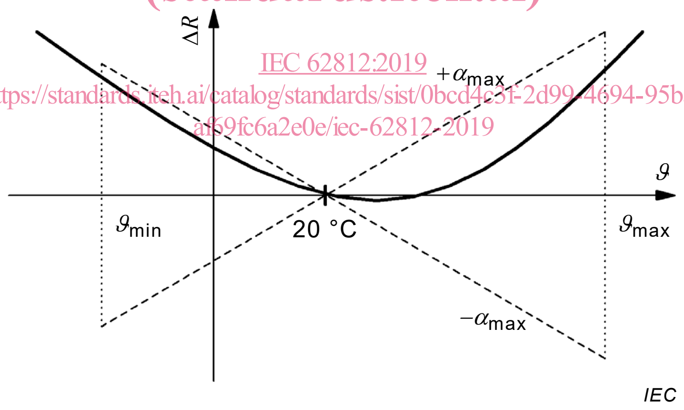
The raised temperature on the unknown resistor due to self-heating not only affects the specimen, but also spreads the heat to the test assembly or mounting and affects those parts of the measurement circuit as well. Therefore, the raised temperature will be root cause of the variation of resistance with temperature, as discussed in 4.4, and of the thermoelectric e.m.f., as discussed in 4.5.

Self-heating is decreased by reducing the measuring current I_M as much as possible while still providing the required voltage for a measurement with the desired accuracy. However, setting the measuring current is not a common feature with resistance meters. Other options to reduce the self-heating are to activate the measuring current for a short period only, as discussed in Clause 5, and of course to enhance the heat flow from the specimen and the test fixture.

4.4 Variation of resistance with temperature

One of the reference conditions prescribed in IEC 60115-1 for measuring the resistance is the reference temperature of 20 °C. For practical reasons, however, most tests and measurements are permitted to be executed under standard atmospheric conditions for testing as defined in IEC 60068-1, which includes a permissible range for the ambient temperature from 15 °C to 35 °C.

If measured with sufficient accuracy, a resistor measured at 15 °C or at 35 °C will not show the same resistance as when measured at 20 °C. In fact, there is a variation of resistance with temperature for almost every type of resistor, which typically does not follow a linear relationship. The slope and the amount of variation depend substantially on the technology and manufacturing of the resistor and in some cases also on the actual resistance.



Key

α	temperature coefficient of resistance
ΔR	resistance change

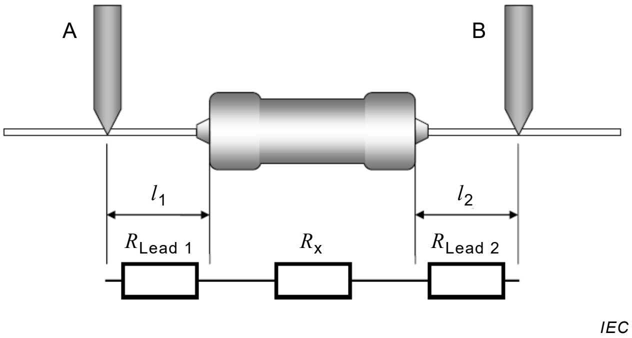
Figure 2 – Variation of resistance with temperature (random example)

As a specification figure for resistors, the limitation of the permissible range for such resistance variation in a given temperature range is usually given by a pair of symmetrical linear slopes through the reference point at 20 °C, $+\alpha_\mathrm{max}$ and $-\alpha_\mathrm{max}$ as shown in Figure 2. The value α_max is the absolute value of the specified temperature coefficient of resistance, or TCR.

EXAMPLE 1 Thick film chip resistors of 100 mΩ or lower are typically offered with a TCR of $500 \cdot 10^{-6}$/K or above. Measuring the resistance at 35 °C results in a possible deviation of ±0,75 % from the resistance at the reference temperature 20 °C. Such a deviation may be acceptable if the relative tolerance of the resistance is given as ±10 %, but not if it is only ±1 %.

High-precision resistors made in thin film or metal foil technology may be offered with a TCR of only $5 \cdot 10^{-6}$/K. Measuring such a resistor at 15 °C or at 25 °C results in a possible deviation of only ±0,0025 % from the true resistance at the reference temperature. This very small deviation may again be unacceptable in light of a specified relative tolerance of those resistors of only ±0,01 %, or even better.

A real resistor not only consists of the resistive element, made of a specific material, but also incorporates conductors on both sides in order to establish the electrical connection. In some cases, these conductors are fixed in shape and effective length and therefore should be included in an overall specification of the resistor. In other cases, such as the axial leaded resistors shown, for example, in Figure 3, the conductors are supplied with generous lengths of lead-wire, of which typically only a part is used in the circuit, requiring a suitable specification of mandatory points of resistance measurement.



Key

A, B	measurement probes
l_1,l_2	distance of the point of measurement from resistor body, as measured in accordance with IEC 60294

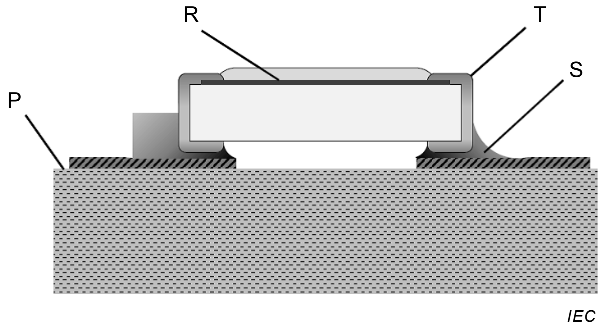
Figure 3 – Resistances on a resistor with lead wires

The lead-wires are usually made of a high conductivity metal, which naturally comes with a TCR much higher than the TCR of the resistive element. A typical choice would be copper with an electrical conductivity of γ_{Cu} = 58 m/Ωmm^2 and a TCR of α_{Cu} = $3800 \cdot 10^{-6}$/K.

EXAMPLE 2 A resistor of 100 mΩ, may be supplied with copper lead wires of 0,5 mm in diameter. With the measurement probes attached at a distance of 5 mm on each side, the pair of lead wires contributes 0,88 mΩ to the total resistance at 20 °C, and 0,93 mΩ at 35 °C, which is almost a potential error of 1 %.

With the measurement probes attached at a distance of 21 mm on each side, the lead wires contribute 3,7 mΩ to the total resistance at 20 °C, and 3,9 mΩ at 35 °C, which is almost a potential error of 4 %.

For SMD chip resistors, the separate contributions may be not as striking as in the above example of a leaded resistor. However, Figure 4 illustrates, for the chip resistor, the presence of the resistive element on the top side and the conductors around each edge to the point of contact with the electrical circuit on the PCB. Naturally, each of these elements is featured with its own electrical conductivity and TCR, which all contribute to the total measurable resistance of a specimen.



Key

R	resistive element
T	termination
S	solder joint
P	printed circuit board

Figure 4 – SMD chip resistor on a PCB

EXAMPLE 3 A chip resistor, size RR3216M, may be manufactured with terminations consisting of a 3 µm nickel layer and a 5 µm tin layer on top, wrapped around the edges. With a termination width of 1,6 mm and an effective conductor length assumed to be 1 mm, the conductor resistance amounts to 7,8 mΩ on each side, or 15,6 mΩ in total. If the resistor was, for example, specified to be 100 mΩ, then this termination resistance would already represent about 15,6 % of it, and every 64 µm difference in the effective conductor length would change that contribution by 1 %.

If the resistor was measured at 35 °C, the combined conductor resistance amounts to 16,8 mΩ, which is due to an effective TCR of approximately $5400 \cdot 10^{-6}$/K for both termination layers combined.

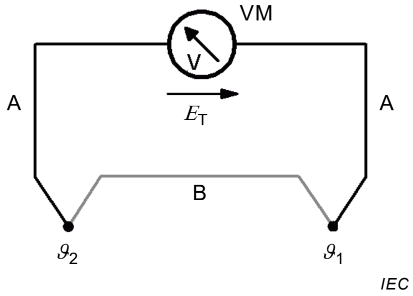
4.5 Thermoelectric e.m.f.

Any solid conductor subjected to a temperature gradient features a displacement of charge carriers through thermal diffusion, leading to a movement of electrons towards the cold end. Hence, an electrical field establishes itself from the hot to the cold end.

Two different materials combined to form a loop with both junctions subjected to different temperatures result in the flow of a continuous thermoelectric loop current. Opening the loop within any one of the materials results in a measurable thermoelectric e.m.f., E_T , as shown in Figure 5.

The thermoelectric e.m.f., known as Seebeck effect, depends on the two involved materials and on the temperature difference between the two junctions. The Seebeck effect is not linear and depends on the actual temperatures. For a limited temperature range, however, it is possible to assume sufficient linearity and therefore to calculate the thermoelectric e.m.f., E_T, from the difference of the Seebeck coefficients α_S of the two joined metals and the temperature difference of their junctions:

$$E_\mathrm{T} = \left(\alpha_\mathrm{SB} - \alpha_\mathrm{SA}\right) \cdot \left(\vartheta_2 - \vartheta_1\right) \qquad (11)$$



Key

VM	voltmeter, measuring the thermoelectric e.m.f., E_T
A, B	wire materials
ϑ_1, ϑ_2	temperature of the wire junctions

Figure 5 – Thermoelectric e.m.f.

Seebeck coefficients can be given as absolute figures or relative to a second material. For metallic conductors, the coefficients typically are in a range of one to a few tens of microvolts per Kelvin, while for doped semiconductor materials they are rather in the order of a millivolt per Kelvin. Table 1 gives the relative Seebeck coefficients α_S of a number of potentially relevant metals joined with platinum, or joined with copper.

Table 1 – Relative Seebeck coefficients of selected metals

Metal	α_S to Platinum μV/K	α_S to Copper μV/K
Chrome nickel	+22	+14,5
Iron	+18,3	+10,8
Brass	+11	+3,5
Copper	+7,5	±0
Silver	+7,3	−0,2
Gold	+7	−0,5
Lead	+4,4	−3,1
Tin	+4,2	−3,3
Aluminium	+3,9	−3,6
Platinum	±0	−7,5
Nickel	−15	−22,5
CuNi44 (e.g. Constantan®[1])	−33	−40,5
The cited figures are stated for a reference temperature of 0 °C. Seebeck coefficients α_S are traditionally also given in mV/100 K.		

Even junctions of laboratory connectors are reported to generate a thermoelectric e.m.f. since the specific materials used for their production are chosen by the manufacturer. Connectors specified for low thermal activity may show coefficients less than a tenth of a microvolt per

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[1] Constantan® is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of this product.