

INTERNATIONAL STANDARD

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**Rotating electrical machines –
Part 27-4: Measurement of insulation resistance and polarization index of
winding insulation of rotating electrical machines**

**Machines électriques tournantes –
Partie 27-4: Mesure de la résistance d'isolement et de l'index de polarisation sur
le système d'isolation des enroulements des machines électriques tournantes**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ROTATING ELECTRICAL MACHINES –

Part 27-4: Measurement of insulation resistance and polarization index of winding insulation of rotating electrical machines

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

FDIS	Report on voting
2/1880/FDIS	2/1890/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.

A list of all parts in the IEC 60034 series, published under the general title *Rotating electrical machines*, can be found on the IEC website.

NOTE A table of cross-references of all IEC TC 2 publications can be found in the IEC TC 2 dashboard on the IEC website.

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

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INTRODUCTION

This document provides guidelines for measurement of the insulation resistance and the polarization index on stator and rotor winding insulation of rotating electrical machines. The document also describes typical insulation resistance characteristics, the effect of influential factors which impact or change these characteristics, and how these characteristics indicate winding condition. It recommends minimum acceptable values of insulation resistance for AC and DC rotating machine windings. Interpretation will depend on the nature of the insulation materials – specifically if the insulation is of the thermoset or thermoplastic type.

Insulation resistance measurement has been recommended and used for over 50 years to evaluate the condition of electrical insulation. It is recommended to track periodic measurements, accumulated over months and years of service or in connection with servicing and overhaul of rotating machines.

Empirical limits verified in practice can be used as a basis for evaluating the quality of stator winding insulation systems in manufacturing. Furthermore, trend evaluation, e.g. diagnostic tests as part of the functional evaluation of insulation systems or in connection with servicing and overhaul of rotating machines, can also provide information on ageing processes, possible repair options and the recommended time interval between tests. These measurements give no indication of local weak points in the insulation system and the trend evaluations cannot be used to predict the time to failure of the winding insulation.

ROTATING ELECTRICAL MACHINES –

Part 27-4: Measurement of insulation resistance and polarization index of winding insulation of rotating electrical machines

1 Scope

This part of IEC 60034 provides recommended test procedures for the measurement of insulation resistance and polarization index of stator and rotor winding insulation of rotating electrical machines.

This document recommends minimum acceptable values of insulation resistance and polarization index of winding insulation valid for fully processed low and high voltage AC and DC rotating electrical machines with a rated power of 750 W or higher.

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 60050-411, *International Electrotechnical Vocabulary – Chapter 411: Rotating machinery*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-411 and the following apply.

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

rated voltage

<for an electric machine> rated line-to-line voltage for a three-phase AC machine, line-to-earth voltage for a single phase machine and rated direct voltage for DC machines or field windings

3.2

insulation resistance

R_{it}

<for an electric machine> capability of the electrical insulation of a winding to resist direct current and is determined by the quotient of the applied direct voltage divided by the total current across the machine insulation, taken at a specified time t from start of voltage application

Note 1 to entry: The voltage application time is usually 1 min (R_{i1}) and 10 min (R_{i10}); however other values can be used. Unit conventions: subscript values of 1 through 10 are assumed to be in minutes, subscript values of 15 and greater are assumed to be in seconds.

Note 2 to entry: Insulation resistance is sometimes abbreviated as IR.

3.3

polarization index

PI

quotient of the insulation resistance measured at two different times, usually $t_1 = 1$ min and $t_{10} = 10$ min after application of the direct voltage, that is an indicator of the condition of the insulation

Note 1 to entry: Other times are discussed in Clause E.2.

3.4

polarization current

I_P

current resulting from polarization processes, which decays with time of DC voltage application at a decreasing rate from an initial value to essentially zero

Note 1 to entry: The polarization current is also called absorption current.

3.5

conduction current

I_G

<for an electric machine> ohmic current that is constant with time and passes through the bulk of the main insulation

3.6

surface leakage current

I_L

ohmic current that is constant with time and passes over the surface of the end windings of the stator winding or between exposed conductors and the rotor body in insulated rotor windings if there are depositions of conductive materials, e.g., moisture or contamination

3.7

capacitive current

I_C

<for an electric machine> current of comparatively high magnitude and short duration (typically < 1 s), which decays exponentially with time of DC voltage application

3.8

stress control coating current

I_S

ohmic current that is constant with time, flowing in parallel to the surface leakage current through a continuous stress control coating on the surface of the end winding insulation between conductor and earth

3.9

total current

I_T

time dependent current, which is usually measured during insulation resistance measurement and is the sum of all current components

Note 1 to entry: The total current is the basis for the determination of the insulation resistance R_{it} and the polarization index PI .

3.10

polarity effect

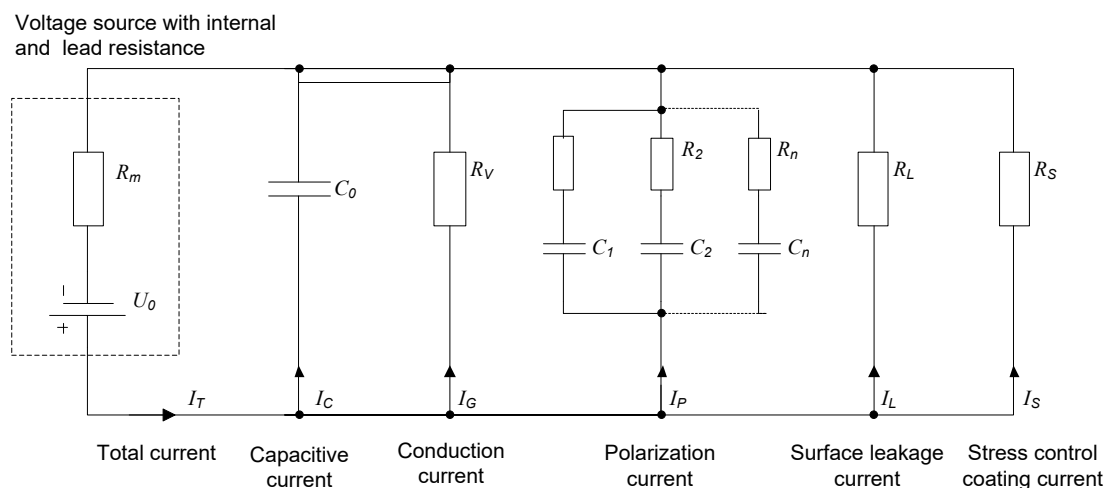
effect of obtaining different values of the insulation resistance R_{it} when the polarity of the insulation resistance meter leads are reversed

Note 1 to entry: This is observed when humidity is present in the insulation. It is caused by a phenomenon known as electro-endosmosis.

4 Insulation resistance – components and influence factors

The insulation resistance of a rotating machine winding is a function of the type and condition of the insulating materials, the insulation system design and the techniques used to manufacture the winding.

The insulation resistance is measured with DC voltage. The measurement of the resistance over time provides information on current components caused by different physical mechanisms. Figure 1 is a schematic showing the different direct current components. Information on the various current components is provided in Annex A.



IEC

Figure 1 – Equivalent circuit diagram of winding insulation in a DC voltage test

5 Polarization index

The polarization index is the quotient of the insulation resistances measured at two different times $t_1 = 1$ min and $t_{10} = 10$ min after application of direct voltage:

$$PI = \frac{R_{i10}}{R_{i1}} \quad (1)$$

Variants of the polarization index definition with a quotient of insulation resistance of other measuring times may be used in special applications and need to be indicated (see Annex E). More measurement points during the 10 min interval may yield additional information.

The polarization index describes the variation of the IR between two specific points in time and therefore, better than with a single insulation resistance value, it may indicate contamination and/or moisture deposition on the winding, or absorbed moisture in the winding. However, it may not indicate internal voids caused by improper impregnation or thermal deterioration.

The polarization index can be used to estimate the suitability of the winding for application of a voltage withstand test or for operation. It may provide information for assessing the condition of the insulation system.

Owing to the negligible polarization currents in the time interval from 1 min to 10 min, the determination of the polarization index may not apply for small machines with random-wound windings, for the field windings in generator rotors, for non-insulated field and squirrel-cage rotor windings and for DC machine armatures.

The polarization index depends on the type of the insulation system, especially on the nature of the insulation materials and procedures used for winding manufacture (for synthetic resin based or shellac- and asphalt based, see 7.1). Furthermore it depends on the kind of stress control coating (see Clause C.3) and the magnitude of the test voltage (see 6.4.1). The influence of the temperature on the polarization index is not significant under the condition that the winding temperature is constant between the 1 min and 10 min readings of the insulation resistance (see 6.1.2).

Before a winding is recommended for a voltage withstand test or for operation, the polarization index should have a minimum value (see recommendations in 8.3).

6 Measurement

6.1 Influences on the measurement of the insulation resistance

6.1.1 General

The resistance measurement result depends on environmental factors, mainly on the winding temperature and on the humidity content of the air. The winding temperature influence can be obtained from empirical data or an experimental measurement and used for the correction of measurement results taken at different temperatures (see 6.1.2).

The air relative humidity affects the surface leakage current and can usually not be estimated, as its effect further depends on the air temperature, surface properties of the insulation and the nature of any surface contamination. For this reason it is generally recommended to perform insulation resistance measurements at winding temperatures above the dew point.

6.1.2 Winding temperature correction

The variation of temperature affects all of the identified current components, except the capacitive current I_C , because an increase in temperature supplies thermal energy, which frees additional charge carriers and so reduces resistivity. Therefore the insulation resistance value of a winding depends on the winding temperature.

To allow a comparison of insulation resistance values obtained at different temperatures it is recommended that all IR values measured be corrected to a common base temperature of 40 °C, if applicable (see Table 1). If the R_i after 1 min of voltage application is > 5 GΩ, or if the R_i for a synthetic resin based insulation system is measured at a temperature less than 40 °C, then no correction is needed [4]. Otherwise the correction factor is calculated using Formula (2):

$$K_T = 0,5^{\frac{40-T}{X}} \quad (2)$$

Where

40 is the base temperature (°C);

T is the winding temperature (°C);

X is the slope parameter for an insulation system (K).

Formula (2) is based on Formula (A.3), taking into account all relevant current components.

NOTE 1 This formula expresses that the IR is reduced by half, if the winding temperature T increases by X Kelvin. The same empirical relation can be equally expressed by exponential functions with other bases, like e. The slope parameter can be directly transformed, in case of a basis e by dividing X with $-\ln(0,5)$.

NOTE 2 Base temperatures other than 40 °C can be used, e.g. 20 °C.

R_i at the base temperature is obtained by multiplying the resistance value measured at a winding temperature T with the correction factor K_T (Formula (3)):

$$R_{ic} = R_{iT} \times K_T \quad (3)$$

where

R_{ic} is the insulation resistance corrected to the base temperature (M Ω);

R_{iT} is the measured insulation resistance at winding temperature (M Ω);

K_T is the temperature correction factor.

The slope parameter X in Formula (2) characterizes the degree of insulation resistance temperature dependency of an individual insulation system. Preferably, this parameter is estimated experimentally. The recommended method is by performing IR measurements at several winding temperatures in the expected range where measurements may be made, including 40 °C, all above the dew point, and plotting the results on a semi-logarithmic scale. From the result of an exponential approximation the slope parameter X can be derived. An example for the procedure is given in Annex B. If experimental data are not available for an insulation system, the values for X in Table 1 can be used, Table 1 is based on empirical data, and there is no apparent reason for the discontinuity at 40 °C.

The temperature correction with an exponential approximation by equations 2 and 3 can cause significant errors with an increasing difference between winding temperature and base temperature. It is recommended to apply this method only for a winding temperature range as given in Table 1, which is derived from experimental measurements.

NOTE 3 If different insulation systems are used in the slot and the end winding regions, then it is the insulation system in the slot region that is relevant for temperature correction.

Table 1 – Values of the parameter X for the temperature correction

Types of insulation system	Slope parameter X K	Temperature range °C
Shellac and asphaltic based	10	10 to 60
Synthetic resin based	No correction ($K_T = 1$)	10 to 40
(e.g. epoxy, polyester, polyesterimide and others)	17	40 to 60

These values are based on experiments and are considered to be a conservative approach, i.e. minimum values. Typically the temperature dependency (Formula 2) is smaller, i.e. the slope parameter is higher.

For the estimation of the polarization index PI , the temperature correction is not required as the difference in winding temperature during the measurement of R_{i1} and R_{i10} is considered to be negligible.

6.2 Measuring equipment

For direct measurement the preferred equipment is an insulation resistance meter. For R_{i1} readings below 5 000 M Ω , a digital instrument should have at least the following characteristics:

- Display: 3 digits
- Accuracy: ± 5 % of reading, ± 5 digits

If no insulation resistance meter is available, the insulation resistance can be obtained from a measurement of voltage and current (indirect measurement). For such indirect measurements

a stabilized DC voltage source, a voltmeter and a micro ammeter can be used. The voltage fluctuation of a real DC voltage source will introduce a variation of $i_c(t) = C_0 \, dU_0/dt$. Since the capacitance C_0 of most high voltage machines is large, a minimum stability and noise is required for the DC supply to neglect this effect. The insulation resistance is calculated from the volt- and ammeter readings using Formula (4).

$$R_{it} = U / I_t \quad (4)$$

where

R_{it} is the insulation resistance (M Ω) at time t;

U is the measured voltage (voltmeter reading) of the DC voltage source (V);

I_t is the measured current (ammeter reading) (μ A) at time t.

For the measurement of high IR values a meter with guard option is recommended, to avoid leakage and capacitive influences from the measuring cable.

The instrumentation shall take no more than 5 s to reach the test voltage.

6.3 Test object and measuring circuit

6.3.1 General

Depending on the aim of the test and the design of the test object, different measuring circuits apply. For checking the recommended minimum IR the test shall be performed on the entire winding. In order to check for insulation problems on each phase winding and between phase windings, measurements shall be performed phase by phase if each phase winding can be easily disconnected from one another. For trending purposes, the same connection shall always be applied.

If possible, external elements such as cables, switches, capacitors, current transformers, etc. shall be disconnected from the winding. Items still connected to the winding need to be recorded.

To obtain insulation resistance measurements on directly water-cooled windings, the water should be removed and the internal circuit thoroughly dried. In some water-cooled windings the manufacturer may have provided a means of measuring the insulation resistance without the need for the coolant to be drained. In general, if the water is not removed then the conductivity of the water should be less than what is recommended by the machine manufacturer. In this case, the water conductivity will largely dominate the insulation resistance; and thus $PI = 1$ and $R_{i10} = 1 \text{ M}\Omega$ may be expected.

In any case the winding elements that are not under test shall be connected with short leads to machine earth to avoid any undesirable effects, such as equalizing currents or AC current induced to test circuit.

6.3.2 Three-phase stator windings

6.3.2.1 Connection for measurements of the entire winding to earth

All phase windings are connected together as shown in Figure 2.

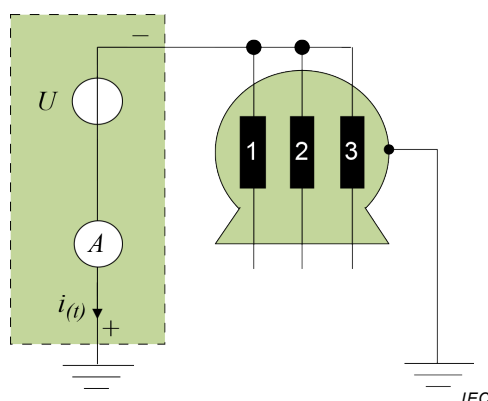


Figure 2 – Connection for testing of the entire winding

6.3.2.2 Connection for phase-to-earth measurements

Testing each phase winding separately (see Figure 3) is the preferred method for trending purposes and to achieve comparative values for the individual phases. The same circuit is applicable for testing more than one phase winding to earth, by connecting the desired phase windings to be tested together and the others to earth.

In case the measuring instrument is equipped with a guard option, instead of connecting the remaining phase windings to earth they can be connected to the guard in order to eliminate the effects from currents between phase windings, like leakage and stress control coating currents. Since this is a deviation from the standard procedure, it has to be noted in the test report.

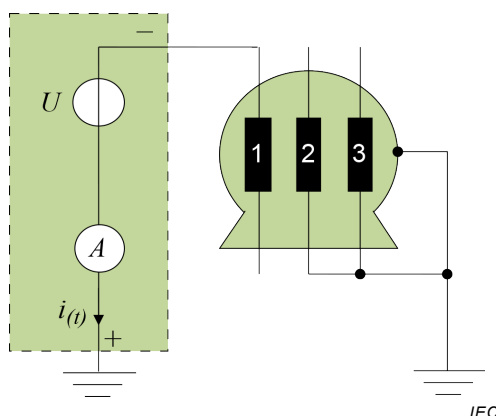


Figure 3 – Connection for phase-to-earth measurement

6.3.2.3 Connection for phase-to-phase measurements

This test is not a standard measurement procedure, however it may provide additional information of a diagnostic nature. See Annex D.

6.3.3 Other windings

Other windings, like field windings or a high voltage rotor winding shall be connected similarly to the phase-to-earth measurement of the stator winding (see 6.3.2.2).

All elements that are not part of the measuring circuit, such as brush rigging from static excitation, need to be disconnected from the test object e.g. by lifting or removing the brushes. Rotating diodes shall be bridged, to avoid problems in the case of winding damage during testing. The same has to be done with permanently installed monitoring equipment such as rotor current monitors or on-line temperature measuring systems.

6.4 Measuring voltage

6.4.1 Type and magnitude

The measurement of the insulation resistance requires the application of a DC voltage. The voltage magnitude shall be restricted to a value appropriate for the voltage rating of the winding and the basic insulation condition. This is particularly important in the case of low voltage machines or wet windings. If the voltage magnitude is too high, it may overstress the insulation and lead to an insulation failure. Guidelines for voltage magnitudes are presented in Table 2.

Table 2 – Guidelines for DC voltage magnitudes to be applied during the insulation resistance measurement

Rated voltage V	DC voltage magnitude V
< 1 000	500
1 000 to 2 500	500 to 1 000
2 501 to 5 000	1 000 to 2 500
5 001 to 12 000	2 500 to 5 000
> 12 000	5 000 to 10 000

NOTE Tests can be performed with higher magnitudes only if it is agreed between test service provider and the customer.

6.4.2 Polarity

Insulation resistance measurements are usually conducted at constant DC voltage having negative polarity. Negative polarity is preferred to accommodate the phenomenon of electro-endosmosis in case of humidity inside the insulation system.

6.5 Measuring time

Readings of the IR are taken after the test voltage has been applied for the specified time, e.g. after one min for insulation resistance R_{i1} and after 10 min for insulation resistance R_{i10} .

6.6 Safety

Due to the polarization effect, the winding insulation will maintain a charge for a long time after the voltage supply has been disconnected. It is important after the test to reduce the test voltage to zero and to earth the test object before the test instrument is disconnected. The earth shall remain applied to the terminals of the phase or winding for at least 4 times the duration of voltage application.

6.7 Measurement procedures

6.7.1 Standard procedure

The test voltage should be applied instantaneously and held constant throughout the test. The test voltage shall be reached in no more than 5 s. The counting of the measuring time starts after reaching the specified test voltage level. The readings are taken after the specified times. There are different procedures for testing all winding phases at the same time and measuring one phase at a time in multiphase windings.

When measuring all phases at the same time in a multiphase winding, or the winding in a single phase winding, after test completion, the test voltage is reduced to zero and for safety reasons, the test object should be immediately short-circuited, earthed and discharged for at least 4 times longer than the time the winding was energized (see 6.6).

In multiphase windings where each phase is tested one at a time (with the other phases earthed), after the test on the first phase is completed, the earth shall be applied and remain applied for at least 4 times longer than the duration of voltage application. As long as the first phase remains earthed, the second and other phases can be tested in turn by connecting the test instrument to it with the other phases earthed. As an alternative, connections can be changed when the discharge current with the terminal earthed is sufficiently low, e.g. 10 nA.

When insulation measurement is an important aspect of maintenance, it is recommended to check the operation of the instrument using high voltage resistances in the range of 100 MΩ. The check should be performed before and after the tests, and is especially important for battery operated instruments.

6.7.2 Special procedures

Other test procedures can be used in order to obtain additional information on the insulation condition. See Annex E.

7 Interpretation of measurement results

7.1 General

The insulation resistance and polarization index results can be used for at least the following purposes:

- a) Estimation of the suitability of a machine for the application of voltage withstand test, or for operation, may be based on obtaining the recommended minimum values for the insulation resistance and/or the polarization index (see 7.2).
- b) The insulation resistance and polarization index history of a given machine, measured at uniform conditions so far as the controllable variables are concerned, is recognized as a useful way of trending some aspects of the insulation condition over years (see 7.3).
- c) The insulation resistance and polarization index values of individual phase windings or of different machines of the same design, measured at uniform conditions so far as the controllable variables are concerned, can be used to compare the insulation conditions.

For these specific purposes a), b) and c) the measurement influences shall be considered (see 7.4).

7.2 Suitability for testing and operation

Insulation resistance and polarization index may be used to estimate the suitability of a machine for the application of a voltage withstand test or for operation. Machines should have both the insulation resistance and the polarization index above the recommended minimum values (see Tables 3 and 4). If the measured values are below the recommended minimum values, a voltage withstand test and operation of the machine are not recommended, unless there is a design reason or there is a past history for such low readings.

Insulation resistance testing may also be used to determine if a winding has failed a voltage withstand test. If the measured values taken after a voltage withstand test are significantly lower than the values before the voltage withstand application, insulation damage may have occurred during the voltage withstand testing, even if the test voltage did not collapse due to high fault currents.

If the measured values are below the recommended minimum values due to dirt or excessive moisture and an insulation defect can be excluded, cleaning and drying the winding may improve the measured results. The insulation resistance readings can be used to monitor the effectiveness of the drying progress.

If the insulation resistance R_{i1} at 40 °C is greater than 5 000 MΩ, the polarization index may be ambiguous and can be disregarded.

For shellac and asphalt based insulation systems, a very high polarization index (for example greater than 8) may indicate that the insulation has been thermally aged, and may have a risk of failure. If physical inspection (tapping on the insulation, for instance) confirms that the insulation is dry and brittle, it is best not to attempt cleaning or voltage withstand testing the winding. Failure may occur at any time if the machine is returned to operation.

7.3 Trending of insulation condition

If the insulation resistance (R_{i1}) history of a machine is available, comparison of the present test result with previous tests will help to assess the insulation condition. It is important, however, to compare tests under similar conditions, that is, winding temperature, voltage magnitude, test duration and relative humidity (see 6.1) and, if possible, the use of identical test equipment. For comparison of tests conducted at different winding temperatures, the results should be corrected to the same base temperature (see 6.1.2).

A sharp decline in the R_{i1} or PI from the previous reading may indicate surface contamination or moisture. When a low PI occurs at an elevated temperature (above 60 °C), a second measurement performed below 40 °C, but above the dew point, is recommended as a check on the real insulation condition.

7.4 Comparison between machines or between phases

If R_{i1} is less than 5 000 MΩ for the complete winding, a significant difference in R_{i1} or PI between identical machines, may indicate surface contamination, moisture or insulation damage. In such a case, the reason for the difference should be investigated.

7.5 Effects at very high values of insulation resistance

Depending on the test voltage level and the condition of the insulation, the measured current may not exceed values in the sub-microampere-range. Any noise from external sources, such as voltage fluctuations generated by the test instrument, but also temperature fluctuations and even electrochemical effects caused by moisture, may generate currents that exceed the currents through the insulation. False readings are a consequence of such.

Especially during longer measurements sessions, the conditions can vary so that the results may lead to misinterpretation.

As general advice, the polarization index is not indicative of insulation condition when the insulation resistance reaches values in the range of 5 000 MΩ and above.

It is advisable to consult the manual of the test instrument. All manufacturers should publish the accuracy of the test instrument. This may also help judging the results.

7.6 Limitations of the insulation resistance test

Insulation resistance test data is useful in evaluating the presence of some insulation problems such as contamination, absorbed moisture, or severe cracking; however, some limitations are as follows:

- a) Insulation resistance of a winding is not directly related to its dielectric strength and if the insulation system of a winding will fail in service. The insulation resistance measurements give no indication of the distribution of weak points within the insulation, e.g. large voids caused by improper impregnation and thermal deterioration.

- b) Windings having an extremely large end winding surface area, large or slow-speed machines, round rotor field windings or machines with commutators may have insulation resistance values that are less than the recommended value. In these cases, historical trending of insulation resistance is useful in evaluating insulation condition.
- c) Because insulation resistance tests are conducted while a machine is at standstill, these tests will not detect problems due to rotation, such as loose coils, or vibration leading to end winding movement.

8 Recommended limits of insulation resistance and polarization index

8.1 General

The following insulation resistance and polarization index values are the lowest values at which the winding is recommended for a voltage withstand test or for operation. In some cases, special insulating materials or designs may provide lower values (e.g. at special designs of stress control coatings, see Clause C.3). Minimum values for such machines should be based on comparison with historic data.

The recommended values are not valid for complete windings which have not yet been impregnated.

8.2 Insulation resistance

Table 3 provides recommended minimum insulation resistance values R_{i1} of an entire winding corrected to the base temperature of 40 °C.

**Table 3 – Recommended minimum insulation resistance values
at a base temperature of 40 °C**

Test object	Minimum insulation resistance R_{i1} MΩ
High voltage shellac-and asphalt based insulation systems and all field windings	rated voltage (kV) + 1
High voltage synthetic resin based insulation systems (form-wound windings)	100
Low voltage random- and form-wound windings and DC armatures	5

If the minimum value of insulation resistance for the complete winding is not met, refer to section 6.3.2.2 for additional measurements that may be made. For more information, refer to Annex D.

8.3 Polarization index

Table 4 provides recommended minimum polarization index values of an entire winding. These values are only valid for insulation systems of high voltage machines, in which a characteristic polarization current I_p can lead to a marked change in the readings of the insulation resistance at 1 min and at 10 min.

If the winding temperature does change appreciably between the 1 min and 10 min readings of the insulation resistance, the values corrected to the base temperature of 40 °C are to be used for the calculation of the polarization index.

Table 4 – Recommended minimum values of polarization index for high voltage insulation systems

Types of high voltage insulation system	Minimum polarization index <i>PI</i>
Shellac and asphaltic based	1,5
Synthetic resin based (e.g. epoxy, polyester, polyesterimide and others)	2,0
NOTE These minimum values are based on the ratio of the 10 min to 1 min R_i readings.	

These recommended minimum values are not applicable for:

- Small machines with random-wound windings, machines with non-insulated field windings, squirrel-cage rotor windings and DC machine armatures (see Clause 5)
- Machines with stress control coatings having galvanic contact with the winding connections (see Clause A.6 and Clause C.3)
- Windings where R_{i1} is $>5\,000\text{ M}\Omega$ (see Clause 7.5).

9 Test report

9.1 Operational aged windings

The test report should, as a minimum, provide the data, the test decision and, if used for trending and comparison of insulation conditions, a statement on the interpretation of the measurement results. The test report should contain the following items:

- Identification information
 - Plant name
 - Machine number
- Date of measurement
- Climatic conditions
 - Ambient temperature
 - Winding temperature
 - Relative and ambient temperature to calculate the absolute humidity and dew point
- Instrument
 - Name, type
 - Manufacturer
 - Serial number
 - Calibration due date
- Test circuit, instrument settings and test conditions
 - Test voltage and polarity
 - Duration, if required
- Insulation characteristics at measurement conditions, and corrected to the base temperature:
 - 1 min insulation resistance
 - 10 min insulation resistance, if applicable
 - Polarization index, if applicable
 - Temperature correction, if applicable

- Graphical display of measurement curves, if applicable
 - Measured current vs. time, preferably in a log-log diagram
 - Measured insulation resistance vs. time, preferably in a log-log diagram
- Name of test personnel
- Document specific information
- Comment section e.g. for deviation from standard test procedure, observations, etc.

It is advisable to store the measurement results in the most original data-format for future reference.

Depending on the type of document, standalone test certificate or part of a condition assessment report, the content of the measurement report may be supplemented by additional information, e.g. operational mode, machine age, etc.

9.2 New windings

The insulation resistance measurement for new windings may be a supplementary part of the high voltage withstand test, with a 1 min insulation resistance test before and after the high voltage withstand test.

Consequently, most of the information required for complete reporting is part of the withstand test protocol. A selection of the required information defined in 9.1 may be sufficient.

Annex A (informative)

Components of the direct current

A.1 Total current I_T

The total current is the sum of all currents caused by the application of the DC test voltage in the test object. It is available for measurement in the leads between voltage source and test object (Figure 1).

The general time characteristics of the total current and the contribution of the components are shown in Figure A.1. Examples for specific insulation conditions are given in Annex C.

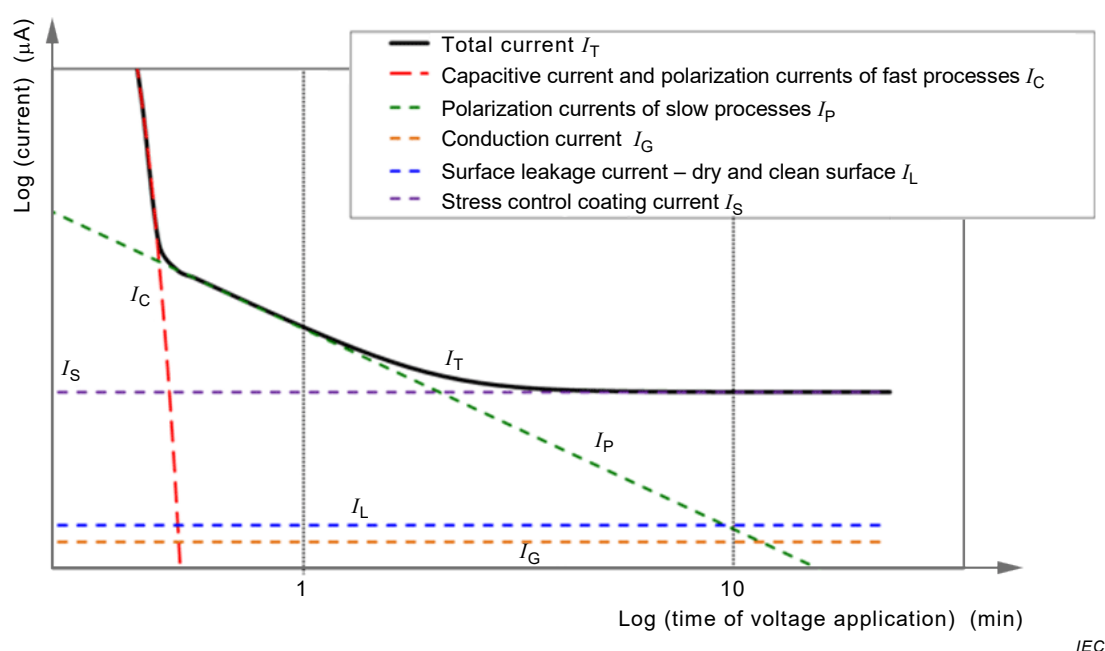


Figure A.1 – Relationships between different currents and time

A.2 Capacitive current I_C

The capacitive current is caused by charging or discharging the capacitance of the winding via the circuit resistance, consisting of the internal resistance of the voltage source and the lead resistances. The capacitive current $i_c(t)$ depends on time (t) in seconds according to Formula (A.1).

$$i_c(t) = \frac{\Delta U_0}{R_m} \cdot e^{-\frac{t}{R_m \cdot C_0}} \quad (\text{A.1})$$

where

U_0 is the voltage (V);

R_m is the internal resistance of the voltage source and lead resistances (Ω);

C_0 is the capacitance (F).

When a voltage step of ΔU_0 is applied to the winding, the capacitive current peak is the quotient of ΔU_0 and the resistance R_m . The time constant of the exponential current decay function is the product of the resistance R_m and the capacitance C_0 . Even for large windings with a capacitance in the range of microfarads, the time constant would not exceed one second or so with typical measurement instruments having a relatively low R_m . Therefore the capacitive current has too short a duration to affect the measurement of the insulation resistance and the polarization index.

A.3 Conduction current I_G

The conduction current is caused by directed movement of electrons and ions in the electric field. At low field magnitudes, conduction is predominantly caused by ions. At high field magnitudes, when approaching the dielectric breakdown strength, electrons increasingly contribute to conduction.

Given that $R_m \ll R_V$, the conduction current I_G of an insulation volume element between parallel electrodes is given by Formula A.2):

$$I_G = \frac{U_0}{R_V} \quad (\text{A.2})$$

where

U_0 is the voltage (V);

R_V is the volume resistance $R_V = \frac{d}{\kappa_V \cdot A} (\Omega)$;

κ_V is the specific volume conductivity (S/m);

d is the distance between electrodes (m);

A is the electrode area (m²).

The conduction current through the insulation bulk depends on the dielectric material, the electric field magnitude, the temperature and the moisture content of the insulation. The specific volume conductivity is not very dependent on the electric field magnitude, as long as the stress during measurement is well below the breakdown strength. The temperature may not have a significant effect if the activation energy of the insulation material is low, in which case the activation energy depends on the mobility of ions and electrons in the insulation material with temperature according to:

$$\kappa_V = \kappa_0 \cdot e^{-\frac{W_a}{k \cdot T}} \quad (\text{A.3})$$

where

κ_V is the specific volume conductivity (S/m);

κ_0 is the material parameter (S/m);

W_a is the activation energy (eV);

k is the Boltzmann constant (eV/K);

T is the absolute temperature (K).

The volume conductivity, and therefore the conduction current, exponentially depends on the activation energy and the temperature (see Formulae A.2 and A.3).

The presence of humidity within the insulation structure increases the conduction current due to the conductivity of the water itself and by an increasing number of ions from the dissociation of internal contaminants and of hydrolytic decomposition products.

increasing humidity content the specific volume conductivity can increase by several orders of magnitude.

A.4 Polarization current I_p

Polarization in solid dielectrics is an effect caused by the electric field, which aligns dipoles either being induced by the field or which exist permanently. The dipole alignment process in the field, called relaxation, requires time, which depends on the inertia inherent to the mechanism. In the equivalent circuit the different mechanisms are represented by R-C series combinations (Figure 1, indices 1,2...n). The relaxation time constants $\tau_j = R_j \cdot C_j$ ($j = 1...n$) vary in a wide range, from extremely fast processes like the electron polarization up to relatively long durations for slow processes like the interfacial polarization, with time constants ranging from milliseconds to hours.

Given that the internal and lead resistances are of negligible influence ($R_m \ll R_j$), the polarization current $i_p(t)$ can be generally expressed as a function of time (t) by Formula (A.4).

$$i_p(t) = \Delta U_0 \cdot \sum_{j=1}^n \frac{1}{R_j} \cdot e^{-\frac{t}{\tau_j}} \quad (\text{A.4})$$

where

U_0 is the voltage (V);

τ_j is the relaxation time constant of a polarization mechanism j , $\tau_j = R_j \cdot C_j$ (s);

R_j, C_j is the characteristic resistance and capacitance of a polarization mechanism j (Ω), (F).

Because the currents of the fast processes decay towards zero in the sub-milliseconds range, for the insulation resistance measurement only slow polarization processes are of relevance. Therefore, only the interfacial polarization effect remains. It is caused by the slow drift of ions and a minor amount of free electrons, which accumulate at the internal interfaces and at the electrodes. As there are different kinds of microscopic and macroscopic interfaces present in insulations with composite dielectrics, the polarization current is a superposition of current components with different magnitudes and time constants. An empirical expression for the polarization current sum is given by Formula (A.5). Some of the time constants may be many minutes or hours.

$$i_p(t) = \beta \cdot \Delta U_0 \cdot C_0 \cdot t^{-n} \quad (\text{A.5})$$

where

β is a factor, representing the insulation and its condition;

U_0 is the voltage (V);

C_0 is the geometric capacitance (F);

n is the exponent representing the insulation and its condition.

As a higher temperature increases ion mobility and electron availability, the polarization current raises with increasing temperature.

Also the presence of humidity and contamination will increase the availability of charge carriers for interfacial polarization.

For dry and clean insulation the polarization current is dominant. Since the polarization current is a straight line in a log-log diagram, the preferred way to display the current graphically is a log(i) versus log(t) diagram.

A.5 Surface leakage current I_L

The surface leakage current is caused by conduction in foreign layers, in case of inherently conducting solid deposits mainly by electrons or, in oil films and wet layers from water, predominantly by ions. Wet surface layers can be formed either by direct wetting or by accumulation of water molecules from the air due to adsorption, hygroscopicity of foreign layers and condensation.

The surface leakage current depends on the surface resistance according to Formula (A.6):

$$I_L = \frac{U_0}{R_L} \quad (\text{A.6})$$

where

U_0 is the voltage (V);

R_L is the surface leakage resistance, $R_L = \frac{l}{\kappa_L \cdot b}$ (Ω);

κ_L is the specific layer conductivity (S·m/m);

l is the length of the layer between electrodes (m);

b layer width (m).

The surface leakage resistance can drop with increasing relative humidity of air in the range between 30 % and 90 % by several orders of magnitude and follows changes in the relative humidity nearly instantly.

When condensation conditions arise (surface temperature < dew point temperature), the surface resistance will further decrease, as the amount of water on the surface increases.

The surface leakage resistance of wet layers depends on the temperature by an empirical exponential relationship.

Dry deposition of layers from intrinsically conducting materials, like copper or carbon dust, may reduce the surface leakage resistance significantly. The properties and dependencies are dominated by electron conduction mechanisms. As metal dust oxidizes with air to metal oxides, its surface leakage resistance is higher than that of carbon dust layers.

The contribution of surface leakage current depends on the insulation condition of the end winding; in the case of a measurement performed on each phase winding with the others connected to earth, this contribution is mainly due to the phase break portion of the end winding.

A.6 Stress control coating current I_S

If a continuous stress control coating covers the complete end winding of a stator, and the coating is in galvanic contact with the winding connections by design, a stress control coating current occurs. Since this specific stress control design is a unique design, the technical background and the consequences for the measurement and the interpretation of insulation resistance and polarization index are outlined in Clause C.3.