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IEEE Recommended Practice for Testing Insulation Resistance of Electric Machinery

IEEE Power and Energy Society

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IEEE Std 43™-2013
(Revision of
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Approved 11 December 2013

IEEE-SA Standards Board

Acknowlegements

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Abstract: The dc voltage tests procedures for the measurement of the insulation resistance and polarization index of insulated stator, and rotor windings and how to interpret the results are described in this recommended practice.

Keywords: armature winding, dc, field winding, IEEE 43™, insulated, insulation resistance, polarization index, rotor winding, stator winding, voltage

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Introduction

This introduction is not part of IEEE Std 43™-2013, IEEE Recommended Practice for Testing Insulation Resistance of Electric Machinery.

Insulation resistance measurement has been recommended and used for more than half a century to evaluate the condition of electrical insulation. Whereas individual insulation resistance measurements may be of questionable value, the carefully maintained record of periodic measurements, accumulated over months and years of service, is of unquestioned value as a measure of some aspects of the condition of the electrical insulation. Originally, in 1950, this recommended practice was published by the AIEE as a guide to present the various facets associated with the measurement and understanding of electrical insulation resistance. The guide was revised in 1961 and again in 1974. During the 1970s, several changes were made to the types of insulation used in electric rotating machines. The insulation resistance characteristics of these newer THERMOSETTING insulation systems are different from the older THERMOPLASTIC systems, and therefore required this substantial revision to the standard for measuring insulation resistance. Other changes include the addition of further description of the testing theory and the removal of suggestions regarding maintenance dry-out procedures for older windings (previously Annex A). Recommendations for maintenance procedures are beyond the scope of this document. With this publication as a recommended practice, the IEEE is presenting and recommending electrical insulation resistance measurement as an important factor in monitoring the condition of electrical insulation in rotating machinery.

This recommended practice describes the theory, procedure, and interpretation of the insulation resistance test. It is intended for the following:

- Individuals or organizations who manufacture rotating machines
- Individuals or organizations who are responsible for the acceptance of new rotating machines
- Individuals or organizations who test and maintain rotating machines
- Individuals or organizations who operate rotating machines

This recommended practice is designed to help organizations and individuals

- Evaluate the condition of the electrical insulation used in rotating machines
- Determine if the electrical insulation of a rotating machine is suitable for return-to-service
- Determine if the electrical insulation of a rotating machine is suitable for high-potential testing

This recommended practice is intended to satisfy the following objectives:

- Promote consistency for insulation test procedures and interpretations
- Provide useful information on proper application of the insulation resistance test
- Provide useful information on the technical theory of insulation resistance testing

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IEEE Recommended Practice for Testing Insulation Resistance of ~~Rotating~~ Electric Machinery

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1. Overview

1.1 Scope

This document describes a recommended procedure for measuring insulation resistance of armature and field windings in rotating machines rated ~~1 hp,~~ 750 W or greater. It applies to synchronous machines, induction machines, dc machines, and synchronous condensers. It does not apply to fractional-horsepower machines.

The document also describes typical insulation resistance characteristics of rotating machine windings and how these characteristics indicate winding condition. It recommends minimum acceptable values of insulation resistance for ac and dc rotating machine windings.

Other IEEE standards that include information on insulation resistance measurement are listed in Clause 2.

1.2 Purpose

The purpose of this recommended practice is to address the following:

a) Define insulation resistance and polarization index testing of the winding of a rotating machine.

b) Review the factors that affect or change insulation resistance characteristics.

c) Recommend uniform test conditions.

d) Recommend ~~uniform~~ information methods for measuring insulation resistance with precautions to avoid erroneous results.

e) Provide a basis for interpreting insulation resistance test results to estimate winding suitability for service or for an overvoltage test. In particular, this standard describes typical insulation problems detected by the insulation resistance test.

f) Present recommended minimum acceptable insulation resistance values and polarization indices for various types of rotating machines.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

~~This recommended practice shall be used in conjunction with the following publications. When the follow-ing standards are superseded by an approved revision, the revision shall apply.~~

~~ASTM D257-99 Standard Test Methods for DC Resistance or Conductance of Insulating Materials.[1]~~

~~ASTM D1711-99 Standard Terminology Relating to Electrical Insulation.~~

ASTM F855, ~~97e1~~ Standard Specifications for Temporary Protective Grounds to Be Used on De-energized Electric Power Lines and Equipment.[1]

IEC 60085, Electrical insulation – Thermal evaluation and designation.[2]

IEEE Std 1™, IEEE Standard General Principles for Temperature Limits in the Rating of Electric Equipment and for Evaluation of Electrical Insulation.[3, 4]

[1] ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (http://www.astm.org/)

[2] IEC publications are available from the International Electrotechnical Commission (http://www.iec.ch/). IEC publications are also available in the United States from the American National Standards Institute (http://www.ansi.org/).

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~~IEC 60085-1: 1984, Thermal evaluation and classification of electrical insulation.[2]~~

IEEE Std 56~~-1977 (Reaff 1991),~~™, IEEE Guide for Insulation Maintenance of Large Alternating-Current Rotating Machinery (10 000 kVA and Larger).~~[3, 4]~~ [5]

IEEE Std 62.2~~1995, IEEE~~ ™, Guide for Diagnostic Field Testing of Electric Power Apparatus – ~~Part 1: Oil Filled~~ Electrical Machinery.

IEEE Std 67~~-1990 (Reaff 1995),~~™, IEEE Guide for Operation and Maintenance of Turbine Generators.

IEEE Std 95~~-1977 (Reaff 1991)~~ ™, Recommended Practice for Insulation Testing of ~~Large~~ AC ~~Rotating~~ Electric Machinery (2300 V and above) with High Direct Voltage.~~[5]~~

IEEE Std 510™, Recommended Practice for Safety in High Voltage and High-Power Testing.

NEMA MG-1, Motors and Generators.[6]

~~IEEE Std 432-1992 (Reaff 1998), IEEE Guide for Insulation Maintenance for Rotating Electric Machinery (5 hp to less than 10 000 hp).~~

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[5] Presently under revision.

[6] NEMA publications are available from Global Engineering Documents (http://global.ihs.com/).

~~[2] IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.~~

~~[3] Presently under revision.~~

~~[4] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.standards.ieee.org/).~~

~~IEEE Std 433-1974 (Reaff 1991), IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Voltage at Very Low Frequency.~~

~~IEEE Std 434-1973 (Reaff 1991), IEEE Guide for Functional Evaluation of Insulation Systems for Large High-Voltage Machines.~~

~~IEEE Std 492-1999 IEEE Guide for Operation and Maintenance of Hydro-Generators.~~

~~IEEE Std 510-1983 (Reaff 1992), IEEE Recommended Practices for Safety in High-Voltage and High-Power Testing.~~

3. Definitions

For the purposes of this ~~recommended practice~~ document, the following terms and definitions apply. The *IEEE* ~~Dictio-nary of Electrical and Electronics Terms~~*Standards Dictionary Online* should be ~~referenced~~ consulted for terms not defined in this clause.[7]

absorption~~(polarization)~~ current (I_A): A current resulting from molecular polarizing and electron drift, which decays with time of voltage application at a decreasing rate from a comparatively high initial value to nearly zero, and depends on the type and condition of the ~~bonding material used in the~~ insulation system.

conduction current (I_G): A current that is constant in time, that passes through the bulk insulation from the grounded surface to the high-voltage conductor, and that depends on the type of ~~bonding material used in the~~ insulation system.

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[7] IEEE Standards Dictionary Online subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

electroendosmosis effect: A phenomenon occasionally observed, more often on older thermoplastic (e.g., asphaltic) windings, when, in the presence of moisture, different insulation resistance values may be obtained when the polarity of the tester leads are reversed. Typically for older wet windings, the insulation resistance for ~~reverse~~ positive polarity, where the ~~ground~~ positive lead is connected to the winding and the negative voltage lead to ground, is much higher than for ~~normal~~ the opposite polarity.

geometric capacitive current (I_C): A reversible current of comparatively high magnitude and short duration, which decays exponentially with time of voltage application, and which depends on the internal resistance of the measuring instrument and the geometric capacitance of the winding.

insulation resistance (IR_t): The capability of the electrical insulation of a winding to resist direct current. The quotient of applied direct voltage of negative polarity divided by current across machine insulation, corrected to 40 °C, and taken at a specified time (t) from start of voltage application. The voltage application time is usually 1 min (IR_1) or 10 min (IR_{10}), 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.

insulation resistance profile (IRP): Insulation Resistance Profile (IRP) is a graph of the IR where the IR is plotted in discrete time increments (such as 5 seconds) over a specified time period (typically 10 min).

~~**geometric capacitive current (I_C):** A reversible current of comparatively high magnitude and short duration, which decays exponentially with time of voltage application, and which depends on the internal resistance of the measuring instrument and the geometric capacitance of the winding.~~

polarization index ($P.I._{t_1/t_2}$): Variation in the value of insulation resistance with time. The quotient of the insulation resistance at time (t_2) divided by the insulation resistance at time (t_1). If times t_2 and t_1 are not specified, they are assumed to be 10 min and 1 min, respectively. Unit conventions: values of 1 through 10 are assumed to be in minutes, values of 15 and greater are assumed to be in seconds (e.g., $P.I._{60/15}$ refers to IR_{60s}/IR_{15s})

surface leakage current (I_L): A current that is constant with time, and which usually exists over the surface of the end-turns of the stator winding or between exposed conductors and the rotor body in insulated rotor windings. The magnitude of the surface leakage current is dependent upon temperature and the amount of conductive material, e.g., moisture or contamination on the surface of the insulation.

4. Safety considerations

Insulation resistance testing involves the application of high~~-~~-direct voltages to machine windings. These windings have capacitive and inductive properties that can lead to hazards that may not be readily apparent. It is not possible to cover all safety aspects in this recommended practice and test personnel should consult IEEE Std 510~~-1983;~~~~[6]~~; ASTM F855~~-97e1~~; manufacturers' instruction manuals; and union, company, and government regulations.

~~[6] Information on references can be found in Clause 2.~~

Before any testing is conducted, the winding insulation must be discharged. It is not safe to begin testing before the discharge current is almost zero and there is no discernible return voltage (less than approximately 20 V) after the ground is removed~~.~~ (in general, the winding should not be left ungrounded). After completion of the test, the winding should be discharged through a suitable resistor, sized to limit the instantaneous current~~ to 1 A~~. A minimum discharge time, which is equal to four times the voltage application duration, is recommended. This time interval is based on the *R* (resistive), *L* (inductive), *C* (geometric capacitive), and absorptive characteristics of the circuit during charging (time of the application of the voltage) and discharging (elapsed time since the removal of the voltage source and subsequent grounding of the winding under test). It is important to remember that the testing is not complete until the winding is discharged and there is no discernible voltage. It is recommended that subsequent~~ ac high-potential~~ testing not be conducted until the winding is fully discharged.

During the test period, all appropriate safety measures for the voltages being used ~~must~~shall be taken. ~~For test voltages 5000 V and above,~~ The lead between the test set and the winding must be appropriately insulated and spaced from ground; otherwise, surface leakage currents and corona loss may introduce errors in the test data. For safety considerations, and to avoid measuring stray currents, the leads may be shielded.

Restriction of personnel access to the high voltages is mandatory. Use of personal protective equipment is recommended, as is the use of hot sticks, insulated ladders, etc. If accessible, the phase neutral and line ends of each winding should be connected together during the test to minimize the effect of high-voltage surge reflections that may result from a winding failure.

The safety measures described are by no means ~~exclusive.~~all encompassing. These are meant only to signify the nature of the hazards involved. It is the responsibility of the users of the test equipment to completely ascertain the possible hazards involved in the testing, to protect personnel from harm, and to eliminate the risk of damage to the equipment.

5. Insulation resistance—general theory

The insulation resistance of a rotating machine winding is a function of the type and condition of the insulating materials used, as well ~~as their application~~ techniques used to apply them. In general, the insulation resistance varies proportionately with the insulation thickness and inversely ~~with~~ proportionately to the conductor surface area.

~~Interpretation of insulation resistance measurements of machine windings and the recommended minimum values of polarization index and insulation resistance are described in Clause 11 and Clause 12, respectively.~~

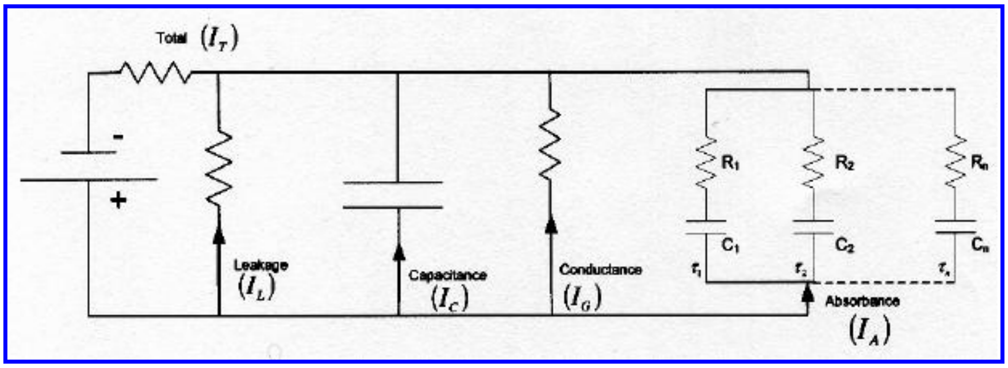
5.1 Components of the measured direct current

The insulating system of a stator winding is comprised of numerous interfaces, which exist between different materials such as mica, glass and polymer matrix of either epoxy or polyester. As a consequence, the electrical conduction process is principally controlled by the interfacial polarization mechanism. When a direct-voltage field is suddenly applied across a stator winding insulating system, space charge build-up occurs at the interfaces due to the difference in the permittivity's and conductivities of the contiguous dielectric materials forming the interfaces (see [B1] and [B2]). First, a rapid voltage division is established across the two abutting dielectrics at the interface because of their difference in permittivity. This is manifest by an almost instantaneous capacitive current, I_c, whose duration is too short to influence the shape of the overall current and thus does not influence the one minute resistivity measurement. This capacitive current decreases exponentially with a time constant equal to the product of the winding's capacitance and the instrumental resistance. The voltage drops across the two dissimilar dielectric layers, constituting the interface, that are characterized by two distinctly different conductivities, lead to the development of two currents of unequal magnitude. This causes charge accumulation or trapping at the interface until the counter field created by the trapped space charge equalizes the currents in the adjacent dielectric strata. The time constant of this process, which is a measure of the time required to achieve equalization of the current magnitudes, is contingent upon the permittivities and conductivities as well as the geometry of the contiguous strata forming the interface. Since there is a multiplicity of dissimilar interfaces within the insulating systems of a stator winding, the overall interfacial polarization mechanism within the insulating systems can be only adequately described by a distribution of relaxation times and, consequently, it is not possible to represent the conduction process in a stator bar by a simplistic *RC* lumped circuit (see Figure 1). Note that the behavior is still further compounded in its complexity in that a similar interfacial polarization mechanism may also take place at the semi-conducting shield and the insulating material interfaces.

~~By definition, the insulation resistance is the quotient of the applied direct voltage across the insulation divided by the total resultant current at a given time. The total resultant current (I_T) is the sum of four differ-ent currents: surface leakage (I_L), geometric capacitance (I_C), conductance (I_G), and absorption (I_A).~~

~~An equivalent circuit for the various currents in an insulation resistance test is shown in Figure 1.~~

~~The geometric capacitance current (I_C) usually does not affect the measurements, because it disappears by the time the first reading is taken at 1 min.~~



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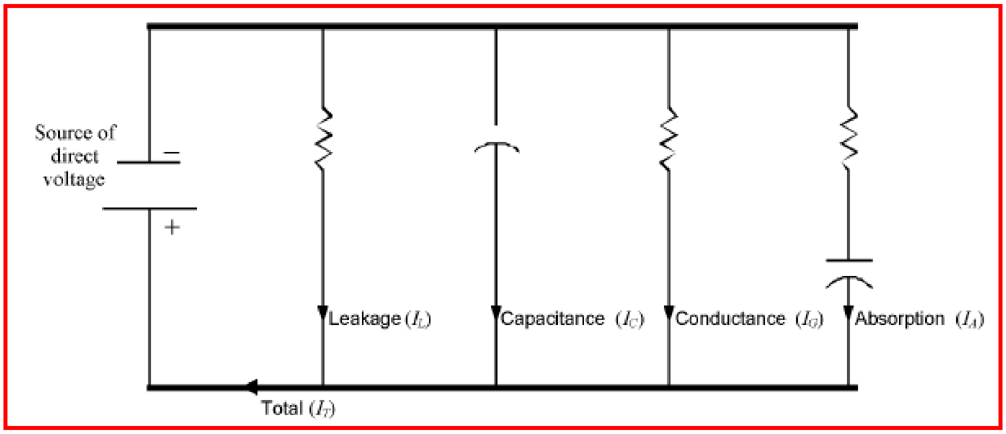

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Figure 1—Equivalent circuit showing the four currents monitored during ~~an~~ insulation resistance test

The distribution of relaxation times is such that even the 10 min measurement falls still within the absorption current, (I_A), range. The absorption current is an inverse function of the time, (t) and is normally expressed empirically as shown in Equation (1).

~~The absorption current (I_A) or polarization current decays at a decreasing rate. The current vs. time relationship is a power function, shown in Equation (1). It may be plotted on a log-log graph as a straight line.~~

$$I_A = K\,t^{-n} \tag{1}$$

where

I_A = ~~is~~ absorption current~~,~~

K = ~~is a~~ function of ~~the particular insulation system and~~ applied ~~test~~ voltage, capacitance and the particular insulating system of the stator bar or winding

t = ~~is~~ time ~~of applied direct voltage,~~

n = an exponent which is a characteristic function of the ~~particular~~ insulated system

At long measurement times (>10 min), the value of I_A is often low enough so that the total current approaches asymptotically the value of the direct conduction current which is the summation of the leakage current along the end arms, I_L, and the conductance current, I_G, through the insulation volume. They constitute the constant finite conduction current that is observed with insulating systems under a constant voltage when applied for extended periods of time. Note that the charge carriers (ions and electrons), that become trapped at the interfaces, are held in deep traps and thus do not contribute significantly to the conductance current, I_G, under long term electrification. However, they can be ejected from the deep traps as the temperature increases.

A current, that can influence adversely the insulation resistance measurements, is the surface leakage current, I_L. This current arises from semi-conducting impurities that may become deposited on the insulation surfaces of stator bars and its adverse effects may be further enhanced by moisture absorption on the insulation surfaces; its magnitude may be of the same order or greater than that of the absorption current, I_A. Frequently, it may become necessary to dry and clean the insulation surfaces to circumvent resistance measurement errors.

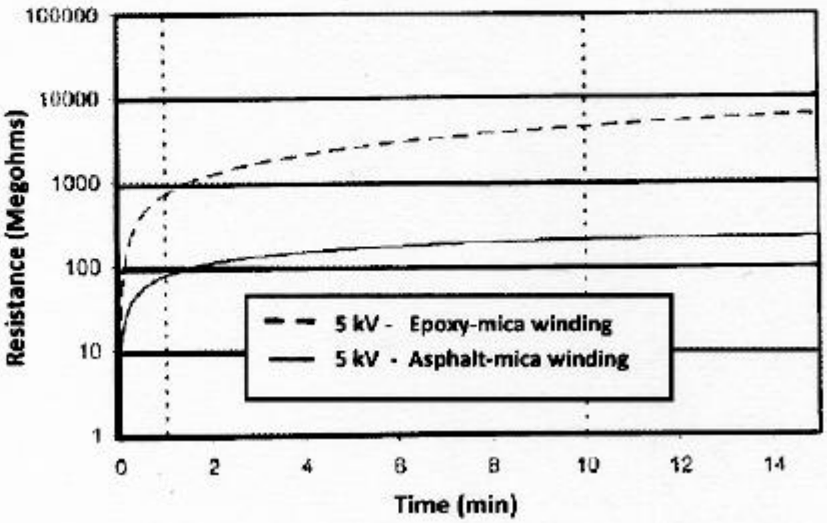

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Figure 2—Insulation resistance measurements at 5 kV for same machine before (asphaltic-mica insulation) and after rewinding (epoxy-mica insulation)

Figure 2 compares at an applied voltage of 5 kV the insulation resistance of an epoxy-mica insulated winding with that of an asphalt-mica insulated winding (see [B3]). As expected, the insulation resistance at both the 1 min and 10 min measurements is substantially higher for the lower loss epoxy-mica system. However, note that in both cases the insulation resistance for times above 10 min tends asymptotically towards a constant value.

As mentioned earlier, in some cases, the stress control coating can have a notable influence on the resistance and polarization index measurement. Figure 3 shows the charging current from a resistance test conducted at 1 kV on a turbo-generator with epoxy bonded ground wall insulation and silicon carbide tape as the stress control system. The hump observed in the middle of the curve on a log-log plot arises from the contribution of the stress control system (see [B4] and [B5]. The value of the insulation resistance is lowered to about one third of its bulk value due to the stress grading system. The *P.I.* for this measurement was 26. The stress control peak moves to shorter times as the voltage of the test increases. When the direct voltage is applied as a step or in the form of a ramp, this peak disappears at voltages greater than 6 kV (see [B6], [B7]). Therefore, more reliable values of the resistance and of the *P.I.* will be obtained at 5 kV or more.

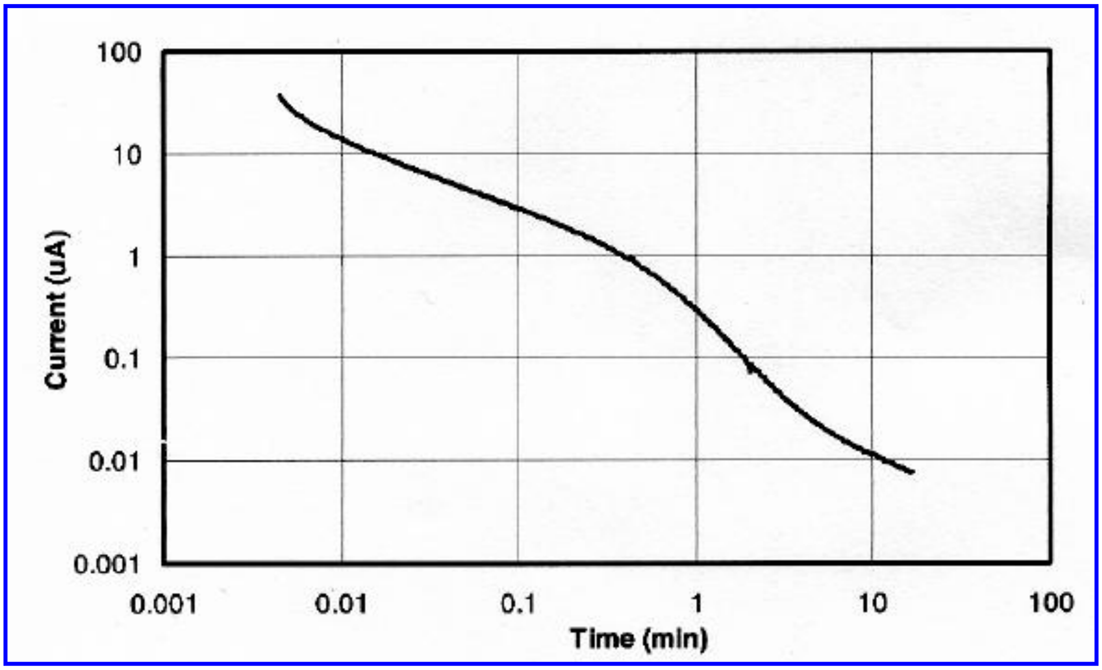

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Figure 3—Measured current for a machine with a strong influence of the stress control coating

~~The absorption current has two components. The first component is due to the polarization of the impregnating materials because the organic molecules, such as epoxy, polyester, and asphalt, tend to change orientation in the presence of a direct electric field. Since these molecules have to strain against the attractive forces of other molecules, it usually takes several minutes after application of the electric field for the molecules to become reoriented, and, thus, for the current supplied polarizing energy to be reduced to almost zero. A second component of the absorption current is due to the gradual drift of electrons and ions through most organic materials. These electrons and ions drift until they become trapped at the mica surfaces commonly found in rotating machine insulation systems. Usually, for clean and dry rotating machine insulation, the insulation resistance between about 30 s and a few minutes is primarily determined by the absorption current.~~

~~Since the absorption current is a property of the insulation material and the winding temperature, a specific absorption current is neither good nor bad. In insulation systems manufactured since about 1970 (usually thermosetting polyester or epoxy bonded), the value of the exponent n of the absorption current, IA = Kt^{-n}, is different from the older thermoplastic (asphalt or shellac bonded) materials. This does not imply that more modern insulation materials are better because the absorption current is lower and the resulting insulating resistance is higher. For example, polyethylene has essentially no absorption current, yet because of its ther-mal limitations, it would be completely unsuitable for application in most rotating machines.~~

~~The conduction current (I_C) in well-bonded polyester and epoxy-mica insulation systems is essentially zero unless the insulation has become saturated with moisture. Older insulation systems, such as asphaltic-mica or shellac mica-folium may have a natural and higher conduction current due to the conductivity of the tapes that back the mica.~~

~~The surface leakage current (I_L) is constant over time. A high surface leakage current, i.e., low insulation resistance, is usually caused by moisture or some other type of partly conductive contamination present in the machine.~~

5.2 Characteristics of the measured direct current

Comparing the change in insulation resistance or total current with the duration of the test voltage application may be useful in appraising the cleanliness and dryness of a winding. If the windings are contaminated with partially conductive material or are wet, the total current (I_T) will be approximately constant with time, since I_L and/or I_G ~~(See Figure)~~ will be much larger than the absorption current (I_A). If the windings are clean and dry, the total current (I_T) will normally decrease with time (see Figure 4), since the total current is dominated by the absorption (i.e., polarization) current (I_A).

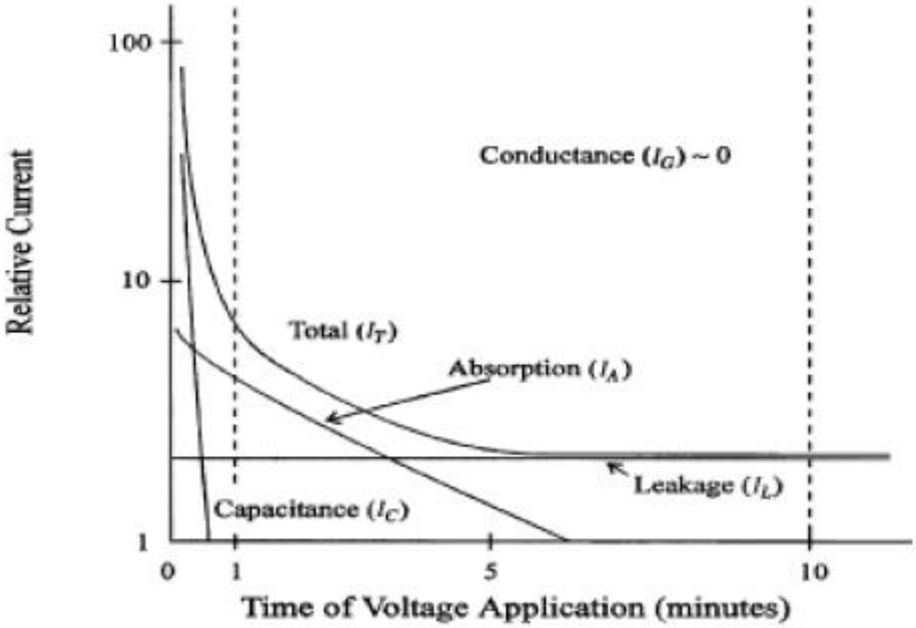


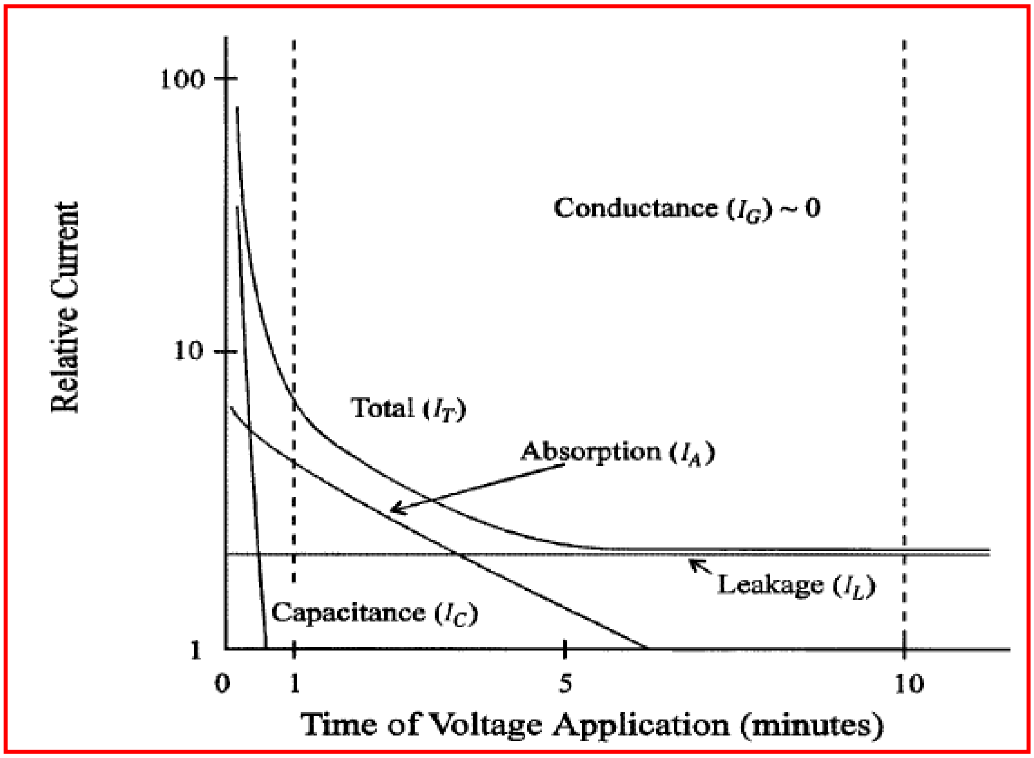
Figure 4—Types of currents for an ~~asphaltic~~ epoxy-mica insulation with a relatively low current

5.3 Insulation resistance readings

The measurement of insulation resistance constitutes a direct-voltage test and the test voltage must be restricted to a value appropriate to the voltage rating of the winding and the basic insulation condition. This is particularly important in the case of small, low-voltage machines, or wet windings. If the test voltage is too high, the applied test voltage may over stress the insulation, leading to insulation failure.

Insulation resistance tests are usually conducted at constant direct voltages ~~of 500–10 000 V~~ having negative polarity. Negative polarity is preferred to accommodate the phenomenon of electroendosmosis.

Guidelines for test voltages are presented in Table 1. Readings of insulation resistance are taken after the test ~~direct~~ voltage has been applied for 1 min.



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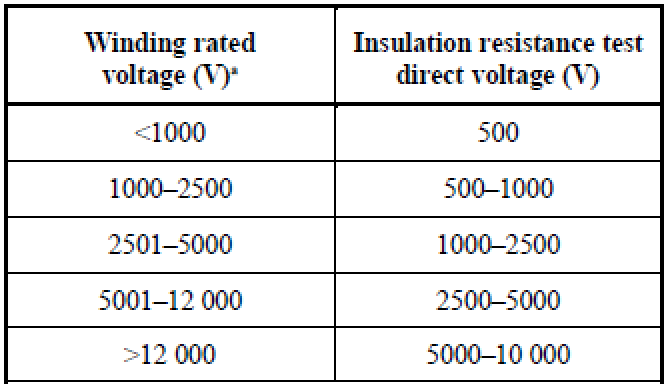
~~Figure 3—Types of currents for an epoxy-mica insulation with a relatively low surface leakage current and no conductance current~~

Table 1—Guidelines for ~~dc~~ direct voltages to be applied during insulation resistance test



Winding rated voltage (V)[a]	Insulation resistance test direct voltage (V)
<1000	500
1000–2500	500–1000
2501–5000	1000–2500
5001–12 000	2500–5000
>12 000	5000–10 000

[a] Rated line-to-line voltage for three-phase ac machines, line-to-ground voltage for single-phase machines, and rated direct voltage for dc machines or field windings.

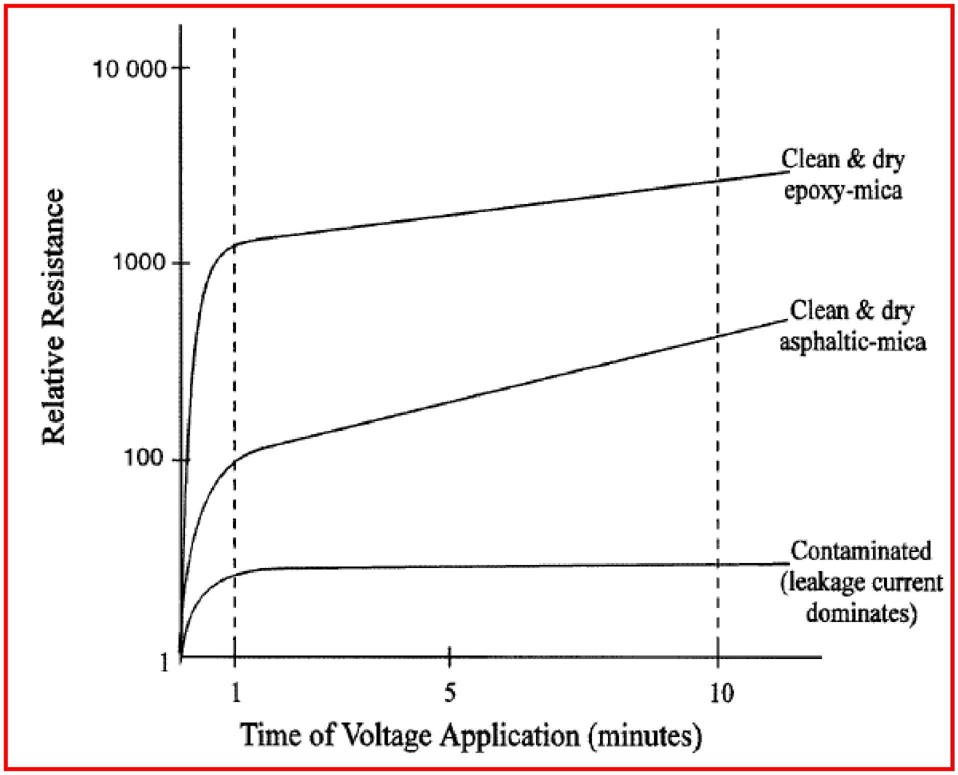
5.4 Polarization index readings

This test applies to new and in-service ac and dc windings that are encased in insulation.

~~The measured insulation resistance will usually rapidly increase when the voltage is first applied, and then gradually approach a relatively constant value as time elapses (see Figure 4). The readings of a dry winding in good condition may continue to increase for hours with a continuously applied constant test voltage. For older types of insulation, a reasonably steady value is usually reached in 10–15 min. Modern types of film-coated wire, as well as epoxy-mica or polyester-mica insulated stator windings, may approach a constant value of insulation resistance in 4 min or less. If the winding is wet or dirty, a low steady value will usually be reached 1 min or 2 min after the test voltage is applied.~~

The polarization index is normally defined as the ratio of the 10 min resistance value (IR_{10}) to the 1 min resistance value (IR_1). (See Annex A for the use of other values.) The polarization index is indicative of the slope of the characteristic curve (see Figure 4) and can be used to assess the insulation condition (see Clause 11 and Clause 12). To provide greater accuracy around the 1 min point and to allow the data to be plotted on log paper, it is also common to take readings at other intervals such as 15 s, 30 s, 45 s, 1 min, 1.5 min, 2 min, 3 min, 4 min, …, and 10 min.

This test may not apply to small random winding machines since the absorption current *IA* becomes negligible in a matter of seconds (see Annex A for further discussion).



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~~Figure 4—Typical insulation resistance measurements for three different machines~~

5.5 Discharge current

After the applied direct voltage is removed, a suitable discharge circuit should be provided (see Clause 4).~~-~~The discharge current manifests itself in the following two components:

a) A capacitive discharge current component, which decays nearly instantaneously, depending upon the discharge resistance.

b) The absorption discharge current, which will decay from a high initial value to nearly zero with the same characteristics as the initial charging current but with the opposite polarity. This decay may take more than 30 min depending on the insulation type and ~~machine~~ size of the test specimen.

6. Factors affecting insulation resistance

6.1 Effect of surface condition

The surface leakage current (I_L) is dependent upon foreign matter, such as oil and/or carbon dust on the winding surfaces outside the slot. The surface leakage current may be significantly higher on large turbine generator rotors and dc machines, which have relatively large exposed creep age surfaces. There may also be an increase in the surface leakage current on machines where a stress-control coating has been applied to the end windings.

Dust (or salts) on insulation surfaces, which are ordinarily nonconductive when dry, may become partially conductive when exposed to moisture or oil, and, thus, can lower the insulation resistance. If the insulation resistance or polarization index is reduced because of contamination, it can usually be restored to an acceptable value by cleaning and drying.

6.2 Effect of moisture

Regardless of the cleanliness of the winding surface, if the winding temperature is at or below the dew point of the ambient air, a film of moisture may form on the insulation surface, which can lower the insulation resistance or polarization index. The effect is more pronounced if the surface is also contaminated, or if cracks in the insulation are present. Note that the effects of moisture contamination on a healthy winding should not preclude obtaining acceptable readings.

Some types of~~ older~~ winding insulation systems are hygroscopic (easily absorb water) and moisture may be drawn into the body of the insulation from the humid ambient air. This is particularly true for the older thermoplastic asphaltic-mica, some thermosetting polyester mica (see [B11]) and shellac mica-folium insulating materials, as well as for some insulating strips used between uninsulated copper conductors in large turbine generator rotors~~.~~; for this reason, resistance or *P.I.* measurements on rotors of large turbine generators may become misleading if the rotor has been exposed to ambient air. Absorbed moisture increases the conduction current (I_G) and significantly lowers the insulation resistance and results in giving *P.I.* values close to 1 (see [B14]).

In-service machines are usually at a temperature above the dew point. When tests are to be conducted on a machine that has been in service, the tests should be made before the machine winding temperature drops below the dew point.

Machines that are out-of-service (without space heaters) are frequently tested when the winding temperature is below the dew point and may have significantly lower than expected insulation resistance and polarization index readings due to moisture contamination (see Clause 11). It may be necessary to dry out these machines to obtain acceptable readings prior to returning these machines to service or performing high-voltage testing. For appropriate dry-out procedures, consult with the equipment manufacturer. The history of the machine, visual inspections, and other test results may help in assessing the potential risk of returning to service a machine with low insulation resistance and/or polarization index readings due to moisture contamination. It is recommended that a machine with low *P.I.* and IR_1 readings *not* be subjected to further high-voltage testing.

6.3 Effect of temperature

6.3.1 General theory

The insulation resistance value for a given system, at any given point in time, varies inversely, on an exponential basis, with the winding temperature. There is a contrast between the temperature dependence of resistivity in metals and non-metallic materials, especially in good insulators. In metals, where there are numerous free electrons, higher temperature introduces greater thermal agitation, which reduces the mean free path of electron movement with a consequent reduction in electron mobility and an increase in resistivity. However, in insulators, an increase in temperature supplies thermal energy, which frees additional charge carriers and reduces resistivity. This temperature variation affects all of the current components identified in 5.1 except for the geometric capacitive current. The insulation resistance value of a winding depends upon the winding temperature and the time elapsed since the application of the voltage. ~~The thermal mass of~~ For example, when the machine ~~being tested is generally so large that~~ has just been stopped, and the operating temperature ~~differential~~ is of the order of ~~the winding between~~ 90 °C – 100 °C, the ~~1 min and~~ temperature can drop significantly during 10 min ~~readings of~~ and this can affect the ~~insulation resistance is negligible, except for measurements during a dryout at rated current~~ *P.I*. In order to avoid the effects of temperature in trend analysis, subsequent tests should be conducted when the winding is near the same temperature as the previous test. However, if the winding temperature cannot be controlled from one test time to another, it is recommended that all insulation test values be corrected to a common base temperature of 40 °C using Equation (2). Though the corrected value is an approximation, this permits a more meaningful comparison of insulation resistance values obtained at different temperatures.

The correction may be made by using Equation (2):

$$R_c = K_T \; R_T \tag{2}$$

where

R_C is insulation resistance (in megohms) corrected to 40 °C,

K_T is insulation resistance temperature coefficient at temperature T °C (from 6.3.2or 6.3.3),

R_T is measured insulation resistance (in megohms) at temperature T °C.

For winding temperatures below the dew point, it is difficult to predict the effect of moisture condensation on the surface, therefore an attempt to correct to 40 °C for trend analysis would introduce an unacceptable error. In such cases, it is recommended that the history of the machine tested under similar conditions be the predominant factor in determining suitability for return to service. However, since moisture contamination normally lowers the insulation resistance and/or polarization index readings, it is possible to correct to 40 °C for comparison against the acceptance criteria (see Clause 12).

There ~~is~~ are no effective means for converting the insulation resistance measured under a specific humidity to the insulation resistance that would occur at a different humidity.

6.3.2 Field measurements for determining K_T

The recommended method of obtaining data for an insulation resistance versus winding temperature curve is by making measurements at several winding temperatures, all above the dew point, and plotting the results on a semi-logarithmic scale. ~~When a logarithmic scale is used for the insulation resistance and a linear scale for the temperature, the test points should approximate a straight line that can be extrapolated to obtain the corrected value at 40 °C.~~

6.3.3 Approximating K_T

The correction factors (K_T) are presented here for two different families of insulation systems labeled respectively "THERMOPLASTIC" and "THERMOSETTING". "THERMOPLASTIC" applies, for example, to asphaltic systems and other systems that were in use prior to the early 1960s. "THERMOSETTING" applies to newer insulations that appeared around the early 1960s. They include epoxy and polyester based systems. Both are presented on Figure 5.

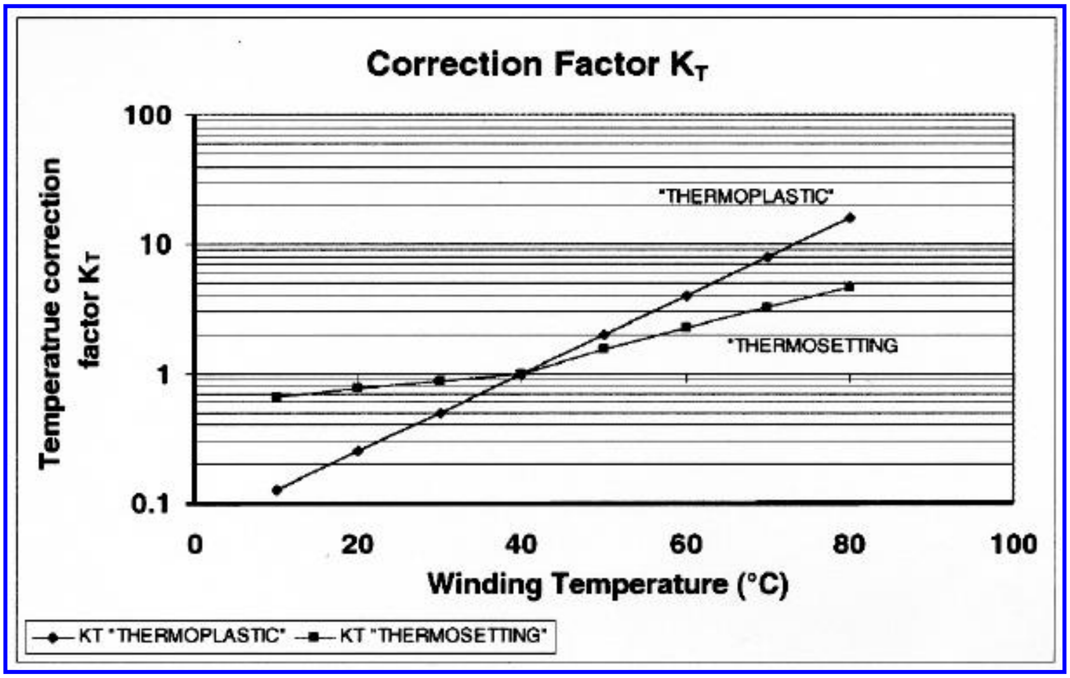

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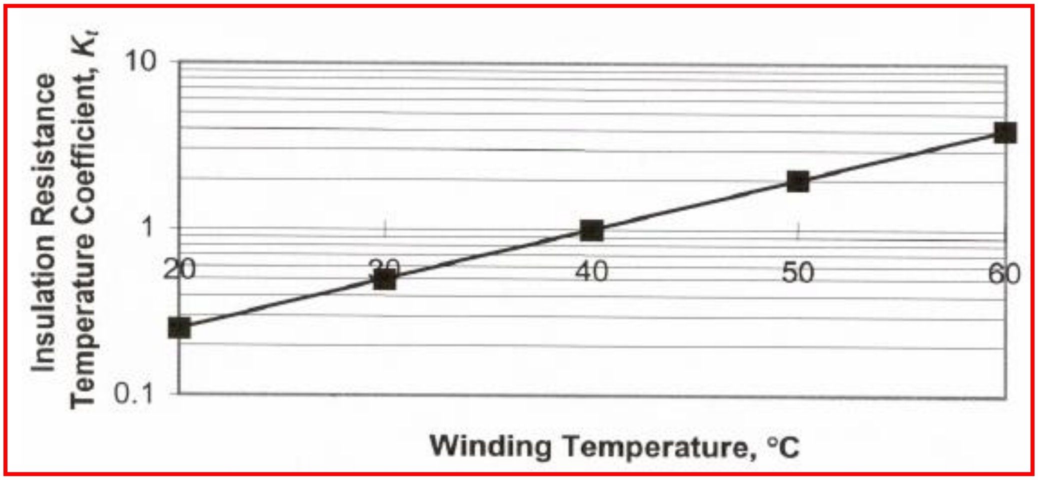
Figure 5—Temperature correction factors for "THERMOPLASTIC" (asphaltic) and "THERMOSETTING" (epoxy or polyester) insulation systems

~~If the temperature effects on the insulation system under test is unknown, an approximate value for the tem-perature coefficient K_T may be obtained by using Figure 5 for resistance halving for each +10 °C increment. Note that this is only an approximation and should not be used to calculate insulation resistance at very large temperature differentials from 40 °C or significant errors could result.~~

~~NOTE—Insulation resistance halving for a 10 °C increase in temperature is based on testing of some of the insulation systems of the late 1950s and may not be strictly true for all insulation systems. More recent measurements have indi-cated a correction factor for insulation resistance halving in the range 5–20 °C. A variation in the K_T factor can lead to significant errors in R_c magnified by the differential between the winding temperature and 40 °C.~~

~~K_T can also be approximated for insulation resistance halving for a 10 °C rise in winding temperature by application of Equation (3).~~



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~~**Figure 5—Approximate insulation resistance coefficient, K_T, for insulation halving for 10 °C rise in temperature**~~

6.3.3.1 Equation for “THERMOPLASTIC” insulation systems

For the THERMOPLASTIC family, K_T can be approximated by Equation (3).

$$K_T = (0.5)^{(40-T)/10} \tag{3}$$

Where

T = Temperature in °C

For example, if the winding temperature at test time was 35 °C, ~~and the insulation was such that the resis-tance halved for every 10 °C,~~ then the K_T for correction to 40 °C would be derived in the following way:

~~or~~

$$K_T = (0.5)^{(40-35)/10} = (0.5)^{5/10} = (0.5)^{1/2} = 0.707$$

6.3.3.2 Equation for “THERMOSETTING” insulation systems [B8]

For thermosetting insulation, the correction factor equations for temperatures above 40 °C differ from those below 40 °C.

For the range of 40 °C < T < 85 °C, is illustrated in Equation (4).

$$K_T(T) = \exp\left[-4230\left(\frac{1}{(T+273)} - \frac{1}{313}\right)\right] \quad (4)$$

where

T = Temperature in °C

Over the other range (10 °C < T < 40 °C), is illustrated in Equation (5)

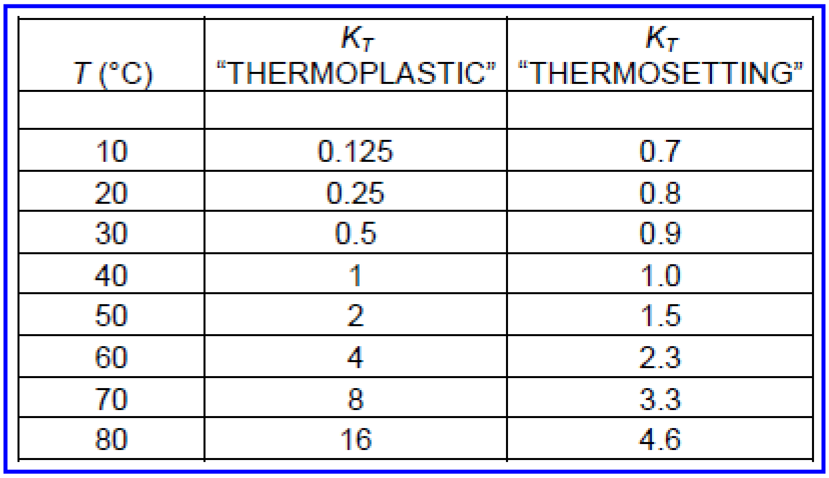
$$K_T(T) = \exp\left[-1245\left(\frac{1}{(T+273)} - \frac{1}{313}\right)\right] \quad (5)$$

where

T = Temperature in ºC

The values used to generate curves on Figure 5 are shown in Table 2. They were calculated with Equation (3), Equation (4), and Equation (5):

Table 2—*KT* versus temperature for “THERMOPLASTIC” and “THERMOSETTING” insulation stator winding systems



T (°C)	K_T “THERMOPLASTIC”	K_T “THERMOSETTING”
10	0.125	0.7
20	0.25	0.8
30	0.5	0.9
40	1	1.0
50	2	1.5
60	4	2.3
70	8	3.3
80	16	4.6

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Equation (4) and Equation (5) have been established by performing tests on single bars or portions of bars. The bars were clean and dry. Therefore, Equation (4) and Equation (5) might not apply to windings affected by moisture and dust. Tests were carried out in three different labs and results were in good agreement (see [B8], [B14], [B15]).

NOTE—Equation (4) and Equation (5) are approximations and could lead to significant errors if used to calculate insulation resistance at temperatures outside the range from 10 ºC to 60 ºC.

6.3.4 Polarization index correction

When the polarization index is used with the insulation resistance to determine the insulation condition, it is not necessary to make a temperature correction to the *P.I.* ~~Since~~ When the machine temperature does not change appreciably between the 1 min and 10 min readings, the effect of temperature on the polarization index is usually small. However, when the initial winding temperature is high, a reduction in the temperature of the insulation system during the test time may result in a substantial increase in the insulation resistance between the 1 min and 10 min readings due to the temperature effect (see 6.3.1). The resulting polarization index may be uncharacteristically high, in which case a repeat measurement at or below 40 °C is recommended as a check of the *P.I.* As stated in 6.2, if either the 1 min or 10 min measurements are taken when the winding temperature is below the dew point, the effects of moisture contamination must be considered during interpretation. For certain insulation systems, absorbed moisture may cause the *P.I.* to drop below 2 and approach the value of 1 (see [B14]).

6.4 Effect of test voltage magnitude

Guidelines for test voltages are presented in Table 1~~ (see 5.3).~~. The value of insulation resistance may decrease somewhat with an increase in applied voltage; however, for insulation in good condition and in a thoroughly dry state, substantially the same insulation resistance will be obtained for any test voltage up to the peak value of the rated voltage.

A significant decrease in insulation resistance with an increase in applied voltage may be an indication of insulation problems. These problems may be due to imperfections or fractures of the insulation, aggravated by the presence of dirt or moisture; or the problems may be due to the effects of dirt or moisture alone or result from other deterioration phenomena. The change in resistance is more pronounced at voltages considerably above rated voltage (see IEEE Std 95~~-1977~~).

6.5 Effect of existing charge on winding resistance measurements

The insulation resistance measurements will be in error if residual charges or unrelaxed polarization exist in the insulation. Therefore, prior to measuring the insulation resistance, windings must be completely discharged. Measure the discharge current at the beginning of the test to help assure that the winding is completely discharged. A residual charge will ~~show as a reverse deflection of~~ affect the insulation resistance ~~meter after connections are made but before~~ reading. This is known as the ~~voltage is applied. Any reverse deflection should be negligible.~~memory effect and it is treated in details in Jonscher A.K. [B9].

After cessation of application of high direct voltage, grounding of windings is important for safety as well as for accuracy of subsequent tests. The grounding time should be a minimum of four times the charge time (see 5.5).

7. Conditions for measuring insulation resistance

Record the ambient temperature, relative humidity, dew point, winding temperature, length of time out-of-service, test voltage, and connection arrangement at the time the test is performed. It is also important to convert the measurement to a 40 °C basis for future comparisons. (For converting insulation resistance values to this temperature (see 6.3).

It is not necessary that the machine be at standstill when generator rotor winding insulation resistance tests are being made. It is often desirable to make insulation resistance measurements when the winding is subject to centrifugal forces similar to those occurring in service. In certain cases, it is practical to make periodic insulation resistance measurements while machines are rotating short circuited for drying. Whenever machines are not at standstill during measurement of insulation resistance, precautions should be taken to avoid damage to equipment and injury to personnel.

To obtain insulation resistance measurements for a directly water-cooled winding, the water should be removed and the internal circuit thoroughly dried. In some cases where water-cooled windings are used, the winding manufacturer may have provided a means of measuring the insulation resistance without need for the coolant water to be drained. In general, if the water is not removed, then the conductivity of the water should be ~~greater~~ less than ~~0.25 µs~~ 0.25µS/cm. More information should be available in the winding manufacturer's manual.

8. Winding connections for insulation resistance tests

It is recommended, when feasible, that each phase be isolated and tested separately. Separate testing allows comparisons to be made between phases. When one phase is tested, the other two phases should be grounded to the same ground as the stator core or rotor body.

When testing all phases simultaneously, only the insulation to ground is tested and no test is made of the phase-to-phase insulation. The phase-to-phase insulation is tested only when one phase is energized and the other phases are grounded.

The connection leads, brush rigging, cables, switches, capacitors, surge arresters, voltage transformers, and other external equipment may greatly influence the insulation resistance reading. It is recommended that measurements of the insulation resistance be made with all external equipment disconnected and grounded. Items still connected to the winding should be recorded to allow future comparisons. In all cases, a common ground should be used to avoid any undesirable effects on the test results due to stray losses in the ground circuit.

9. Methods of measuring insulation resistance

9.1 Direct measurement

- Direct measurement of insulation resistance may be made with the following instruments:
- Direct-indicating megohmmeter with self-contained hand or power-driven generator
- Direct-indicating megohmmeter with self-contained battery
- Direct-indicating megohmmeter with self-contained rectfier, using a regulated line powered supply
- Resistance bridge with self-contained galvanometer and batteries

9.2 Calculated measurement

Insulation resistance may be calculated from readings of a voltmeter and microammeter using an external (well-regulated) direct-voltage supply.

NOTE—Recommended value of voltage regulation (line) is less than or equal to 0.1%. Deviations from this may lead to ambiguous results due to unpredictable losses from the charging currents associated with fluctuations in the applied voltage (see ~~Annex C~~ Clause 10).

The voltmeter-ammeter method is a simple method for the determination of the insulation resistance by measurement of the voltage impressed across the insulation and the current through it. A source of constant direct voltage is required, and the voltmeter must be selected to suit the maximum and minimum voltages that may be used. The ammeter is usually a multirange microammeter selected to measure the full range of currents that may be encountered at the voltages used.

The microammeter must be on the highest range or short circuited during the first few seconds of charge so that it will not be damaged by the capacitive charging current and the initial absorption current. When the microammeter is at test voltage, precautions should be taken to help ensure the safety of the operator.

The resistance is calculated from Equation (6).

$$IR_t = E_{(t)}/I_{(t)} \tag{6}$$

where

$IR_{(t)}$ is the insulation resistance in megohms,

$E_{(t)}$ is the voltmeter reading in volts,

$I_{(t)}$ is the ammeter reading in microamperes (*t*) seconds after application of the test voltage.

10. Precautions

A finite amount of time is required to bring the voltage impressed on the insulation to the desired test value. Full test voltage should be applied as rapidly as possible and held constant throughout the test.

Test instruments in which the test voltage is supplied by motor-operated generators, batteries, or rectifiers are usually used for making tests of over a 1 min duration. It is essential that the voltage of any test source be constant to prevent fluctuation in the charging current (see 3.3 and Annex A of IEEE Std 95). Stabilization of the supplied voltage may be required.

Where protective resistors are used in test instruments, their effect on the magnitude of the voltage applied to the insulation under test should be taken into account. The voltage drop in the resistors may be an appreciable percentage of the instrument voltage when measuring a low insulation resistance.

11. Interpretation of insulation resistance and polarization index test results

The insulation resistance and polarization index tests can be used for at least two purposes:

a) The insulation ~~resistance~~ test 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.

b) Estimation of the suitability of a machine for the application of appropriate overvoltage tests or for operation may be based on a comparison of present and previous *P.I.* and/or *IR*1 values will support assessments of insulation condition.

11.1 Monitoring insulation condition

If the insulation resistance history of the machine is available, comparison of the present test result with previous tests will support concerns about the insulation condition. It is important, however, to compare tests under similar conditions, that is, winding temperature, voltage magnitude, voltage duration, and relative humidity (see Clause 6). For comparison of tests conducted at different winding temperatures, the results should be corrected to the same temperature (see 6.3).

A sharp decline in the IR1 or P.I. from the previous reading may indicate surface contamination, moisture, or severe insulation damage, such as cracks. When a low *P.I.* occurs at an elevated temperature (above 60 °C), a second measurement below 40 °C, but above the dew point, is recommended as a check on the real insulation condition (see 6.3).

For tests conducted under similar conditions, a steady increase in the IR_1, i.e., a decrease in the absorption current with age may indicate decomposition of the bonding materials, especially when the insulation materials are of the thermoplastic (asphaltic-mica or shellac mica-folium) type.

11.2 Suitability for operation or continued testing

When the insulation resistance history is not available, recommended minimum values of the *P.I.* or IR_1 may be used to estimate the suitability of the winding for application of an overvoltage test or for operation (see Clause 12). If the IR_1 or *P.I.* is low because of dirt or excessive moisture, it may be improved to an acceptable value by cleaning and drying~~.~~ (See IEEE Std 56, IEEE Std 62.2, and IEEE Std 67). When drying insulation, the *P.I.* can be used to indicate when the drying process may be terminated, i.e., the *P.I.* results have exceeded the recommended minimum. If the IR_1 is low due to severe insulation deterioration or damage, operation and overvoltage testing of the machine are not recommended.

~~Machines rated 10 000 kVA and less should have either a value of the polarization index or a value of the insulation resistance (at 40°C) above the minimum recommended values (see Clause 12) for operation or further overvoltage tests.~~

Machines ~~rated above 10 000 kVA~~ should have both the polarization index and the insulation resistance (at 40 °C) above the minimum recommended values (see Clause 12) for operation or further overvoltage testing.

If the IR_1 value (at 40 °C) is greater than 5000 MΩ, the *P.I.* may be ambiguous and can be disregarded (see 12.2.2).

For varnished cambric, shellac mica-folium, or asphaltic stator windings, a very high *P.I.* (for example, greater than 8) may indicate that the insulation has been thermally aged, and may have a high 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 overvoltage testing the winding. Failure may occur at any time if the machine is returned to service.

~~It may be possible to operate machines with P.I. and IR_1 values lower than the recommended minimum val-ues; however, it is not recommended by this standard. In all cases where the test values fall below the recom-mended minimum values, investigations should be undertaken to determine the cause of such low readings. History of the winding, visual inspections, and other test results should be used to determine advisability of returning the unit to service.~~

11.3 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. Unless the defect is concentrated, it is impossible to specify the value of insulation resistance at which the insulation system of a winding will fail.

b) Windings having an extremely large end arm 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 *IR*1 is invaluable in evaluating insulation condition.

c) A single insulation resistance measurement at one particular voltage does not indicate whether foreign matter is concentrated or distributed throughout the winding.

d) Direct voltage measurements, such as the *IR* and *P.I.* tests, may not detect internal insulation voids caused by improper impregnation, thermal deterioration, or thermal cycling in form-wound stator coils (see Annex B).

e) ~~Because~~ When 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.

12. Recommended minimum value of polarization index and insulation resistance

12.1 Minimum values

The recommended minimum *P.I.* and the recommended minimum value of IR_1 of an ac or dc rotating machine winding are the lowest values at which a winding is recommended for an overvoltage test or for operation.

In some cases, special insulating materials or designs may provide lower values. Minimum values for these designs should be based on comparison with the historic test values.

12.2 Polarization Index

The recommended minimum values of *P.I.* for ac and dc rotating machines are listed in Table ~~2.~~3. Table 3 is based on the thermal class of the insulating materials and, with the exception of non-insulated field windings, applies to all insulating materials regardless of application.

Table 3—Recommended minimum values of polarization index for ~~all machine components[a]~~ insulation per thermal classes ~~per IEC 60085-01: 1984~~ machine components [a]

Thermal class rating [b,c,d]	Minimum *P.I.*
Class 105 A	1.5
Class 130 B and above	2.0
~~Class F~~	~~2.0~~
~~Class H~~	~~2.0~~

[a] The P.I. test is not applicable to non-insulated field windings (see 12.2.1).

[b] IEC 60085-01

[c] IEEE Std 1

[d] NEMA MG-1

~~NOTE—If the 1 min insulation resistance is above 5000 MΩ, the calculated P.I. may not be meaningful. In such cases, the P.I. may be disregarded as a measure of winding condition (see 12.2.2).~~

12.2.1 Applicability of polarization index on field windings

The typical purpose of the insulation resistance and polarization index tests is to determine whether or not an insulation system is suitable for operation or overvoltage testing. The windings of ~~some~~ most squirrel-cage induction machinery rotors are ~~often~~ not insulated from the rotor body; therefore, a polarization index cannot be performed on these ~~induction machinery~~ rotor windings ~~or field windings.~~. Similarly, a polarization index test is not applicable to dc armatures that have an exposed copper commutator that is by necessity not encapsulated in insulation. If however, the rotor winding is ~~insulated from the rotor body~~ encased in insulation, as in wound induction rotors and salient pole machines with windings wrapped with tapes or sheet material, a polarization index test is applicable. The field windings of many very large turbine generators and salient pole motors and generators with strip-on-edge windings are made with exposed copper that is not encapsulated in insulation. Though isolated from ground and other components via insulating strips, the immense surface area of the non-insulated copper does not exhibit an absorption current (I_A), in comparison to the leakage current (I_L), when subjected to a direct voltage. The absence of the absorption current alters the IR characteristic curve (see Figure 4) such that there will be very little change in the *IR* value from the 1 min to the 10 min reading. Therefore, the *P.I.*, which describes the slope of the *IR* curve, is not applicable to non-insulated field windings and dc machine armatures.

On the other hand, many other types of field windings do not have appreciable amounts of exposed conductors. These designs use conductors that are fully encapsulated in insulation and have a characteristic absorption current (I_A). For these machines, the *P.I.* can be a worthwhile test for assessing the condition of the insulation system. The recommended minimum, based on the thermal class rating of the field winding insulation, should be used as a reference.

12.2.2 Applicability of polarization index when IR_1 is greater than 5000 MΩ

When the insulation resistance reading obtained after the voltage has been applied for 1 min (IR_1) is higher than 5000 MΩ, based on the magnitude of applied direct voltage, the total measured current (I_T) can be in the submicroampere range (see Figure 3). At this level of required test instrument sensitivity, small changes in the supply voltage, ambient humidity, test connections, and other non-related components can greatly affect the total current measured during the 1 min –10 min interval required for a *P.I.* Because of these phenomena, when the IR_1 is higher than 5000 MΩ, the *P.I.* may or may not be an indication of the insulation condition and is therefore not recommended as an assessment tool.

12.2.3 Effects of continuous voltage stress control systems [B10]

In some cases, specifically for Roebel-bar windings when the winding overhang is very short, the complete winding overhang may be treated with stress control material. If the stress control material has electrical contact with the bare copper at the ends of the bars (see [B10]), the surface leakage current (*IL*) may be much larger than the absorption current (*IA*). In this case, the total current (*IT*) will be approximately constant with time and the *P.I.* could be close to 1. Thus the presence of the stress control material over the entire end winding reduces the usefulness of the *P.I.* test.

NOTE—The incorrect application of this system may eventually lead to signs of electrical tracking. Winding suppliers must prove suitability for application of such a continuous voltage stress control system prior to offering it as a standard product. Such a continuous voltage stress control system is applicable only for new stator windings and may not be appropriate to be used as a repair method.

12.3 Insulation resistance

The minimum insulation resistance after 1 min, $IR_{1\ \mathrm{min}}$, for overvoltage testing or operation of ac and dc 1 min machine stator windings and rotor windings can be determined from Table 4.

The actual winding insulation resistance to be used for comparison with $IR_{1\ \mathrm{min}}$ is the observed insulation 1 min resistance, corrected to 40 °C, obtained by applying a constant direct voltage to the entire winding for 1 min.

The ~~minimum~~ insulation resistance of one phase of a three-phase armature winding tested with the other two phases grounded ~~should~~ could be ~~approximately twice~~ lower than three times that of the entire winding~~. If each~~ due to the phase ~~is tested separately and guard circuits are used on the two phases not under test,~~ to phase contributions to the ~~observed minimum resistance should be three times the entire winding~~ total current.

Table 4—Recommended minimum insulation resistance values at 40 °C (all values in MΩ)

Minimum insulation resistance (megohms)	**Test specimen**
$IR_{1\ \mathrm{min}} = kV + 1$	For most windings made before about 1970, all field windings, and others not described below
$IR_{1\ \mathrm{min}} = 100$	For most ac windings built after about 1970 (form wound coils)
$IR_{1\ \mathrm{min}} = 5$	For most machines with random-wound stator coils and form wound coils rated below 1 kV and dc armatures

NOTE 1—$IR_{1\ \mathrm{min}}$ is the recommended minimum insulation resistance, in megaohms, at 40 °C of the entire machine winding (all 1 min phases).

NOTE 2—*kV* is the rated line-to-line rms voltage for three-phase ac machines, line-to-ground voltage for single-phase machines, and rated direct voltage for dc machines or field windings

NOTE 3—It may not be possible to obtain the above minimum *IR*1 min values for stator windings having extremely large end arm surface areas, or for dc armature windings with commutators. For such windings trending of historical *IR*1 min values can be used to help evaluate the condition of their insulation

NOTE 4—The values in Table 4 may not be applicable, in some cases, specifically when the complete winding overhang is treated with stress control material (see 12.2.3)

NOTE 5—The values in the above table do not apply to “green” windings before global vacuum impregnation treatment.

~~2—kV is the rated machine terminal to terminal voltage, in rms kV~~

Annex A

(informative)

Variants in polarization index

The polarization index (*P.I.*) is traditionally defined as the ratio of the 10 min insulation resistance (IR_{10}) to the 1 min insulation resistance (IR_1), tested at a relatively constant temperature. In older insulation materials, such as asphaltic-mica, the absorption currents often take 10 min or more to decay to nearly zero (see Figure 2). In more modern insulation systems for form-wound stators, and especially in random-wound machines, the absorption current may decay to nearly zero in 2 min–3 min (see Figure 4). Thus, for modern insulation, some users calculate a variant of the conventional *P.I.* The variants include, but are not limited to, those shown in Equation (A.1) and Equation (A.2).

$$P.I. = IR_1/IR_{30s} \tag{A.1}$$

where

$P.I.$ is the polarization index,

IR_1 is the insulation resistance reading after the application of voltage for 1 min,

$IR_{30\,\mathrm{s}}$ is the insulation resistance reading after the application of voltage for 30 s.

$$P.I. = IR_5/IR_1 \tag{A.2}$$

where

$P.I.$ is the polarization index,

IR_5 is the insulation resistance reading after the application of voltage for 5 min,

IR_1 is the insulation resistance reading after the application of voltage for 1 min.

The distinguishing features are the shorter times the direct voltage is applied and thus the shorter time that the winding must be grounded (see 6.5). Since in modern windings the absorption current is essentially zero after a few minutes, by using shorter times for the *P.I.* ratio, the test time can be considerably shortened without any loss of information about the degree of contamination or moisture absorption present. Another variation is to record the insulation resistance every minute and discontinue the test when a stable (three consecutive readings) *IR* has been measured. Users are encouraged to collect data employing shorter time ratios, to enable suitable pass-fail criteria to be developed in the future.

There are limitations in applying these other ratios:

a) There is no standard for what time intervals the *IR* values are to be recorded. Different organizations use different ratios

b) There is no agreed upon pass-fail criteria, as has been established for the traditional *P.I.*

~~c) Users are encouraged to collect data employing shorter time ratios, to enable suitable pass-fail criteria to be developed in the future.~~

Annex B

(informative)

Direct versus alternating voltage testing

Direct-voltage testing is normally done by applying a direct-voltage source between the test specimen conductors and ground and using a dc ammeter to measure the total current. The ratio of the test voltage to the test current will reflect the total resistance between the test specimen and ground. Resistance is determined by Equation (B.1).

$$R = \rho L/A \tag{B.1}$$

where

R is resistance,

P is resistivity of the material,

L is length of the path,

A is cross-sectional area.

Because the resistivity values of the dirt, oil, and water that often contaminate the end winding areas of rotating machinery are quite low, direct-voltage testing of a contaminated winding normally results in a high surface leakage current and subsequent low resistance reading. This property makes direct-voltage testing a viable method for determining the extent of contamination to an insulation system. In addition, if the insulation system utilizes a cotton-backed tape with mica as the primary electrical insulation, a direct-voltage test might reveal whether or not the cotton has absorbed moisture and has a lower resistivity. Note that most windings manufactured after 1970 do not have these hygroscopic tapes, and a direct-voltage test will not normally detect problems internal to the insulation system, such as thermal deterioration.

Since the primary electrical insulation used in the design of form-wound stator windings is mica, and mica has virtually infinite resistivity (thus a good insulator), only one layer of mica tape would prohibit any direct current. Therefore, if a void exists within the insulation due to improper impregnation, thermal deterioration, or thermal cycling, a direct-voltage test would be unable to detect it. If however, there exists a severe crack through the entire insulation, it is possible that an electrical track would be established between the copper conductors and ground, and would appear as a low resistance.

When a high alternating voltage is connected between the terminals of the test specimen and ground, the capacitance of the test specimen dominates the current. Capacitance is determined by Equation (B.2).

$$C = \varepsilon A/d \tag{B.2}$$

where

C is capacitance,

ε is dielectric permittivity of the material, *A* is cross-sectional area,

d is the thickness of the material.

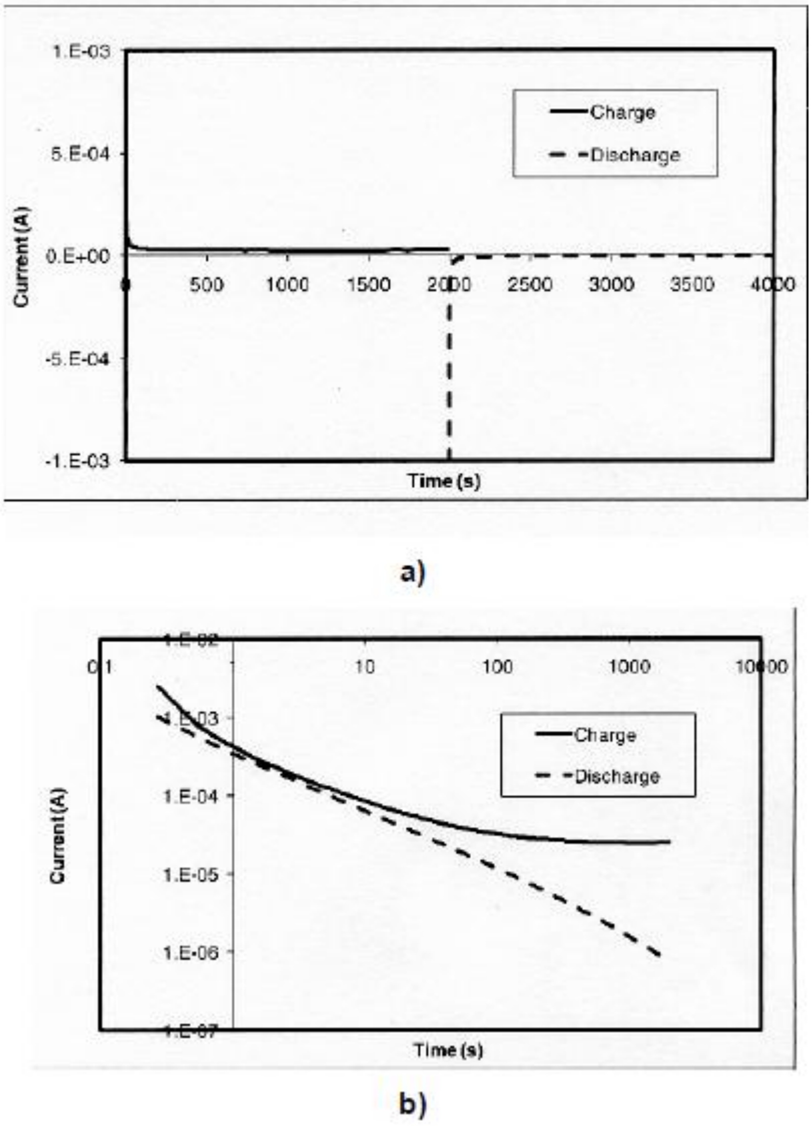
Since the dielectric permittivity of an insulation system is greatly affected by the presence of voids and/or water, an alternating-voltage test is more sensitive than direct-voltage tests with regard to detection of internal insulation problems associated with all types of insulation systems. Because of the different test capabilities, both ~~a dc~~ direct and ~~an ac~~ alternating voltage tests should be conducted to more completely assess the condition of an insulation system.

Annex C

(informative)

Monitoring charge and discharge currents

After the applied direct voltage is removed, the discharge current can be monitored as a function of time using a suitable discharge circuit. As mentioned in 5.5, the discharge current manifests itself in two components: a capacitive discharge current component, which decays nearly instantaneously, depending upon the discharge resistance and the absorption discharge current, which will decay from a high initial value to nearly zero with the same characteristics as the initial charging current but with the opposite polarity. Normally, neither the surface leakage nor the conduction current affects the discharge current. Figure C.1 below shows the charge and discharge currents for the three phases of a 50 MVA hydro-generator in linear scale (a) and in logarithmic scale (b). The separation between the charge and discharge currents allows visualizing the magnitude of the leakage current.



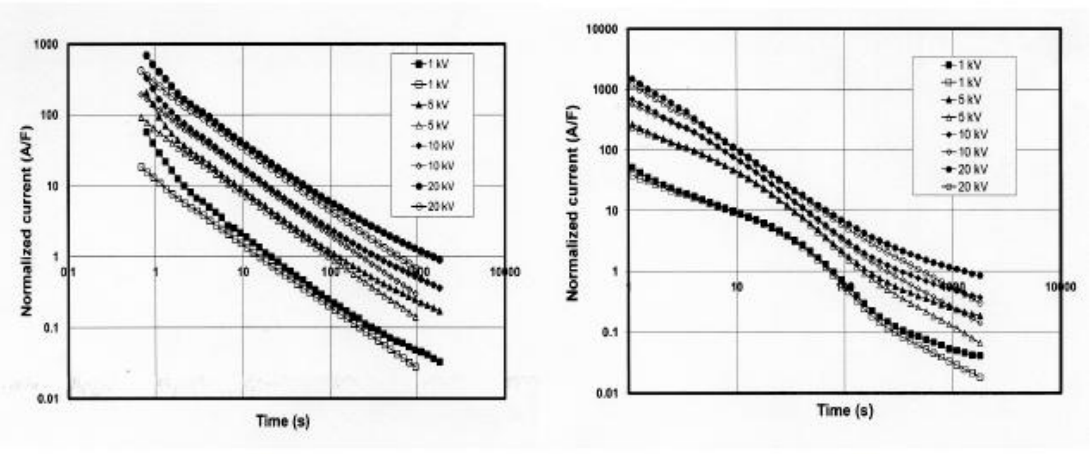
(New)

Figure C.1— Charge and discharge currents after a step voltage of 2.5 kV for the three phases of a 50 MVA hydro-generator: a) linear scale; b) logarithmic scale with the discharge time reset to zero and using a positive value for the discharge current

Since the discharge current is not affected by the surface leakage current along the end turns, an abnormally high value translates to an internal problem such as lack of curing, thermal aging, mechanical damage or moisture absorption within the bulk insulation wall. Obviously, to point out what is an abnormally high absorption current, the expected magnitudes of the absorption current of the various insulation technologies in a satisfactory condition need to be known. A useful parameter to quantify the discharge current is the normalized discharge resistance (see [B5]) given by Equation (C.1):

$$RC_{dis} = \frac{U_o C}{I_{dis}} \tag{C.1}$$

U_o is the applied voltage during charge, C is the winding capacitance and I_{dis} is the 1 min discharge current. Modern epoxy-mica insulation systems are characterized by particularly low dissipation factor and accordingly RC_{dis} should be above 2000 s when measured at room temperature (see [B8]). However, in some cases, as mentioned previously in 5.1, the stress control system has a dominating influence on the normalized resistance values, both in charge and discharge. It results in much lower normalized resistance values than what would be expected. Figure C.2 shows polarization/depolarization current (PDC) measurements for voltage levels from 1 to 20 kV for two similar modern epoxy-mica bars, one with iron oxide stress control paint (Figure C.2a) and the other one with SiC tape added on the stress control paint (Figure C.2b). One can see that the type of stress control system has a large impact on both the shape and the magnitude of the polarization and depolarization currents for modern epoxy-mica insulated windings. Indeed, the 5 kV resistance for the bar with the SiC tape was three times lower than for a similar bar with only the ferrous oxide paint as stress control system. Also the polarization index was strongly affected by the type of stress grading system, yielding much higher value than expect for the bar with the SiC tape. A three times increase in resistance was measured for the bar with the SiC tape when guarded measurements were used (see Table C.1).



a) b)

(New)

Figure C.2—Normalized charge (filled symbols) and discharge currents (open symbols) for the same epoxy-mica bar: a) with ferrous oxide stress control system; b) with a SiC tape added on the ferrous oxide paint (reprinted from [B5])

Table C.1— Dielectric parameters for the measurements shown in Figure 5 at 5 kV and for the same measurements with a guarded electrode (reprinted from [B5])

	PI	RC_{dis}	RC_{dis} guarded
No SiC tape	5.6	4090	4750
SiC tape	13	1210	3900

~~The regulation of power supplies used in insulation resistance (IR) measuring equipment is important because variations in the test voltage translate into variations in the measurement. This can be seen by considering the relationship in Equation (C.1):~~

$$i_{(t)} = C\frac{dv(t)}{dt} \qquad \text{(C.1)}$$

~~where~~

~~$i_{(t)}$~~	~~is the current response,~~
$\frac{dv(t)}{dt}$	~~is variation in voltage,~~
~~C~~	~~is capacitance of the object under test.~~

~~This variation in the current due to voltage fluctuations is translated into a variation in the insulation resis-tance (apparent resistance R_A) according to Equation (C.2):~~

$$R_A = \frac{Vdc}{Idc + i(t)} \qquad \text{(C.2)}$$

~~where~~

~~I_{dc}~~	~~is the current of interest due to the insulation resistance,~~
~~$i(t)$~~	~~is the capacitive current,~~

~~*Vdc*~~ ~~is the applied direct voltage.~~

~~Combining these relationships gives the variation in the apparent resistance shown in Equation (C.3):~~

$$\boxed{R_A = \frac{Vdc}{Idc + C[dv(t)/dt]} \qquad (C.3)}$$

~~The regulation can be stated as a percentage of the applied voltage and calculated from values found in gen-eral practice. As most IR measurements are not more than 2% accurate, this accuracy can be used for the variation in the apparent resistance.~~

~~For example, in stator winding insulation systems constructed using modern materials, the lowest IR value generally encountered is approximately 100 MΩ, a test voltage often used is 5 kV, and large machines have a typical capacitance of approximately 0.25 µF. These numbers give an~~ ~~*i(t)*~~ ~~of 1 µA which, to maintain mea-surement accuracy, necessitates a dv/dt << 4 V/s. The regulation would therefore be 4 V/s in 5 kV, or 0.08% regulated.~~

~~Most IR measurements are made at frequencies below 1 Hz, so these results apply to a low-frequency regu-lation of the supply, i.e., susceptibility to slowly varying fluctuations in the line voltage. It follows that the 50/60 Hz ripple in the supply may only have a minor impact when considering supply regulation, since the bandwidth of the measurement limits the impact of fluctuations at these frequencies.~~

Annex D

(informative)

Insulation resistance profiling (IRP)

Using information obtained during a *P.I.* test, the Insulation Resistance versus Time can be plotted in discrete increments (such as 5 s) over a specified time period (typically 10 min), resulting in a graph which may be referred to as an “Insulation Resistance Profile” or IRP (see [B12] and [B13]). In addition to the standard *IR* value and the Polarization Index (PI) value and similarly to the monitoring of charge and discharge currents (see Annex C), an IRP may provide useful information as to the condition of the insulation system especially when the insulation resistance exceeds 5000 Megohms. To obtain an accurate IRP the voltage and current must be monitored throughout the test. An accurate calculation of the insulation resistance at each sample point can then be made. Higher resolution metering capabilities and use of very low ripple power supplies combined with voltage and current measurements at each point minimizes any external influence effects during the insulation resistance test, thus, allowing the capture of an accurate IRP.

This technology has not advanced sufficiently at the time of publication to give guidelines on specific profiles for different types of defects, but it is anticipated that future IEEE standards will address this.

Annex E

(informative)

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