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IEEE Std 43-1974)

IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery

Sponsor

Electric Machinery Committee
of the
IEEE Power Engineering Society

Approved 6 March 2000

IEEE-SA Standards Board

Abstract: This document describes the 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. Contained within this document is the general theory of insulation resistance (IR) and polarization index (P.I.), as well as factors affecting the results, test procedures, methods of interpretation, test limitations, and recommended minimum values.
Keywords: absorption current, conduction current, discharge current, geometric capacitive current, insulation resistance, polarization index, surface leakage current

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Introduction

(This introduction is not part of IEEE Std 43-2000, IEEE Recommended Practice for Testing Insulation Resistance of Rotating 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 insulation systems are different from the older 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:

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

The revision to this recommended practice was prepared by a working group of the Materials Subcommittee of the Electric Machinery Committee of the IEEE Power Engineering Society. Working group personnel were

Vicki Warren, *Chair*

William Bartley
Thomas Bishop
Robert Draper
Guanzhong Gao
Trilok C. Garg
James Grant
Gary Griffith
Gary Heuston
Alan M. Iverson
Ken Jackson
Wayne Johnson
Chaman L. Kaul
Walter Martiny
William McDermid
Charles Millet
Beant Nindra
Madan Rana
Larry Rodland
David Schump
Susan Soergel
Greg C. Stone
George Stranovsky
Chuck Wilson
John Wilson
Daniel I. Young*

*Chair Emeritus

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The following members of the balloting committee voted on this recommended practice:

Vaino Aare
Edwin Averill
Roy L. Balke
William H. Bartley
Kevin D. Becker
Karl W. Berger
Thomas H. Bishop
Paul G. Cummings
Paul L. Dandeno
James H. Dymond
James S. Edmonds
Franklin T. Emery
Jorge Fernandez-Daher
Guanzhong Gao
Trilok C. Garg
Nirmal K. Ghai
Brian E. B. Gott
James Grant
Franklin H. Grooms
Bal K. Gupta
Howard B. Hamilton
Thomas J. Hammons
Richard A. Huber
Alan M. Iversen
Chaman L. Kaul
Rigsby Kavanaugh
Tim Keck
Stephen B. Kuznetsov
Peter H. Landrieu
Walter J. Martiny
William R. McCown
William McDermid
Lloyd McSparran
Edward J. Michaels
J. R. Michalec
Charles Millet
Gerhard J. Neidhoefer
Nils E. Nilsson
Beant S. Nindra
J. L. Oldenkamp
James A. Oliver
William B. Penn
Madan Rana
Robert H. Rehder
Laurence Rodland
Charles M. Rowe
David E. Schump
Manoj R. Shah
John Shea
Jan Stein
Ken Stenroos
Greg C. Stone
James E. Timperley
Paul Vollmar
Paul Dieter Wagner
Vicki Warren
Richard F. Weddleton
Charles A. Wilson
John Wilson
Edward J. Woods
Daniel I. Young
Martin Zgraggen

The final conditions for approval of this standard were met on 6 March 2000. This standard was conditionally approved by the IEEE-SA Standards Board on 30 January 2000, with the following membership:

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Akio Tojo
Hans E. Weinrich
Donald W. Zipse

*Member Emeritus

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Robert E. Hebner

Noelle D. Humenick
IEEE Standards Project Editor

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IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery

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

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 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.

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2. References

This recommended practice shall be used in conjunction with the following publications. When the following 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.

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]

IEEE Std 62-1995, IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus—Part 1: Oil Filled Power Transformers, Regulators, and Reactors.

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

IEEE Std 95-1977 (Reaff 1991), IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery With High Direct Voltage.[5]

IEEE Std 118-1978 (Reaff 1992), IEEE Standard Test Code for Resistance Measurements.

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

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.

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[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 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/).

[5]Presently under revision.

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3. Definitions

For the purposes of this recommended practice, the following terms and definitions apply. The IEEE Dictionary of Electrical and Electronics Terms should be referenced for terms not defined in this clause.

3.1 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.

3.2 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.

3.3 electroendosmosis effect: A phenomenon occasionally observed, more often on older 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 polarity, where the ground lead is connected to the winding and the negative voltage lead to ground, is much higher than for normal polarity.

3.4 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: values of 1 through 10 are assumed to be in minutes, values of 15 and greater are assumed to be in seconds.

3.5 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.

3.6 polarization index ($P.I._{t2/t1}$): 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}).

3.7 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, i.e., 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.

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Before any testing is conducted, the winding insulation must be discharged. It is not safe to begin testing before the discharge current is zero and there is no discernible return voltage (less than approximately 20 V) after the ground is removed. 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 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. 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 technique. In general, the insulation resistance varies proportionately with the insulation thickness and inversely with 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

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 different 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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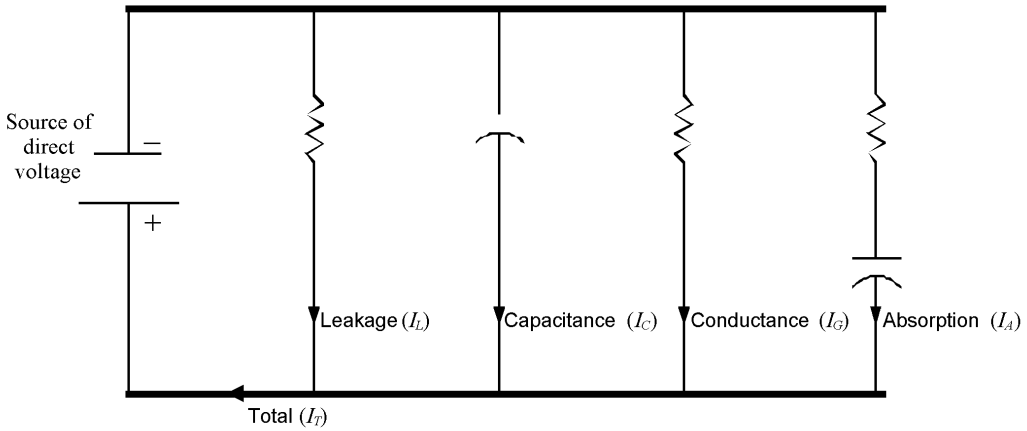

Figure 1—Equivalent circuit showing the four currents monitored during an insulation resistance test

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.

$$I_A = Kt^{-n} \tag{1}$$

where

I_A is absorption current,
K is a function of the particular insulation system and applied test voltage,
t is time of applied direct voltage,
n is a function of the particular insulation system.

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, $I_A = Kt^{-n}$, 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 thermal limitations, it would be completely unsuitable for application in most rotating machines.

The conduction current (I_G) 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.

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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 or wet, the total current (I_T) will be approximately constant with time, since I_L and/or I_G (see Figure 2) 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 3), since the total current is dominated by the absorption (i.e., polarization) current (I_A).

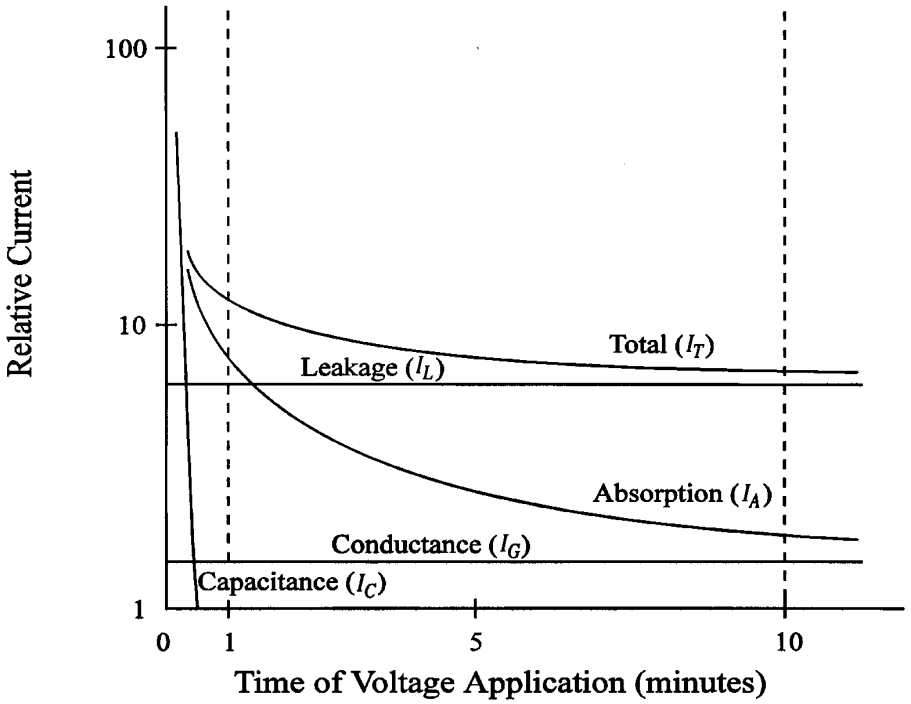

Figure 2—Types of currents for an asphaltic-mica insulation

5.3 Insulation resistance readings

The measurement of insulation resistance constitutes a direct-voltage test and 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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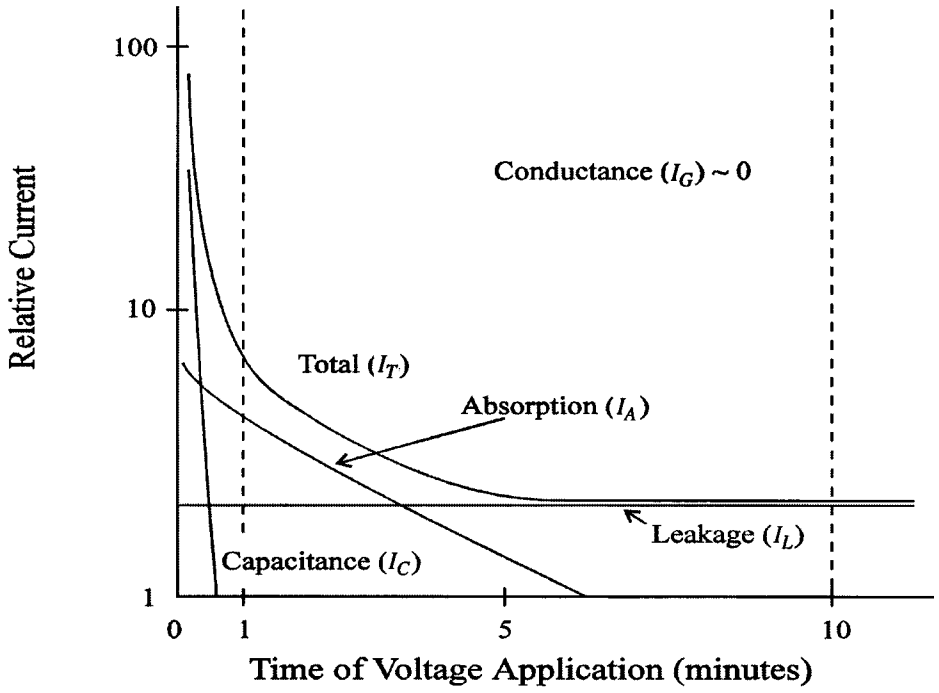

Figure 3—Types of currents for an epoxy-mica insulation with a relatively low surface leakage current and no conductance current

Table 1—Guidelines for dc 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

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

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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.

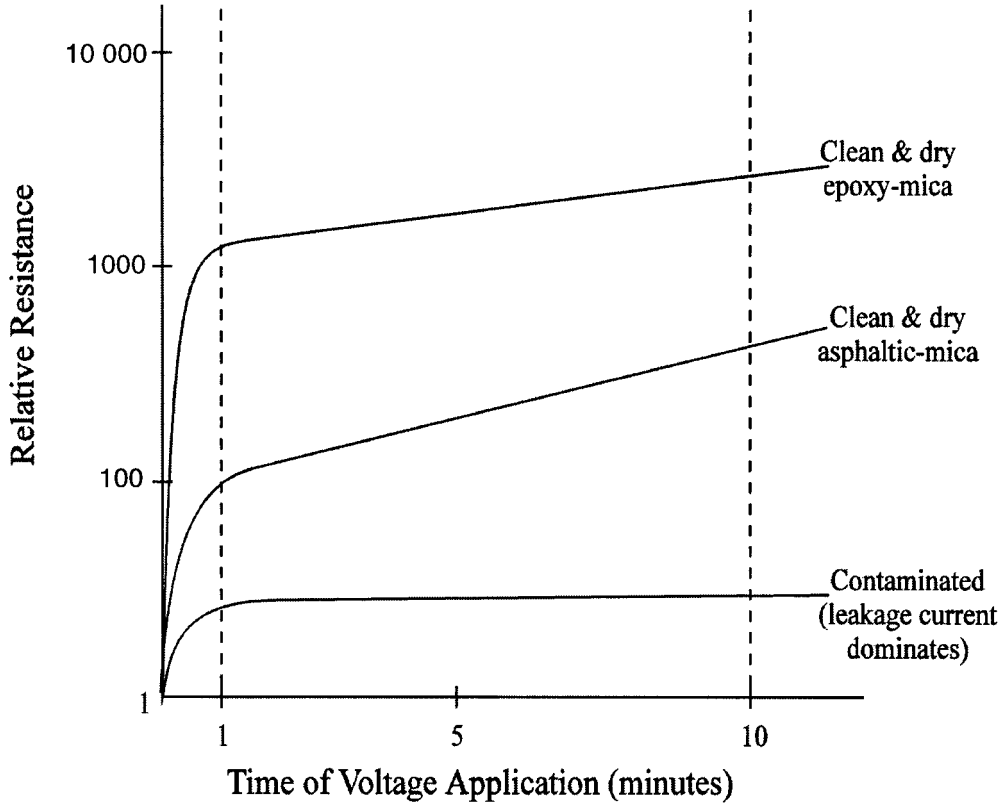

Figure 4—Typical insulation resistance measurements for three different machines

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 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 creepage surfaces. There may also be

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an increase in the surface leakage current on machines where a stress-control coating has been applied to the endwindings.

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 asphaltic-mica and shellac mica-folium insulating materials, as well as for some insulating strips used between uninsulated copper conductors in large turbine generator rotors. Absorbed moisture increases the conduction current (I_G) and significantly lowers the insulation resistance.

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 the machine being tested is generally so large that the temperature differential of the winding between the 1 min and 10 min readings of the insulation resistance is negligible, except for measurements during a dryout at rated current. 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 temper-

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ature 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 6.3.2 or 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 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

If the temperature effects on the insulation system under test is unknown, an approximate value for the temperature 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 indicated 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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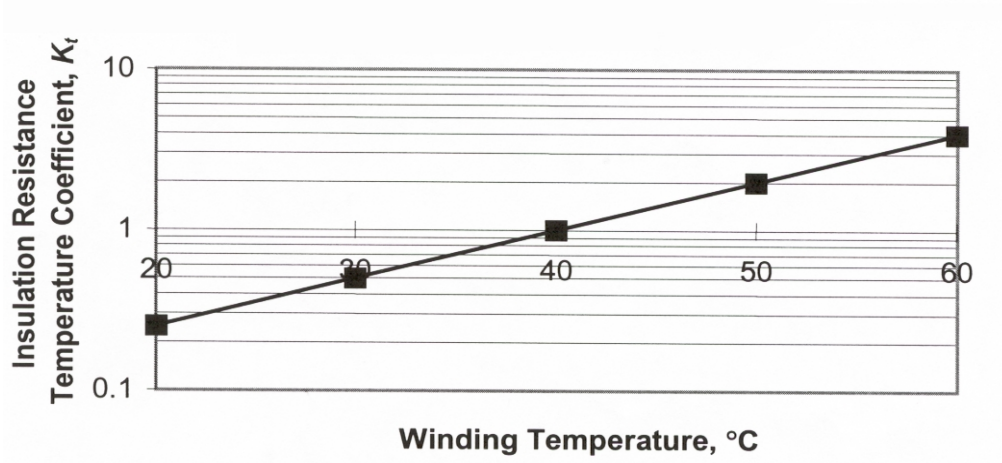

Figure 5—Approximate insulation resistance coefficient, K_T, for insulation halving for 10 °C rise in temperature

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

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

or

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

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 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.

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).

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6.5 Effect of existing charge on winding resistance measurements

The insulation resistance measurements will be in error if residual charges 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 assure that the winding is completely discharged. A residual charge will show as a reverse deflection of the insulation resistance meter after connections are made but before the voltage is applied. Any reverse deflection should be negligible.

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 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 than 0.25 μs/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. 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.

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9. Methods of measuring insulation resistance

9.1 Direct measurement

Direct measurement of insulation resistance may be made with the following instruments:

a) Direct-indicating megohmmeter with self-contained hand or power-driven generator

b) Direct-indicating megohmmeter with self-contained battery

c) Direct-indicating megohmmeter with self-contained rectifier, using a regulated line powered supply

d) 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).

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 ensure the safety of the operator.

The resistance is calculated from Equation (4).

$$IR_{(t)} = E_{(t)} / I_{(t)} \tag{4}$$

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 1 min duration. It is essential that the voltage of any test source be constant to prevent fluctuation in the charging current (see Annex C). Stabilization of the supplied voltage may be required.

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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 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.

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 IR_1 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. 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 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).

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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 values; however, it is not recommended by this standard. In all cases where the test values fall below the recommended 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, 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 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 endwinding 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 material 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. Table 2 is based on the thermal class of the insulating materials and, with the exception of noninsulated field windings, applies to all insulating materials regardless of application.

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Table 2—Recommended minimum values of polarization index for all machine components[a] insulation classes per IEC 60085-01: 1984

Thermal class rating	Minimum *P.I.*
Class A	1.5
Class B	2.0
Class F	2.0
Class H	2.0

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

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 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 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. If however, the rotor winding is insulated from the rotor body, as in wound induction rotors and salient pole machines, a polarization index test is applicable. The field windings of many very large turbine generators 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 noninsulated 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 noninsulated field windings.

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 1). 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 1–10 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.

12.3 Insulation resistance

The minimum insulation resistance after 1 min, $IR_{1\ min}$, for overvoltage testing or operation of ac and dc machine stator windings and rotor windings can be determined from Table 3.

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The actual winding insulation resistance to be used for comparison with $IR_{1\ min}$ is the observed insulation 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 be approximately twice that of the entire winding. If each phase is tested separately and guard circuits are used on the two phases not under test, the observed minimum resistance should be three times the entire winding.

Table 3—Recommended minimum insulation resistance values at 40 °C (all values in MΩ)

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

NOTES
1—$IR_{1\ min}$ is the recommended minimum insulation resistance, in megohms, at 40 °C of the entire machine winding

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

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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 3). In more modern insulation systems for form-wound stators, and especially in random-wound machines, the absorption current may decay to nearly zero in 2–3 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,
$IR_{30\ s}$ 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.

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.

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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,
ρ 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 endwinding 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 and an ac test should be conducted to more completely assess the condition of an insulation system.

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Annex C

(informative)

Regulation in power supplies used for insulation resistance measurement

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):

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

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 resistance (apparent resistance R_A) according to Equation (C.2):

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

where

Idc 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):

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

The regulation can be stated as a percentage of the applied voltage and calculated from values found in general 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 measurement accuracy, necessitates a $dv/dt << 4$ V/s. The regulation would therefore be 4 V/s in 5 kV, or 0.08% regulated.

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Most IR measurements are made at frequencies below 1 Hz, so these results apply to a low-frequency regulation 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.

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