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IEEE Recommended Practice for Insulation Testing of AC Electric Machinery (2300 V and Above) With High Direct Voltage

IEEE Power Engineering Society

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**Electric Machinery Committee
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Abstract: This recommended practice provides information on the use of high direct voltage for proof tests and for periodic diagnostic tests on the groundwall insulation of stator (armature) windings in ac electric machines.

Keywords: electric machine windings, electrical insulation, high direct voltage

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Introduction

[This introduction is not part of IEEE Std 95-2002, IEEE Recommended Practice for Insulation Testing of AC Electric Machinery (2300 V and Above) With High Direct Voltage.]

Traditionally, the insulation of rotating machines has been tested for dielectric strength with alternating voltage. In 1952, attention was directed to testing with direct voltage. Since then, high direct voltage has been widely used. Many reports of procedure and results are found in the IEEE Transactions with expressions of widely differing opinion.

In 1957, the Insulation Subcommittee of the IEEE Rotating Machinery Committee appointed a working group to review the existing literature and to prepare a guide for the conduct and interpretation of high direct-voltage insulation tests. It was found that many methods of making the tests have been used and that there was no uniform opinion of their relative merits.

In 1971, the Insulation Subcommittee of the IEEE Rotating Machinery Committee appointed a working group to revise the existing guide to a recommended practice.

In 1996, the Materials Subcommittee of the IEEE Electric Machinery Committee appointed a working group to revise the existing recommended practice. The document has been updated in a number of respects and typical test results using the ramped voltage test method have been included.

At present there is wide usage of high direct voltage for insulation testing, but there are still areas of disagreement regarding the utility of such tests. In this recommended practice every effort has been made to state facts and to indicate what is not certain. This document gives the present opinion and evaluation of high direct-voltage insulation testing of a large number of investigators with experience in a wide area of test activities.

Many of those who have used the methods described in this recommended practice have found them to be satisfactory and a valuable addition to other test procedures. It is hoped that the use of this recommended practice will achieve more uniform results and a fuller understanding and appreciation for the benefits of the high direct-voltage dielectric test.

A general discussion of test procedures, a comparison between alternating and direct-voltage testing, and requirements for high voltage power supplies may be found in Annex A of this recommended practice. For background information on overvoltage testing, see Clause 8 of IEEE Std 56-1977 and see IEEE P62.2/D23.^a

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WARNING

Due to high voltage used, dielectric tests should be conducted only by experienced personnel, and adequate safety precautions should be taken to avoid injury to personnel and damage to property.

IEEE Recommended Practice for Insulation Testing of AC Electric Machinery (2300 V and Above) With High Direct Voltage

1. Overview

1.1 Scope

This recommended practice provides uniform methods for testing insulation with high direct voltage. It applies to stator (armature) windings of ac electric machines rated 2300 V or higher. It covers acceptance testing of new equipment in the factory or in the field after installation, and routine maintenance testing of machines that have been in service.

1.2 Purpose

The purpose of this recommended practice is to:

- a) Provide uniform procedures for performing high direct-voltage acceptance tests and routine maintenance tests on the main ground insulation of windings of ac electric machines.
- b) Provide guidance in analyzing the variations in measured current versus applied voltage so that the condition of the insulation can be more effectively assessed.
- c) Compare direct-voltage testing with alternating voltage testing.

1.3 Application and limitations

Testing of machine insulation may be conducted in the factory, in the field during installation, as a condition of acceptance, to verify the efficacy of repairs or maintenance, after a system disturbance or extended outage, and/or on a routine basis during the lifetime of the machine.

High direct-voltage acceptance tests are generally performed to provide some assurance that the winding insulation has a minimum level of electrical strength. Because the inherent electrical strength of sound insulation is well above the usual proof test value, failure during an acceptance test at an appropriate voltage indicates the insulation is unsuitable for service.

The use of controlled high direct-voltage tests (e.g., stepped or ramped voltage tests) offers certain advantages over proof-type acceptance tests. By observing measured current during the controlled application of voltage, variations in current versus applied voltage may be useful in diagnosing certain insulation defects and modes of deterioration. Controlled overvoltage tests may also afford the possibility of detecting impending insulation problems by recognizing abnormalities in the measured current response, thereby allowing the test to be discontinued prior to insulation failure.

Insulation problems that may be detected by controlled direct-voltage tests include:

- Cracks or fissures
- Surface contamination
- Uncured resin
- Moisture absorption
- Delamination
- Voids

There has been limited experience in detecting delaminations and voids by the means of controlled direct-voltage tests. See [B32], [B33].

High direct-voltage tests may be preferred over alternating-voltage (e.g., 50 Hz or 60 Hz) tests for the following reasons:

- a) The supply unit for the direct voltage is relatively small and lightweight, making it suitable for transport to most field locations.
- b) Fewer partial discharges occur during direct-voltage tests as compared to alternating-voltage tests, thus less damage to the insulation results from the direct-voltage test.
- c) If insulation breakdown occurs during testing, direct-voltage tests cause less damage because the capacity of the test supply is small and the energy discharged into the fault is largely that stored in the capacitance of the winding under test.
- d) Variations in measured current versus applied voltage provide meaningful information regarding the nature of insulation defects and modes of deterioration.
- e) Comparison of test results with previous results of tests performed on the same machine may give an indication of the rate of insulation system deterioration.
- f) Overvoltages that are likely to occur in the stator windings are generally of a surge nature that appear to correlate well to direct-voltage stresses rather than alternating-voltage stresses.

Some disadvantages and limitations of high direct-voltage testing are as follows:

- a) Under some conditions, expertise is required to properly interpret the test results.
- b) High direct-voltage tests electrically stress the stator endwindings according to the relative resistivities of the dielectric material and the winding surface. The resulting stress distribution does not duplicate that experienced by the machine when in operation or when tested using alternating voltage.
- c) Cracks or fissures may not be detected until they are contaminated with moisture, dirt, or other conductive materials.
- d) Some high direct-voltage tests may not detect internal insulation voids caused by improper impregnation, thermal deterioration, or thermal cycling in form wound stator coils.
- e) Any tests conducted while a machine is at standstill may not detect problems related to rotation, such as loose coils/bars or endwinding vibration.

2. References

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

ANSI C50.10-1990, General Requirements for Synchronous Machines¹

ANSI/IEEE Std C57.12.90-1999 Standard Test Code for Liquid-Immersed Distribution, Power and Regulating Transformers

ASTM D257-99, Standard Test Methods for DC Resistance or Conductance of Insulating Materials²

IEC 60034-1 (1999), Rotating Electrical Machines—Part 1: Rating and Performance³

IEEE Std 4TM-1995, IEEE Standard Techniques for Dielectric Tests.^{4,5}

IEEE Std 43TM-2000, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery

IEEE Std 56TM-1977 (R1991), IEEE Guide for Insulation Maintenance of Large Alternating-Current Rotating Machinery 10 000 kVA and Larger

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

IEEE P62.2/D23 Draft Guide for Diagnostic Field Testing of Electric Power Apparatus: Electrical Machinery⁶

IEEE Std 112TM-1996, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators

IEEE Std 115TM-1995, IEEE Guide: Test Procedures for Synchronous Machines

IEEE Std 433TM-1974, IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Voltage at Very Low Frequency

IEEE Std 510TM-1983, IEEE Recommended Practices for Safety in High-Voltage and High-Power Testing

NEMA MG 1-1998, Motors and Generators (including Revisions 1 and 2)⁷

¹ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

²ASTM 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/>).

³IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembe, 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.

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⁶This IEEE standards project was not approved by the IEEE-SA Standards Board at the time this publication went to press. For information about obtaining a draft, contact the IEEE.

⁷NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (<http://global.ihs.com/>).

3. Definitions

3.1 absorption (polarization) current (i_A): Current that results from polarized atoms and molecules becoming displaced and aligned when a dielectric is placed in an electric field. Upon application of a voltage step, the absorption current decays from a comparatively high initial value to nearly zero. The initial magnitude and rate of decay depend on the type, condition, dimensions, and temperature of the insulation.

3.2 absorption coefficient (K): The absorption current measured 1 minute after the application of a constant electric stress, divided by the applied voltage and the geometric capacitance.

3.3 absorption exponent (n): The exponent of the time in minutes that defines the rate of decay of the absorption current following the application of a constant electric stress.

3.4 absorption ratio (N): The ratio of the absorption current after 1 minute divided by the absorption current after 10 minutes where the times are measured from the application of the constant electric stress. The base 10 logarithm of the absorption ratio N is equal to the absorption exponent n .

3.5 acceptance proof test: A pass/fail type of test made on a new or repaired winding before allowing the machine to be placed in service. The test may be performed at the factory, after field installation, or both (see ANSI C50.10-1990⁸).

3.6 breakdown current (i_B): The current discharged as a result of insulation failure. The peak value of this current may be very high, reflecting the energy stored in the capacitance of the winding. Normally, this current cannot be accurately measured.

3.7 breakdown voltage: The voltage at which a disruptive discharge takes place through the volume or over the surface of the insulation.

3.8 conduction (leakage) current (i_C): The sum of the volume conduction current and the surface conduction current.

3.9 controlled overvoltage test (e.g., stepped or ramped voltage tests): A test in which the magnitude of the applied direct voltage is manually or automatically increased above the peak value of the nominal line-to-ground rms rating of the insulation system. During such tests, measured current is continuously monitored for indications of insulation defects or deterioration. If insulation failure appears imminent, an attempt may be made to stop the test before damage due to breakdown occurs.

3.10 electric strength (dielectric strength): The maximum applied voltage an insulation system can withstand without failure.

3.11 electroendosmosis: The migration of moisture within a stationary solid material, under the influence of an applied electric field, toward an electrode. The net movement of water molecules is generally toward the negatively-charged electrode.

3.12 geometric capacitance: The capacitance of a geometric arrangement of the electrodes where the effect of the relative dielectric constant of the insulation system has been included. The capacitance value measured at 50 Hz or 60 Hz is sufficiently accurate for use in connection with direct-current measurements [B29].

3.13 geometric capacitive current (i_C): A reversible component of measured current that is equal to the rate of change of applied voltage times the winding-to-ground geometric capacitance. Following an applied

⁸Information on references can be found in Clause 2.

direct-voltage step, the geometric capacitive current is of comparatively high magnitude and short duration. It decays exponentially. The decay time constant is the product of the series resistance of the charge/discharge path (including the internal resistance of the test supply) and the geometric capacitance of the winding.

3.14 high direct voltage: A unidirectional voltage whose magnitude is greater than the peak value of the nominal rms line-to-ground rating of the insulation system under test.

3.15 insulation resistance (IR_t): The resistance of an insulation to current resulting from an applied direct voltage. It is defined in IEEE Std 43-2000 as the ratio of applied direct voltage to measured insulation current where the current measurement is taken at time t , specified from the start of voltage application. The insulation resistance measurement should be corrected to 40 °C.

3.16 maintenance proof test: A pass/fail type of test performed to verify that the stator winding is suitable for future operation. A maintenance proof test is usually made at a lower voltage than the acceptance proof test.

3.17 measured current: The sum of all currents at a specific time resulting from an applied voltage across an insulation. It includes the absorption, geometric capacitive, and volume and surface conduction current components. Measurements are usually made using a microammeter.

3.18 overvoltage (overpotential): A voltage whose magnitude is above the nominal rating or maximum operating voltage of an apparatus. A direct overvoltage exceeds the peak value of the alternating frequency rms line-to-ground value.

3.19 polarization index: The ratio of the insulation resistance at time t_2 to the insulation resistance at time t_1 . If t_2 and t_1 are not specified, they are assumed to be the 10-minute and 1-minute values, respectively. The polarization index may be used to assess insulation condition and moisture absorption.

3.20 proof test (withstand test): A pass/fail type of test performed to verify that the electric strength of the insulation system meets or exceeds a predetermined minimum value.

3.21 ramp test (ramped voltage test): A controlled overvoltage test in which direct voltage is increased from zero, or from an initial constant value, at a continuous rate (typically 1 kV/minute). The measured current versus applied voltage is usually plotted with an X-Y recorder to permit observation and analysis of the current response as the test progresses.

3.22 relative dielectric constant (relative permittivity): The relative dielectric constant of an insulating material is defined as $\epsilon_r = C/C_o$, where C is the capacitance between two parallel plates having the space between them filled with the insulating material under discussion, and C_o is the capacitance for the same parallel plates where these are separated by vacuum.

3.23 step test (stepped voltage test): A controlled overvoltage test in which the direct voltage is increased in a series of uniform or graded steps. The first voltage step is usually maintained for 10 minutes to determine the absorption ratio, insulation resistance, and polarization index. Subsequent voltage steps and their duration may be chosen to linearize the effect of the absorption current on the current versus voltage response.

3.24 surface conduction current: The component of measured current that flows over the endwinding surfaces of the stator coils or bars. The magnitude of the surface conduction current depends on the applied voltage as well as the degree of conductive surface contamination, such as dirt and moisture.

3.25 volume conduction current: The continuous, irreversible component of measured current that flows through the volume of the insulation when a potential exists across the insulation. Its magnitude depends on the composition and condition of the insulation system.

4. Test preparations

4.1 Safety precautions required for high direct-voltage tests

WARNING

Due to high voltage used, dielectric tests should be conducted only by experienced personnel and adequate safety precautions should be taken to avoid injury to personnel and damage to property.

Prior to performing a high voltage test, barriers must be in place to restrict access to the testing area and machine under test. This safety measure is necessary to prevent personnel from inadvertently coming into contact with energized equipment (see IEEE Std 510-1983).

Test personnel should be advised that application of a high direct voltage results in a stored charge in the capacitance of the winding under test. De-energizing the test source will not immediately de-energize the winding. The stored charge may be hazardous to equipment and/or personnel. Windings that have been tested with direct voltage must be fully discharged and solidly grounded before being handled by personnel.

Ungrounded objects in the vicinity of the winding under test should be solidly connected to ground to prevent induced voltages.

Before making a high direct-voltage test, the stator winding should be deemed suitable for high voltage testing. Insulation resistance and polarization index should be at or above the minimum values specified in IEEE Std 43-2000.

A machine should not be placed in service after a high direct-voltage test until the winding has been grounded for an appropriate period of time. If a high alternating-voltage test is to follow a high direct-voltage test, it is advisable to double the minimum grounding time to ensure that the absorbed charge does not contribute to insulation failure during the subsequent alternating-voltage test. This may occur if the residual direct voltage, superimposed on the peak alternating voltage, exceeds the electric strength of the insulation.

4.2 Influencing factors

Factors affecting the condition of the winding should be evaluated prior to performing a high direct-voltage test.

4.2.1 Temperature

A direct-voltage test should be made at winding temperatures at or below 40 °C, unless otherwise agreed upon between the user and the manufacturer.

Insulation resistance and dielectric absorption vary with temperature. Therefore, consistent temperatures are required for accurate and comparable current measurements. Winding temperatures near ambient are preferred. Otherwise, measured resistance values must be normalized before comparison (see IEEE Std 43-2000).

4.2.2 Relative humidity

Surface conduction current over endwindings, support insulators, etc., is increased under conditions of high humidity, particularly if conductive contamination is present. Because it is difficult to maintain a standard humidity for correlation of current measurements on successive tests, some users prefer to keep the windings dry by maintaining the winding temperature slightly above ambient (e.g., 5 °C). When a machine is idle for long periods, it may be heated to prevent condensation and/or moisture absorption [see IEEE Std 56-1977 (R1991)].

High direct-voltage tests are most valid when made under humidity conditions similar to those under which the machine will operate. When in service, the machine will generally operate above the dew point. However, if cracks or fissures are believed to exist in the groundwall insulation, it may be desirable to carry out tests under conditions of high ambient humidity and low winding temperature to promote ingress of moisture into the fissures and cracks to enable them to be detected.

4.2.3 Surface contamination

Contaminants (e.g., oil, carbon, brake dust, dirt, insects, etc.) combined with moisture can cause an undesirable increase in surface conduction current during direct-voltage tests. Contamination may increase voltage stresses in endwindings, especially if moisture is present.

The winding may be cleaned before testing if it is deemed that a clean condition is the standard upon which measurements from preceding and succeeding tests will be compared.

If oily or flammable contamination could present a fire hazard, in view of the possibility of a flashover during the test, the winding should be cleaned before testing.

The winding should be cleaned if contaminants cause insulation resistance to fall below the minimum value recommended in IEEE Std 43-2000.

Consideration may be given to testing both before cleaning, for easiest detection of incipient faults and identification of repairs required during the time out of service, and again after cleaning and drying and any other work, for final assurance of fitness for service.

4.2.4 Uncured resins and other coatings

Certain uncured resins, varnishes, and other coatings may cause high conduction currents during direct-voltage tests. Coatings and bonding resins should be completely dry and cured before tests are made. In spite of efforts to cure the resins prior to testing, anomalous current versus voltage curves have been reported during controlled overvoltage tests [B22]. After a number of months in service these signs usually disappear.

4.2.5 Disposition of rotor

The stator winding may be tested with or without the rotor in place. However, if the rotor will be removed for other reasons, it may be preferable to perform the test after the rotor has been removed to permit better observation of the stator winding during the test.

4.3 Gas-cooled machines

4.3.1 Air-cooled machines

Time out of service, temperature, and humidity are important factors when making measurements using high direct voltages because these factors influence moisture condensation on the surface of and absorption by the insulation.

4.3.2 Hydrogen-cooled machines

Hydrogen-cooled machines may be tested in a hydrogen, carbon dioxide, or air environment. Hydrogen or carbon dioxide of suitable pressure should be maintained during the test to ensure the effectiveness of striking distances. If the test is being performed for contractual purposes, agreement should be reached between the parties involved regarding the type of gas and pressure. For comparative purposes, tests should be performed with the same gas at the same gas pressure.

4.4 Liquid-cooled machines

4.4.1 Water-cooled windings

If a power supply were available with sufficient capacity to energize the winding, the conduction current drawn by the hoses would be so high as to mask completely any conduction paths in the stator groundwall insulation. Nevertheless, the test would still be valid for proof test (hipot) purposes.

When testing water-cooled windings, a common procedure is to have the insulating hoses drained and thoroughly dried internally prior to the test to avoid electrical tracking, in accordance with the recommendations of the manufacturer. Alternately, the hoses or water connections may be removed prior to the test.

Some users and manufacturers prefer that water of proper conductivity be circulated at rated flow during the test to avoid overheating pockets of stagnant water. In this case, the test supply will require additional current capacity. Some users test with 50 Hz or 60 Hz voltage or possibly 0.1 Hz voltage to avoid the above mentioned problems.

In some cases, the winding manufacturer has provided an insulated water header such that the water header and the winding are at the same voltage during the test, thus avoiding electric stress on the hoses.

4.4.2 Oil-cooled windings

In the case of oil-cooled machines, the oil dielectric forms a parallel circuit with the winding insulation. The normal procedure is to keep the cooling oil circulating through the winding and hoses during the test. An oil-cooled winding should be tested in accordance with the manufacturer's recommendations.

4.5 Isolation of the winding from cables and auxiliary equipment

The sensitivity of current measurements to any weakness in the winding will be improved by eliminating external equipment from the test. Therefore, it is preferable to exclude any items that can readily be disconnected and to apply separate tests appropriate to them. If auxiliary equipment is included in the test and weakness is detected, the weakness should be located by sectionalizing.

Potheads, bus insulators, and other conductive paths must be dry and carefully cleaned, and may be fitted if necessary with temporary guard electrodes consisting of a band of semi-conducting, self amalgamating tape applied to the surface of the insulator and separated by approximately 2 mm from the ground electrode of the

insulator. Each guard electrode must then be attached to the low voltage guard circuit of the high direct-voltage supply. Alternatively, porcelain surfaces may be coated with silicone compound to reduce conduction due to condensed moisture on the surface.

Oil-filled apparatus, such as generator step-up transformers, should not be included in stator winding tests when current measurements are made because the resulting current readings may be erratic and may not provide valid results. If it is impractical to isolate an oil-filled transformer, the maximum test voltage should not exceed the transformer test voltage specification given in ANSI/IEEE Std C57.12.90-1999.

Surge arresters and surge capacitors must be disconnected prior to any tests using high direct voltages. Surge arresters have resistive elements and possibly gaps. Surge capacitors have discharge resistors. These elements are in parallel with the winding under test and will invalidate the current measurements.

It is important to record all cables and auxiliary equipment included in each test to assure proper comparison with tests made at other times.

4.6 Sectionalizing the winding

Under certain conditions, tests may be made on the entire winding. However, one objection to testing all phases simultaneously is that only the ground insulation is tested. No test is made of the phase-to-phase insulation as is done when one phase is tested with other phases grounded.

It is usually preferable for each winding phase to be isolated and tested separately. This typically requires that the wye-connection at the neutral end of the winding be broken and separated from the neutral grounding transformer. Testing one phase at a time improves the sensitivity of the test and allows comparison between phases.

Testing all phases at once is appropriate for small machines and for machines with inaccessible neutral connections. In these situations, the winding phases should be shorted together at the line end to avoid voltage reflections in the event of insulation failure or flashover.

If separation of phases is unusually difficult or impractical for a particular machine, it may be done once to establish a reference. Thereafter, all phases may be tested together until a deviation from normal is observed.

5. Test equipment and connections

5.1 High direct-voltage test equipment

General information regarding high direct-voltage test equipment is given in IEEE Std 4-1995.

5.1.1 Power source to direct-voltage test equipment

The ac supply to the direct-voltage test equipment must provide constant, non-fluctuating voltage if accurate dc measurements are to be made. The ac supply circuit should be free from intermittent loads and transients. Regulating transformers, electronic regulators, or combinations of these may be used. Commercially available regulators perform best when their apparent power capacity matches or exceeds the load. Otherwise, ambiguities in the direct voltage test data may result due to unpredictable fluctuations in geometric capacitive current and absorption current associated with fluctuations in the applied high voltage.