IEEE Standards

IEEE Std 95™-2002
(Revision of IEEE Std 95-1977)

95™

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

IEEE Power Engineering Society

Sponsored by the
Electric Machinery Committee

IEEE

Published by
The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

12 April 2002

Print: SH94982
PDF: SS94982

Recognized as an
American National Standard (ANSI)

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1 August 2002
American National Standards Institute

Approved 20 March 2002
IEEE-SA Standards Board

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*

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Print: ISBN 0-7381-9245-4 SH94982
PDF: ISBN 0-7381-3246-2 SS94982

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

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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 Machines[1]

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 Materials[2]

IEC 60034-1 (1999), Rotating Electrical Machines—Part 1: Rating and Performance[3]

IEEE Std 4™-1995, IEEE Standard Techniques for Dielectric Tests.[4,5]

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

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

IEEE Std 62™-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 Machinery[6]

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

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

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

IEEE Std 510™-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]

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[1] ANSI 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/).

[2] 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/).

[3] 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.

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[6] This 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.

[7] NEMA 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 C50.10-1990[8]).

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_{tc}): 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

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[8] Information 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 $\varepsilon_r = C/C_o$, 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.

A source utilizing 50 Hz or 60 Hz system frequency is preferable to a non-synchronized source, such as a separately driven station service generator, because of the effect of variable frequency upon voltage regulators and electronic test equipment. A low-amperage (e.g., 15 A), 50 Hz or 60 Hz power source will supply the usual equipment used for high direct-voltage tests on electric machine insulation.

5.1.2 High direct-voltage supply

A source of adjustable high direct voltage is required. The voltage control should provide for changing the voltage in small increments. If it is desired to raise the voltage continuously rather than in steps, some means of smooth variation is necessary. Stepless voltage increases, in ramped or other functions of time, can be arranged with certain direct-voltage supplies.

The polarity of the high-voltage output may be either positive or negative. Historically, negative polarity has been preferred for high direct-voltage tests because of the phenomenon of electroendosmosis (negative polarity is considered to be more searching). If test results will be compared to previous or future results, the tests should be made using the same polarity. The test report should indicate the polarity used.

A test set with a well-regulated (0.1 percent line regulation or better) high voltage output is recommended. See A.3 for additional information regarding voltage supply and current measuring requirements.

5.1.3 Direct-voltage measurements

The direct-voltage test set should be provided with a high voltage measurement circuit calibrated in kilovolts. For best sensitivity, the instrumentation should be capable of measuring kilovolts with several ranges available. If the test equipment includes an overvoltage relay trip, the relay should be set and calibrated.

It is occasionally desirable to check the calibration of the test set kilovoltmeter. This may be done by using a sphere-gap (see IEEE Std 4-1995).

A sphere-gap may be used as an overvoltage limiter during proof tests if the gap is increased 10 to 20 percent above the calculated gap for the maximum test voltage. The gap allowance ensures there will be no needless flashovers.

NOTE—When current measurements are to be made, the sphere-gap should be omitted from the test circuit.

5.1.4 Direct-current measurements

The total current is typically measured in microamperes. For improved sensitivity, the current meter should have several current ranges available. If the test set includes an overcurrent trip, it should be calibrated and set high enough to avoid inadvertent trips during the test. Interruption during the test could cause a surge and may overstress the insulation.

Current measurements are greatly improved if a recorder with a time or voltage base is used. In particular, a recorder facilitates determination of an accurate average when current is fluctuating because of supply voltage unsteadiness.

5.2 Discharge and grounding provisions

Appropriate discharge and grounding provisions should be available for use upon completion of the test and in case of an emergency during the test. A discharge stick with a discharge resistor is usually furnished with the direct-voltage test supply. The stick should be insulated and safe for use up to the maximum test voltage. A high-voltage resistor having 1000 to 6000 Ω/kV of maximum test voltage should be provided. The wire that connects the discharge resistor to ground should be extra flexible and have generous current-carrying capacity and physical strength, such as stranded No.12 AWG. Broken strands will be obvious if the ground cable is uninsulated. The clamping device used to connect the ground wire to plant ground should be sufficiently strong and secure to prevent unintentional disconnection of the discharge stick from ground.

The winding should be discharged through the discharge resistor until the voltage is reduced to zero. On some test sets, opening the main breaker automatically inserts a resistive grounding device. When either an automatic or manual grounding scheme is incorporated into the test set, an external grounding device (without a resistor) must be available for solidly grounding the winding after a test and for emergency use.

Grounds left in place after completion of tests may be unattended. All personnel who might come into contact with these leads should be advised of their purpose and importance (see 6.4).

5.3 High-voltage test connection to the winding

The phase under test should be energized at both the line and neutral ends simultaneously whenever practical. Other phases should be grounded at both ends. Connecting both ends of the winding together minimizes possible damaging surges in the event of failure or flashover during the test. Where a connection between line and neutral is very difficult, tests may be made by connecting the supply to only one end of the winding. Extra precautions should be taken to avoid external flashover of the test circuit when only one end of the winding is energized. Testing only a portion of a large machine winding is desirable to limit the available discharge energy.

High-voltage test connections should contribute minimal leakage current and corona loss. High-voltage leads should be spaced a minimum of 100 mm plus 25 mm per 10 kV of test voltage from grounded surfaces. Test connections should be supported in the clear so that they are visible to the tester, without solid insulation wherever possible. Where solid insulation is used, it must be dry and of generous surface length.

The use of large diameter wire for test leads will reduce corona. The use of conductors insulated with materials such as polyethylene will reduce corona because the insulation effectively increases the diameter of the test lead. Using large-diameter or insulated test leads may be particularly beneficial in situations involving minimum clearance from grounded surfaces. When test lead insulation not specifically designed for high voltage applications is used, the test leads should be treated as if they were bare. Also, the insulation may become damaged during the test and is thereafter unsuitable for normal use.

Corona can be reduced by rounding off sharp projections and terminals with masses of either conducting or insulating material. Connections exposed when sectionalizing a winding should be carefully treated to eliminate sharp contours. Semi-conducting plastic or putty, shaped to spherical contour, may be used. Lead foil or rounded metallic caps or tubes may be used to cover sharp ends (aluminum foil should be avoided because it crinkles and creates undesirable points). Polyethylene sheeting wrapped around exposed conductors has been found to be effective in preventing corona.

The effect of corona on measurements can be reduced by enclosing terminals, etc., in conducting shields that are connected to a guard circuit that is insulated from the measuring circuit.

At high elevations, corona is more severe and all precautions to minimize it may be necessary.

After the test leads are in place but before connecting them to the winding, conduction current due to test connections should be checked at several voltage levels up to the highest voltage to be used. Record the results of this test.

A typical circuit configuration for high direct-voltage tests is shown in Figure 1.

5.4 Test connection to ground

Ground connections must be strong and secure to ensure the safety of personnel. In addition, inadequate grounding could compromise test data quality and interpretation. All ground leads and connectors must be mechanically strong and so arranged that they cannot be broken or removed by accident or error. The ground lead is usually No. 12 AWG flexible stranded conductor or larger. The ground connections should be visible. For this reason, tape and rubber clip insulators should not be used on leads used for ground connections. The conductor strands should be visible at lugs and clips and not covered in any way.

The test set chassis should be connected to the closest station ground. If the high voltage output of the test set is connected directly to the machine terminals then the test set chassis should also be connected directly to the frame of the machine under test. This ground is for the protection of the operator of the test equipment and must be secure and continuous.

During a high direct-voltage test, it is possible for nearby ungrounded coils, metallic objects, or semiconducting varnished surfaces to develop voltages which could give dangerous shocks. It is therefore recommended that in the area within 3 meters of the test leads or the machine winding under test that all spare parts, pieces of equipment, tools, etc., that cannot be removed, be grounded while the test is in progress. The following auxiliary equipment should be grounded to the machine frame:

a) Stator resistance temperature detectors or thermocouples
b) Other devices associated with the stator winding
c) Current transformer secondary windings
d) Rotor winding (both terminals) and shaft
e) Test set chassis
f) Objects close enough to become charged

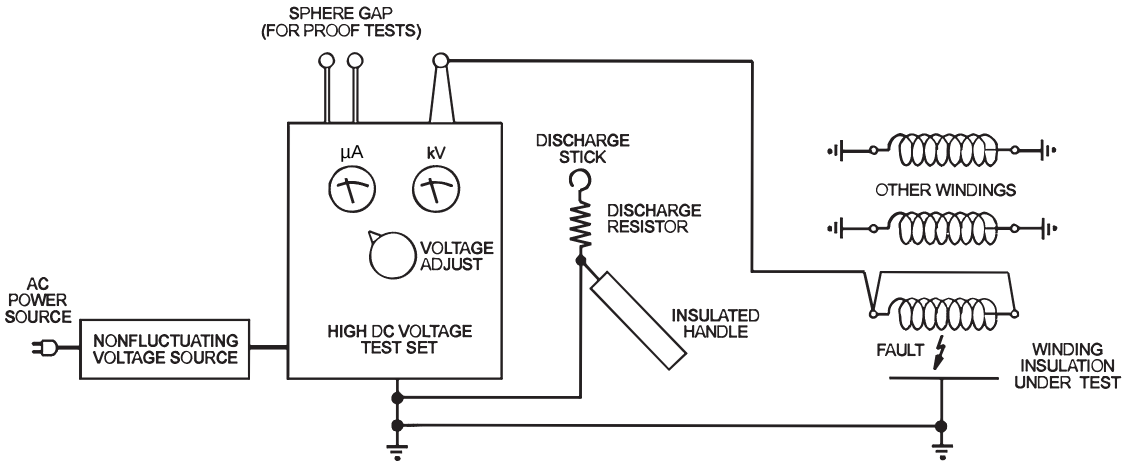

Figure 1—Typical connection diagram for high direct-voltage tests

6. Test procedure: proof tests

Prior to performing any high direct-voltage tests, the stator winding should be deemed suitable for high voltage testing according to IEEE Std 43-2000. Test preparations, connections, preliminary tests, etc., are to be made as described in Clause 4 and Clause 5.

6.1 Test voltage for acceptance proof testing

Testing of new equipment, either in the factory or in the field, is governed by the appropriate equipment test code. See IEC 60034-1, ANSI C50.10-1990, and NEMA MG 1 Part 3. For acceptance tests, the direct-voltage test level is 1.7 times the alternating frequency (rms) test value (50 Hz or 60 Hz). See A.1.3.

6.2 Test voltage for maintenance proof testing

For equipment that has been in service, the test voltage may depend upon the type and condition of insulation, equipment history, desired service reliability, etc. In general, an alternating voltage test ranging from 125 to 150 percent of the rated rms line-to-line voltage (E) has proven adequate. This is approximately equal to 65 to 75 percent of $2E + 1000$ V, depending on the voltage rating of the equipment to be tested. The direct-voltage test value for maintenance tests is 1.7 times the alternating voltage (rms) maintenance test value (50 Hz or 60 Hz).

The test voltage for maintenance proof testing under special conditions of insulation age, damage, or in light of other considerations may require variation from the range indicated. It is suggested that the original equipment manufacturer be consulted in these circumstances.

6.3 Voltage application

The application of test voltage should be gradual, should avoid exceeding the maximum test set current, and should avoid unnecessarily tripping the overvoltage or overcurrent relays in the test set which could introduce undesirable surges. The duration of either acceptance or maintenance proof tests is typically 1 min. The timing begins when the target test voltage is reached.

6.4 Discharging and grounding

Upon completion of the high direct-voltage test, the test supply output voltage control should be reduced to zero. It must be recognized, however, that eliminating the test source will not remove the stored charge from the winding. The winding is not safe until it has been completely discharged and solidly grounded. Unless the winding is properly discharged and grounded, it should be considered dangerous and must not be handled by personnel. The danger exists for an indeterminate period of time.

After the supply voltage control has been reduced to zero, the specimen voltage should be allowed to decay to half value through the series resistance of the test equipment (e.g., the series resistance associated with the voltmeter). The winding should then be discharged to ground through a suitable discharge resistor, ordinarily provided with the direct voltage test supply. Once the winding has been fully discharged and the voltage reduced to zero, the winding should be solidly grounded. Refer to 5.2 for information regarding discharge and grounding equipment and connections.

The ground connection should be kept in place until the absorbed charge is completely dissipated. This may require several hours, depending upon the dielectric material and its condition, the size of the winding, the test duration, and the magnitude of the applied direct voltage. If the ground connection is removed before sufficient time has elapsed, a recovery voltage may build up which can be dangerous to personnel who might touch the winding or damaging to the insulation if it were placed in service or subjected to subsequent tests.

Dissipation of residual absorbed charge cannot be accelerated by applying an alternating voltage or a direct voltage of opposite polarity from the test voltage. Excessive internal voltage gradients may be introduced across the winding insulation if either of these techniques is attempted.

Typically, a minimum grounding time of at least 2 h or 4 times the direct-voltage test duration, whichever is greater, is recommended to ensure that no significant energy remains stored in the winding. For smaller machines, a shorter time may be acceptable, but the user should be satisfied that no safety hazard exists.

6.5 Test results

Acceptance and maintenance proof tests are conducted on a withstand basis. If no evidence of distress or insulation failure is observed by the end of the total time of voltage application, the winding is considered to have passed the test.

6.6 Insulation failure

Electrical insulation failure or breakdown is usually indicated by a sharp capacitive discharge at the failure location. There are times, however, when failure or partial failure is indicated by a large, abnormal change in measured current or by erratic behavior of measured current.

Do not assume that a faulted winding has been completely discharged. Be sure that the winding is properly discharged and grounded, as described in 6.4, before being handled by personnel or before voltage is reapplied. Refer to Clause 8 for fault locating methods.

7. Test procedure: controlled overvoltage test

7.1 Test method

A controlled overvoltage test (sometimes referred to as either a dc leakage or absorption test) is a high direct-voltage test in which the applied voltage is changed in a controlled manner. The voltage may be manually increased in a series of steps or automatically ramped up to the maximum test level.

During controlled overvoltage tests, the measured current versus applied voltage is monitored as the test progresses. Abnormalities or deviations in the current response may indicate insulation problems. When performed under suitable conditions, the test provides information regarding the present condition of the stator winding insulation. The test may also serve as a proof test; if the insulation system withstands the maximum prescribed test voltage, it may be deemed suitable for operation until the next scheduled maintenance outage.

In some cases, a controlled overvoltage test may offer the possibility of detecting an impending insulation problem and thereby allow the test to be halted prior to damaging insulation breakdown. However, because unexpected insulation failure can occur during the test, it is important to be aware of the possible need to make repairs before the machine can be returned to service.

7.2 Test setup

Test equipment and connections, preliminary tests, etc., are to be made as described in Clause 4 and Clause 5.

7.3 Measured current

During high voltage testing, the measured current is the sum of geometric capacitive current, absorption current, and conduction current. The geometric capacitive current is that component attributable to the winding-to-ground capacitance and is equal to the rate of change of applied voltage times the geometric capacitance, or

$$i_C = C \times dV/dt$$

The capacitance C depends on the stator winding conductor-to-core geometry (i.e., size, shape, and spacing) and the applicable relative dielectric constant (see A.1.3.4).

Following an applied voltage step, the geometric capacitive current decays exponentially to zero in seconds. The geometric capacitive current represents a stored reversible energy and is not usually considered in evaluating the condition of the insulation.

The absorption current response to a stepped voltage is similar to the geometric capacitive current response except that the absorption current takes minutes to hours to decay to a negligible value. It is comprised of reversible and irreversible components. The expression for absorption current (in amperes) with respect to an applied voltage step is:

$$i_A = KCVt^{-n}$$

where

K is the absorption coefficient, determined by type and temperature of the winding insulation
C is the geometric capacitance (in farads)
V is the applied voltage step (in volts)
t is the time of the applied voltage step (in minutes)
n is the absorption exponent of the winding insulation (typically ranging from 0.5 to 0.9 for asphalt; 0.8 to 1.6 for polyester; 1.0 to 1.9 for resin rich epoxy) [B23]

The volume conduction and surface conduction components of the measured current are continuous, irreversible currents resulting from a voltage being applied across an imperfect insulation. Volume conduction currents pass through an insulation's volume and its defects. Surface conduction current flows over the winding surfaces. Surface conduction and volume conduction currents will vary depending on temperature, humidity, degree of contamination, and voltage stress, as well as on the quality and condition of the insulation being tested. The conduction currents of high-quality insulation will, in general, be small, linear (i.e., proportional to the applied voltage), and constant with respect to time. As the insulation starts to age and weaken, these currents will increase, and at some voltage level, will become nonlinear as evidenced by a positive increase in the slope of the current versus voltage curve. A significant increase with test voltage may indicate an impending problem with the insulation system.

7.4 Test voltage for controlled overvoltage testing

Because controlled overvoltage tests are normally done as maintenance tests rather than acceptance tests, the maximum applied voltage should be no higher than the value recommended in 6.2.

7.5 Initial voltage level

There are two generally accepted initial voltage levels used in stepped and ramped voltage testing.

7.5.1 Zero initial voltage level

The controlled high direct voltage is started at zero volts and increased to the desired maximum voltage according to the established test procedure. If a prior test was made of the winding to verify its suitability for overvoltage testing, the winding must be completely discharged before the overvoltage test is performed.

7.5.2 Initial voltage at polarization index level

In this method, an initial voltage step (equal to 30 percent or less of the maximum test voltage) is applied and held constant until the insulation resistance and polarization index are determined. Once the winding has been declared suitable for high voltage testing according to IEEE Std 43-2000, the controlled voltage is increased from the existing voltage level.

7.6 Voltage increments

Controlled overvoltage tests may be performed in a variety of ways. For example, the applied test voltage may be increased in a series of steps or as a linearly increasing voltage. Additional voltage application procedures are also possible. Each test method offers advantages and disadvantages. The three techniques commonly used for high direct-voltage testing are the uniform-time step, graded-time step, and ramped voltage test methods.

7.6.1 Uniform-time voltage step test

This method involves application of the high direct voltage in a series of uniform voltage steps at regular time intervals. Current readings are taken at the end of each interval and the current versus voltage curve is hand plotted on graph paper. During and after testing, the curve is examined for increases or other variations in conduction current versus applied voltage response that may indicate insulation weakness.

The initial voltage step is used to measure the polarization index and establish that the winding is suitable for controlled overvoltage testing. Subsequent voltage steps should not exceed 3 percent of the final test level and should be held for a period of one minute before proceeding to the next step. Adjustments to the voltage setting at each step should be made within the first 10 s. In making the voltage adjustment, allow for some increase in the final value due to the effective series resistance of the test set. It may be necessary to set the voltage approximately five to ten percent below the desired value to allow for voltage increases during the time interval. Once set, the voltage steps should not be readjusted because complex geometric capacitive current and absorption current conditions will be introduced and may cause erratic current readings.

Current measurements are made at the end of each time interval. A plot of current versus voltage is recorded on graph paper. If log-log coordinate graph paper is used, the curve should be nearly linear. Voltage steps are made in succession until the final voltage level is reached or the recorded current deviates from linear and impending breakdown is suspected.

Dielectric absorption may dominate the current measurements and mask significant variations in conduction current. To minimize this effect, the test voltage may be held at each level long enough to allow the absorption current to decay to a negligible value. For older asphalt-mica and shellac mica-folium windings, it is suggested that the time interval be extended to 3 min due to the slower decay of the absorption current for these insulating materials.

7.6.2 Graded-time voltage step test

It is usually not practical to hold each voltage step long enough to make the absorption current negligible. To avoid introducing error from incomplete absorption current decay and to shorten the time required to obtain current versus voltage curves, complex volt-time schedules were developed. The basic idea of these test schedules is to adjust the voltage, in steps, according to a diminishing time schedule so the absorption component of the measured current is linearized, i.e., proportional to the applied voltage. By following a predetermined test schedule, relative changes in conduction current become more readily discernible. Although the graded-time step test is more difficult to perform than the uniform-time step test, it does reduce the total test time and results in better assessment of the conduction current.

The graded-time step test procedure, described in detail in A.2, may be summarized as follows. The initial voltage step, 30 percent or less of the maximum test voltage, is applied and held constant for 10 min. Current measurements are recorded at 0.5, 0.75, 1.0, 1.5, and 2.0 min, and each minute thereafter up to 10 min. The measured values are immediately plotted on a log-log scale. A smooth curve is fitted to the measurements following the 8-min reading. This curve is extrapolated to 10 min. Three points are read from the smooth curve to be used in determining the conduction component of the measured current. The conduction current is subtracted from the 1- and 10-min current readings to obtain the absorption current (geometric capacitive current is assumed to have decayed to zero). The measured and calculated currents are then used to determine the absorption ratio. Once the absorption ratio is determined, the time schedule to be used for the remainder of the test may be selected. The test is continued through the successive voltage steps up to the desired maximum voltage level or until the recorded current deviates from linear and impending breakdown is suspected.

The time duration at each voltage step is variable and is determined by the characteristics of the insulation. Using the information in Table A.1, graded-time step test schedules appropriate to the particular insulation system should be selected.

Even with the improved volt-time schedules, controlling test time intervals and voltage increments, as well as visually reading from a meter and averaging a fluctuating insulation current, may result in poor test data accuracy. Subtle deviations in the current versus voltage response may be impossible to detect. Moreover, the human factor makes it difficult to exactly reproduce previous test conditions and current measurements. Uncertainty decreases confidence in the data, or worse, may even lead to improper assessment of insulation condition.

7.6.3 Ramped voltage test

The principal advantages of the ramped voltage test over the conventional stepped voltage methods are that it gives better control and improved warning of impending failure to avoid damage to the insulation. Elimination of the human variable from the time, voltage, and current parameters yields overall test results which are much more accurate and repeatable. In addition, the slow and continuous increase in applied voltage (typically 1 kV per minute) is less apt to result in unpredictable damage to insulation than the voltage increments of the step method (approximately 1 kV per second).

The ramped voltage test method can be considered a step test in which the voltage steps and time intervals are made very small. As the size of the voltage and time increments approaches zero, a voltage ramp is formed. A programmable high direct-voltage test set is used to automatically ramp the high voltage at a preselected rate. Insulation current versus applied voltage is recorded with an *X-Y* plotter, providing continuous observation and analysis of the current response as the test progresses. The application of a ramped voltage, instead of discrete voltage steps, automatically linearizes the geometric capacitive and absorption components of the current so that small, meaningful variations in the measured current are more easily observed.

Any variation in the rate of rise of the applied voltage will create a nonlinear change in current and thereby reduce the accuracy of the test results, thus a stable and well-regulated high voltage supply is essential.

7.7 Discharging and grounding

Upon completion of a controlled overvoltage test, the test supply output voltage control should be reduced to zero, and the winding should be discharged and grounded as described in 6.4.

7.8 Test results

Breakdown voltage cannot always be projected from the curve; hence, unpredictable insulation failure may occur during the test. This is especially true for insulation defects in the slot portion of the windings or in cases of clean, dry cuts in the endwinding insulation. See 6.6 for more information on insulation failures. See Clause 8 for fault locating methods.

7.8.1 Interpretation of stepped voltage test results

A number of measured current versus applied high direct-voltage test results are given in Figure 2 through Figure 14. Note that numerical values of voltage and current are not shown as they differ from machine to machine. The examples have been provided to illustrate typical current versus voltage characteristics.

When the controlled overvoltage test has been successful, the following interpretations may be applied:

a) For a winding in good condition, the measured current versus applied voltage response will usually be a smooth curve with rising characteristics. Conduction current should be negligible up to the maximum value of applied test voltage. The apparent increase in current with respect to voltage is dependent upon the scales used for plotting. When comparisons will be made with previous tests, identical scales should be used. When there is no abrupt deviation from the smooth curve, breakdown is probably not imminent and the test may be continued until the recommended maximum voltage is reached.
b) Any deviation from a smooth curve should be viewed as a warning of possible approach to the breakdown voltage of the insulation. See Figure 2 and Figure 3. Deviations should be confirmed by further measurements at one or more voltage increments. It should be remembered that warnings are sometimes obtained within as little as 5 percent below the breakdown voltage. When the deviation is confirmed, the test should be stopped if possible breakdown is to be avoided.
c) The most usual indication of approach to breakdown is an accelerating rate of increase of current with respect to voltage. This type of behavior is associated with windings at ambient temperature in air of normal to high humidity. To obtain an indication of the breakdown voltage, the plotted current curve may be extrapolated to the vertical, with somewhat accelerating curvature for the sake of conservatism (see Figure 2). If the predicted breakdown voltage is below the recommended maximum test voltage, the trend should be verified by one more voltage step. If the extrapolation still shows a low breakdown voltage, the test should be stopped to avoid possible breakdown.
d) Current should be monitored for any tendency to rise with time during constant voltage application because this could indicate imminent breakdown.
e) A very abrupt drop in conduction current is rarely found; but when it occurs above the peak operating voltage for the winding, it may indicate approaching insulation failure (see Figure 3). No method is known for estimating the breakdown voltage in this case; it can only be assumed that failure is imminent. One more voltage step should be made. On confirmation of the occurrence of this phenomenon, the test should be stopped if possible breakdown is to be avoided.
f) Abrupt, unexpected insulation breakdown may occur before the current curve approaches the vertical. In some cases this occurs where there is mechanical abrasion, cracking, or acute mica migration. Hence, if breakdown is to be avoided, the test should be terminated conservatively when preliminary inspection shows that such conditions possibly exist.
g) If possible breakdown is indicated, it should be confirmed that the measurements are not being affected by corona from test connections, insulation of test leads, etc. Such problems can be avoided by proper placement, insulation and preliminary testing of the leads (see 5.3).

h) Tests are usually made individually on each phase of the winding. Differences in current characteristics between the phases not attributed to corona, temperature, or humidity are usually attributed to the condition of the insulation (see Figure 4).

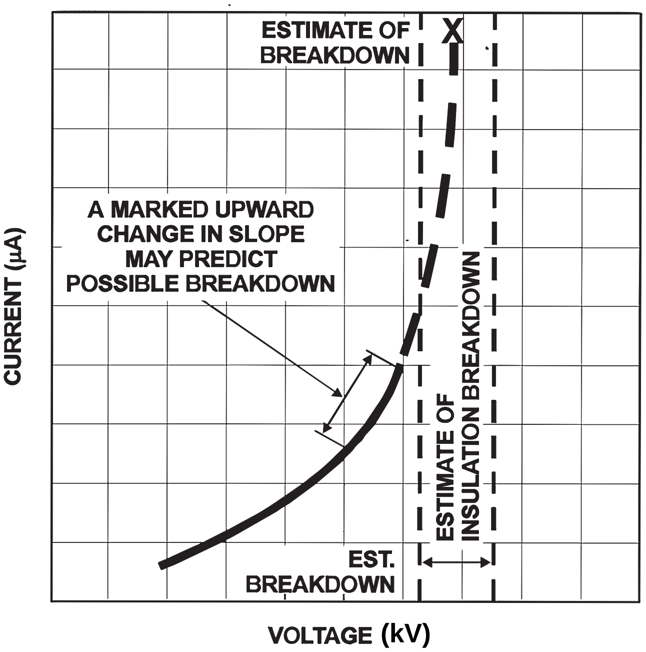

Figure 2—Winding first appears in good condition, then shows warning of breakdown

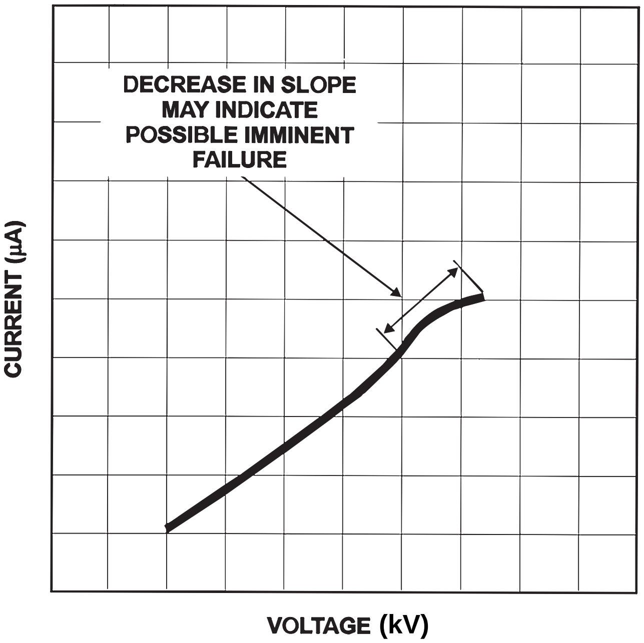

Figure 3—Decrease in slope of measured current may indicate imminent insulation failure

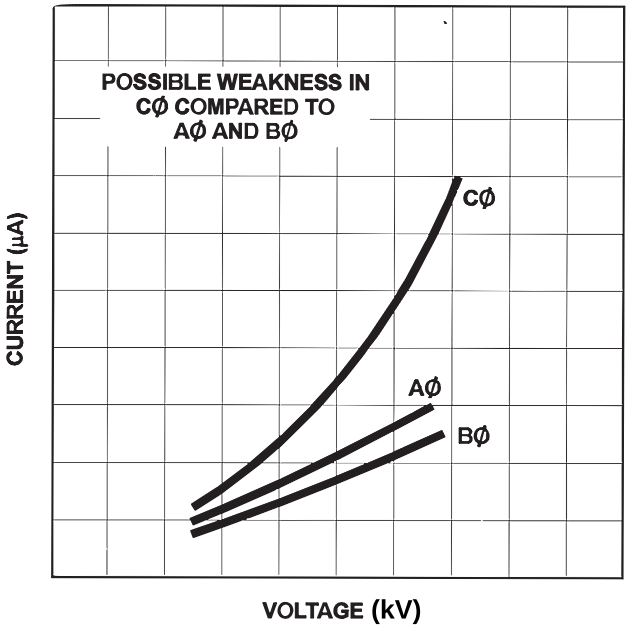

Figure 4—Plot of controlled overvoltage test on three phases tested separately

7.8.2 Interpretation of ramped voltage test results

A series of examples has been provided to demonstrate how the results of ramped voltage tests may be interpreted. The curve shown in Figure 5 is a typical response of new epoxy-mica insulation when tested with a ramped voltage. The curve represents the sum of the geometric capacitive, absorption, and conduction currents. The geometric capacitive current is constant and proportional to the winding capacitance *C* times the ramping rate (*dV*/*dt*) of the applied voltage. The geometric capacitive current produces a positive offset in the *I*-*V* (current versus voltage) curve. The absorption current component is linear and gradually increases with voltage. In a ramp test, the geometric capacitive current and the absorption current constitute the majority of the total measured current for a winding in good condition, whereas the surface conduction and volume conduction current components are very low, or possibly negligible, up to the maximum test voltage. In general, the smooth, almost linear curve indicates the stator winding groundwall insulation is in good condition.

The current response shown in Figure 6 is typical of new asphalt-mica insulation. As noted in the discussion of Figure 5, the geometric capacitive current is constant and proportional to $C \times dV/dt$. The absorption current component of the asphalt-mica insulation, while linear, accounts for a greater percentage of the total measured current. This result is typical and is indicated by the steeper slope of the *I*-*V* curve. As expected for new insulation, the conduction current is negligible up to the maximum test voltage. This characteristic curve represents sound, high-quality asphalt-mica stator winding insulation.

Figure 7 displays a very nonlinear current versus voltage response curve for an asphalt-mica winding. The sudden increase in conduction current at a relatively low test voltage suggests the groundwall insulation of a single coil/bar may be cracked or otherwise damaged. The test was terminated early to avoid the possibility of permanently faulting the insulation.

Figure 8 represents a typical ramped voltage test response of aged asphalt-mica insulation. Compared to the curve of new asphalt-mica, shown in Figure 6, the aged insulation exhibits a gradual increase in conduction current, an indication that general deterioration of the insulation has taken place. The nonlinear conduction current versus test voltage response is due to many minute discontinuities, similar to the one shown in Figure

7. As the applied voltage is increased, the slope of the conduction current will continue to rise in a nonlinear manner. Insulation breakdown will occur as the current asymptotically approaches the vertical. Testing should be halted well before this point is reached.

Figure 9 shows the ramped voltage test results from an asphalt-mica winding that absorbed moisture while out of service for an extended period of time. Heaters were not used during the outage. The conduction current response increases exponentially with respect to the applied voltage. To avoid insulation failure, the test was stopped prior to reaching the recommended maximum test voltage.

The curve in Figure 10 is an example of a ramped voltage test for a stator winding with insufficiently cured repairs (e.g., epoxy resin patch) to the epoxy-mica groundwall insulation. After allowing the repairs to fully cure, the test was repeated and the *I-V* curve was found to be linear to the maximum test voltage.

The test response in Figure 11 exemplifies an epoxy-mica insulation with severely contaminated endwindings. The nonlinear current response indicates excessive surface conduction current.

Figure 12 illustrates the ramped voltage test results for epoxy-mica insulation with a crack in the groundwall insulation. The *I-V* curve appears linear almost until the point where insulation breakdown was reached. A few minor spikes in the measured current were observed before the stator winding insulation failed to ground.

The *I-V* response in Figure 13 displays a nonlinear characteristic that is different from the usual conduction current effects. The test curve appears normal as the applied voltage is initially increased from zero to a few kilovolts. However, as the voltage approaches a certain value, the slope of the curve sharply increases. The test voltage continues to ramp up and then the slope of the curve eventually levels off again. The ending slope of the *I-V* curve is essentially the same as the initial slope. This nonlinear response to the applied test voltage has been associated with delaminated polyester-mica insulation.

The *I-V* response in Figure 14 at the higher test voltages shows the effect of audible discharges on the endwindings of a polyester-mica winding under conditions of low relative humidity (18 percent). This example also illustrates the use of the alternate test procedure in which the ramp is initiated immediately following the measurement of polarization index without discharging the specimen.

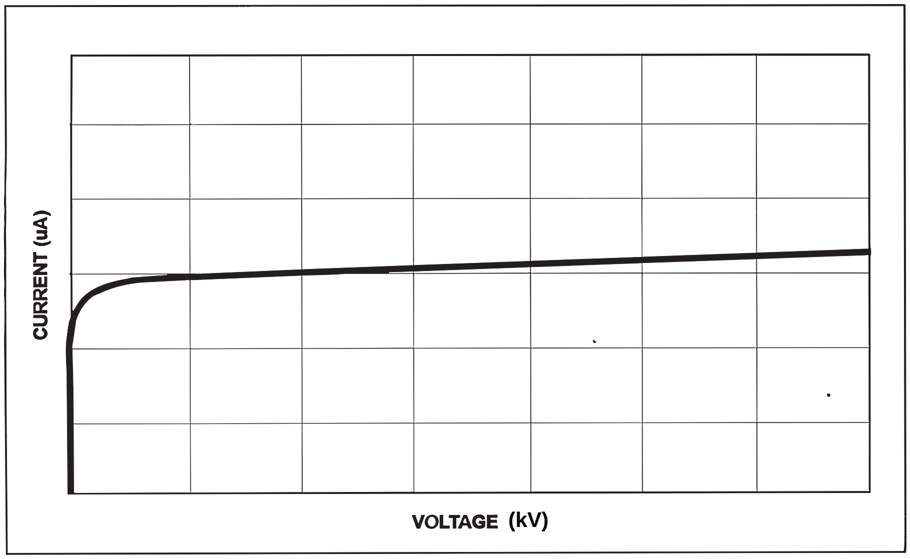

Figure 5—Typical ramped voltage test result for epoxy-mica winding insulation (where the absorption current component is relatively small)

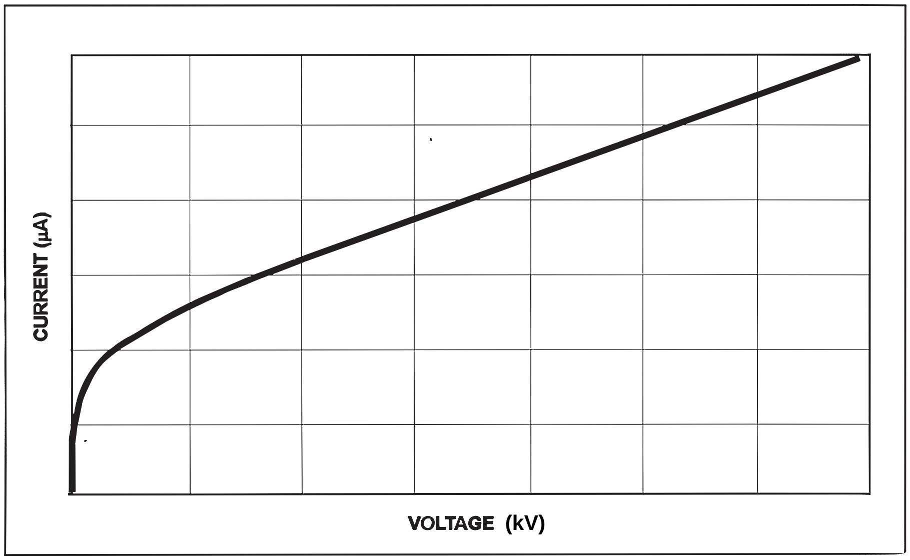

Figure 6—Typical ramped voltage test result for asphalt-mica winding insulation (where the absorption current component is relatively large)

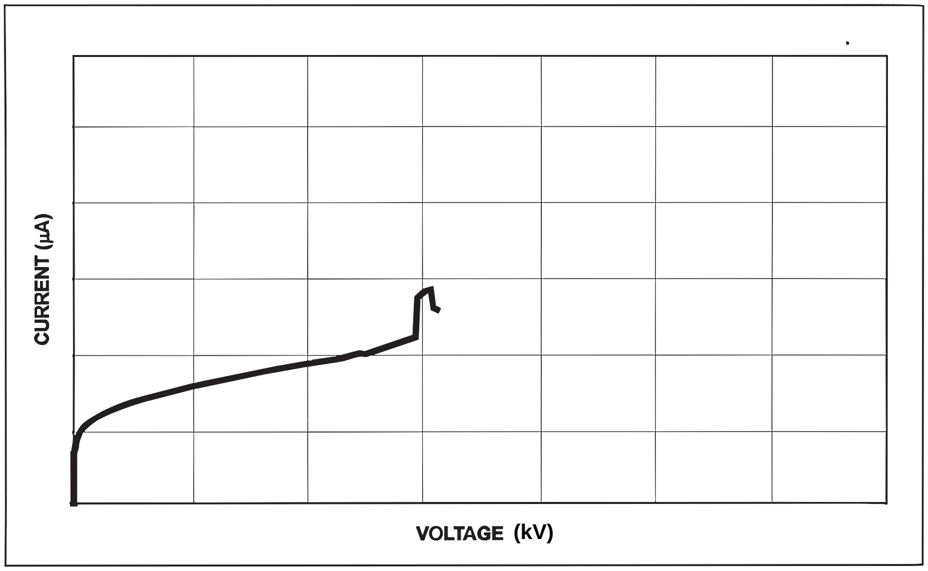

Figure 7—Example of ramped voltage test result for asphalt-mica insulation with a localized weak spot

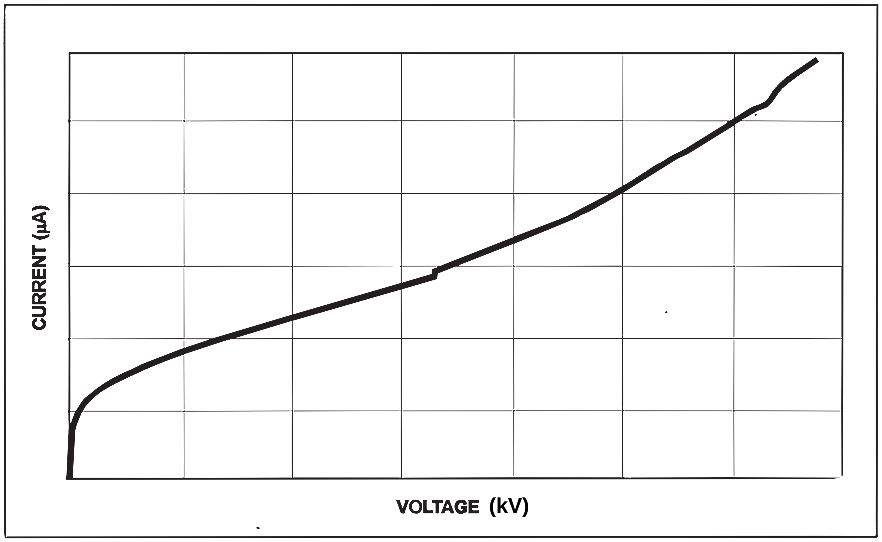

Figure 8—Example of ramped voltage test result for aged asphalt-mica insulation

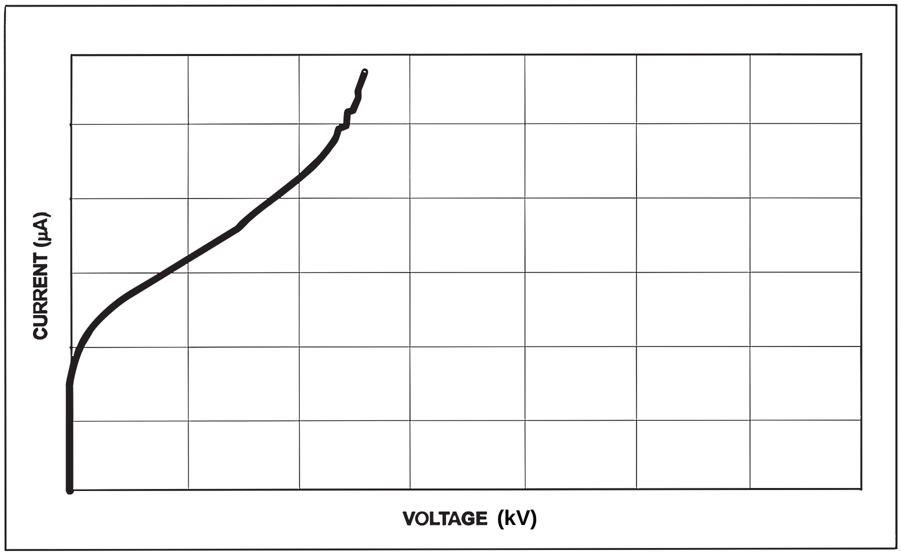

Figure 9—Example of ramped voltage test result for wet asphalt-mica insulation

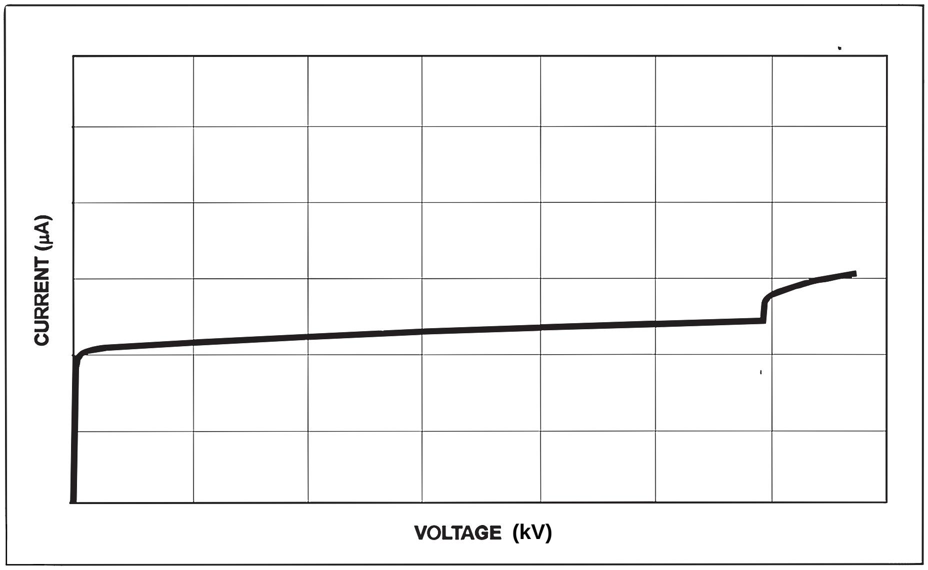

Figure 10—Example of ramped voltage test result for an epoxy-mica winding with an incompletely cured repair (i.e., epoxy patch)

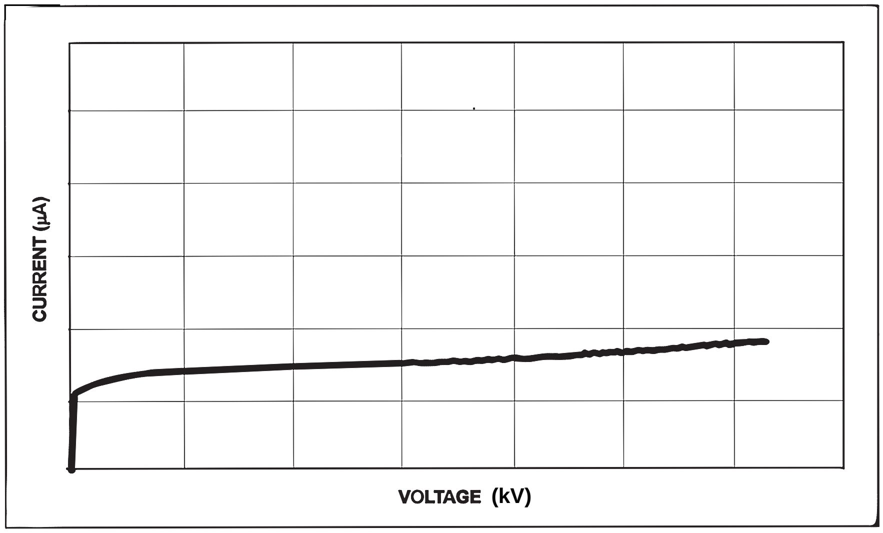

Figure 11—Example of ramped voltage test result for epoxy-mica winding with contaminated endwindings

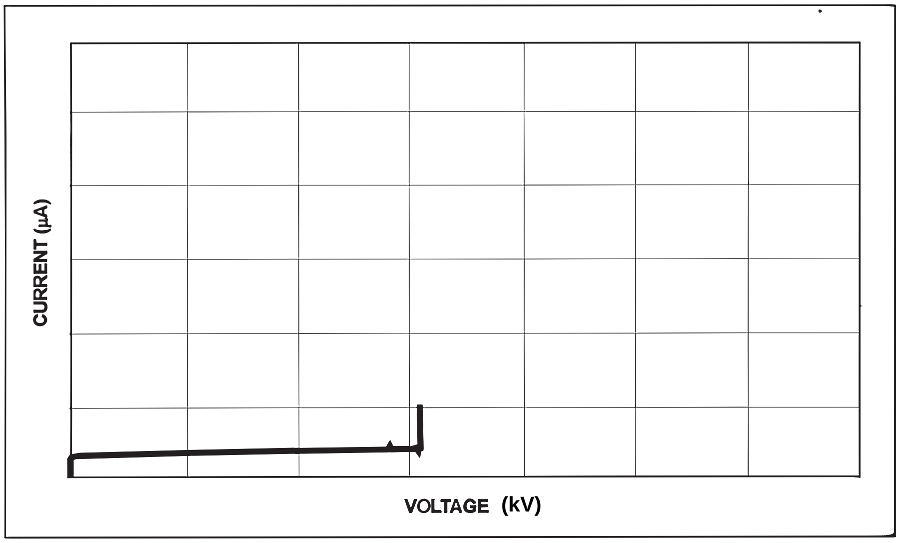

Figure 12—Example of ramped voltage test result for epoxy-mica winding with cracked insulation

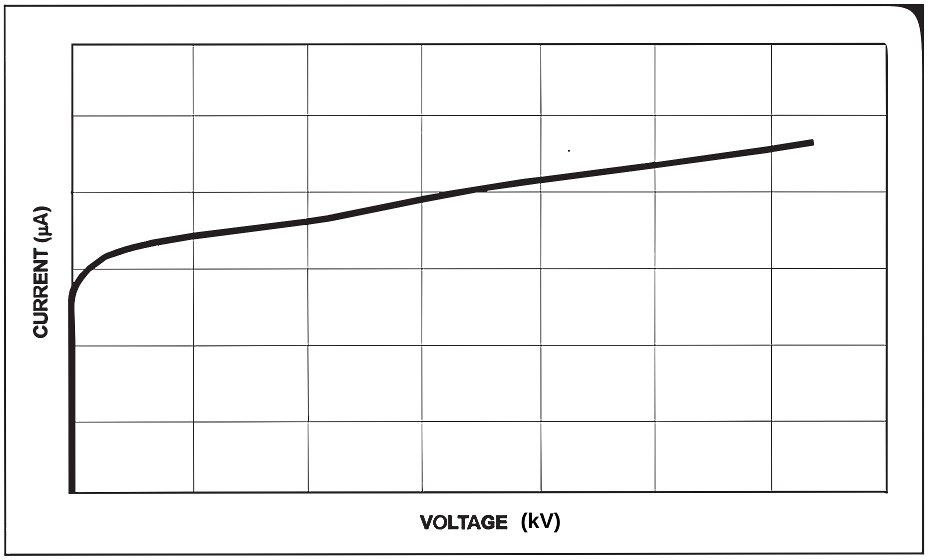

Figure 13—Example of ramped voltage test result for polyester-mica winding with delaminated insulation

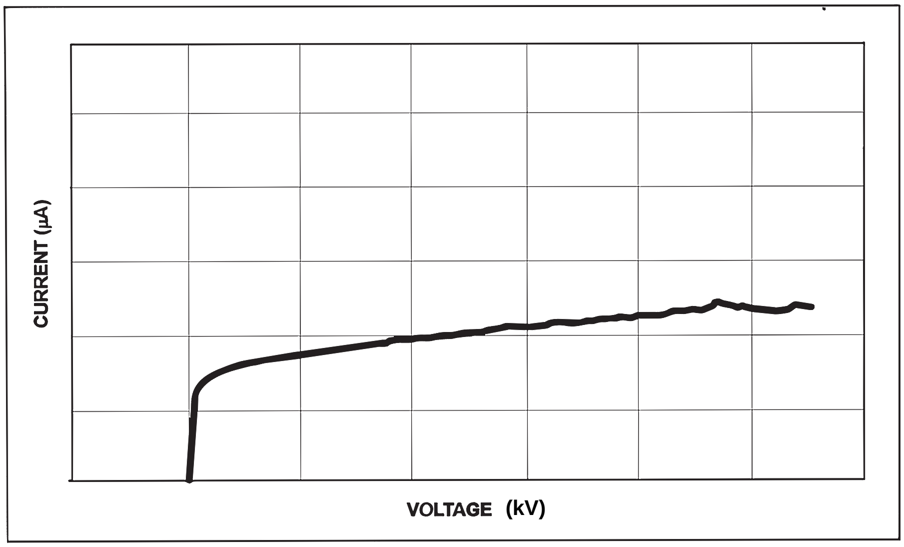

Figure 14—Example of surface discharge on endwinding of polyester-mica winding in low relative humidity (alternate test procedure with ramp initiated immediately following measurement of polarization index without discharging the specimen)

7.9 Use of controlled overvoltage tests

Controlled overvoltage tests are often used to obtain benchmark *I-V* curves, providing the characteristic response of the insulation system while it is new and in good condition (oftentimes, problems with a new installation are revealed by high direct-voltage tests before potentially damaging alternating-voltage proof tests are performed). Once the benchmark response has been established, future changes in conduction characteristics may be used to detect and diagnose deterioration of the stator winding. In some cases, the best benchmark test will be the one that is made after a period of time in service as it is not unusual for resins associated with the insulation of the connections to be less than fully cured prior to service. The *I-V* curves of individual phases may be compared to one another as well as to previous test curves, giving evidence as to the severity and rate of deterioration.

While no single diagnostic test can successfully detect all types of stator winding insulation deterioration, routine high direct-voltage testing has proven to be an effective means for reducing in-service failures. When done properly, maintenance tests can identify stator windings that are approaching failure, without accelerating the deterioration process.

8. Fault location

When insulation failure occurs during a test, the test voltage should be reduced immediately to prevent unexpected and undesired voltage buildup across the winding insulation and a repeat of the flashover.

It may be advantageous to have several observers stationed near the machine to assist in rapidly identifying the location of the fault. However, do not assume that a faulted winding has been de-energized. Be sure it is properly discharged and grounded according to 6.4 of this recommended practice before handling by personnel or before voltage is reapplied.

The number of repeat tests should be limited to avoid possible damage to the remainder of the winding from surges that may occur when the winding discharges as a result of the fault.

When the fault must be located to determine the cause of failure or to make a repair, it may be necessary to employ methods that can make it visible, such as the following:

a) Apply alternating voltage using an ac test set. Slowly increase the voltage until the faulted area flashes to ground. Locate the arc by the sound, smoke, or flash of light. Record the flashover voltage. This method usually works unless the fault exhibits a very low resistance to ground.
b) If the failure has resulted in a low resistance path between the winding conductor and ground, it may be possible to use a clip-on ammeter at the coil-to-coil series connections to trace the fault to a particular slot. Alternatively, induction coils are sometimes useful for tracing the fault to a particular slot.
c) If the failure is arcing or sparking, a directional ultrasonic sensor can be used to help to locate the failure. Once in the vicinity of the failure, the arcing may be visible.
d) For low resistance grounds, apply voltage from a low voltage power source capable of supplying up to 10 amperes. Watch for smoke and possibly fire.
e) If no smoke or fire is visible during the above step, open the wye or delta connections and identify the failed phase using an insulation resistance tester or ohmmeter. Measure the resistance from both the line and neutral ends of the failed phase to ground with a low resistance bridge. The ratio of the two measurements will indicate how far into the phase the failure is located. Trace the phase and determine which coil is in the right position. This method is not very accurate.
f) Probing with a length of grounded metal wire or foil fastened to an insulating rod, such as a ground stick, can be helpful in locating the point of failure external to the slot. The probe can be at ground potential with winding energized or vice versa. If the faulted winding will not support voltage, then the probe should be energized and the winding grounded. The use of a Tesla coil (high voltage spark coil) to locate small, hard to see failures in the end windings can be helpful.
g) An infrared detector may be useful for pinpointing heating at the site of the failure.

If the failure cannot be readily located, the winding must be successively divided and tested until the faulted portion of the winding or specific coil is located. When the failed coil has been identified, it must be electrically isolated so that the remaining parts of the winding can be tested to the predetermined maximum voltage. If the winding is to be returned to service, the faulted coil must either be repaired, replaced, or permanently bypassed. In the latter case it may be necessary to bypass additional coils so as to satisfy the requirements of the protective relaying or to minimize vibration. Note that one end arm of the faulted and bypassed coil is normally cut to prevent a possible turn-to-turn fault. See [B20], [B24].

9. Suggested test record

A suggested test record includes:

a) Operating designation (station/location)
b) Serial number of equipment
c) Equipment rating, type of insulation
d) Manufacturer’s name
e) Date of test
f) Time of test
g) Test voltage and duration
h) Leakage current at end of test
i) Test connection and connected apparatus (if any)
j) Temperature of winding
k) Time at this temperature
l) Temperature and humidity of environment

m) Gas type and pressure
n) Time out of service
o) Test equipment description

Comments regarding the following are also of value:

a) Reason for test
b) Visual inspection
c) Physical condition of winding and insulation
d) Insulation resistance and polarization index prior to test
e) Pertinent history of equipment
f) Date winding was installed
g) Observations of distress, corona, etc., during test
h) Result of test and action taken
i) Recommendations for maintenance, operation, or future test activity

Annex A

(informative)

Test procedures

A.1 General discussion of test procedures

Test procedures and experience leading to the use of high direct voltage are discussed in the following paragraphs. A comparison of high direct-voltage versus alternating-voltage test methods is given.

A.1.1 Proof tests

For many years the use of power frequency (50 Hz or 60 Hz) overvoltage proof tests has been the conventional method of acceptance testing for new windings and of routine maintenance testing for windings already in service. Proof tests are intended to search for flaws in the material and for manufacturing defects, and to demonstrate in a practical manner that the insulation tested has a certain agreed upon electrical strength. A primary requirement of such a test is that it should be discerning and effective in detecting flaws at or below a minimum specified strength without damaging sound insulation.

Proof test voltages are intended to be sufficiently high to break down insulation that has an insufficient factor of safety with respect to the operating voltages, transient overvoltages, and further deterioration to be expected in service. It should be recognized that both power frequency voltage and direct-voltage proof tests are empirical in nature and do not necessarily check the adequacy of the design or the inherent breakdown voltage level of the insulation system.

A.1.2 Routine maintenance tests

Planned maintenance tests are used to assess stator winding insulation condition, identify maintenance needs, and prevent in-service failures. Information obtained from these tests can be used to take advantage of and perhaps even extend the full reliable life of the stator winding. Benefits of planned maintenance testing include:

a) Successive tests provide a means of evaluating the extent and rate of insulation deterioration. This is particularly important when judging the risk of delaying actions, such as extending the time between outages.
b) Maintenance activities can be justified, prioritized, and scheduled according to their relative urgency. For example, test results may indicate that one particular machine should be rewound before others.
c) When test results reveal low measured electric strength, machine operating conditions can be restricted or surge protection can be installed to protect against insulation damage or further deterioration.
d) It may be practical to make localized repairs or to cut out or replace weak coils when test results indicate local rather than general insulation weakness.

A.1.3 Relationship between direct and alternating overvoltage tests

Voltage levels for power frequency (50 Hz or 60 Hz) proof tests specified in IEC, ANSI, IEEE, and NEMA standards are based on many years of experience. It is because of these established alternating-voltage standards that a relation between the power frequency voltage and direct-voltage methods is sought. The relationship between the withstand voltage level using high direct voltage and the equivalent withstand voltage using power frequency voltage cannot be precisely stated because the relationship is dependent on many factors (e.g., insulation type, age, and condition).

The lack of a precise equivalence should not cause concern because the purpose of overvoltage tests is to demonstrate that the insulation can withstand the usual conditions to be expected in service rather than to establish the precise value of electrical strength. In studies, the electrical strength has been found to correlate with impulse strength. Therefore, a direct-voltage proof test may indicate ability of the insulation to withstand surges and short-time overvoltages approximating the same peak value. The test overvoltage value also provides for insulation deterioration during a further period of operation.

The proper high direct-voltage proof test for insulation need not necessarily be related to the corresponding power frequency voltage proof test by the ratio of the electrical strength of sound insulation under power frequency voltage stress to that under direct-voltage stress. However, some investigators assert that until a known equivalence can be established, the direct-voltage test cannot be considered comparable in searching ability to the established power frequency voltage tests.

Direct voltage acts to search out a faulty area in the insulation by establishing a conduction current from that area. Although small currents may aggravate damage and lead to breakdown if the voltage is raised to a high enough level, this usually does not occur unless the weakness is significant and should be found. High temperature of the insulation usually increases the conductance of any solid insulation remaining in the fault path; direct current conduction in fissures, however, may be reduced rather than increased by an increase in temperature.

A.1.3.1 Ratio of direct test voltage to power frequency test voltage

The ratio of direct breakdown voltage to power frequency (rms) (50 Hz or 60 Hz) breakdown voltage has been reported to vary from 1 to 3 (see [B22], [B26], [B28], [B39], [B44]) while in [B11] it is reported that in some cases the ratio can exceed 3. This was determined from tests comparing predicted direct-voltage strengths with actual power frequency voltage (rms) strengths of machine insulation containing incipient faults, and from tests comparing direct-voltage and power frequency voltage (rms) strengths of large numbers of intact samples of new and used insulation. Further research is required to correlate the physical characteristics of breakdown locations with the associated range of ratios. In general, it appears that:

a) The higher ratios occur in well-compacted insulation. This reflects the thermal instability caused by partial discharges and dielectric losses leading to lower breakdown voltages in the case of alternating voltage.
b) Ratios in the region of 1.41 correspond, as would be expected, to conditions emulating an open air gap in a uniform field (where direct voltage equals the peak value of the alternating voltage).
c) Ratios less than 1.41 correspond to internal or surface creepage paths, open or closed in fissures, along which maintained direct-voltage stress may have some peculiar property of establishing a considerable (but not necessarily destructive) conduction current.

The well-compacted slot portions of armature coils appear to have an average electrical strength ratio of direct voltage to power frequency voltage (rms) between 2 and 3. However, in a machine winding the series coil or bar connections and leads external to the slots cannot approach the same conditions of mechanical compaction and electrical strength in their ground insulation. For testing complete armature windings of rotating machines, therefore, the ratio between direct voltage and power frequency voltage (rms) defined in this recommended practice is 1.7 for both acceptance and maintenance tests.

A.1.3.2 Voltage gradients: alternating versus direct

When applying a test voltage to any insulating structure, the matter of voltage gradients becomes a factor to be considered. Does a direct-voltage test stress the insulation in the same manner as an alternating voltage test, and is the stress as severe [B41]?

In a direct-voltage test, the stress distribution is a function of the winding insulation resistivity and surface conditions. For alternating voltage tests, the stress distribution is essentially capacitive. In the slot portion of the winding, the voltage gradient is similar for both the alternating and direct voltage tests. However, in the endwindings the stress distribution is quite different depending on the nature of the test voltage. In the case of an alternating voltage test, the potential on the surface of the endwinding reaches the full applied test voltage at a point very near to the stator iron. Thus, the endwinding insulation is subjected to minimal voltage across its thickness. In the direct voltage case, the maximum voltage on the endwinding surface is reached at the maximum distance from the stator iron. Thus, the endwinding insulation is stressed at a higher level, particularly near the stator core. Some consider that this type of stress on the endwindings may result in unnecessary failures during direct voltage tests.

A.1.3.3 Acceptance testing using high direct voltage

There has been a great quantity of test experience over a period of several decades which has been obtained by manufacturers, some of whom have made extensive use of high direct voltage during and immediately following manufacture of electric equipment. In most cases this has been in proof testing. All of the reported experience indicates very satisfactory results.

A.1.3.4 Comparison of direct-voltage and alternating-voltage test results

Direct-voltage testing is normally done by connecting a direct-voltage source between the test specimen conductors and ground and using a direct-current ammeter to measure the total current to ground. The ratio of the test voltage to the test current once the latter has reached a constant value will reflect the total resistance between the test specimen and ground. Resistance (R) is dependent upon the resistivity of the material (ρ), the length of the path (L), and the cross-sectional area (A) as evidenced in the following formula:

$$R = \rho L / A$$

Because the resistivities of the dirt, oil, and water that often contaminate the endwinding areas of electric machinery are usually quite low, direct-voltage testing of a contaminated winding normally results in a high surface conduction current and, therefore, a low resistance reading. This property makes direct-voltage testing a viable method for determining the extent of surface contamination on an insulation system.

In addition, if the insulation system utilizes a cotton-backed tape with mica as the primary electrical insulator, 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.

It has been reported [B4] that the relative magnitude of the absorption coefficient reflects aging of shellac bonded mica insulation systems. Such a relationship in the case of asphalt-mica has not been obvious [B22].

The usual primary electrical insulating material (e.g., mica) used in the insulation design of form-wound stator windings has very high resistivity. Therefore, if a void exists within the insulation due to improper impregnation, thermal deterioration, or thermal cycling, a direct-voltage test, other than possibly a ramp test, would be unable to detect it. If, however, there exists a severe crack through the entire insulation, then it is possible that an electrical track would be established between the copper conductor and ground and appear as a low resistance.

However, when a high alternating-voltage is connected between the terminals of the test specimen and ground, the capacitance of the test specimen can cause capacitive current to be greater than the resistive current. In such cases, the capacitive current tends to mask changes in the resistive current. Capacitance (C, in picofarads) is dependent upon the relative dielectric constant of the insulating material (ε_r), the surface area of the electrodes (A), and the thickness of the insulating material (d) as determined from the following formula for a parallel plate capacitor where the physical dimensions are in centimeters:

$$C = \frac{\varepsilon_r A}{3.6\pi d}$$

Because the relative dielectric constant of an insulation system is greatly affected by the presence of voids and/or moisture, an alternating-voltage test is generally more sensitive than conventional direct voltage tests with regard to detection of most internal insulation problems associated with all types of insulation systems. It has been reported (see [B32], [B33]) that careful interpretation of the results of ramped direct-voltage tests can also detect internal voids or delamination of the insulation.

A.2 Detailed procedure for the graded-time step test

It is desired to obtain only the true conduction current during a controlled overvoltage test. However, procedures require a compromise between allowing too brief a time at each voltage and maintaining each voltage for a very long time so that absorption is practically complete and only conduction current remains. If complete absorption were approached, it would consume many hours of test time. The graded-time method, in a reasonable time, will provide a curve related to the true conduction current. For those who desire to add this refinement to the test, the following program is presented. Note that all preliminary tests, test connections, safety precautions, and interpretations of test results are the same as for the controlled overvoltage test using the simpler uniform-time step method.

The initial voltage step is 30 percent or less of the maximum. For 13.8 kV machines, the initial step should not exceed 10 kV dc phase-to-ground. This voltage is maintained constant for 10 min during which time the measured current is observed. The time should be logged from the initial voltage application to the winding.

Adjustments to the voltage setting on each step should be made within the first 10 s. It is generally necessary to set the initial voltage approximately 5 to 10 percent below the desired value to allow for voltage increase during the decay of the absorption current and to end each step at the desired test voltage.

The measured current should be recorded at 0.5, 0.75, 1.0, 1.5, and 2.0 min and each minute thereafter up to 10 min during the initial voltage step. These values are plotted as read during the test on log-log coordinate graph paper (see Figure A.1).

A smooth curve is drawn through the most points following the 8-min reading. This curve is extrapolated to 10 min. Figure A.2 shows a full-scale template for a “ship’s curve” which may be used in drawing smooth curves of the proper shape.

Three points are read from the smooth curve to be used in the calculation of the conduction component of the measured current. These values are the total currents at 1.0, 3.16, and 10 min. They are substituted in the following formula for the total conduction current:

$$i_{tc} = \frac{(i_1 \times i_{10}) - (i_{3.16})^2}{(i_1 + i_{10}) - 2i_{3.16}}$$

Subtract i_{tc} from the 1- and 10-min total current readings to obtain the current due to absorption (geometric capacitive current is assumed to be negligible). These values will then be used to calculate the absorption ratio N as follows:

$$N = \frac{i_{A_1}}{i_{A_{10}}} = \frac{\text{(absorption current at 1 min)}}{\text{(absorption current at 10 min)}}$$

As soon as the preceding calculations are completed and N has been determined, the time schedule to be used for the remainder of the test may be selected from Table A.1.

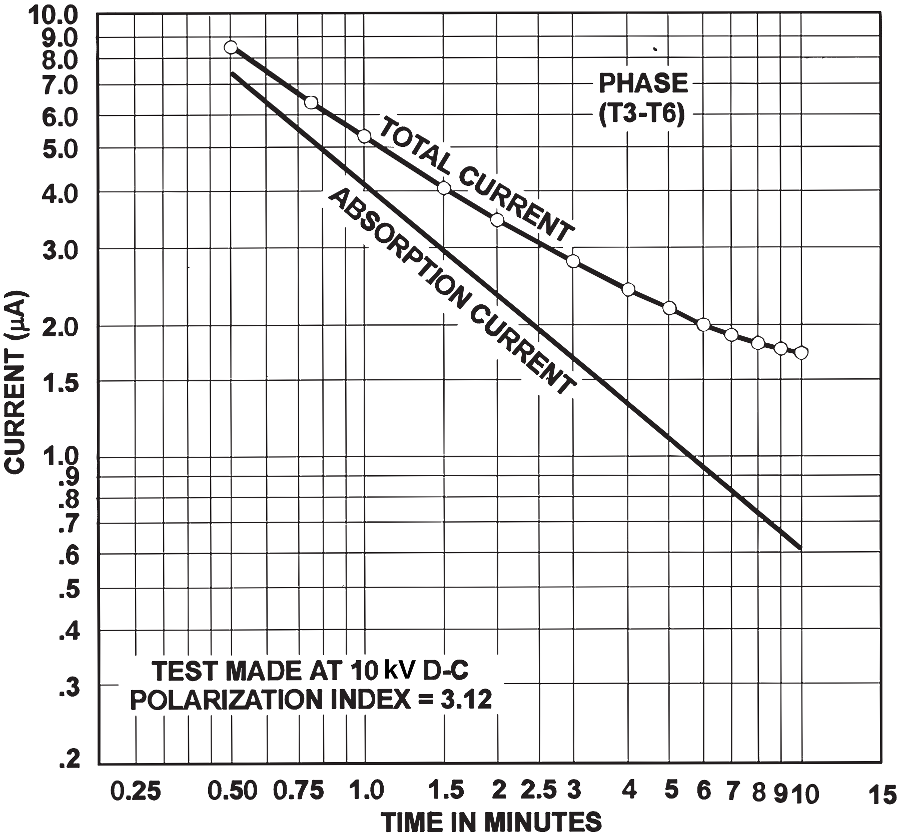

Figure A.1—Test curve for determining absorption current

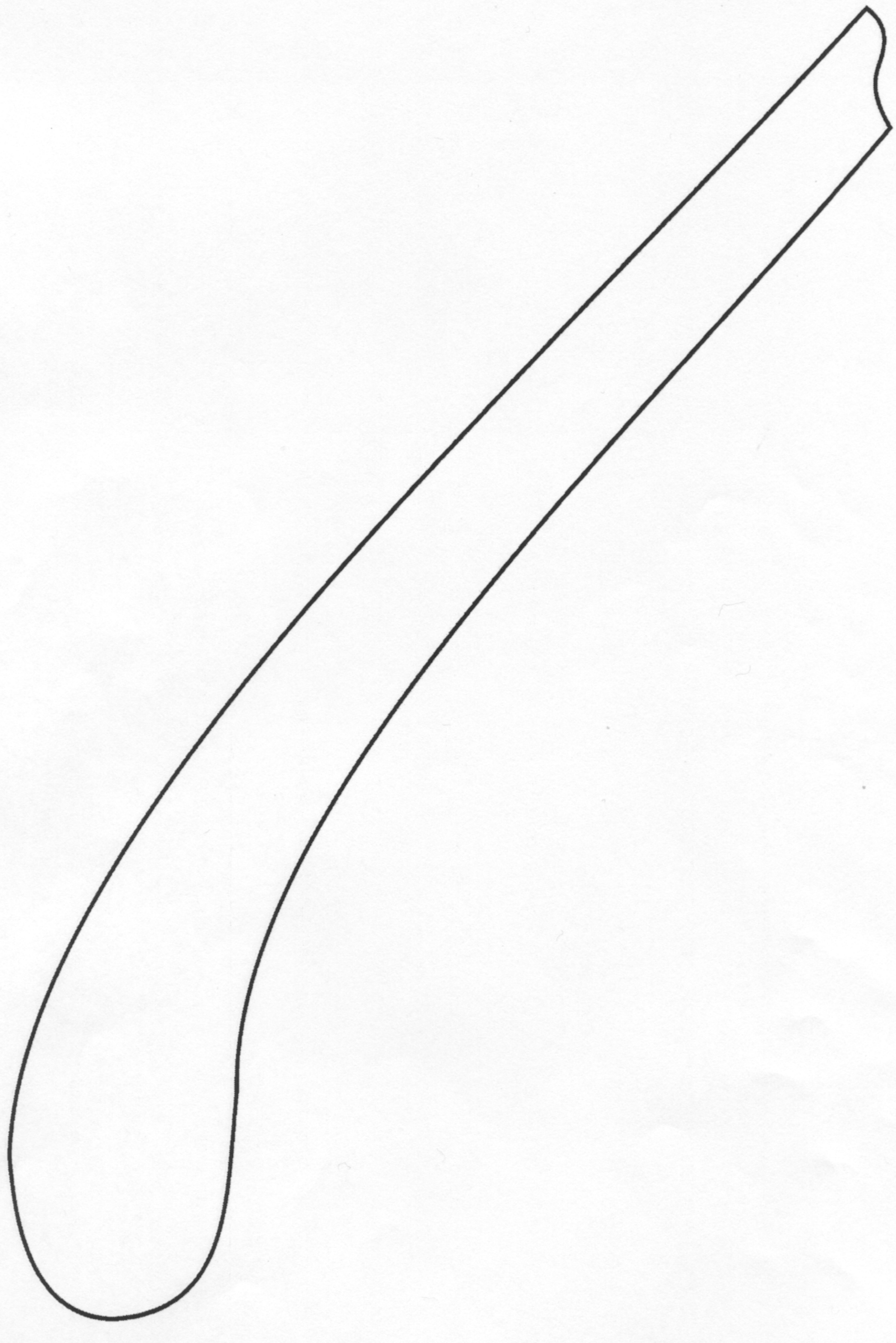

Figure A.2—Ship's curve template for drawing dielectric absorption curves

After the 10-min reading has been taken, immediately increase the voltage to the level of the second step. This may occur at some point during the calculation but should not be neglected; otherwise, the test results will be invalidated. If the elapsed time approaches the period indicated for the end of the second step and the N has not been calculated, choose some arbitrary value for N, such as 5, and follow that time schedule until the calculation is completed. Any necessary correction may be made at the end of the step following the completion of the calculation. Generally, this calculation will take 2 to 3 min once one becomes proficient, and no problems of delay in the determination of the time schedule will arise.

The test should be continued through the successive voltage steps up to the maximum voltage level previously agreed upon. Each voltage change should be made as quickly as possible to conform to the ideal of instantaneous voltage application.

The behavior of the current should be observed continuously to allow for the variations due to line-voltage swings. By interpolating these swings, more accurate results may be obtained. Test results are plotted as shown in Figure A.3.

It is important to graph the data as it is recorded. If the current should increase rapidly the test should be terminated before flashover occurs. Accepted practice dictates that if the slope of the current doubles between two successive data points, termination of the test is warranted.

Using modern portable computers it is possible to construct a spread sheet to record the data, perform the necessary calculations, and graph the results while the test is being performed. Suggestions to this end are as follows: record the current at 0.5, 0.75, 1.0, 1.5, 2.0, 3.16 (3 min, 10 s), 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, and 10.0 min. Plot the data as it is recorded and make sure that the data produces a reasonable curve. If a reasonable curve is obtained the data at 1.0, 3.16, and 10.0 min can be inserted directly into the formulae for absorption current and absorption ratio. Once the absorption ratio has been determined the time values can be read from Table A.1 and the test can continue without delay. Continue recording the current and reviewing the graph so that if the current increases rapidly the test can be terminated.

For further information and an example of this test procedure see [B16].

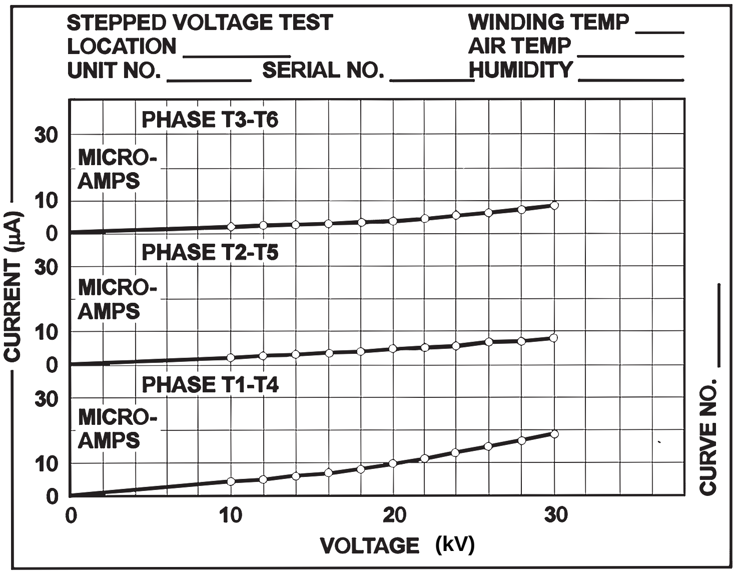

Figure A.3—Example results of a graded-time stepped voltage test

Table A.1—Elapsed time at the conclusion of each voltage step

Voltage percentage of first step	**Absorption ratio *N***															
	2		**3**		**4**		**5**		**6**		**7**		**8**		**9**	
	(min)	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**
100	10		10		10		10		10		10		10		10	
120	13	14	13	27	13	36	13	44	13	49	13	54	13	58	14	2
140	15	56	16	21	16	39	16	53	17	4	17	14	17	22	17	30
160	18	17	18	55	19	21	19	42	19	59	20	13	20	25	20	36
180	20	24	21	12	21	47	22	14	22	37	22	56	23	12	23	26
200	22	19	23	18	24	1	24	34	25	2	25	25	25	46	26	4
220	24	4	25	14	26	4	26	43	27	17	27	45	28	9	28	31
240	25	42	27	1	27	59	28	45	29	23	29	55	30	24	30	49
260	27	12	28	41	29	47	30	38	31	21	31	58	32	30	32	59
280	28	37	30	15	31	28	32	25	33	13	33	54	34	30	35	2
300	29	57	31	44	33	3	34	7	34	59	35	44	36	24	36	59
320	31	12	33	8	34	34	35	43	36	40	37	29	38	12	38	51
340	32	23	34	27	36	0	37	14	38	16	39	9	39	56	40	38
360	33	31	35	43	37	22	38	41	39	48	40	45	41	35	42	20
380	34	35	36	55	38	40	40	5	41	16	42	17	43	11	43	58
400	35	36	38	4	39	55	41	25	42	40	43	45	44	42	45	33
420	36	35	39	10	41	7	42	42	44	2	45	10	46	11	47	5
440	37	31	40	14	42	17	43	56	45	20	46	32	47	36	48	33
460	38	25	41	15	43	23	45	8	46	35	47	51	48	58	49	58
480	39	17	42	14	44	28	46	17	47	48	49	8	50	18	51	21
500	40	8	43	11	45	30	47	23	48	59	50	22	51	35	52	41
520	40	56	44	6	46	30	48	28	50	8	51	34	52	51	53	59
540	41	42	44	58	47	29	49	31	51	14	52	44	54	3	55	15
560	42	28	45	50	48	25	50	31	52	19	53	52	55	14	56	28
580	43	11	46	40	49	20	51	30	53	21	54	58	56	23	57	40

Table A.1—Elapsed time at the conclusion of each voltage step *(continued)*

Voltage percentage of first step	**Absorption ratio *N***															
	2		**3**		**4**		**5**		**6**		**7**		**8**		**9**	
	(min)	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**
600	43	54	47	28	50	13	52	28	54	22	56	2	57	30	58	50
620	44	35	48	15	51	4	53	24	55	22	57	5	58	36	59	58
640	45	15	49	1	51	54	54	18	56	19	58	6	59	40	61	4
660	45	53	49	45	52	44	55	11	57	16	59	5	60	42	62	9
680	46	31	50	28	53	32	56	3	58	11	60	3	61	43	63	13
700	47	8	51	10	54	18	56	53	59	5	61	0	62	43	64	15
720	47	43	51	51	55	4	57	42	59	58	61	56	63	41	65	16
740	48	18	52	32	55	48	58	30	60	49	62	50	64	38	66	15
760	48	52	53	11	56	32	59	18	61	39	63	43	65	34	67	13
780	49	25	53	49	57	14	60	3	62	28	64	35	66	25	68	10
800	49	58	54	26	57	55	60	48	63	17	65	26	67	22	69	6
820	50	29	55	3	58	36	61	33	64	4	66	16	68	14	70	1
840	51	0	55	38	59	16	62	16	64	50	67	6	69	6	70	55
860	51	30	56	13	59	55	62	58	65	35	67	54	69	57	71	48
880	52	0	56	40	60	33	63	40	66	20	68	41	70	47	72	40
900	52	29	57	21	61	10	64	20	67	6	69	27	71	35	73	31
920	52	57	57	54	61	46	65	0	67	46	70	13	72	23	74	22
940	53	25	58	26	62	23	65	39	68	29	70	58	73	10	75	11
960	53	53	58	58	62	58	66	18	69	10	71	41	73	57	75	59
980	54	20	59	29	63	32	66	56	69	50	72	24	74	42	76	46

Table A.1—Elapsed time at the conclusion of each voltage step *(continued)*

Voltage percentage of first step	Absorption ratio *N*															
	10		**11**		**12**		**13**		**14**		**15**		**16**		**20**	
	(min)	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**
100	10		10		10		10		10		10		10		10	
120	14	5	14	8	14	10	14	13	14	15	14	17	14	19	14	25
140	17	36	17	42	17	47	17	52	17	56	18	0	18	4	18	17
160	20	46	20	54	21	2	21	9	21	16	21	22	21	28	21	48
180	23	39	23	51	24	1	24	11	24	20	24	29	24	36	25	3
200	26	20	26	34	26	48	27	0	27	11	27	22	27	32	28	5
220	28	50	29	7	29	23	29	38	29	52	30	4	30	16	30	57
240	31	11	31	31	31	50	32	7	32	23	32	38	32	51	33	39
260	33	24	33	47	34	8	34	28	34	46	35	3	35	19	36	13
280	35	30	35	56	36	20	36	42	37	2	37	21	37	39	38	41
300	37	31	37	59	38	26	38	50	39	12	39	33	39	53	41	1
320	39	25	39	57	40	26	40	52	41	17	41	40	42	2	43	17
340	41	15	41	49	42	21	42	49	43	16	43	41	44	5	45	27
360	43	0	43	37	44	11	44	42	45	11	45	38	46	4	47	32
380	44	42	45	21	45	57	46	31	47	2	47	31	47	58	49	33
400	46	19	47	1	47	40	48	16	48	49	49	20	49	49	51	30
420	47	53	48	38	49	19	49	57	50	32	51	5	51	36	53	24
440	49	24	50	11	50	55	51	35	52	12	52	47	53	20	55	14
460	50	52	51	42	52	28	53	10	53	49	54	26	55	1	57	1
480	52	18	53	10	53	58	54	42	55	23	56	2	56	38	58	45
500	53	41	54	35	55	25	56	11	56	55	57	36	58	14	60	27
520	55	1	55	58	56	50	57	39	58	24	59	6	59	46	62	6
540	56	19	57	18	58	13	59	4	59	51	60	35	61	17	63	42
560	57	35	58	37	59	34	60	26	61	15	62	1	62	45	65	16
580	58	50	59	53	60	52	61	47	62	38	63	26	64	11	66	48

Table A.1—Elapsed time at the conclusion of each voltage step *(continued)*

Voltage percentage of first step	**Absorption ratio *N***															
	10		**11**		**12**		**13**		**14**		**15**		**16**		**20**	
	(min)	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**	**(min)**	**(s)**
600	60	2	61	8	62	9	63	6	63	59	64	48	65	35	68	18
620	61	12	62	21	63	24	64	23	65	17	66	9	66	57	69	46
640	62	21	63	32	64	37	65	38	66	34	67	27	68	17	71	13
660	63	29	64	41	65	49	66	51	67	50	68	44	69	36	72	37
680	64	35	65	50	66	59	68	3	69	3	70	0	70	53	74	0
700	65	39	66	56	68	7	69	14	70	16	71	14	72	9	75	21
720	66	42	68	1	69	15	70	23	71	27	72	26	73	23	76	41
740	67	44	69	5	70	20	71	30	72	36	73	38	74	36	77	59
760	68	44	70	8	71	25	72	37	73	44	74	47	75	47	79	16
780	69	43	71	9	72	28	73	42	74	51	75	56	76	57	80	32
800	70	42	72	9	73	30	74	46	75	57	77	3	78	6	81	46
820	71	39	73	8	74	32	75	49	77	1	78	9	79	14	82	59
840	72	35	74	7	75	32	76	51	78	5	79	14	80	20	84	11
860	73	30	75	4	76	30	77	51	79	7	80	18	81	26	85	22
880	74	24	76	0	77	28	78	51	80	8	81	21	92	30	86	32
900	75	17	76	55	78	25	79	50	81	9	82	23	83	33	87	41
920	76	10	77	49	79	21	80	47	82	8	83	24	84	36	88	49
940	77	1	78	42	80	17	81	44	83	7	84	24	85	37	89	55
960	77	52	79	35	81	11	82	40	84	4	85	23	86	38	91	1
980	78	41	80	26	82	4	83	35	85	1	86	21	87	37	92	5

NOTES:
1—Time at end of first step: 10 min
2—Voltage increment: 20 percent of first step.

A.3 High voltage power supplies, power conditioners, and filtering in the current measuring instrumentation used for controlled high direct-voltage tests

The intent of A.3 is to provide some basics to help the test engineer understand and evaluate competing power supply technologies for their suitability to the tests to be performed.

The power supply must provide the test operator with the voltage versus time profile required for the tests to be performed. The power supply must operate correctly and safely under the specific test conditions, with as little deviation from the profile as practical, within the prevailing economic constraints. The voltage profile may be a constant, series of steps, linear ramp, or any other characteristic deemed useful in high voltage testing. See Figure A.4 for examples of voltage profiles. Some power supplies may provide multiple profiles, while others may provide only one.

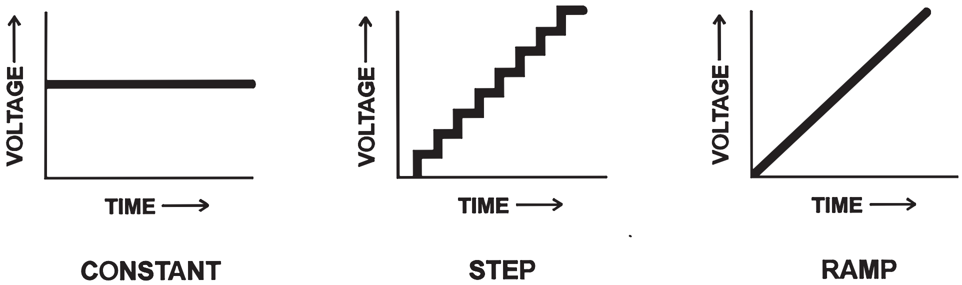

Figure A.4—Examples of voltage versus time profiles that may be used in high direct-voltage testing

High direct-voltage proof tests are often used to verify that an insulation system has a minimum level of electrical strength. Because specimen current is usually not measured during proof tests, the supply voltage may exhibit minor fluctuations without adversely affecting the outcome of the test. However, when performing controlled high direct-voltage tests, such as stepped or ramped voltage tests, accurate current measurements are necessary to properly diagnose the quality and condition of the insulation. Thus, a stable and well-regulated supply is necessary to avoid introducing errors into the current measurement. High direct-voltage power supply technology has improved significantly since such tests were first used to assess insulation condition. Whereas electrostatic generators were once considered state-of the-art, modern electronic power supplies provide better performance for less cost as well as smaller size and weight.

Power supplies fall into two broad categories: unregulated and regulated. Each of these categories can be subdivided based on the design approach taken by the power supply manufacturer. Because the test engineer is usually concerned about test results rather than power supply design details, this discussion will be limited to unregulated versus regulated power supplies.

A.3.1 Unregulated versus regulated power supplies

A.3.1.1 Unregulated power supplies

The simplest power supplies do not have their output voltages regulated. That is, if the line (input) voltage changes by some percentage, the output voltage will change by about the same percentage. If the load current of the power supply changes, the output voltage will usually change significantly. Also, some of the voltage noise on the line will appear at the output. Beyond basic filtering, unregulated power supplies take no special care to reduce the residual line-related alternating voltage components (ripple) that are inherent in the basic AC-to-DC conversion process. Unregulated power supplies are not suitable for many high direct voltage tests, as changes in line voltage and load will often add unacceptable error to the measurement results. However, at the highest test voltages, unregulated power supplies may be the only available choice, or if a regulated power supply is available, it may not be economically feasible.

A.3.1.2 Regulated power supplies

Modern regulated power supplies have electronic circuitry to keep their output voltages constant under changing conditions of line voltage and load current. In addition, significant suppression of ripple is usually a side product of the regulation process. Specifications (to be discussed later) such as line regulation, load regulation, and ripple rejection provide a means of comparing the performance of different power supplies. Regulated power supplies are often mandatory if current measurements made during high direct voltage tests are to be meaningful.

While differences exist in the design and implementation details of regulated power supplies, Figure A.5 shows the basic block diagram elements for a typical modern regulated high direct-voltage power supply.

The regulation process attempts to reduce the error voltage to as close to zero as practical. If the error voltage could be maintained at exactly zero, the high voltage output would follow the voltage profile reference exactly. In practice, the error voltage will not be exactly zero and there will be some difference between the profile reference and the high voltage output. The goal of the power supply designer is to reduce this difference sufficiently so that it has no significant effect on the test results.

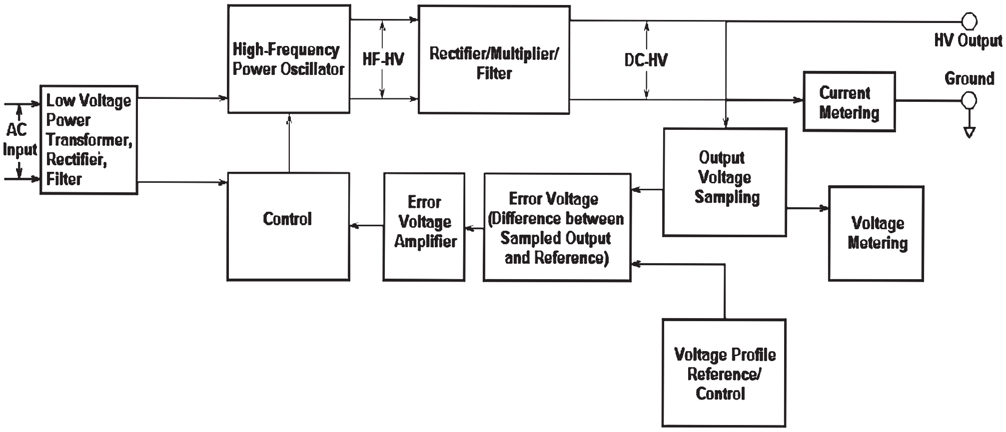

Figure A.5—Block diagram of a typical modern regulated high direct-voltage power supply

A.3.2 System transients

Transient voltage changes occur routinely on the power system as loads are switched in or out, generators are brought on line or taken out of service, or the grid is reconfigured. The transient voltages generated by these operations will tend to generate transient noise spikes on the output voltage of any power supply. If this noise is not eliminated, it may adversely affect test results. The voltage spikes can cause charging current spikes in the device being tested, and these spikes may not be distinguishable from the currents caused by corona, discharge in insulation voids, local insulation breakdown, etc. The power supply must suppress these system transients such that they do not obscure the test results.

A.3.3 Power conditioners

Power conditioners process the power line voltage before it is applied to the power supply. This processing may range from keeping the output voltage relatively constant over a range of input voltages to providing a pure, constant, isolated sinewave voltage, regardless of input voltage waveform, input voltage changes, or load current waveform. Some conditioners include energy storage to allow the alternating voltage output to ride though momentary loss of input power.

Power conditioners use various techniques including the ferroresonant (constant voltage) transformer, tap switching, or electronic switching techniques followed by sine-wave reconstruction to provide well-regulated, isolated line-frequency output. Depending on the application, each technique has weaknesses which may affect power conditioner performance. For instance, under non-linear loads with high crest factors (i.e., the ratio of peak current to rms current), the output voltage waveform of ferroresonant transformer-based power conditioners may flattop, reducing the peak voltage of the sinewave. This condition may cause voltage regulation problems for some power supplies. The best performance with the least problems may be had from the fully-isolated switching power conditioners, at the expense of higher cost.

The proper use of a power conditioner can greatly reduce line voltage variations and transients that are presented to the input of the power supply, and thus improve the power supply performance over what it would be without the conditioner.

A.3.4 Power supply specifications

Over the years, a number of criteria have been developed to specify power supply performance. The most commonly cited steady-state specifications are line regulation, load regulation, and ripple rejection. Although the response of the power supply to line transients is also important, this information is rarely provided. A good ripple rejection characteristic often indicates good line transient performance; however, good ripple rejection does not guarantee good transient response.

A.3.4.1 Line regulation

For high voltage testing, line regulation is the maximum steady-state amount that the output voltage or current will change as a result of a specified change in input line voltage (usually for a change from 105 V to 125 V or from 210 V to 250 V, unless otherwise specified). Regulation is given either as a percentage of the output voltage or current, or as an absolute change, ΔE or ΔI. See [B13].

Line voltage changes usually occur slowly, although switching operations and load changes on the power grid can cause quasi-step changes in the line voltage. The low-pass filter formed by the output resistance of the power supply and the capacitance of the specimen under test prevents the output voltage from changing instantaneously. However, any change in output voltage will result in changes in the geometric capacitive, absorption, and conduction currents of the test specimen. While the change in conduction current will almost certainly be negligible, the change in geometric capacitive and absorption currents may be large enough to make accurate measurements difficult. Thus, the dynamic line regulation of the power supply is a critical parameter.

Consider the following example. For a direct voltage of 5000 V on a generator winding, a typical conduction current might be 1µA. Assume that the nominal line voltage input to the high voltage power supply is 115 V and that this line voltage changes from 105 V to 125 V over some period of time (see Figure A.6).

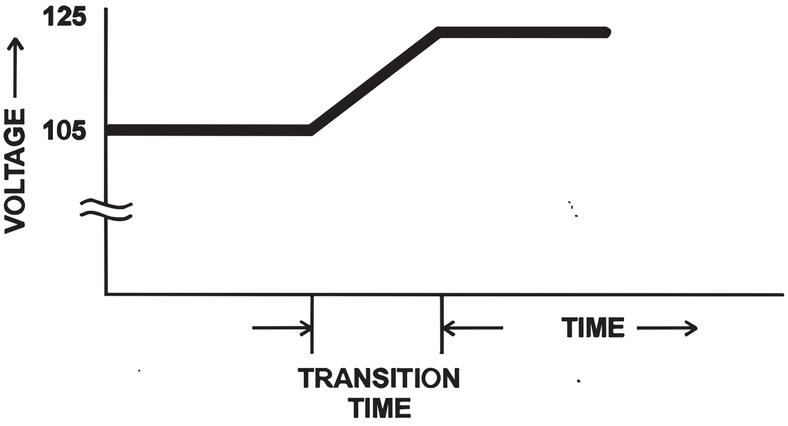

Figure A.6—Power supply AC line voltage change versus time

This 20-V change represents a 17.4 percent change in the line voltage. If the power supply has a line regulation of 1.0 percent, there will be a line-induced change at the 5000-V output of the power supply of 0.174 × 0.01 × 5000, which equals 8.7 V. The effect this voltage change would have on the current measurement would depend primarily on the capacitance of the winding and how fast the output voltage changes. The latter depends on how fast the line voltage changes and the output resistance of the power supply, which is connected to the capacitance of the winding.

The fundamental equation defining geometric capacitive current in a capacitor is

$$i_C = C \times dV / dt$$

where

i_C is the geometric capacitive current
C is the capacitance of the winding
dV/dt is the rate-of-change of the voltage across the capacitor

If the line-induced change in output voltage occurred over a ten-minute period, the voltage rate-of-change would be

$$dV / dt = \frac{8.7\ \text{V}}{10\ \text{min} \times 60\ \text{s/min}} \cong 0.015\ \text{V} / \text{s}$$

The geometric capacitive current into a 1µF capacitor during the time the line voltage is changing would be

$$i_C = (1 \times 10^{-6}\text{F})(0.015\ \text{V} / \text{s}) = 1.5 \times 10^{-8}\text{A} = 0.015\ \mu\text{A}$$

For a 1 µA conduction current, the increase in geometric capacitive current would add about a 1.5 percent error to the measurement. If the voltage change occurred over a 1-min period instead of 10 min, the error would be ten times as much, or about 15 percent. In addition, the effects of line-voltage change induced absorption current would add additional measurement error. If the voltage change is not linear, the situation rapidly becomes very complicated. Predictions of the effects on the measurements become difficult, if not impossible to make, other than in very general terms. Because the rate-of-change of the line voltage is generally unknown, this example shows that the line regulation of the power supply needs to be very small to ensure that the error on the conduction current measurement remains negligible. To allow for the wide variety of possible line-voltage-change versus time profiles, it is recommended that the line-voltage regulation be 0.1 percent or better. Further improvements can be gained by using a power conditioner which significantly reduces the measurement error by greatly reducing the voltage variations seen by the power supply.

A.3.4.2 Load regulation

Load regulation specifies how much the power supply voltage will change as the load current is varied from some minimum value (usually zero) to some maximum value (usually the current rating of the power supply). The load regulation specification is generally unimportant in high direct voltage testing because, until corona or insulation breakdown occurs, the load current is small and changes very little.

A.3.4.3 Ripple rejection

For high voltage testing, ripple is defined as the periodic deviation from the arithmetic mean value of the voltage. The amplitude of the ripple is defined as half the difference between the maximum and minimum values. The ripple factor is the ratio of the ripple amplitude to the arithmetic mean value. See [B13]. Ripple on the voltage of the power supply gives rise to ripple current in the test specimen. Because the components of ripple current are at line frequency or greater, and the instruments measuring the current are generally band-limited well below the line frequency, ripple current cannot normally be seen directly on either analog or digital meters. However, the indirect effects can be quite serious.

In even the best power supplies, ripple is slightly non-sinusoidal and non-symmetrical about the time axis (vertical asymmetry), with the degree of deviation from a true sinusoid depending on the design of the power supply. The average value of the measured direct current plus ripple current will, therefore, be different (usually higher) when ripple is present than when ripple is absent. Thus, the presence of ripple inherently increases the error of the measurement. For example, assume it is desired to measure the conduction current in a generator winding. We will use the 1 µA typical conduction current from the previous line regulation example. Assume there is only 1 volt peak of not-quite-sinusoidal ripple at 60 Hz on the power supply output. Using the geometric capacitive current equation with a winding capacitance of 1 µF, the ripple current would be about 380 µA peak, a value of current more than two orders of magnitude greater than that of the direct current being measured. Because the presence of ripple changes the average value of the output voltage, the error cannot be eliminated by filtering out the ripple in the current measuring instrumentation. This example illustrates that a very small amount of vertical asymmetry in the ripple current can introduce an error to the measured value of conduction current that can easily swamp the true conduction current. An offset of one percent in the peak ripple current could result in a reading of 4.8 µA, a 480 percent error. This error could lead the test operator to erroneously conclude that the winding was damaged.

With the use of active components in the current measuring instrumentation, the situation may be even worse. Using the above example, but not considering the AC ripple current, it would be reasonable to set the full-scale current range of the measuring instrumentation to 5 µA or less. If the measuring circuits were not specifically designed to eliminate ripple current from reaching the instrumentation, the front-end amplifier might easily clip one side of the current waveform, resulting in a current waveform similar to that shown in Figure A.7.

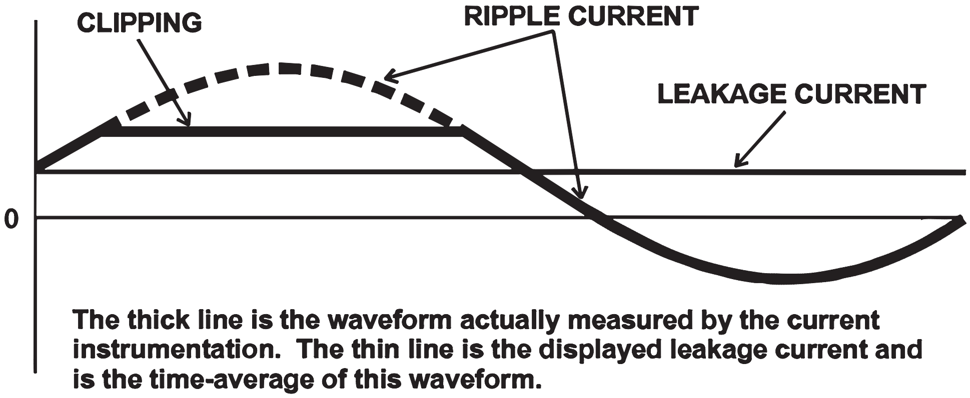

Figure A.7—Current waveforms associated with conduction current, ripple current, and input amplifier clipping

If the input filtering of the current metering instrumentation is inadequate, the ripple rejection characteristics of the power supply must be quite stringent to avoid errors induced by clipping. In the above example, only 1 V of ripple produced nearly 500 µA peak of ripple current. One volt of ripple riding on a typical test voltage of 5000 V (a very realistic possibility) is only 0.02 percent.

While the above problem exists because of insufficient ripple rejection in the power supply, from a technology standpoint it is usually easier to provide ripple filtering at the input of the current measuring instrumentation than to tighten up the power supply ripple rejection specification.

The above examples assumed a current measurement of about 1 µA. If, on the other hand, the current being measured were 1 mA, the same error due to ripple would be less than 0.5 percent of the current being measured. Therefore, the significance of the power supply ripple rejection depends on the current being measured. If relatively large direct currents are being measured, the ripple rejection requirement of the power supply for a specified measurement error is much less than if a small current is being measured.

A.3.5 Filtering in the current measuring instrumentation

If the objective is to only measure the direct component of current in the specimen, the easiest way to eliminate unwanted transient current from the measurement without introducing additional error is to incorporate a low-pass filter into the current measuring instrumentation. A simple *R-C* filter with a time constant of 10 s, for example, has a cutoff frequency of 0.0159 Hz. This filter would significantly reduce the amplitude of any AC components of input current such as 50 Hz or 60 Hz noise.

On the other hand, it may be desired to observe higher frequency signals such as the discharges that can occur in an insulation prior to failure so that the test may be halted before the insulation actually fails. In this case, a bandwidth of several hertz would be useful. A simple *R-C* filter with a 5 Hz cutoff frequency would have a time constant of 32 milliseconds. This filter would attenuate the line frequency about 50 dB less than the 10 s *R-C* time constant filter. Consequently, for a 5-Hz bandwidth, a simple *R-C* filter would be inadequate. A more complicated filter would be required to meet the 5-Hz bandwidth requirement and at the same time adequately remove the line frequency sufficiently to avoid the problems discussed in A.3.4.3.

Annex B

(informative)

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