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An American National Standard

IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage

Sponsor
Rotating Machinery Committee
of the
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Foreword

(This foreword is not a part of IEEE Std 95-1977, Recommended Practice for Insulation Testing of Large AC Rotating Machinery 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.

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 doubtful. 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 will result in a factual appraisal of the high direct voltage dielectric test.

A general discussion of test procedures and a comparison between alternating and direct voltage testing may be found in the appendix. For background information on overvoltage testing see IEEE Std 56-1977, Guide for Insulation Maintenance for Large AC Rotating Machinery, Section 5.

This document was originally developed by a working group of the Insulation Subcommittee of the IEEE Rotating Machinery Committee. The members of this working group were:

C. L. Sidway, *Chair*
B. R. Loxley, *Secretary*

C. E. Asbury
J. S. Askey
B. M. Cain
A. W. W. Cameron
E. B. Curdts
J. L. Kuehlthau
H. M. Marsden
G. L. Moses
E. R. Scattergood
W. Schneider
H. R. Tomlinson
H. P. Walker
W. A. Weddendorf
E. S. Yates

This revision was prepared by a working group of the Insulation Subcommittee. The members were:

R. F. Sharrow, *Chair*

J. M. Brown
A. W. W. Cameron
E. B. Curdts
R. J. Hillen
W. J. Sheets
G. Wolff

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.

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IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage

1. Scope

This recommended practice presents uniform methods for testing insulation with direct voltages higher than 5000 V.[1] It applies to large ac rotating machines rated at 10000 kVA or greater and rated at 6000 V or higher.[2] It covers acceptance testing of new equipment in the factory or in the field after erection, and routine maintenance testing of machines that have been in service.

2. Purpose

The purpose of this recommended practice is:

1) To provide uniform procedures for performing high direct voltage acceptance tests and routine maintenance tests on the main ground insulation of windings of large ac machines
2) To provide uniform procedures for analyzing the variations in measured current so that any possible relationship of the components of these variations to the condition of the insulation can be more effectively studied
3) To define terms which have a specific meaning as used in this document

3. Definitions

The following definitions are based on those in common use which have been modified to be more specific for the purpose of this recommended practice.

absorption current (or component): A reversible component of the measured current, which changes with time of voltage application, resulting from the phenomenon of “dielectric absorption” within the insulation when stressed by direct voltage. See IEEE Std 62-1958, Guide for Making Dielectric Measurements in the Field, Section 6.

acceptance proof test: A test applied to new insulated winding before commercial use. It may be performed at the factory or after installation, or both. See American National Standard General Requirements for Synchronous Machines, ANSI C50.10-1977.

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[1] For insulation resistance measurements at direct voltages below 5000 V, see IEEE Std 43-1974. Recommended Practice for Testing Insulation Resistance of Rotating Machinery.

[2] These methods have been found applicable to equipment of smaller size and lower voltage.

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

capacitive current (or component): A reversible component of the measured current on charge or discharge of the winding which is due to the geometrical capacitance, that is, the capacitance as measured with alternating current of power or higher frequencies. With high direct voltage this current has a very short time constant and so does not affect the usual measurements. See IEEE Std 62-1958, Section 6.

controlled overvoltage test (dc leakage, measured current, or step voltage test): A test in which the increase of applied direct voltage is controlled and measured currents are continuously observed for abnormalities with the intention of stopping the test before breakdown occurs. See Section 6.2.

electric strength (dielectric strength): The maximum potential gradient that the material can withstand without rupture.

high direct voltage: A direct voltage above 5000 V supplied by portable test equipment of limited capacity.

leakage (conduction) current: The non-reversible constant current component of the measured current which remains after the capacitive current and absorption current have disappeared. Leakage current passes through the insulation volume, through any defects in the insulation, and across the insulation surface.

maintenance proof test: A test applied to an armature winding after being in service to determine that it is suitable for continued service. It is usually made at a lower voltage than the acceptance proof test.

measured current: The total direct current resulting from the application of direct voltage to insulation and including the leakage current, the absorption current, and, theoretically, the capacitive current. Measured current is the value read on the microammeter during a direct high voltage test of insulation.

overvoltage (overpotential): A voltage above the normal rated voltage or the maximum operating voltage of a device or circuit. A direct test overvoltage is a voltage above the peak of the alternating line voltage.

polarization index: The ratio of the insulation resistance of a machine winding measured at 1 min after voltage has been applied divided into the measurement at 10 min. See IEEE Std 43-1974.

proof test (withstand test): A “fail” or “no fail” test of the insulation system of a rotating machine made to demonstrate whether the electrical strength of the insulation is above a predetermined minimum value.

4. Preparations for Test: Test Connections

4.1 Proof Test Preparations

The preparations required for proof tests are simpler than when current measurements are made in conducting controlled overvoltage tests. If proof tests are to be made without current measurement, only those sections marked by an asterisk need to be consulted.

4.2 Air-Cooled Machines

4.2.1 *Temperature of the Winding*

4.2.1.1

A direct voltage test should be made at winding temperatures not in excess of 40°C unless otherwise agreed upon between the user and the manufacturer.

4.2.1.2

Temperature is important when making leakage measurements at high direct voltages because it influences humidity and moisture condensation on the surface of the insulation. Insulation resistance and dielectric absorption vary with temperature, so that constant temperature is required for accurate and comparable measurements. Hence, temperatures near ambient are preferred; otherwise, resistance values must be corrected to a common base temperature. See IEEE Std 43-1974, Section 4.

4.2.2 *Humidity.*

The insulation resistance and the polarization index should be at or above the minimum value recommended in IEEE Std 43-1974 before making a high direct voltage test. Surface leakages on end windings, etc, are increased if moisture is allowed to settle on them, particularly if any dirt is present. It is difficult to attain a standard degree of humidification for close correlation of measurements on successive tests. For these reasons, some users prefer to keep windings dry until tested by maintaining their temperature *slightly above* ambient. When machines are idle for long periods, they may be heated to prevent absorption of moisture. See IEEE Std 43-1974, Appendix. Overvoltage tests will be most significant when made under humidity conditions approaching those under which the machine will operate. The usual procedure when proof tests are made is to keep the winding dry both prior to the test and when in service.

4.2.3 *Dirt on the Winding*

4.2.3.1

When dirt is present, the effect of moisture on the surface is to increase the amount of leakage current. It is usually desirable to reduce such currents by avoiding moisture condensation. Accumulation of dirt on the winding may increase test voltage stresses in end windings, especially if moisture is present.

4.2.3.2

If dirt that is oil soaked or otherwise flammable appears to present a fire hazard, in view of the possibility of a flashover during the test, the winding should be cleaned before testing.

4.2.3.3

The winding may be cleaned before testing if it is considered that the clean condition is a standard upon which measurements from successive tests can confidently be compared.

4.2.3.4

The winding should be cleaned if dirt is found responsible for insulation resistance below the minimum value recommended in IEEE Std 43-1974. Consideration may be given to testing both before cleaning, for easiest detection of incipient faults and indication of repairs required during the time out of service, and testing again after cleaning and drying and any other work for final assurance of fitness for service.

4.2.4 *Varnish and Other Coatings.*

The presence on the windings of certain varnishes, etc, in the uncured state, causes high leakage currents. Such coatings should be allowed to dry and cure thoroughly before tests are made.

4.2.5 *Disposition of Rotor.*

The machine may be tested with or without the rotor in place. However, if the rotor is to be removed during an overhaul for other reasons, it is preferable to test the stator winding after the rotor has been removed. The winding can then be better inspected and observed, and it is possible to use fire-fighting equipment more effectively, although fire has very seldom occurred during high direct voltage tests.

4.3 Hydrogen-Cooled Machines

Hydrogen-cooled machines may be tested in hydrogen, in carbon dioxide, or in air. Hydrogen or carbon dioxide of suitable pressure should be applied for tests to maintain effectiveness of the striking distances. The procedures for air-cooled machines listed in Section 4.2 should be observed.

4.4 Liquid-Cooled Armature Windings

The procedures listed in Section 4.2.6 should be observed when the machine is tested. For water-cooled windings the normal procedure is to have the insulating hoses dried internally prior to the test. If water of acceptable conductivity is flowing through the insulating hoses during the test, equipment rated for approximately 100 mA is required.

4.5 Isolation of the Winding from Cables and Auxiliary Equipment

4.5.1

It is preferable to exclude from the test any items that can readily be disconnected in the tune available and to apply separate tests appropriate to them. The sensitivity of current measurements to any weakness in the winding will be reduced by the inclusion of external elements. Pothead and busbar insulators and other creepage surfaces must be dry and carefully cleaned, and may be guarded as indicated in IEEE Std 62-1958. Porcelain surfaces may be coated with silicone compound to reduce leakage currents due to condensed moisture on the surface. If auxiliary equipment is included in the test and weakness is detected, the weakness should be located by sectionalizing. If isolation is difficult and the leakages of the connected item and of the windings are of the same order (one not more than twice the other), they may be tested individually to provide reference data and tested together thereafter until deviation from normal is detected.

4.5.2

Oil-filled apparatus should not be included in the test when current measurements are made because current readings may be erratic and may not provide significant results.

4.5.3

If it is impractical to isolate an oil-filled transformer, the maximum test voltage should not exceed the transformer test voltage specification given in IEEE Std 262-1973 (ANSI C57.12.90-1973), Test Code for Distribution, Power, and Regulating Transformers.

4.5.4

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

4.6 Sectionalizing the Winding

The sensitivity of fault detection becomes greater as the winding portion upon which current measurement is made becomes smaller.

4.6.1

It is recommended that on large machines each phase be isolated and tested separately. The neutral end of each phase winding should be disconnected whenever practical. Testing one phase at a time gives a comparison between phases which is useful in evaluating the condition of the winding and for historical records.

4.6.2

Tests may be made on the entire winding at one time under certain conditions, although this procedure is not the preferred method. One objection to testing all phases at a time is that only ground insulation is tested and no test is made of the phase-to-phase insulation as is made when one phase is tested at a time with other phases grounded. Testing all phases at a time is applicable for small machines and for machines that have inaccessible neutral connections. In this case the three line leads of the winding should be connected together to avoid surges at an open end in the event of failure or flashover.

4.6.2.1

If separation of phases is unusually difficult, it may be done once to establish a reference and all phases tested together thereafter until some deviation from the normal is found.

4.6.2.2

A comparison of the leakage current in the three phases may be obtained when all phases are tested at the same time if special connections are made as shown in Fig 1 and if the direct current is measured on each phase. This method reduces test time. It requires special instrumentation technique and does not provide a phase-to-phase test.

4.7 Discharge of the Winding

4.7.1

Following a high direct voltage test, the winding should be grounded for a minimum time period equal to or greater than 4 times the accumulated test period, but in no case less than 1 h to ensure that no significant energy remains stored in the winding.

4.7.2

Unless the winding is grounded, the energy stored in the winding which has been tested will be dangerous for periods of several hours. Opening the test source will not remove voltage from the winding because of the stored energy in it. The winding will not be safe to personnel without grounding until completely discharged.

4.7.3

If the ground is removed too soon, a voltage will build up in the winding and may reach a high value. Such voltage would be dangerous to personnel who might touch the winding and could damage the winding if under such condition it were placed in service or given other tests.

4.8 Test Equipment

General information on high direct voltage insulation test equipment is given in IEEE Std 62-1958, Section 6.

4.8.1 *Power Source to DC Test Equipment*

4.8.1.1

The ac circuit should be free from intermittent loads and transients.

4.8.1.2

The ac supply to the direct voltage test equipment must have constant non-fluctuating voltage if accurate dc measurements are to be made. Regulating transformers, electronic regulators, motor generators, or combinations of these may be used. Commercially available regulators perform best when their apparent power capacity matches the capacity of the load.

4.8.1.3

Normal system frequency is preferable to a nonsynchronized source, such as a separately driven house generator, because of the effect of variable frequency upon voltage regulators and electronic test equipment.

4.8.1.4

A low-ampere 115 V 60 Hz power source will supply the usual equipment for high direct voltage tests on rotating machine insulation.

4.8.2 *High Direct Test Voltage*

4.8.2.1

A source of adjustable direct voltage is required. Usually a variable auto-transformer is provided in the ac supply circuit.

4.8.2.2

If it is desired to raise voltage continuously rather than in steps, some means of smooth variation is necessary. A geared drive is advantageous. A motor-driven variable autotransformer will raise voltage in a uniform series of small steps. Stepless voltage increases, in linear or other functions of time, can be arranged with certain direct voltage supplies, electrostatic generators in particular.

4.8.2.3

The voltage control should be arranged for a small voltage change between steps, for example, a variable autotransformer of many turns. Such equipment of the required current rating and designed for 240 V usually has more turns and will give smaller steps than when using autotransformers designed for 120 V.

4.8.2.4

The high-voltage polarity of the test set may be either positive or negative. If test results are to be compared, the test should be made with the same polarity. The test report should indicate the polarity used.

4.8.3 *Direct Voltage Measurement*

4.8.3.1

The dc test set should be provided with a high voltage measurement unit calibrated in kilovolts on the voltmeter. Voltage instrumentation should be capable of measuring kilovolts with several ranges available.

4.8.3.2

It is occasionally desirable to check kilovoltmeter calibration. This may be done by means of a sphere-gap. See IEEE Std 4-1969 (ANSI C68.1-1968), Techniques for Dielectric Tests. The calibration sphere-gap may serve as an overvoltage limiter during the test if the gap is increased 20 percent above the calculated gap for the maximum voltage.

At this setting there will be no needless flashovers. Resistance of approximately 100 000 Ω to 1 MΩ should be connected in series with the sphere-gap to limit surges.

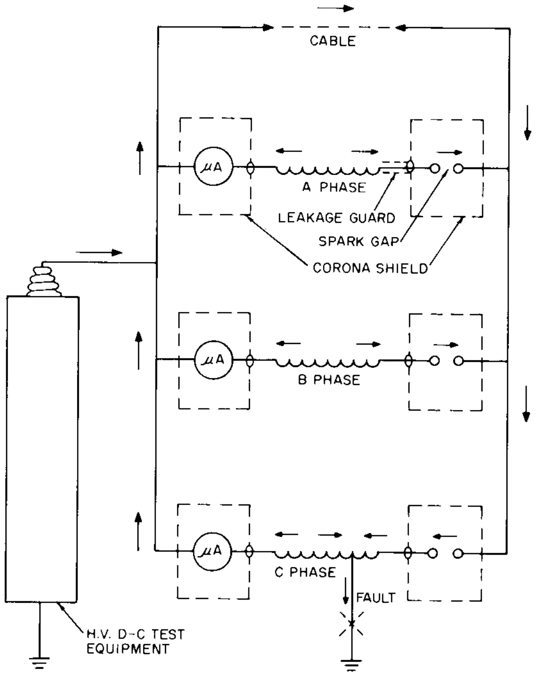

Figure 1—Typical Circuit for High Direct-Voltage Test of Three Phases of Machine Winding Tested Simultaneously
(Three microammeters can be replaced by one with switching. Arrows indicate discharge current through fault)

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

4.8.3.3

If the test equipment includes an overvoltage relay trip, it should be set and calibrated.

4.8.4 *DC Measurement*

4.8.4.1

The total current is measured in microamperes. The ammeter should have several current ranges when controlled overvoltage tests are to be made.

4.8.4.2

For special controlled overvoltage testing, when three phases are metered and tested simultaneously, the microammeter is placed in the high voltage side of the dc supply with appropriate insulation, electrostatic shielding, and guarding. One meter or recorder may be switched between several output leads, and meter ranges changed by insulated controls. See Fig 1.

4.8.4.3

Current measurements are greatly facilitated if a recorder can be used with a time or voltage base. In particular, a recorder permits the determination of an accurate mean when current is fluctuating because of supply voltage unsteadiness.

4.8.4.4

Current measurements may also be made by means of a calibrated cathode-ray oscilloscope across a resistor in the ground connection of the test set. The presence of corona may be detected by characteristic waveform. It should be noted, however, that pulses similar to corona pulses have been observed on application of direct voltage to certain insulations. These may be significant at even a small fraction of the direct voltage test level.

4.8.4.5

If the test set includes an overcurrent trip, it should be calibrated and set high enough to avoid an inadvertent trip during the test. Interruption would cause a break in the current curve and could possibly overstress the winding insulation undesirably.

4.8.5 *Ground Provisions of the Test Set*

4.8.5.1

A substantial grounding provision should be made available for use at the conclusion of the test, and a grounding device should be instantly available for use in emergency.

4.8.5.2

A grounding stick with a discharge resistor is usually provided. The stick should be insulated and safe for the maximum test voltage. The winding should be discharged initially through the resistor until voltage is reduced to zero and then connected directly to ground. A resistor of 1000 to 6000 Ω/kV of maximum test voltage should be used with the grounding stick. The ground wire connected to the discharge resistor should be extra flexible and have generous current-carrying capacity and physical strength such as No 12 or No 14 B&S gauge.

4.8.5.3

On some test sets, opening the main breaker automatically closes a resistance grounding device. When an automatic or manual grounding switch with a resistor is incorporated in the test set, a grounding stick (without a resistor) should be available for emergency and for visible protection.

4.9 High-Voltage Test Connection to the Winding

4.9.1

The phase under test should be energized at both line and neutral ends whenever practical. Other phases should be grounded at both ends. Connecting both ends of the winding together and testing only a portion of a large machine winding is desirable to limit the discharge and thereby to minimize 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 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.

4.9.2

High-voltage test connections should have minimum leakage current and corona loss.

4.9.2.1

High-voltage leads should be spaced a minimum of 4 in plus 1 in per 10 kV of test voltage from grounded surfaces where practical.

4.9.2.2

Test connections should be supported in the clear, without solid insulation wherever possible. Where solid insulation is used, it must be dry and of generous surface length.

4.9.2.3

The use of large diameter wire for test leads will reduce corona.

4.9.2.4

Corona on test leads can be reduced by the use of conductors insulated with materials such as polyethylene. This is particularly important with reduced clearance from grounded surfaces. When test lead insulation not designed for high voltage is used, the test leads should be treated as if they were bare. The insulation reduces corona because of its diameter. However, the insulation may be damaged and unsuitable for normal use after the test.

4.9.2.5

Corona can be reduced by rounding off sharp projections and terminals with masses of conducting material. Semiconducting plastic, such as moist asbestos 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 crinkles and creates undesirable points.) Connections exposed when sectionalizing a winding should be carefully treated to eliminate sharp contours.

4.9.2.6

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

4.9.2.7

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

4.9.3

Leakage current resulting from test connections should be checked at several points up to the highest voltage to be used, after leads are in place before connecting to the winding for test. Record the result of this test.

4.10 Test Connection to Ground

Ground connections must be strong and secure for the safety of personnel. In addition, inadequate grounding could be responsible for incorrect test data and resulting conclusions.

4.10.1

Both ends of any portion of the armature winding not under test should be grounded whenever practical.

4.10.2

Ground the following auxiliary equipment to the machine frame:

1)Armature temperature detector coils or thermocouples
2)Other devices associated with the winding
3)Current transformer secondaries
4)Rotor winding and shaft
5)Test set frame (see Section 4.8.4)

4.10.3

Certain objects close enough to become charged should be grounded.

WARNING: 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 10 ft of the test leads or the machine winding under test that all spare parts, pieces of equipment, tools, etc, which cannot be removed, be grounded while the test is in progress.

4.10.4

The test-set frame should be connected to the station ground. In addition, the test set frame should 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.

4.10.5

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 6 B&S gauge flexible stranded conductor or larger. The continuity of ground connections should be observed. For this reason, tape and rubber clip insulators should *not* be used on leads used for ground connection. The strands should be visible at lugs and clips and not covered in any way. Additional ground leads with clamps or connectors of ample size to preclude accidental breakage or disconnection should be provided for discharge of winding. See Section 4.5.1. Such grounds are often left in place after the tests have been completed when the winding may be unattended. All personnel who might come into contact with these leads should be advised of their purpose and importance.

5. Test Procedure: Proof Tests

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

5.1 Test Voltage for Acceptance Proof Testing

New equipment either in the factory or in the field is governed by the appropriate equipment test code. See ANSI C50.10-1977. The ratio between the test direct voltage and the power frequency (rms) test value for acceptance tests is 1.7. The direct test voltage is 1.7 times the power frequency (rms) code test voltage.

5.2 Test Voltage for Maintenance Proof Testing

For equipment that has been in service, the test voltage varies depending upon the type, condition of insulation, equipment history, desired service reliability, etc. In general, a power frequency test voltage ranging between 125 percent and 150 percent of rated (rms) terminal voltage has proven adequate. The direct test voltage for maintenance tests is calculated by multiplying the power frequency (rms) test voltage by 1.7.

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

Acceptance or maintenance proof tests may be applied as such or as a continuation of controlled overvoltage tests as covered in Section 6.

5.3 Voltage Application

Application of test voltage should be gradual, should avoid exceeding the maximum test set current, and should avoid unnecessarily tripping the overcurrent device in the test set which could introduce undesirable surges.

Duration of either acceptance or maintenance proof tests should be 1 min. Timing is to start when test voltage is reached.

Reduction of test voltage at end of test should not be abrupt. Voltage should be allowed to decay to at least half value before the winding is grounded.

5.4 Grounding

Initial grounding should be made through the resistor provided. After initial grounding, the winding should be solidly grounded to the frame of the machine as described in Section 4.5.1. See Section 4.8 for information about grounding equipment and connections.

5.5 Test Results

Acceptance and maintenance proof testing is conducted on a purely withstand basis. If no evidence of distress or failure is observed by the end of the total time of voltage application, the test is taken as satisfactory.

5.6 Failure

Complete failure is usually indicated by a sharp capacitive discharge at the point of failure. There are times, however, when failure or partial failure may be indicated by a large abnormal change in leakage current or by erratic leakage current observed on the meter.

When failure location is not readily observable by capacitive discharge or other signs of distress, such as smoke or glowing creepage path, systematic segregation of the winding may be required to locate the specific portion or coil involved.

Application of a low value alternating potential may assist in locating the point of failure. The circuit should have devices to limit currents to 6 to 10 A to prevent burning of the core iron or coil insulation.

Probing with a length of grounded metal foil fastened to an insulating rod, such as a ground stick, can be helpful in locating the point of failure. The probe can be at ground potential with winding energized or vice versa. If the winding will not support any voltage, then the probe should be energized.

5.7 Suggested Test Record

A suggested test record includes:

1)Serial number of equipment
2)Equipment rating, type of insulation
3)Manufacturer's name
4)Date of test
5)Time of test
6)Test voltage and duration
7)Leakage current at end of test
8)Test connection and connected apparatus (if any)
9)Temperature of winding
10)Time at this temperature
11)Temperature and humidity of environment
12)Time out of service
13)Test equipment description

Comments regarding the following are also of value:

1)Reason for test
2)Visual inspection
3)Physical condition of winding and insulation
4)Resistance and polarization index prior to test
5)Pertinent history of equipment
6)Date winding was installed
7)Observations of distress, corona, etc, during test
8)Result of test and action taken
9)Recommendations for maintenance, operation, or future test activity

6. Test Procedure: Controlled Overvoltage Test

6.1 Controversy in Interpretation

It should be pointed out that there is some controversy in the interpretation of the controlled overvoltage test results. Many operators have found that this test is a very useful maintenance tool, while others question its value. The following procedure describes one of several methods of controlled overvoltage testing used. Another method acceptable to other users is described in the appendix.

6.2 Test Method

The controlled overvoltage test, sometimes referred to as a dc leakage test or a step voltage test, is a high direct voltage test in which the voltage is increased in a specified manner, during which time the measured current is observed. This type of test, done under suitable conditions, provides a record of the condition of the winding for present and future use and may permit prediction of breakdown voltage if it is within or slightly above the test voltage. Conclusions are reached by recognition of abnormalities or deviations in the curve determined by current, measured in microamperes, versus applied voltage, measured in volts, plotted as the test progresses. When winding has uninsulated conductors, deviations in the curve can be expected.

It is recommended that an initial voltage be applied and held constant until the polarization index is determined and that the voltage be then increased at a rate not exceeding 3 percent of the final test level in each minute. If this cannot be done at a constant rate, equal 1 min steps should be used. The smaller the steps, the greater the probability of warning of approach to breakdown. Voltage should be raised to the recommended maximum level or until abnormalities are observed. The recommended maximum voltage is 1.25 to 1.50 times the rated alternating voltage times 1.7. See Section 5.2, first paragraph.

It is often, but not always, possible to terminate the test before breakdown of defective insulation.

It is important that, since unexpected failure can occur, there be adequate provision for repair at the time the test is made.

The total test time required is from 30 to 45 min per phase.

6.3 Initial Voltage Step

Apply the initial voltage step of approximately one-third of the recommended maximum voltage. Maintain this voltage constant for 10 min to obtain the polarization index. The polarization index may also be determined prior to the test by means of insulation resistance measurements. See IEEE Std 43-1974.

Read the current at 1 min and at 10 min to provide data for calculating the polarization index from which an evaluation of insulation condition at relatively low voltage may be obtained.

The polarization index is the ratio of the 1 min current reading to the 10 min current reading. A value of at least 2.0 for Class B and Class F or 1.5 for Class A insulation will indicate reasonably clean and dry insulation. See IEEE Std 43-1974. If lower values of polarization index are obtained, the test should be stopped and the reason determined. See IEEE Std 43-1974 and IEEE Std 56-1977, Guide for Insulation Maintenance of Large AC Rotating Machinery. Heating the winding slightly above ambient may prevent moisture condensation, which is often a cause for a low polarization index. If the polarization index is still low, it indicates the possibility of excessive dirt or moisture in the winding. The winding should not be tested until it has been dried out. See IEEE Std 43-1974, Appendix. The winding should be cooled to ambient prior to testing.

After the initial 10 min step, if the polarization index is satisfactory, commence the uniform or equal-step voltage increase.

Adjustments to the voltage setting for each step should be made within the first 10 s. In making the voltage adjustment, allow for some increase in value due to regulation of the test set. Voltage steps, once set, should not be adjusted or complex charging-current conditions will be introduced which may cause erratic current readings. Read the voltage at the *end* of each step.

6.4 Current Measurement

Current readings should be taken at the *end* of each step.

6.5 Plotting the Data

The data obtained at the end of each step should be plotted *immediately* during the test. Many operators use linear cross-section paper with current expressed in microamperes as the ordinate and voltage expressed in kilovolts as the abscissa. A special log-log coordinate paper is available which provides determination of insulation resistance without calculation. It standardizes the scale of the coordinates. See the appendix, Fig A.1.

Consideration should be given to the use of a current recorder. Recording may be on a time basis, but a voltage base has some advantages. To obtain full advantage of smooth time-function voltage increase, a current recorder is practically essential.

Record the test data. See Section 5.7.

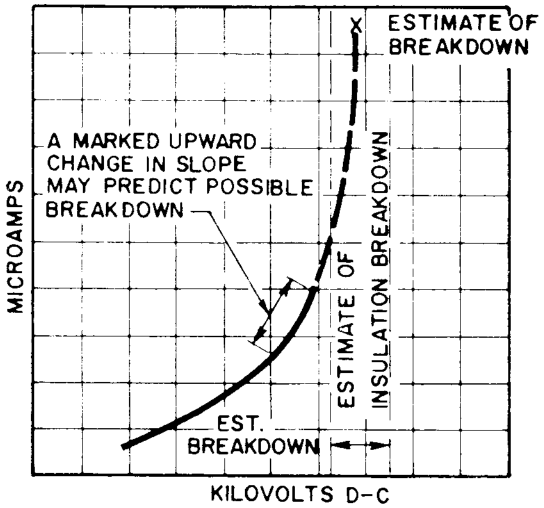

FIGURE 2

Figure 2—Winding First in Good Condition Shows Warning of Breakdown

6.6 Interpretation

Breakdown voltage cannot always be predicted from the curve; hence, unpredicted failure may occur. When this method has been successful, the following interpretations have applied.

1) For a winding indicated as being in good condition, the plot of the measured current versus applied voltage will usually produce a smooth curve with rising characteristics; see Fig 2. The apparent rise is dependent upon the scales used for plotting. When comparisons are to 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; see Section 6.2, second paragraph.
2) Any deviation from a smooth curve should be viewed as a warning of possible approach to the breakdown voltage of the insulation; see Figs 2 and 3 and Section 6.2, first paragraph. This deviation 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.
3) The most usual indication of approach to a breakdown voltage is an accelerating rate of increase of current with voltage. See Fig 2. 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 Fig 2. If the predicted breakdown voltage is as low as the recommended maximum test voltage, the trend should be verified by *one more* voltage step. If the extrapolation still shows a low value, the test should be stopped if possible breakdown is to be avoided.
4) Current should be watched for any tendency to rise with time during constant voltage application because this would indicate imminent breakdown.

5) A very abrupt drop in leakage current is rarely found; but when it occurs above the peak operating voltage for the winding, it may indicate approaching breakdown of the insulation. See Fig 3. No method is known for estimating the breakdown voltage in this case and 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.
6) Cases of abrupt breakdown before the current curve approaches the vertical may occur. 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.
7) In case of any indication of approach to possible breakdown, it should be confirmed that the cause does not lie in corona from test connections, insulation of test leads, etc. Proper placing and insulation of test leads, as described in Section 4, and preliminary tests of leads alone at the maximum voltage will avoid this type of error. See Section 4.9.2.
8) When there is no indication of impending breakdown, the test may be continued to the recommended maximum *proof test* value. See Sections 5.1 and 5.2.
9) The test is usually made individually on each phase of the winding. Differences in curve characteristics between the phases not attributed to corona, temperature, or humidity are usually attributed to the condition of the insulation. See Fig 4.

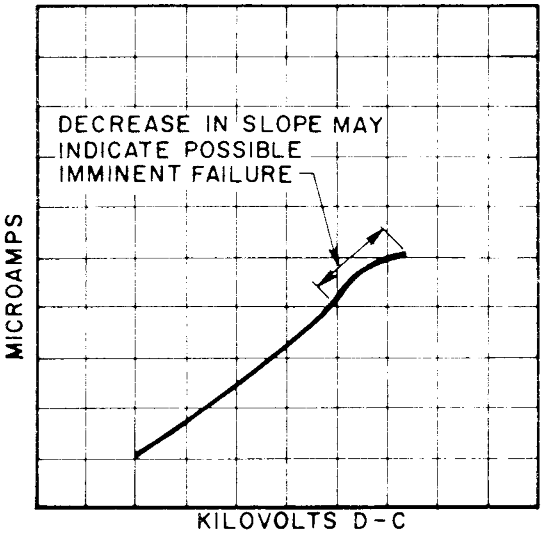

Figure 3—Winding Slope Decrease May Indicate Imminent Failure

6.7 Other Methods of Testing and Interpretation

Other methods of interpreting the test results are sometimes used. When tests have been made in the past, a repetition of the previous test method may be desirable so that results may be compared.

The interpretation of controlled overvoltage tests may also be made by plotting the insulation resistance (calculated from test voltage and current) versus applied voltage instead of current versus applied voltage. See Fig 5.

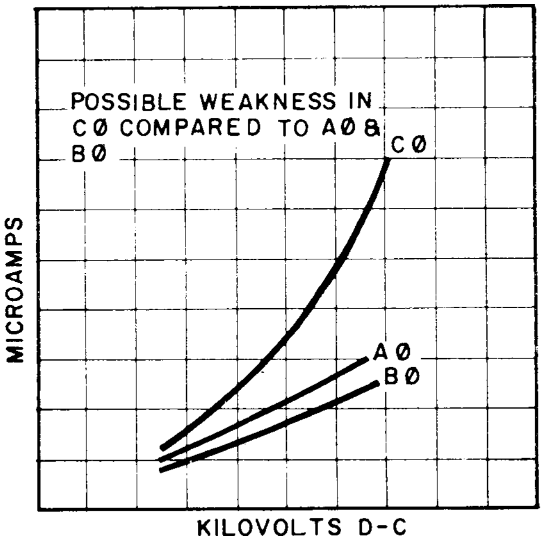

Figure 4—Plot of Overvoltage Test on Three Phases Tested Separately

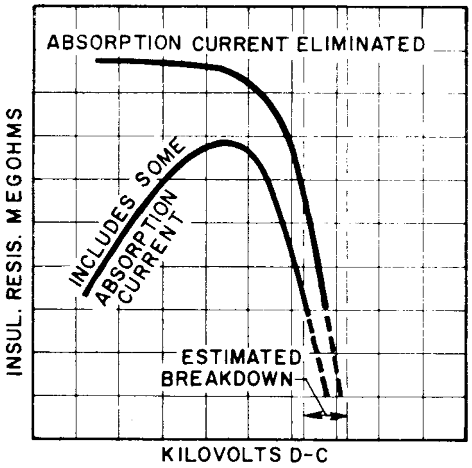

Figure 5—Plot of Insulation Resistance as Calculated from Current Values Recorded during Overvoltage Test

Another acceptable method uses a graded-time interval between voltage steps. See the appendix, Section A2.

6.8 Fault Location

When breakdown has occurred, the following procedure should be followed to locate the fault:

1) After a failure, the test voltage should be reduced immediately to prevent unexpected voltage buildup and to prevent a repeat of the flashover or failure until observers are in position to identify the fault location
2) It is an advantage to have several observers stationed near the machine to assist in rapidly identifying the location of the fault

3) 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
4) If the failure cannot be readily located by observation of flash or discharge when direct voltage is applied, it is often practical to use low alternating voltage, with current limited to 6 to 10 A, to locate the point of failure; if this does not identify the point of failure, then the winding must be successively divided and tested until the point of breakdown is located (see Section 5.6, third and fourth paragraphs).
5) When the failed coil has been located, it must be electrically isolated so that the remainder of the winding can be tested to the predetermined maximum voltage
6) The isolated coil should be grounded and the winding made electrically continuous where the coil had been in the circuit
7) Avoiding corona at these connection points is important and may be difficult to accomplish (see Section 4.9)

6.9 Safety Precautions During High Direct Voltage Tests

Personnel should be advised before the test that after application of high direct voltage there will be a residual charge in the winding which is dangerous and that de-energizing the test source will *not* immediately de-energize the machine winding under test.

Windings which have been tested must be solidly grounded before being approached by personnel.

There is a possibility that after a test, if a ground is removed before minimum grounding time, there will be a voltage buildup to a level that will be dangerous to personnel or equipment.

Ground should be kept in place until the winding is discharged. This may require several hours, depending upon the size of the machine winding. See Section 4.7, first paragraph.

Objects close to the machine under test should be grounded. See Section 4.10.3.

Upon completion of the high direct voltage test, the test voltage control should be turned to zero.

After the voltage has decayed to half value, the winding should be discharged through the special discharge resistor ordinarily provided with the test set. See Section 4.8.5.2.

The winding may be solidly grounded as soon as the voltage has been reduced to zero.

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 puncture when the alternating voltage test is applied. Otherwise, the absorbed charge, superimposed upon the peak alternating voltage dielectric stress, may exceed the electric strength of the winding.

A machine should not be placed in service after a high direct voltage test until the winding has been grounded, as described in Section 4.7, first paragraph.

Dissipation of the absorbed charge cannot be accelerated by the application of alternating potential or by the application of direct voltage with reversed polarity. Severe insulation voltage gradients will be introduced in the winding if this is attempted.

7. Standards References

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IEEE Std 115-1965, Test Procedure for Synchronous Machines

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Annex A

(Informative)

(This appendix is not a part of IEEE Std 95-1977, IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage.)

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, and a comparison of high direct voltage with the established alternating voltage test method is given.

A.1.1 Routine Maintenance Testing

The advantage of planned maintenance testing is the use of the full reliable life of the ground insulation of the winding.

A rewind may be deferred to a more convenient time until justified by the extent and rate of deterioration, as shown by successive tests which provide a means of judging the risk of delay.

It is sometimes practical to make localized repairs or to cut out or replace weak coils when tests show local rather than general weakness.

When machine tests show low measured strength, operating conditions can be limited or surge protection can be installed.

Maintenance programs can be scheduled according to the relative urgency for repair.

A.1.2 Overvoltage Testing and Electric Strength

Overvoltage tests are accepted as a means for providing assurance that the winding insulation has a certain level of electrical strength. Since the inherent electrical strength of sound insulation is well above the usual proof test value, proof tests at appropriate voltage cause failure of *only* that insulation unsuitable for service.

A.1.3 Proof Tests

For many years power frequency overvoltage proof tests have been the commonly accepted method of acceptance testing for new windings and of routine maintenance testing. Overvoltage power frequency potential proof test values specified in IEEE, NEMA, and ANSI 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.

Proof tests are intended to search for the existence of 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 coil insulation that has an insufficient factor of safety with respect to the operating voltages, over-voltages, 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.1.4 Relationship Between Direct Current and Alternating Current in Overvoltage Tests

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 composed of many factors.

The lack of a precise equivalence should not cause concern because the purpose of proof tests is to demonstrate that the insulation can withstand the overvoltages to be expected in service rather than to establish the precise value of electrical strength. The electrical strength has been found in cases studied to be associated 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 in 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.

Some investigators point out 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 leakage 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; dc conduction in fissures, however, may be reduced rather than increased by an increase in temperature.

A.1.4.1 *Ratio of Direct Test Voltage to Power Frequency Test Voltage.*

The ratio of direct test voltage to power frequency (rms) test voltage has been reported to vary from 1 to 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 (1) the higher ratios occur in well-compacted insulation; (2) 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); and (3) 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) leakage current.

Values of 2.0 to 3.0 have been used widely for the ratio of direct to power frequency (rms) test voltages in the cable industry.

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 cross 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) suggested in this recommended practice is 1.7 for acceptance and maintenance tests.

A.1.4.2 *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. In the case of a direct voltage, the voltage distribution may be different from that under applied alternating voltage.

Notwithstanding this limitation, there are many practical and economic advantages of using high direct voltage for testing ac apparatus. High direct voltage test equipment is small, compact, and provides an economical test which may serve to evaluate the physical condition of the insulation.

In contrast, in power frequency voltage proof testing procedures it is the usual practice to check test voltages with the winding under test connected to the test circuit to evaluate possible distortion or peaking of the voltage wave. No such test is necessary with direct voltage testing.

A.1.5 Controlled Direct Overvoltage Tests

The use of the controlled direct overvoltage test appears to offer the possibility of a warning of breakdown of an incipient fault by observation of leakage current, especially the conduction component, during step-by-step or controlled application of voltage.

Many investigators have found relationships permitting such prediction; however, some others have failed to find such relationships and have challenged their existence.

A routine maintenance program has economic advantages which are not dependent on either accuracy in prediction of breakdown voltage or certainty in avoiding breakdown.

A.1.6 Acceptance Testing Using High Direct Voltage

There has been a great quantity of test experience over a period of several years 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.2 Alternate Test Procedure: Controlled Overvoltage Test and Graded-Time Method

It is desirable to obtain only the true leakage current on 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 leakage 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 leakage current component. 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 outlined in Sections 4 and 6 for the controlled overvoltage test using the simpler uniform rate-of-rise method.

The initial voltage step is approximately 30 percent of the maximum (for 13.8 kV machines it is usually 10 kV direct voltage). 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 absorption test 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. These values are plotted as read during the test on log-log coordinate graph paper. See Fig A.1. A smooth curve is drawn through the most points following the 8 min reading. This curve is extrapolated to 10 min. Fig A.2 shows a full-scale template for a “ship's curve” which may be used in drawing smooth curves of the proper shape without delay.

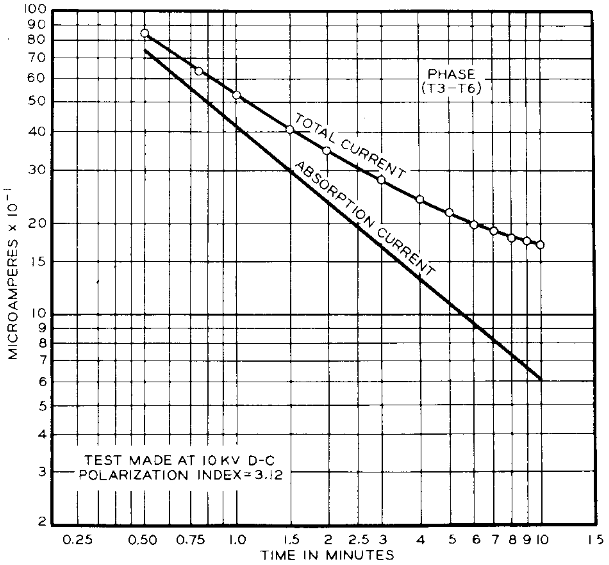

Figure A.1—Measured Current Recorded at Intervals

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 conduction component:

$$C = \frac{A}{B} = \frac{(i_{1.0} \times i_{10.0}) - (i_{3.16})^2}{(i_{1.0} + i_{10.0}) - 2i_{3.16}}$$

Subtract *C* from the 1 and 10 min total current readings to obtain the currents due to absorption. These values will then be used to calculate the absorption ratio *N* as follows:

$$N = \frac{ia_{1.0}}{ia_{10.0}} = \frac{(\text{absorption current at 1 min})}{(\text{absorption current at 10 min})}$$

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

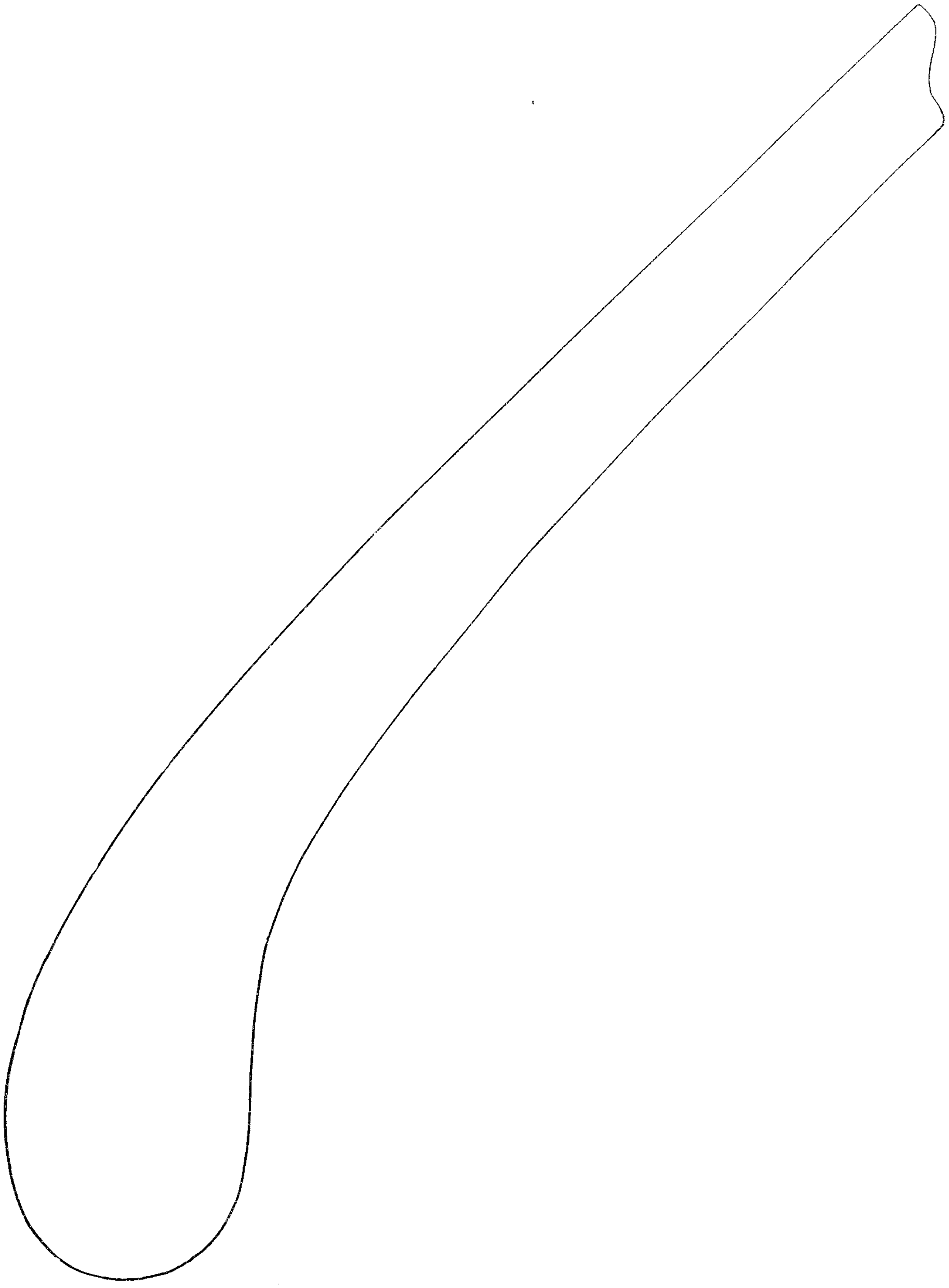

Figure A.2—Ship's Curve Template for Drawing Dielectric Absorption Curves

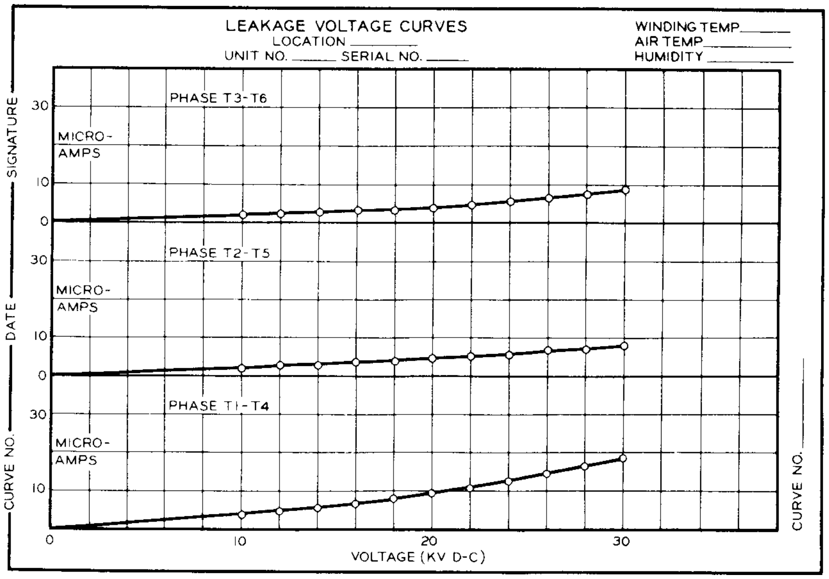

Figure A.3—Test Results of Leakage Voltage Curves

When the 10 min reading has been taken, immediately increase the voltage to the level of the second step.

This will 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 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 continually to allow for the variations due to line-voltage swings. By interpolating these swings, more accurate results may be obtained.

Test results are plotted in Fig A.3.

Table A.1—Elapsed Time at the Conclusion of Each Voltage Step

Voltage Percent 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
600	43	54	47	28	50	13	52	28	54	22	56	2	57	30	58	50

Voltage Percent 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)**
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

Voltage Percent of First Step	**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

Voltage Percent 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)**
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
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

Voltage Percent of First Step	Absorption Ratio *N* 10 (min)	10 (s)	11 (min)	11 (s)	12 (min)	12 (s)	13 (min)	13 (s)	14 (min)	14 (s)	15 (min)	15 (s)	16 (min)	16 (s)	20 (min)	20 (s)
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.