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IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Voltage at Very Low Frequency

Sponsor
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of the
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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

Foreword

(This foreword is not a part of IEEE Std 433-1974. Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Voltage at Very Low Frequency.)

The Working Group on Very Low Frequency Testing was organized by J. C. Botts, then Chairman of the Insulation Subcommittee, Rotating Machinery Committee of the IEEE Power Engineering Society. Mr Botts served as the initial Chairman of the group that first met October 6, 1970. After considering existing literature, available test equipment, and known test experience, the work of the group proceeded. Following the format of IEEE Std 95-1962, Guide for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage, responsibility to draft the several sections was accepted individually by several participants. R. J. Hillen accepted the chairman position of the group at the February 3, 1971, meeting. Progress has been steady, and in this sixth revision, it is hoped a workable, useful document has been prepared.

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1. Scope and Purpose

Design innovations and rating increases of rotating machines continuously increase the need to develop improved methods of testing insulation for serviceability. Research in the last 15 years evolved a method of 1/10 Hz overpotential testing to supplement traditional power-frequency testing and to complement direct-voltage testing. A background for VLF (very low frequency) testing is available in the technical literature. (See Section 11.)

VLF testing permits advantageous application of more easily transportable equipment both in weight and size as compared to non-resonant power-frequency testing.

This document provides a uniform method of VLF testing in order to obtain consistent results, accumulate meaningful experience, and lead to establishment of standards of test level.

References as listed in Section 10. are necessarily those which have been issued at the time this document was written. When subsequent revisions of the references are issued, they should be used in place of those indicated unless, due to a change in scope, they no longer apply.

The purposes of this recommended practice are:

1) To define terms that have a specific meaning in VLF testing
2) To describe VLF-test equipment and wave shape
3) To provide a uniform procedure for testing the armature insulation of large ac machines with VLF voltage
4) To recommend constants for relating VLF tests to power-frequency and direct-voltage tests to obtain equally effective test levels

This document applies to large ac rotating machines rated at 10 000 kVA or greater and rated 6000 V or higher.[1] It covers acceptance testing of new equipment in the factory or on-site after erection. This recommended practice also covers routine maintenance testing of machines that have been in service.

[1]VLF test may be applicable to rotating machines of lower rating and other electrical equipment.

2. Definitions

The following definitions are based on those in common use; they have been modified as necessary to be more specific for VLF testing.

acceptance proof test: A dielectric test applied to a new armature winding before commercial use.

capacitance: Capacitance, as used here, and distinguished from power-frequency capacitance, is that value which would result from a measurement at VLF, that is, 0.1 Hz ± 25 percent. In magnitude, it would tend to be greater than the power-frequency capacitance, to the extent of increased contributions made by dipole and interfacial polarizations.

dielectric test (proof test): A high-voltage test applied to the insulation of an armature winding.

NOTE — See ANSI C50.10-1965 , General Requirements for Synchronous Machines.

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

very-low-frequency test (VLF test): A test made at a frequency considerably lower than the normal operating frequency.

NOTE — In order to facilitate communication and comparison among investigators, this document recommends that the very low frequency used be 0.1 Hz ± 25 percent.

waveform (wave shape) (of a periodic function): For purposes of this procedure the function shall be considered to be of approximate sine-wave form.

NOTE — See IEEE Std 115-1965 , Test Procedure for Synchronous Machines, Section 2.40.

withstand voltage test: A high-voltage test that the armature winding must withstand without flash-over or other electric failure at a specified voltage for a specified time and under specified conditions.

NOTE — See IEEE Std 270-1966 , Definitions of General (Fundamental and Derived) Electrical and Electronics Terms.

3. Preparations for Test

3.1 Air-Cooled Machines

A VLF acceptance or maintenance proof test should be made at winding temperatures not to exceed 40 °C, unless otherwise agreed upon between the manufacturer and the user.

The usual procedure when VLF tests are made is to keep the winding dry prior to the test. (See Section 5.2.)

The winding should be inspected and cleaned before testing.

Contamination of the winding may increase test-voltage stresses in end windings, especially if moisture is present.

In view of the possibility of a flashover during the test, dirt that is oil soaked presents a fire hazard.

The presence on the windings of varnish or other surface coatings in the uncured state may cause high leakage currents. Such coatings should be allowed to dry and cure thoroughly before tests are made.

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 armature winding after the rotor has been removed. The winding can then be better inspected and observed, and it would be possible to use fire-extinguishing equipment more effectively, if necessary.

3.2 Hydrogen-Cooled Machines

Hydrogen-cooled machines may be tested in hydrogen, in carbon dioxide, or in air. When using hydrogen or carbon dioxide, suitable pressure should be applied for tests to maintain the effectiveness of the striking distances. The procedures listed in Section 3.1 for air-cooled machines should be observed.

When testing in air, it is recommended that the machine be sufficiently open and accessible to allow extinguishing of flame, in the event that fire occurs. Testing should not be done in a closed machine at elevated air pressure due to the greatly increased hazard of serious flame damage resulting from additional oxygen availability at elevated pressure.

3.3 Liquid-Cooled Armature Windings

Precautions listed in Sections 3.1 and 3.2 should be observed when the machine is tested.

On water-cooled armature windings it is necessary to have water of normal low conductivity flowing in the winding during the test or to have the hoses dried internally prior to test. (See Section 5.2.)

On oil-cooled armatures it is not necessary to have the oil circulating during test; however, the hoses should be full of oil or completely empty to prevent the possibility of internal arcing.

There should not be vacuum on the liquid systems during a high-voltage test; otherwise, there is danger of internal flashover of the hoses.

3.4 Isolation of the Winding from Cables and Auxiliary Equipment

It is preferable to exclude from the test any items that can readily be disconnected in the time available and to apply separate tests appropriate to them. Surge arrestors and capacitors should be disconnected.

Pothead and bus-bar insulators and other creepage surfaces should be dry and clean.

3.5 Sectionalizing the Winding

When feasible, each phase should be isolated and tested separately with other phases grounded. The two ends of each phase should be connected together, whether the phase is to be tested or grounded. Testing one phase at a time gives a comparison between phases that is useful in evaluating the condition of the winding and is useful for historical records.

Testing all phases at one time is suggested for machines only if the neutral connections are inaccessible. 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.

When testing all phases at one time, only ground insulation is tested, and no test is made on the phase-to-phase insulation as when each phase is tested separately with other phases grounded.

4. Safety Considerations

4.1 Area Isolation

Precautions must be taken to prevent anyone from coming in proximity of any part of the circuit or apparatus while the test is being made.

The test area must be protected by approved warning tape, and a sufficient number of guards should be stationed to protect other personnel.

4.2 Grounding Precautions

WARNING — ***Discharge of winding precautions:*** **Following a VLF test, the windings tested should be discharged by grounding for at least 15 min to ensure that no significant energy is stored in the armature winding.**

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

4.3 Grounding Provisions

A substantial grounding device should be made available for use at the conclusion of the test; also a grounding device should be readily available for use in emergency.

Ground leads with clamps or connectors of ample size should be used to preclude accidental breakage or disconnection. Such grounds may be left in place after the tests have been completed and the winding may be unattended, provided that all personnel who might come in contact with these leads are advised of their purpose and importance.

The ground wire should be extra flexible, uninsulated, and have generous current-carrying capacity and physical strength. Wire size No 6 AWG or larger is recommended.

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.

4.4 Safety Checklist

A safety checklist should be available for review prior to and after testing.

5. General Test Considerations

5.1 Possibility of Failure to Pass Test

Since unexpected failure can occur, it is important that there be adequate provision for repair at the time the test is made. (See IEEE Std 56-1958 (Reaff 1971), Guide for Insulation Maintenance for Large AC Rotating Machinery (ANSI C50.25-1972), and the appendix (Section A1.)

5.2 Condition of Winding

It may be advisable to perform a PI (polarization index) test before high-voltage test. For a complete discussion, see IEEE Std 43-1974 , Recommended Practice for Testing Insulation Resistance of Rotating Machinery and IEEE Std 56-1958 (Reaff 1971).

Conductor-cooled armature windings, using water for the coolant, have an additional electrical leakage path in the columns of water through the connecting hoses. This will grossly affect the insulation resistance reading. In order to obtain a meaningful resistance measurement, the water must be removed from the winding and the internal circuit thoroughly dried.

5.3 Test-Voltage Determination

The ratio between the VLF test crest voltage and the power-frequency test rms voltage for proof tests should be agreed upon by supplier and receiver. The presently suggested value is 1.63, or $1.15\sqrt{2}$. (See the next to last paragraph in Section A2 of the appendix.)

Acceptance proof testing for new equipment, either in the factory or field, is governed by the appropriate equipment test code, for example, as in ANSI C50.10-1965 , General Requirements for Synchronous Machines.

For maintenance proof testing, the test voltage depends 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 proved adequate. See IEEE Std 56-1958 (Reaff 1971).

6. Test Equipment

6.1 Equipment Specifications

VLF-test equipment should be rated in terms of the maximum VLF crest voltage it is capable of generating, the maximum capacitive load in microfarads, and minimum leakage resistance in megohms at which it may develop its rated voltage. (Assuming negligible series inductance at 0.1 Hz.)

The equipment should be capable of producing an alternating voltage having a frequency of 0.1 Hz ± 25 percent. The waveform shall conform to IEEE Std 4-1968, Techniques for Dielectric Tests, Section 4. (ANSI C68.1-1968).

6.2 Instrumentation

The equipment should include instrumentation to measure the instantaneous value of output voltage. Maximum error should be less than ± 3 percent of full scale.

6.3 Protection of Equipment and Test Specimen

Means should be provided to prevent the closing of test-set contactors or switches unless the output voltage control is at zero. Provision should be made for immediate tripping of the test set if the output current exceeds predetermined values.

The proper overload-current-relay setting for the test load may be selected to shut off the test voltage when failure occurs.

A sphere gap may serve as an overvoltage limiter during the test if the gap is increased 10 to 20 percent above the calculated gap for the maximum voltage. At this setting there should be no needless flashovers. Resistance of 100 000 Ω to 1 MΩ should be connected in series with the sphere gap to limit surges.

6.4 Power Source to the VLF-Test Equipment

The ac supply circuit should be free from significant voltage fluctuations. Normal station service will meet requirements of the usual equipment for VLF tests.

6.5 Operation Check

It is desirable to check kilovoltmeter calibration. This can be done by use of a sphere gap. See IEEE Std 4-1968.

When the VLF-test equipment has been set up, its proper operation verified, and all connections have been checked, then the winding may be connected.

7. Test Connections

7.1 Ground Connections

Ground connections should meet the specifications given in Section 4.3.

The frame of the machine under test should be solidly grounded.

The frame of the test set should be solidly grounded.

The phases of the winding that are not under test should be grounded. Ground the following auxiliary equipment to the machine frame:

1) Armature temperature-detector coils and thermocouples
2) Other devices associated with the winding
3) Current-transformer secondaries
4) Rotor winding and shaft

7.2 High-Voltage-Test Connections

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

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

8. Test Procedure

8.1 Voltage Application

The voltage should be applied to the winding starting with a value sufficiently low, less than 5 percent of the test voltage, to prevent overvoltages due to switching transients.

The test voltage should be raised to the specified value gradually at a uniform rate in not more than 1 min. It should be maintained at the selected test voltage for the specified standard I rain test time and then promptly decreased to zero and the winding grounded. (See Section 4.2). To avoid the possibility of switching transients, which may affect the test results, the winding should not be de-energized suddenly.

In the event of a failure, the test voltage should be reduced immediately to prevent voltage buildup and to prevent a repeat of the flashover or failure. Carefully inspect winding for location of fault before further testing is done.

When failure occurs at a very low voltage, or when a high-resistance failure occurs, the overload-current relay may not trip. However, failure will usually be indicated by a marked drop in the voltmeter reading. In such case, the test voltage should be returned to zero in accordance with the second paragraph of Section 8.1 above.

8.2 Fault Detection

In the event of a failure, carefully inspect winding for location of fault before further testing is done.

The failure may not be readily located by observation of flashover discharge when VLF is applied. It is often practical to use power-frequency voltage (230 V) with current limited to about 10 A to identify the point of failure. If the failure point cannot be otherwise located, then the winding may be successively divided and tested until the point of breakdown is located.

The number of repeat tests should be limited to avoid possible damage to the balance of the winding from surges that may occur when the winding discharges.

On repeat tests it is recommended that several observers be stationed at safe distances from the machine to assist in rapidly identifying the location of the fault.

When the failed coil has been located, it should be electrically isolated so that the balance of the winding can be tested to the VLF crest test voltage. The isolated coil should be grounded and the winding made electrically continuous where the coil had been in the circuit.

9. Test Results

9.1 Interpretation

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 winding is considered satisfactory.

9.2 Suggested Test Record

The suggested test record includes:

1) Serial number of machine under test
2) Machine rating, type of insulation
3) Manufacturer's name
4) Date of test
5) Time of test
6) Test voltage and duration
7) Test connection and connected apparatus (if any)
8) Temperature of winding
9) Temperature and humidity of environment
10) Test equipment description

9.3 Comments to Be Recorded

Record comments regarding:

1) Reason for test
2) Visual inspection
3) Physical condition of winding and insulation
4) Resistance and PI prior to test if applicable (See IEEE Std 43-1974)
5) Pertinent history of equipment
6) Date of winding installation

7) Observations of distress, corona, etc, during test
8) Result of test and action taken
9) Recommendations for maintenance, operation, or future test activity

10. Standards References

IEEE Std 4-1968, Techniques for Dielectric Tests (ANSI C68.1-1968)

IEEE Std 43-1974, Recommended Practice for Testing Insulation Resistance of Rotating Machinery

IEEE Std 56-1958 (Reaff 1971), Guide for Insulation Maintenance for Large AC Rotating Machinery

IEEE Std 62-1958, Guide for Making Dielectric Measurements in the Field

IEEE Std 95-1962, Guide for Insulating Testing of Large AC Rotating Machinery with High Direct Voltage

IEEE Std 100-1972, Dictionary of Electrical and Electronics (ANSI C42.100-1972)

IEEE Std 115-1965, Test Procedure for Synchronous Machines

IEEE Std 270-1966, Definitions of General (Fundamental and Derived) Electrical and Electronic Terms

ANSI C50.10-1965, General Requirements for Synchronous Machines

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Annex A
(Informative)

A.1 General Principles of High-Voltage Testing

Proof tests are made to determine whether apparatus insulation has enough margin of integrity that it will not be likely to fail in service before the next test period.

The justification for a proof test is that it searches out an incipient failure during a planned outage rather than at an inconvenient time, and with less risk of damage to adjacent parts of the equipment than from machine or system fault current.

Many years of experience with power-frequency high-voltage testing have resulted in the establishment of voltage levels and times of application that give reasonable assurance of insulation free from defects. The standard factory power-frequency acceptance proof-test voltage is twice rated voltage plus 1000 V. An acceptance test on equipment newly installed is commonly made at a magnitude of 75 to 85 percent of the factory test. Maintenance proof tests made after a period of service will ordinarily be at some lesser value.

Successfully passing an acceptance or maintenance proof test does not guarantee against failure before the end of the next service interval. Experience has shown, however, that many weak spots are found in this way. Stated another way, proof testing means fewer service failures.

A.2 Comparison of Power-Frequency, VLF, and Direct-Voltage Testing

The voltage gradient in composite insulation under alternating-voltage stress is controlled by the capacitance and resistance of the various elements of the insulation. Under constant direct-voltage stress, the leakage current is controlling once equilibrium is established. An advantage of alternating-voltage testing is that it stresses the end turns of the insulation in the same way as normal service.

An alternating voltage high enough to cause ionization will cause degradation of the insulation; the degradation has been found to be proportional to the frequency. This fact has been suggested as a disadvantage of power-frequency testing, but the usual duration of application of voltage is 1 rain and unless tests are made very often or at excessive voltage, the amount of degradation produced by testing during the life of the equipment should be negligible.

A significant disadvantage of power-frequency testing where large volumes of insulation are concerned is that a nonresonant test set large enough to supply the charging power becomes so heavy as to be not easily portable.

When high direct voltage is applied to insulation, only a limited number of flashes of ionization occur within voids in the insulation. This is an advantage of direct-voltage maintenance testing.

Other advantages of direct-voltage testing are: (1) in the event of breakdown there is less disruptive effect to material adjacent to the fault, and (2) the direct-voltage-test equipment for high voltage is much less bulky than power-frequency equipment for the same service.

A disadvantage of direct-voltage testing, when the voltage is held constant, is that the voltage may not distribute itself in the insulation the way power-frequency alternating voltage does. Specifically, it has been found that with direct voltage the entire end turn section of rotating machinery is stressed, whereas with alternating voltage, the voltage across the insulation wall of the coils in the end winding reduces going away from the slot. So far as the slot portion is concerned, it has been found that for short-time tests, the stress distribution is essentially capacitive, the same as for 60 Hz. Thus the disadvantage of direct-voltage testing relates to the voltage distribution along the coil length rather than the voltage distribution across the ground-wall insulation.

In an attempt to combine the advantages of power-frequency and direct-voltage testing and eliminate the disadvantages, the use of VLF testing was investigated. It was found that for the insulation systems commonly used in high-voltage armature windings, the stress distribution for frequencies as low as 0.1 Hz may not be significantly different from that at 60 Hz.

Another consideration is the equivalence of 0.1 Hz and direct voltage with 60 Hz; in other words, what voltages impose equal duty on the insulation. The accepted voltage ratio of direct voltage/60 Hz is 1.7 and the 0.1 Hz (crest)/ 60Hz (rms) ratio is approximately 1.63. The ratios are not exact and the phenomena involved are complex; results are different for different configurations and service experience of insulation. The ratios given have been found to give good results on high-voltage armature windings. (In studying 0.1 Hz test performance, various investigations have found ratios of 1.0 to 1.4 between VLF rms and power-frequency rms test voltage; the value 1.15 is recommended, thus giving the specified crest/rms ratio $1.15\sqrt{2} = 1.63$.)

A comparison of the three types of tests is given in Table A-1.

Table A-1—High-Voltage Tests, Withstand for 1 min

	60 Hz (rms)	**dc**	**0.1 Hz (crest)**
Test voltage	E	$1.7E$	$1.63E$
End turn stress	little of end turn stressed	most of end turn stressed	intermediate between 60 Hz and dc
Number of bursts of ionization (in voids)	7200	few	12