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IEEE Recommended Practice for Voltage-Endurance Testing of Form-Wound Bars and Coils

Sponsor

Voltage Endurance Committee
of the
Dielectrics and Electrical Insulation Society

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Abstract: The voltage endurance testing of form-wound bars and coils for use in large rotating machines is covered.
Keywords: electrical insulation, form-wound bars, form-wound coils, voltage endurance testing

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Introduction

(This introduction is not part of IEEE Std 1043-1996, IEEE Recommended Practice for Voltage Endurance Testing of Form-Wound Bars and Coils.)

The voltage endurance test for full size stator bars and coils has been used by generator manufacturers and users for almost 40 years. The first version of the recommended practice was issued in 1985. Its use over the years showed that the recommended practice needed to be clarified, and ambiguities needed to be eliminated. The present version has attempted to do this. Compared to the first version, there are no major differences in the testing procedure.

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IEEE Recommended Practice for Voltage-Endurance Testing of Form-Wound Bars and Coils

1. Overview

1.1 Scope

This recommended practice covers the voltage endurance testing of form-wound bars and coils for use in large rotating machine stator windings. Such testing is defined for machines with a nominal voltage rating up to 30 000 V. These tests are to be applied at 50 Hz or 60 Hz and may be done at either room temperature or elevated temperature. (Testing at 50 Hz or 60 Hz may yield different times to failure for comparable samples.) The specimen to be tested should be representative of the bars or coils used in the machine, and should include the complete insulated bar and external grading construction that the machine winding would have. Special features different than those used in the machine should not be added to the test specimens.

1.2 Purpose

The purpose of this recommended practice is to define a voltage endurance test method for use on insulated, form-wound bars and coils for installation in large rotating machine stators. These voltage endurance tests may be applied to representative specimens of form-wound, insulated bars and coils for either new machines or machines to be rewound. The intent of this document is to define the specimen, the associated testing equipment, and the procedure for performing these voltage endurance tests. Specific numerical values for acceptable voltage endurance lifetimes are not recommended at this time. The voltage and temperature of the test, the minimum acceptable lifetime, and the number of specimens to be tested should be established prior to testing (see 7.5).

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2. References

The following publications shall be used in conjunction with this standard. When the following standards are superseded by an approved revision, the revision shall apply.

ASTM D1868-93, Standard Method for Detection and Measurement of Partial Discharge (Corona) Pulses in Evaluation of Insulation Systems.[1]

IEEE Std 4-1995, IEEE Standard Techniques for High-Voltage Testing (ANSI).[2]

IEEE Std 43-1974 (Reaff 1991), IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery (ANSI).

IEEE P286 (D12/1-7-97), Draft Recommended Practice for Measurement of Power-Factor Tip-Up of Rotating Machinery Stator Coil Insulation.[3]

IEEE Std 930-1987 (Reaff 1995), IEEE Guide for the Statistical Analysis of Electrical Insulation Voltage Endurance Data (ANSI).

3. Definitions

3.1 groundwall insulation: The main high-voltage electrical insulation that separates the copper conductors from the grounded stator core in motor and generator stator windings.

3.2 semiconductive slot coating: The partially conductive paint or tape layer in intimate contact with the groundwall insulation in the slot portion of the stator core. This coating ensures that there is little voltage between the surface of the coil or bar and the grounded stator core.

3.3 stress control coating: The paint or tape on the outside of the groundwall insulation that extends several centimeters beyond the semiconductive slot coating in high-voltage stator bars and coils. The stress control coating often contains silicon carbide particles that tend to linearize the electric field distribution along the coil or bar endturn. The stress control coating overlaps the semiconductive slot coating to provide electrical contact between them.

3.4 test temperature: The temperature of the heater plates mounted on the stator coil or bar, as measured by a temperature sensor embedded within the heater plate.

3.5 voltage endurance: The time-to-failure of the groundwall insulation under a high electrical stress.

4. Testing equipment

Voltage endurance testing imposes specific requirements on the testing equipment in order that the results will be valid and the variance will be minimized. A practical testing equipment arrangement is described below and illustrated in figure 1.

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[1]ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA.

[2]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

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

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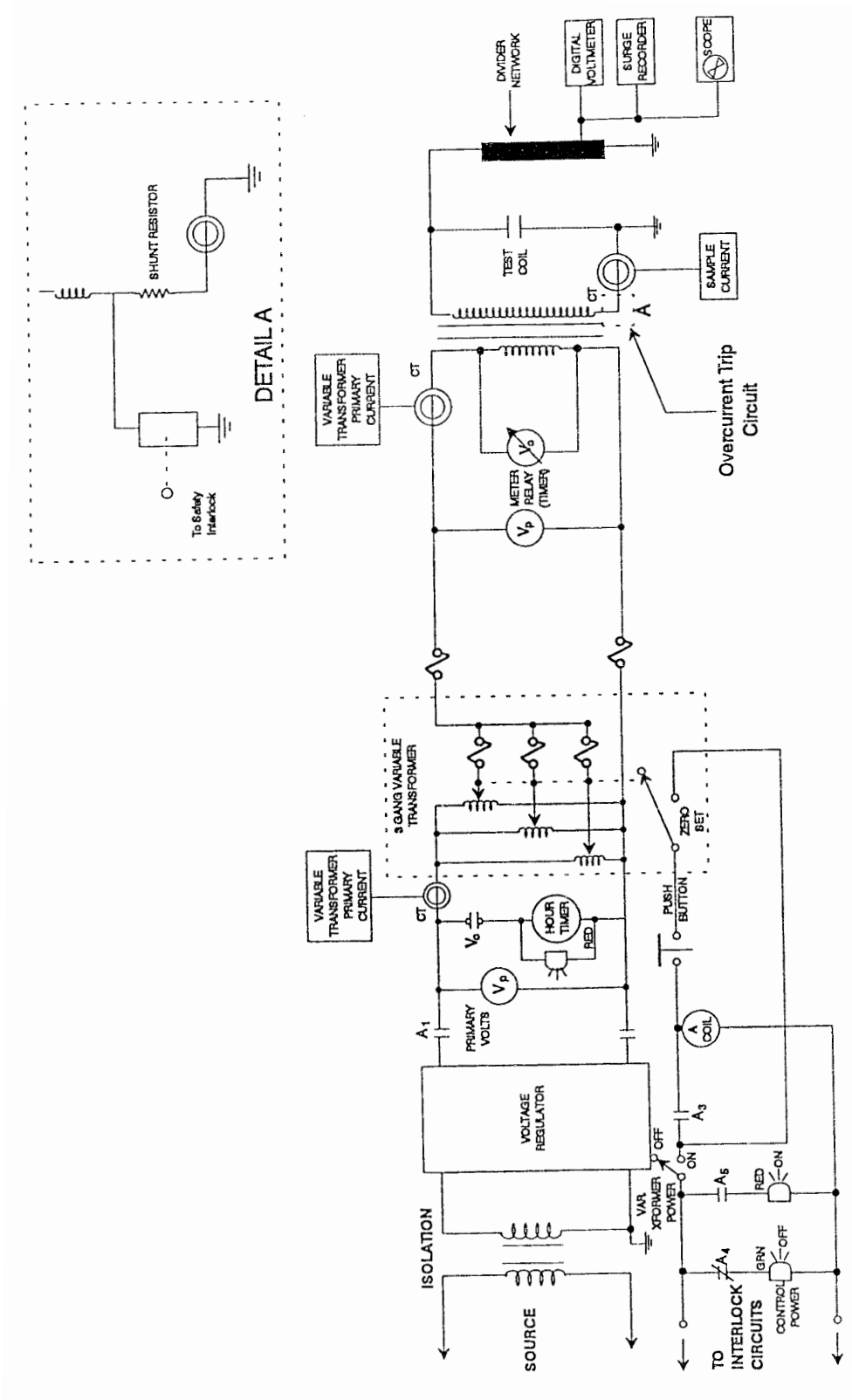


Figure 1—A suggested circuit arrangement of the voltage endurance test

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To ensure accuracy and traceability, it is necessary for the test laboratory to establish and maintain calibration and accuracy records for all relevant test equipment.

4.1 Power supply

A power supply with a variable output voltage should be used that can be set precisely and that will remain at the same output voltage level for the duration of the test, which may extend to thousands of hours. The root-mean-square (rms) input voltage should be regulated to ± 1.5%. The ratio of peak-to-peak voltage to rms voltage should be equal to $2\sqrt{2}$ within ±5% and should be stable over the duration of the test. Note that a difference greater than ± 5% may result in shorter insulation life due to a greater number of voltage harmonics.

The volt-ampere rating of the high-voltage transformer is dependent on the specimen load. The specimen load may affect the waveshape. The transformer's response in turn determines the harmonic content of the voltage waveform. Waveform distortion is primarily caused by the odd harmonics, with the third and fifth harmonics predominating. For voltage waveforms to meet a $2\sqrt{2}$ ± 5% requirement, the third harmonic amplitude will normally be no greater than about 10% of the amplitude of the fundamental. Means are available for improving the waveshape, including adjusting the capacitance on the primary or the secondary of the transformer.

The important features of a typical power supply arrangement are identified in figure 1. Voltage application is best accomplished with a variable transformer feeding a step-up transformer. A hand-operated autotransformer is suitable for voltage control, but motor operation with adjustable rate-of-rise is a convenient feature that offers a smooth voltage ramp.

4.2 Protection

In addition to a primary breaker in the supply, there should be a suitably rated contactor feeding the variable transformer. The contactor coil should have the following trip contacts wired in series:

a) The contact from an adjustable overcurrent trip circuit that operates from the neutral side of the high-voltage winding. The trip value is set just above the normal current level (150% suggested maximum) on initial energization. This protection should operate fast enough to minimize damage to the specimen from the fault current when the specimen fails.
b) A contact from a large, emergency-trip button of the "mushroom" type that is mounted in a prominent location on the front of the control panel to de-energize immediately the high-voltage supply if necessary.
c) An interlock contact that prevents entry into the test cage/area while the transformer is energized.
d) A zero-position limit contact on the variable autotransformer to prevent energization in any position but the zero-voltage position.

4.3 Metering

4.3.1 Voltage

A direct and accurate measurement of the high-voltage that is applied to the specimens is required. A potential transformer or capacitive voltage divider on the high-voltage side of the step-up transformer should be connected to a good quality meter (± 1%) on the control panel. Alternatively, a suitable high-voltage voltmeter can be connected directly across the specimen. The equipment calibration shall be in terms of peak-to-peak voltage divided by $2\sqrt{2}$.

Applied voltage during the test shall be determined within an uncertainty of 1.5% of full scale and monitored during the test in such a way as to ensure no more than a specified variation (± 2% recommended)

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occurs. The applied voltage waveshape may not be exactly sinusoidal. Therefore, although the voltage specification should be in terms of the rms voltage, the actual measurement should be in terms of the peak-to-peak applied voltage since this is the single quantity that best determines the amount of partial discharge. Such a measurement might be made by an oscilloscope with a suitable voltage divider.

Another practical means of measuring peak-to-peak voltage, requiring a high-voltage capacitor, a dc milliammeter, and a low-voltage diode bridge rectifier, is shown in figure 2. This circuit will provide a sufficiently accurate indication of voltage, provided that the voltage waveshape does not have harmonics large enough to create intermediate reversals of slope between each peak and the succeeding peak of the opposite sign.

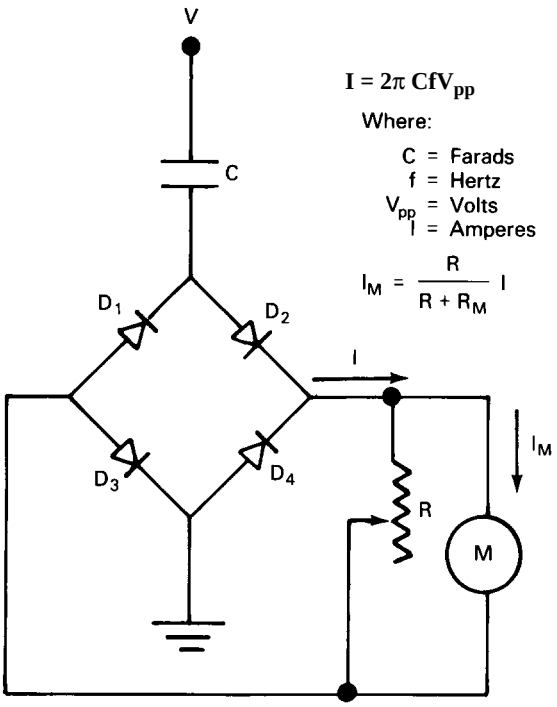


Figure 2—Peak-to-peak voltmeter

4.3.2 Current

Metering of the load current on the high-voltage side of the transformer is desirable and is facilitated by introducing between the neutral terminal of the high-voltage winding and ground either a current transformer and ammeter or a directly connected milliammeter. Usually ± 5% precision is sufficient in this case. The current meter may have a bypass switch to protect it from fault currents that result from a specimen failure. This switch should be in the bypass position except when a reading is required. The current measuring device is to be in series with the recommended overcurrent sensor [see 4.2, item a)].

4.3.3 Elapsed time

The test time of the specimens are monitored either by an elapsed time meter with a resolution of 0.1 h or a computer-controlled data acquisition system with a resolution of 0.1 h. The test time measuring system is connected across the input to the variable autotransformer, and consequently, it only operates when the specimens are energized. It stops when the supply is shut off or is tripped off by a specimen failure.

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4.3.4 Temperature

The temperature of the heater plates, measured as described in 5.4, will be recorded. The temperature of the heater plates is the voltage endurance test temperature.

4.3.5 Recording

The important test parameters of voltage and temperature should be recorded on a chart recorder or on a data acquisition system since the voltage endurance test is often left unattended. The test voltage and temperatures should be recorded in a computer file, chart, or in a printout at least once every 15 min. The time-to-failure will be recorded with a resolution of 0.1 h.

If electrical power to the specimen is interrupted or the temperature deviates from that required, the event and an explanation for the event should be recorded.

4.4 Temperature control

If the tests are to be performed at an elevated temperature, the test temperatures are controlled to within ± 2 °C by means of heated plates that are clamped to the slot-section sides of the specimens. It is recommended that the plates be 1 cm thick to achieve good thermal contact along the length of the plates, and to enable temperature measurement (see figure 3). These plates also provide the ground connection to the specimen. Heating is provided by attaching resistive strip heaters controlled by a thermostat to the outside surface of each pair of plates. A heat-transfer paste or putty should be used between the strip heaters and the heater plates. The heating portion of the strip heaters shall cover at least 75% of the length of the heater plates.

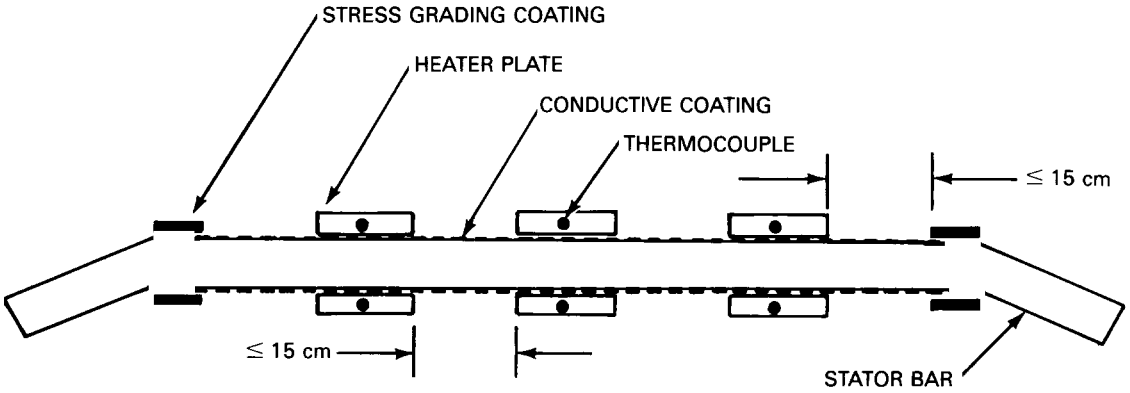


Figure 3—Application of heater plates to a stator bar

To achieve the desired plate temperature with heaters having a lower power rating, thermal insulation may be placed over the plates, but not over the entire specimen.

If the temperature of the heater plates deviates by more than ±2 °C, then it is recommended that the voltage applied to the test specimens be interrupted for the duration of the deviation.

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5. Specimen preparation

For the purpose of this procedure, every effort should be made to test the entire bar or coil. However, this may not be practical in the case of very large bars or coils.

When the slot length (i.e., the straight portion of the bar or the coil that would normally be in the slot of the stator core) of the actual production bar or coil is 250 cm or less, the test specimens shall be the actual production or prototype bars or coils, including all insulation components of the finished bars or coils, but not including any special slot-support components normally applied to or used with the bars or the coils. All the strands in the conductor shall be electrically connected at both ends.

When the slot length of the actual production bar or coil is greater than 250 cm and sufficiently long test bays are not available to accommodate the entire bar or coil, sections of actual bars or coils may be tested. These sections will include all insulation components that are normally applied to or used with them. Each section will have an effective slot length consistent with table 1. All the sections cut from the bar/coil will be subjected to the voltage endurance test. The sections tested shall include the ends of the bar or coil. About 50 cm of additional length is required at each cut end to allow for a stress control coating and electrical clearance. All the strands in the bar or coil shall be electrically connected at both ends. A suitable method of applying stress grading at the end of each cut section shall be established prior to test.

Table 1—Recommended testing lengths for bars or coils

Slot length (cm)	Test length
0–250	Test entire bar or coil
250–350	Test one section with 250 cm effective slot length
350–600	Cut into two equal lengths
> 600	Cut into two or more sections with at least 250 cm active slot length

To determine whether the bar or the coil will pass or fail, all slot sections of the original bar or coil will be treated as one specimen. For example, if four coils or bars are required for the test and each coil or bar should be cut into two pieces, all eight pieces should be tested. Failure of any one piece constitutes failure of the original uncut bar or coil.

5.1 Pretest evaluation

The tests in 5.1.1 through 5.1.4 may be performed prior to performing the voltage endurance test.

5.1.1 Electrical proof test

A predetermined ac voltage may be applied to the bar or prepared section of the bar as a proof or withstand test in accordance with IEEE Std 4-1995. A value of 110% of the voltage selected for endurance testing is recommended. This voltage is then maintained at the required value for 1 min.

5.1.2 Dissipation factor measurement

If required, dissipation factor (power factor or tangent delta) tip-up and capacitance measurements shall be performed in accordance with IEEE P286.[4]

[4]Information on references can be found in clause 2.

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Note that it may not be practical to attempt dissipation factor measurements in the vicinity of other apparatus operating at high voltage.

5.1.3 Insulation resistance

If required, insulation-resistance measurements shall be in accordance with IEEE Std 43-1974.

5.1.4 Partial discharge

If required, partial-discharge quantities can be measured. Partial-discharge tests shall be carried out at room temperature at a minimum of rated line-to-ground voltage. Methods for measuring partial-discharge activity are described in ASTM D1868-93.

5.2 Electrode system

5.2.1 High-voltage electrode

The high voltage may be applied to the shorted conductors (or strands) of each coil through a maximum 1000 Ω, 10 W resistor for the purpose of suppressing voltage surges to other bars/coils when one bar/coil fails. As an alternative, an inductor may be used for this purpose, if it is shown that it does not give rise to resonances.

5.2.2 Ground electrode

The clamp-on metal heater plates shall be grounded to form a part of the ground electrode (see figure 3). The conduction surface built into the coil or the bar forms the remainder of the ground electrode. Plates shall be mounted on each side of the active test section to provide electrical grounding, and to distribute the heat uniformly over the specimen surface. Refer also to 6.1. If the test is performed at room temperature and the test temperatures are not monitored, the slot section should be grounded through clamp-on metal plates or by wrapping metal foil or wire around the length of the slot section. The gaps between individual wraps of the foil or wire shall not exceed 15 cm.

5.2.3 Stress control coating

The stress control coating supplied with the production bars shall be the only stress grading used unless the bar must be cut, in which case a suitable method for applying stress control coatings on each new cut section shall be established prior to testing. Refer also to 7.3.3.

5.3 Application of heater plates

5.3.1 Length

The metal heater plates should be uniformly distributed over the surface of the slot portion of the bar or the coil, with no more than 15 cm between adjacent plates and with the plates no further than 15 cm from the stress-relief coating at each end (see figure 3).

5.3.2 Uniformity of contact

The heater plate sections may be attached to the test specimen by suitable (for example 1/4"–20) threaded rods across each pair of heaters plates, on which the nuts are tightened. The threaded rods shall be spaced no more than 30 cm apart along the length of each plate. Care should be taken to ensure good contact between the heater plates and the bar or the coil. This can be checked by ensuring that a 0.2 mm feeler gauge cannot be inserted between the bar or the coil and the heater plates at any position.

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5.4 Thermocouple application

Thermocouples for monitoring specimen temperature shall be placed in holes that are at least 4 cm deep and centrally located in the edges of the heater plates, as shown in figure 3. At least one thermocouple is placed in each pair of opposed heater plates. Heat transfer paste or putty should be used to ensure good thermal contact between the thermocouple and the metal plate. The thermocouple temperature is defined to be the temperature of the heater plates, and thus, the test temperature.

6. Voltage endurance testing and safety considerations

The test setup should conform to all local safety codes. As a minimum, the following should be considered.

6.1 Grounding

The following metal parts shall be grounded to a common point by an equipment grounding conductor rated for the fault current of the associated test equipment:

a) Conducting surface of the specimens
b) Power supply return
c) Voltage metering circuits
d) Metallic support structures
e) Heater plates
f) Protective fences

The path to ground from circuits, equipment, and enclosures shall be permanent and continuous.

6.2 Discharging considerations

A portable ground conductor should be used to solidly ground the test specimen after the high voltage has been removed and before the test specimen is handled.

6.3 Test areas, lights, and interlocks

Because this test is unattended most of the time, it is imperative that the test area be interlocked in such a way that access to the test area is not possible while the specimens are energized. Consideration should also be given to the following:

a) Posted signs
b) Flashing red beacon lights
c) Trip beams and shutdown interlocks
d) Safety fences and guards on high-voltage conductors
e) Locked access gates
f) Notice to security guards of the hazard
g) Posted instructions for safety shutdown by security personnel or others in case of fire or other emergency
h) Key-locked start switches to prevent restarting except by authorized personnel

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6.4 Experience

Personnel shall be trained in the safe use of the test setup. Connections should be checked by a second knowledgeable person.

6.5 Failure currents and trip circuits

See 4.2.

6.6 High-voltage test-lead connections

The following requirements should be taken into consideration when connecting test leads:

a) Test lead connections should be well made to prevent accidental separations during the test.
b) Test lead connections should be supported, if necessary, on adequate standoffs or tied in place with high dielectric-strength cords or tapes.
c) High-voltage leads should be kept well clear of grounded surfaces to prevent corona discharges or flashover to ground.

6.7 Health concerns

The test may produce ozone. The area shall be ventilated to prevent a health hazard.

7. Test procedures

7.1 Temperature stabilization

The heater plates on the specimens shall be brought to the appropriate test temperature and allowed to stabilize at the test temperature prior to the application of the test voltage. The heater plate temperature is measured as described in 5.4. The time required for this to occur will clearly depend on the sample structure, but should be chosen so that the heater-plate temperatures are within ±2 °C of the specified test temperature before voltage application.

7.2 Application of voltage

7.2.1 Rate of application

The test voltage should be applied in a sufficiently gradual manner (see IEEE Std 4-1995) so that no significant overshoot or spikes of voltage will result from the turn-on process.

7.2.2 Initial observation of stability

The stability of the voltage should be verified as discussed in 4.3.1.

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7.3 Failure

7.3.1 Failure location and verification

Failure of a specimen occurs when any puncture of the groundwall insulation develops. This will result in the overcurrent detection system interrupting current to the high-voltage transformer. Specimen failure should be verified by an attempt to reapply voltage by increasing it gradually from zero. A specimen insulation puncture will prevent the reapplication of full test voltage. Locating the failure site is desirable; arcing or heating at the failure site is often visible as the reapplied voltage is raised. When specimen failure has been verified, if established before the test, the failed sample shall be isolated to continue testing on the remaining samples.

7.3.2 Failed specimen observations

Each failed specimen shall be examined to ensure that the failure is valid for statistical interpretation. This may require some specimen dissection in the area around the insulation puncture to identify the failure location and its cause, if possible.

7.3.3 Maintenance of stress control and semiconductive slot coatings

A stress control coating is usually applied to the outer surface of the coil or bar beyond the grounded semiconductive slot coating. These stress grading and slot coatings may take the form of paints or tapes, or a combination of the two. During the voltage endurance test, deterioration may occur involving the stress grading and/or slot coatings, which does not result in insulation failure. It should be determined at the beginning of the test whether or not deterioration involving the stress grading and slot coatings is to be monitored and repaired periodically during the progress of the voltage endurance test.

7.3.4 Insulation failure involving stress control coating

During the voltage endurance test, an insulation failure may occur where the failure path meets the outer surface in the stress grading area. Alternatively, the failure may occur within 50 mm of the interface between the semiconductive slot coating and the stress control coating. Such insulation failures shall be considered to have involved the stress control coating. It should be determined at the beginning of the test whether or not insulation failures involving the stress grading shall be considered as specimen failures for the purpose of the test. However, some erosion or discoloration of the stress control coating during the voltage endurance test is normal, and is not considered as an insulation failure (see 7.3.3).

7.3.5 Physical measurements

The thickness of the insulation wall (ground plus turn plus strand) shall be determined at or near the voltage endurance failure site. The thickness is defined at the location shown in figure 4.

7.4 Suggested test records

The following items are suggested for inclusion in test records:

a) Ambient temperature and humidity in the test area, if the specimens are tested at room temperature
b) Applied voltage, expressed in equivalent rms, i.e., peak-to-peak divided by $2\sqrt{2}$
c) Frequency of applied voltage in hertz
d) Total endurance time of each sample
e) Results of any preliminary or intermediate diagnostic tests or measurements
f) Observations of failure locations
g) Observations on the nature of failure or of stress-grading damage

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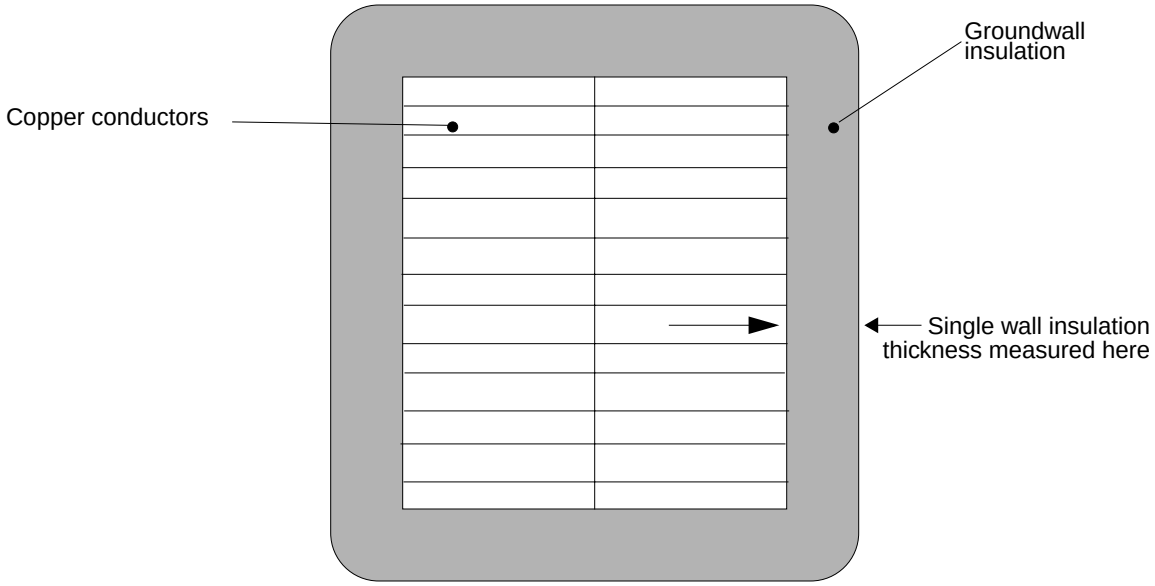


Figure 4—Cross-section of a stator bar or coil

h) Voltage endurance test temperature, i.e., the temperature of the thermocouples embedded in the heater plates
i) Minimum and maximum test voltage and test temperature during the test

It will also be desirable to include other information, such as the nature of the samples, the nature of the electrodes, and the nature of the stress-grading material.

7.5 Test parameters to be defined

The following parameters should be established prior to the commencement of testing of the specimens:

a) Test temperature
b) Test voltage and frequency
c) Acceptable time-to-failure
d) Maintenance of slot and stress-grading coatings
e) Diagnostic tests required before and after the voltage endurance test
f) Number of specimens
g) Specimen length
h) Disposition of failed samples
i) Treatment of insulation failures in stress grading area (see 7.3.4)

8. Data analysis and consideration for interpretation

8.1 Test data

The result of this test is the time-to-failure for each bar, or for the first leg of coil, or for the first section of a cut-up bar or coil.

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8.2 Analysis of data from many samples

8.2.1 Data analysis

When five or more identical coils or bars have been tested, the data can be analyzed rigorously using statistical methods. The Weibull probability distribution with two parameters is usually used to summarize the test data—the scale parameter (α) and the shape parameter (β). The failure data can also be plotted on a probability paper. Probability plotting and methods to estimate the parameters are discussed in IEEE Std 930-1975.

8.2.2 Comparison tests

Objective comparisons between the failure data from two different types of coils or bars are possible using statistical procedures. IEEE Std 930-1987 describes the method required to determine if two (or more) sets of failure data differ significantly. Plotting the different sets of failure data on the same probability graph paper is also useful. The greater the difference in times-to-failure between two sets of data, the fewer are the number of specimens that will be required.

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Annex A

(informative)

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