IEEE Guide for Functional Evaluation of Insulation Systems for AC Electric Machines Rated 2300 V and Above

IEEE Power Engineering Society

Sponsored by the
Electric Machinery Committee

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IEEE-SA Standards Board

Abstract: A procedure that may be used to evaluate and compare insulation systems used, or proposed for use, in large ac electric machines is described in this guide.
Keywords: ac, accelerated aging, armature winding, electric machine, electrical insulation, electromechanical, functional evaluation, stator winding, thermal endurance, thermal expansion, thermomechanical, voltage endurance

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Introduction

This introduction is not part of IEEE Std 434-2006, IEEE Guide for Functional Evaluation of Insulation Systems for AC Electric Machines Rated 2300 V and Above.

During operation, the electrical insulation of large ac machines is continuously subjected to electrical, thermal, mechanical, and environmental stresses. These stresses initiate aging mechanisms that cause irreversible changes in the electrical and physical properties of the insulation, eventually leading to degradation and failure. To perform satisfactorily, an insulation system must retain an adequate level of electrical and physical strength throughout its expected service life.

Manufacturers of large machines continually strive to develop and employ better materials, designs, and manufacturing processes to improve the performance and reduce the cost of their insulation systems. When changes are made to a service-proven insulation system, it is necessary to evaluate the effects of these changes. Functional tests provide a means of evaluating an insulation system by exposing it to factors of influence that simulate or are characteristic of actual service conditions. This guide establishes the basis for evaluating the aging of the electrical insulation system as a result of these influences. It is recognized that this guide does not describe all of the functional tests currently in use by manufacturers of large ac machines, and that additional tests may be required to achieve a complete evaluation and classification of a new insulation system. The functional tests described in this guide are, however, in widespread use.

This revision of the guide updates the previous edition mainly to clarify the intent and performance of the different functional tests. Future revisions are contemplated to include additional functional tests, and details of test procedures and analysis of results.

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IEEE Guide for Functional Evaluation of Insulation Systems for AC Electric Machines Rated 2300 V and Above

1. Overview

1.1 Scope

This guide describes a procedure that may be used to evaluate and compare insulation systems used, or proposed for use, in large ac electric machines.

The tests outlined herein are applicable to the groundwall insulation systems applied to form-wound, pre-insulated armature (stator) winding coils and/or bars of generators, motors, and synchronous condensers rated 2300 V or higher.

The basic component of these insulation systems is usually mica combined with reinforcing, bonding, and impregnating materials. This guide is based on the experience of the industry with mica-based systems; any evaluation of other insulation systems should, however, consider the recommendations of this guide.

This guide is not intended for use as a manufacturer's quality assurance test plan. Nor should it be used for specifying or procuring armature winding coils/bars.

1.2 Purpose

During operation, an insulation system is subjected to electrical, thermal, mechanical, and environmental stresses that act and interact to cause irreversible changes in the properties of the insulation. The applied stresses initiate aging mechanisms that eventually lead to failure. The purpose of this guide is to provide a means of evaluation in which groundwall insulation systems, as described in 1.1, are exposed to influencing factors that simulate or are characteristic of actual service conditions. This guide establishes the basis for evaluating the aging of the electrical insulation system as a result of these influences.

2. Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ASTM D149-97A (Reaff 2004), Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies.[1]

IEC 60034-18-1:1992, Rotating Electrical Machines—Part 18: Functional Evaluation of Insulation Systems—Section 1: General Guidelines.[2]

IEEE Std 4™-1995, IEEE Standard Techniques for High-Voltage Testing.[3, 4]

IEEE Std 4A™-2001, Amendment to IEEE Standard Techniques for High-Voltage Testing.

IEEE Std 275™-1992, IEEE Recommended Practice for the Thermal Evaluation of Insulation Systems for AC Electric Machinery Employing Form-Wound Preinsulated Stator Coils for Machines Rated 6900 V and Below.

IEEE Std 286™-2000, IEEE Recommended Practice for the Measurement of Power Factor Tip-Up of Electric Machinery Stator Coil Insulation.

IEEE Std 429™-1994, IEEE Recommended Practice for Thermal Evaluation of Sealed Insulation Systems for AC Electric Machinery Employing Form-Wound Coils for Machines Rated 6900V and Below.[5]

IEEE Std 1043™-1996 (Reaff 2003), IEEE Recommended Practice for Voltage Endurance Testing of Form-Wound Bars and Coils.

IEEE Std 1310™-1996 (Reaff 2004), IEEE Recommended Practice for Thermal Cycle Testing of Form-Wound Stator Bars and Coils for Large Generators.

IEEE Std 1553™-2002, IEEE Standard for Voltage-Endurance Testing of Form-Wound Coils and Bars for Hydrogenerators.

3. General considerations

3.1 Factors causing deterioration

Deterioration of the insulation in large ac electric machines is caused by thermal, mechanical, electrical, and environmental stresses. These stresses initiate aging mechanisms that permanently change the physical, chemical, and electrical characteristics of the insulation and eventually lead to failure. Ideally, functional evaluation tests would duplicate all aging mechanisms that occur in service. In practice, this is often difficult to achieve. Experience has shown that multiple aging factors may combine and interact, significantly affecting the deterioration process as well as the rate of deterioration. Given the synergistic nature of the various aging factors, stresses applied sequentially will not lead to failure times equal to those that would occur were the stresses to act simultaneously. A further impediment toward duplicating the service environment is that similar equipment may be used in many different applications and operated under varying degrees of severity, making it difficult to establish typical service conditions and modes of deterioration.

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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 (http://www.astm.org/).

[2] IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http:// www.ansi.org/).

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[5] IEEE Std 429-1994 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181 (http://global.ihs.com/).

3.2 Functional tests

This guide describes the following types of functional tests:

- voltage endurance
- thermal endurance
- thermomechanical endurance
- electromechanical endurance.

Interactions between the different aging factors are minimized in the separate tests of this guide by maintaining all stress factors at normal service levels except for the one factor being evaluated. This does not preclude the use of a periodic diagnostic test to determine an end point or to compare pre-aged test specimens against unaged specimens.

Each deteriorating effect should be tested separately; that is, a dedicated sample should be evaluated for each functional test described in this guide. If desired, however, additional pre-aged specimens may be tested to determine the combined effects of multiple aging stresses.

3.3 Accelerated aging

In functional testing, test specimens are subjected to the specified aging stress, typically using either continuous or cyclical stress exposures to represent service aging. Diagnostic tests are periodically conducted to evaluate the extent of deterioration. In order to determine the effect of the aging factors on an insulation system in a reasonable length of time, it may be necessary to increase the magnitude or frequency of the applied stress. However, the more the stresses are accelerated, the less the test conditions resemble service conditions. Thus, it is imperative that the aging stresses not be accelerated to such a degree that erroneous or inconclusive results are obtained. The procedures outlined in the guide are intended to provide a compromise between too much acceleration and too long of a test period.

3.4 Environmental influences

Environmental influences include gas atmosphere, moisture, oil vapor, carbon dust, brake dust, and other contaminants. Large machines often have closed cooling systems that permit control of contaminants. The environment of a power station is likely to be more severe than that inside the machine in its effect on insulation. Separate environmental tests are not included in this guide (but may be added in future revisions). It is expected that the insulation system evaluated will withstand normal environments and contaminants. Tests for insulation systems designed for use in open ventilated machines, where contaminants may be present, may be devised to evaluate the effect of these substances.

For simplicity, the tests described in this guide are normally conducted in air. However, it is recognized that the stator windings of some machines operate throughout their lifetimes in an atmosphere of hydrogen. Although testing in a hydrogen atmosphere is more complicated than testing in air, mechanisms of insulation breakdown for some materials may be significantly different than from those in air. Nothing in this guide should be construed as preventing testing in a hydrogen atmosphere if it is believed that this factor may be important in providing more realistic test results.

3.5 Test samples

A minimum of five specimens should be included in each test sample. However, better statistical results are obtained with seven to ten specimens. Therefore, if feasible, a larger sample size is desirable. A sufficient number of specimens should be used initially to provide for all the destructive periodic checks that will be made.

The geometry (e.g., shape and thickness) of an insulation system may affect its dominant aging characteristics. Thus, the specimens used for functional evaluation should be actual production or prototype bars or coils or sections, including all insulation components used in the finished winding. A typical multi-turn coil or bar specimen would be constructed with insulated stranded conductors, including turn insulation and transpositions, if necessary. Groundwall thickness should be representative of the voltage class to be studied. A typical length for this type of specimen would be 75 cm to 125 cm for a machine rated 13.8 kV. Specimens for lower voltage machines may be shorter in length.

If electrical measurements such as electric strength or dissipation factor will be used to assess insulation degradation, the test specimen should be manufactured with appropriate electrodes, or the electrodes may be added to the specimens later.

3.6 Interpretation of results

Comparisons between two insulation systems tested in different laboratories may not be meaningful unless all factors and test conditions are carefully controlled. The greatest value of functional evaluations may be obtained by comparing a new insulation system with a service-proven insulation system.

Several IEEE and IEC guides and recommendations suggest using a relative measure of life when introducing a new insulating material or insulation system (see IEEE Std 275-1992, IEEE Std 429-1994, and IEC 60034-18-1:1992-02[6]). It is recognized that no test program exists for determining the absolute and precise design life of a new insulation system. Generally, various accelerated aging tests are performed using a combination of available industry documents together with the equipment manufacturer's internal evaluation methods.

The end-point criterion, or determination of when a specimen has failed, may be voltage breakdown, partial loss of mechanical strength, or other criterion or combination of criteria. The same standards should apply to all specimens. The diagnostic test method and end point should be appropriately selected to indicate significant deterioration of the insulation system. The end point should be selected to indicate a degree of deterioration of the insulation that has reduced its ability to withstand a stress encountered in actual service. It should not be set so high that unreasonably short time-to-failure values are obtained. The diagnostic tests should determine properties that can be conveniently measured with reasonable accuracy and cost.

In the analysis of results, no single functional test or procedure is capable of providing the information needed to make a dependable classification of the insulation systems used in ac electric machines. The proper weighting to be applied to the results and interpretations of the several tests in this guide must depend on the specific type, size, and duty cycle of the rotating machine in which the insulation system will be used.

3.7 Testing safety

WARNING

High-voltage tests may pose a hazard to equipment and personnel. Therefore, all tests must be performed by qualified personnel using proper safety precautions. To prevent inadvertent contact with energized equipment, tests must be performed within a restricted high-voltage testing area.

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[6] For information on references, see Clause 2.

4. Voltage endurance

Electrical aging may be initiated by one or more mechanisms, including the effects of partial discharges within or adjacent to the insulation, electrical tracking, electrolysis, space charges, and increased temperatures produced by high dielectric losses. As a result, the processes that lead to electrical aging and, ultimately, failure are often complex and difficult to predict.

Voltage endurance testing of insulation systems is typically conducted at voltages higher than normal operating stress in order to accelerate the degrading effects of electric stress. By conducting a series of tests at different voltages, a relationship of life versus stress may be plotted. Although this relationship cannot be accurately extrapolated to obtain an expected life at operating stress, different insulation systems tested under the same conditions can be compared over the range of test voltages.

To allow for separate evaluation of the voltage endurance results, accelerated mechanical or thermal degradation is not included in this test. The specimens are tested at room temperature or at normal service temperature. Care must be taken that dielectric losses at high stress do not raise insulation temperatures excessively.

While this clause establishes the principles involved in the voltage endurance evaluation of insulation systems for high-voltage rotating machines, several different approaches are being followed in the industry (see IEEE Std 1043-1996 and IEEE Std 1553-2002). Therefore, a specific test method is not completely defined. An outline of the parameters that must be considered and the variables that must be controlled in performing this type of evaluation are presented.

4.1 Time dependence of electric strength

The withstand capability of solid insulation under ac electric stress depends on the time of exposure at a given stress level. The actual breakdown mechanism often varies with the duration of voltage application. For example, at short times, such as under impulse conditions, the breakdown value approaches the intrinsic electric strength. This may be defined as the condition of instability resulting when conduction electrons gain energy from the applied electric field faster than they lose energy to the surrounding insulation medium.

With longer exposure time, on the order of minutes, the streamer breakdown failure mechanism occurs. In this case, the insulation breaks down at the edges of the high-voltage electrode and the local field at the tip of the discharge channel is much greater than the average field—perhaps approaching the intrinsic breakdown strength of the insulation. Local (partial) breakdown occurs and propagates through the dielectric, resulting in complete insulation failure.

Thermal breakdown may occur at still longer times. This is caused by an instability that occurs when the rate of internal heat generated at some point within the dielectric exceeds that at which the heat is conducted away from it.

Finally, for times approaching the service life, breakdown is due to erosion by discharges and electrochemical attack. Electric stress in voids in the insulation structure may break down the gas, producing ions and electrons, which are attracted to the instantaneous cathode and anode surfaces in the void. Both types of charged particles are sufficiently energetic to break chemical bonds in the insulation surface. In addition, corrosive and conducting chemical products formed by various reaction mechanisms dissolve or combine with condensed water vapor to contribute to deterioration and breakdown.

4.2 Preparation of test specimens

Sections of stator bars or coils to be used for voltage endurance tests should be of suitable length and all the strands in the conductor electrically connected or brazed together. Silver paint or highly conductive graphite-filled paint may be used to short the strands together.

The outer grounding electrode should encircle the entire specimen circumference (see Figure 1). Full slot length, in the case of a complete coil or bar, may be used. The electrode should be applied to the surface of the specimen to achieve complete contact without air spaces. The slot coating must be overwrapped with foil or wire, or silver paint may be used. Tests should incorporate a suitable guarding technique in the extended area to facilitate measurement of the dissipation factor of the specimen at intervals during the testing period (see IEEE Std 286-2000). During the voltage endurance test, the guard is eliminated.

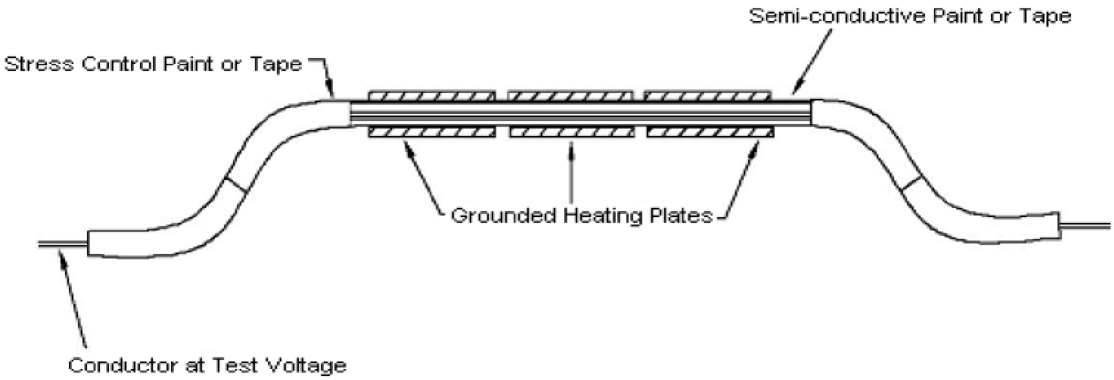

Figure 1—Method of application of heating plates to a stator bar. The test object could also be a half coil, full coil, or a straight section.

The edges of the electrode area must be effectively graded to prevent failures at the edge due to high-voltage stresses resulting from field distortion. The grading system may consist of suitable paint, tape, or stress relief cones. The electrodes and voltage grading system should be renewed periodically if deterioration occurs.

The specimens may be mounted in a fixture to simulate the conditions that the bar would experience in the slot of a machine. If test bars are mounted in a fixture, the electrode should extend about 13 mm beyond the edges of the fixture.

4.3 Application of voltage

During voltage endurance testing, a power-frequency voltage is applied to the specimens. Voltage regulation of ± 3% or better without distorting the sine wave is required (see IEEE Std 4-1995). Actual voltage regulation should be reported in the results. To obtain a complete picture of voltage endurance, the time-to-failure should range from 1 min to 10 000 h. Several methods may be used to determine the electric strength over this time range, as given in following list. Results of tests made by different methods on the same system generally fall on a straight line on a semi-log or log-log plot.

a) *Step-by-step increasing voltage* (see ASTM D149-97A). The time intervals generally used between voltage steps are 1 min, 1 h, 1 d, and 1 week. The equivalent breakdown voltage is found by subtracting from the observed breakdown a fraction of the step voltage, as determined from the table in Annex C.

b) *Fixed voltage* (see ASTM D2275-01). The test voltage is applied and held constant until specimen failure.

c) *Steady voltage rise* (see ASTM D149-97A). The voltage is increased continuously at a fixed rate of rise until specimen failure. Typically, the starting voltage is half the expected breakdown voltage.

4.4 Test results

A widespread variation in time-to-failure for any given voltage stress level is expected. Therefore, a statistically significant number of failure times must be obtained (at least five for each voltage level). The relationship between failure time and voltage follows the inverse power law. The data may be presented as a plot of breakdown voltage versus time-to-failure, using either a semi-log or log-log plot. The results of different insulation systems can be presented and compared on the same graph.

Voltage endurance tests are informative, although time-consuming. Electrical aging may be accelerated by testing at a higher frequency than that experienced in normal service. However, radically elevated stress levels may initiate insulation-aging mechanisms that are significantly different from those experienced in normal service. Acceleration of the stress level is only permissible when it does not significantly change the aging mechanism.

5. Thermal endurance

It is generally recognized that the thermal life of an insulation system is an inverse function of the operating temperature to which it is exposed. The loss of insulating ability will usually be evidenced by a change in the electrical and/or mechanical characteristics, either of which can impair the operation of the electric machine.

Thermal endurance tests provide a means for determining the rate at which important properties of an insulation system deteriorate irreversibly as a function of temperature and time. Different types of criteria may be used to measure the degradation. This clause describes a test method by which insulation systems for large high-voltage machines can be compared in their ability to withstand thermal exposure. By subjecting representative specimens of various insulation systems to accelerated aging temperatures, comparative evaluations can be made.

5.1 Test exposure

The test specimens should be placed in ventilated air-circulating ovens whose temperatures can be regulated to approximately ± 3 °C.

The coils/bars shall be supported in the oven in such a way that the entire specimen surface is exposed to the air.

In order to make statistically valid comparisons of insulation systems, tests should be conducted at a minimum of three temperatures. Aging temperatures in the range of 120 °C to 240 °C are recommended as being sufficiently accelerated for the types of machines covered by this guide.

5.2 Electrical and physical measurements

Specimens will be removed periodically and subjected to various diagnostic tests, the results of which can then be plotted as a function of time. There are many measurements that can be made, and a few examples follow:

a) The physical dimensions of the specimens can be measured. This is a nondestructive test.

b) Dissipation factor and capacitance can be measured as a function of voltage at various temperatures (see IEEE Std 286-2000). This is a nondestructive test.

c) Short-time electric strength, either at room temperature or at operating temperature. This is a destructive test.

d) Specimens can be subjected to longtime exposure to voltage after thermal aging periods. It should be recognized that it may be desirable to combine thermal endurance with voltage-endurance exposure (see Clause 4).

e) Physical integrity is perhaps one of the most important requirements for an insulation system. Therefore, it is recognized that a test to measure some mechanical property is desirable. This may involve removal of the insulation and preparation of test specimens for mechanical tests thereof, or subjecting the test coil/bar to some mechanical load. One test of physical integrity involves removal of the insulation from one side of the coil/bar and then very carefully cutting it into a “dog bone” shape (e.g., 200 mm to 250 mm long overall, 25 mm to 50 mm wide at each end, 15 mm to 25 mm wide, and 100 mm to 150 mm long in the center). The prepared sample is placed in a tensile testing machine and pulled until the insulation layers separate. The shape of the specimens must be absolutely identical from one test to another. Once a database of the results of many tests is established, inferior insulation caused by poor impregnation, contamination, or other defects is easily detected.

6. Thermomechanical endurance

Thermomechanical stresses are created when differential thermal expansion and/or contraction causes relative movement between the stator winding conductor, groundwall insulation, and core iron. Such movement may result in damage to the insulation by breaking the adhesive bond between the copper conductor and insulation or by delaminating the layered insulation structure itself. The effect of thermomechanical stresses on a particular insulation system is primarily a function of the following:

a) Mechanical characteristics of the insulation system

b) Differential thermal expansion between the copper conductor in the stator coil/bar and the iron in the armature core

c) Number of thermal cycles

d) Degree of tightness of the winding in the slot

In general, insulation delamination is more prone to occur in the region of the coil/bar at the ends of the stator core. As the winding expands axially, the insulation in the slot is restrained to various degrees by friction with the iron and, in the case of insulation systems that receive final heat cure after the coils/bars are installed in the core, due to bonding to the slot and locking-in at each radial air vent. This difference in restriction of movement imposes a tensile shear load on the insulation at the core ends, which may cause separation between layers of tape or between layers of mica or both. Upon cooling, the slight relative movement between adjacent components in the insulation groundwall may not completely reverse to close the opening because of the inelastic nature of the insulation system, direction of the tape spiral, etc. Successive thermal cycles may increase the opening or crack, until finally the opening extends through sufficient layers to render the insulation unreliable. Beyond the ends of the core, the insulation tends to move with the conductor and, therefore, tape separations and cracking in this area are less likely to occur.

Service damage from thermomechanical forces is most pronounced in machines operating under conditions of fluctuating load and conductor temperature. Such machines are generally conventionally cooled turbine and hydrogenerators, synchronous condensers, and synchronous motors. Therefore, functional tests for thermomechanical endurance should simulate the conditions in these types of machines (see IEEE Std 1310-1996).

6.1 Test requirements

A fundamental requirement of a functional test is that it should have the same degrading effects as service, by the same mechanisms, but in a much shorter time frame. An accelerated test must produce logical and consistent relationships between the in-service operating conditions and the test conditions. Therefore, factors that might initiate insulation failure by mechanisms other than by thermomechanical degradation should be minimized as much as possible. It is especially important to exclude degradation caused by electrical stresses or temperatures significantly above service levels, except as part of a periodic test to determine an end point.

Construction details of the insulation such as groundwall thickness, bracing and cooling of the coil ends, and use of supplementary materials and surface treatments (such as slippery materials) for assembly may also affect the deterioration process. Because thermomechanical degradation is affected by interactions between the various components of the insulation system, an evaluation cannot be made of the insulation alone, but only of the entire system. Therefore, the tests should be made on full-sized coil/bar sections wound in model slots, as in an actual generator or motor, which give similar temperature gradients and can be adjusted for control of slot clearance.

6.2 Variables that affect insulation degradation

Factors that may influence the rate and extent of insulation degradation during a thermomechanical functional test include the frequency of differential thermal expansion/contraction cycles, amplitude of differential expansion/contraction cycles, and tightness of windings in the slot.

The rate of degradation is expected to increase nearly proportionally with frequency of the differential expansion/contraction cycles. In order to shorten the duration of the test, the frequency should be chosen as high as practical, the limit determined by the thermal time constant of the system.

An increase in the amplitude of the differential expansion/contraction cycles will increase the rate of degradation, although the quantitative relationship is indeterminate and may not be the same for different insulation systems. Therefore, caution should be used when evaluating results from tests with greater differential expansions/contractions than those experienced in service.

A common practice with large high-voltage generator models has been to increase the peak value of the temperature to increase the severity of the differential expansion/contraction cycle. However, if this change brings the insulation temperature significantly above that encountered in service, a change of the mechanical properties of the insulation may affect its ability to withstand the cycling and the high temperature may cause a significant degree of thermal aging during the test period. Any increase in amplitude of the differential expansion/contraction cycles should, therefore, preferably be done without raising the average temperature of the insulation. One way to achieve this involves simultaneously heating the conductors and cooling the core iron, alternating with a period with no cooling or no heating, during which the system will approach an isothermal condition.

The tightness of the winding in the slots also affects insulation degradation. By adjusting the tightness of windings at one end of the slot with negative clearance and the other end with excessive clearance, the rate of degradation can be increased. Caution should be used when evaluating test results for different insulation systems unless actual normal slot clearances are similar.

6.3 Test arrangement

Two types of thermomechanical cycling test equipment are in general use. One involves a stack of actual core laminations (or channels to simulate slots) of similar length to the cores of the machines involved. The full-length core model is fitted with several full-size coil sides and equipped with means for heating and cooling the parts and measuring the resulting movements.

Another approach utilizes a structure representing a short length of one or more slots of a machine, containing a short coil specimen or specimens that are heated and cooled while being moved back and forth by correlated mechanical means. Such a device is essentially a length multiplier, reproducing the mechanical action experienced by a coil side at the end of a slot when subjected to equivalent temperature cycling.

6.4 Test specimens

Test specimens should be actual coil sides or bars, or portions cut from them. If special test bars must be used, the cross section of the coil, insulation thickness, surface treatment, slot fillers, and wedges should be representative of a normal stator winding. The bracing of the coils should also be as close to actual practice as possible.

When using full-length core model test equipment, the length of the slots and the specimens must be great enough to produce movements at least equal to those that will occur in operation of the actual machine.

For length-multiplier test equipment, specimen length must suit the particular equipment, and is usually about 60 cm. The slot length of the equipment should be a minimum of 30 cm to simulate conditions near the end of the actual machine slot.

Benchmark tests or measurements of the specimens should be made prior to assembly. For example, if electric strength is to be used to determine the end point, then a conventional power frequency high-potential withstand test should be conducted prior to beginning the thermal endurance test.

6.5 Heating and cooling

Differential thermal expansion of the insulation system may be accomplished by heating the conductors of the coils uniformly along their length either electrically or with hot fluid. The effect of this heating can be augmented by simultaneously cooling the iron core, for instance, by circulating cool water through embedded cooling tubes. The core or simulated slot structure may be heated via embedded electric resistance heaters. Air blast or water cooling may be used on the coil sides, cores, and end windings. Relaxation of the thermally-stressed system occurs after conductor heating is ceased, and will take place more quickly if core cooling is also stopped.

In order to control the thermal cycles, at a minimum, temperatures of the conductors (hot-spot and average temperature) and the iron surface in the slots should be continuously measured.

6.6 Duration of the cycle

A reasonable length of time for one cycle would be between 55 min and 95 min. For example:

a) Apply heat for 25 min to 40 min to reach operating hot-spot temperature (120 °C to 180 °C).

b) Hold at hot-spot temperature for 10 min to 15 min.

c) Cool to rated generator operating cold gas temperature for 20 min to 40 min.

6.7 Number of cycles

The number of cycles to the end point will depend upon the type of insulation tested and the severity of the test. When there is no acceleration of the degradation except for cycling, the number of cycles is normally on the order of several thousand. With acceleration, the number of cycles can be reduced by one or two orders of magnitude.

6.8 Thermal expansion

Movement of the surface of the coil insulation at the ends of the slots should be measured directly with micrometers, both absolutely and relative to the iron core. It is also recommended to measure the movements of the conductors relative to the insulation surface, for example, with the use of embedded magnetic probes. Lead foils may be embedded in the insulation at various stages of taping. X-ray photographs at the beginning of the test, and at various times and temperatures during the test will then provide indication of the relative movements of various layers of the insulation and other components.

6.9 Electrical properties

Electrical properties such as insulation resistance, polarization index, dissipation factor, dielectric constant, and electric strength are temperature dependent. Therefore, periodic measurements of these properties should be made at consistent temperatures, typically ambient temperature. Given the time required for the system under test to thermally stabilize, these measurements should not be made more frequently than would be needed to indicate a change.

Considering the long duration of thermomechanical tests (typically on the order of months), temperature control and recording, and forced mechanical movement in conductors are usually completely automated. Self-balancing potentiometer-type instruments may be adapted for temperature recording and control of heaters and coolers, according to temperature sensors installed in the core and the core specimens. Such instruments may also be used to control mechanical movement according to temperature by the use of a differential transformer or equivalent device for position feedback.

6.10 End point criteria

The electric strength of the insulation is generally used to determine the end point of the thermomechanical cycling test. Therefore, it is suggested that specimens be tested periodically with an alternating voltage of $2E + 1$ kV or a direct voltage of $1.7 \times (2E + 1)$ kV [B21][7] for 1 min, and continually cycled until failure occurs. The use of electric strength as an end point may be impractical in situations involving the length-multiplier type of model, especially if the short specimens do not have sufficient creepage distance to prevent surface flashover during the withstand test. The proper sizing of test specimens to provide adequate creepage distance is preferred. However, if this is not feasible, visual examination may be used to determine an end point; this method is somewhat subjective and may lead to variability in the results. In some situations, manufacturers test electric strength by immersing specimens in oil. However, exposure to oil changes the surface condition of the specimen and may alter the results of the thermomechanical cycling test. Therefore, testing for end of life in oil is discouraged.

If an end point has not been reached by the withstand test, specimens may be subjected to a voltage breakdown test or a voltage endurance test, preferably together with control specimens that have not been subjected to a thermomechanical cycling test. Any significant reduction in electric strength, as compared with the untested specimens, may be taken to indicate some degree of weakening by the thermomechanical cycling, or by the thermal cycling inherent in it. This method has been found to provide useful comparisons when other means of detecting degradation give little or no indication.

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[7] The numbers in brackets correspond to those of the bibliography in Annex A.

A visual examination of the coil insulation and measurements of relative motion after the cycling should be included as part of the evaluation of the insulation systems that are being compared.

6.11 Evaluation

Using the test described in this subclause, two or more types of insulation systems may be ranked in terms of thermomechanical cycling damage, according to time to given degree of damage, or extent of damage produced in a given time or number of cycles. Test conditions must be kept highly consistent to afford valid comparisons.

Test specimens should include at least one reference insulation system that is accurately representative of insulation of known service performance with respect to thermomechanical cycling deterioration.

The number of specimens of each type, which must be tested for valid results, depends upon the consistency of fabrication and processing of the specimens and of the insulation, which they represent. For meaningful conclusions, statistical analysis is usually used to determine the number of specimens required and to evaluate the final test data.

7. Electromechanical endurance

During machine operation, electromechanical forces can lead to stator winding insulation damage and eventual failure. Normal load currents produce forces that set up winding vibration and may result in fatigue or wear of the insulation due to abrasion. Vibration damage can occur in the stator slots and/or in the end windings. Large impact forces produced by a sudden short circuit can crack or fracture insulation. Short-circuit forces are usually most damaging at the slot exit position. The damaging effects of electromechanical forces can be mitigated by the support of an end winding bracing system and effective slot wedges.

7.1 Test conditions

In order to compare the electromechanical endurance of different insulation systems, test specimens must be subjected to damaging forces. Thus, test procedures should be devised so that the support and wedging devices are less than adequate.

To the extent possible, ambient conditions should duplicate those occurring in operation. While it is not necessary to test in the normal operating atmosphere, it is preferable to test at the normal room temperature.

7.2 Impact (sudden short circuit)

When a machine suffers a sudden short circuit, both the slot insulation and end winding insulation can be damaged. A particularly vulnerable area is where the coil or bar emerges from the slot. Unless the end winding packing and bracing system is very robust, some movement will occur in the end windings, allowing the bar to deflect. The loading on the bar in this situation will be as the loading for a cantilever beam.

Figure 2 shows a test apparatus that may be used to drop a load onto a specimen bar mounted as a cantilever beam. Deflection can be controlled by a suitable restraint, if so desired. It is recommended that the initial height D of the dropping mass be held constant and that its value in grams be fixed. An overvoltage test may be applied after each blow using the apparatus clamp as a suitable and convenient electrode. The specimen bar is usually turned over after each test blow in order to alternate the direction of specimen movement. The number of blows before the test specimen fails a voltage withstand test can be used as a criterion for comparison of different systems. Although this test does not duplicate short-circuit conditions, it is simple and reproducible and has proven useful for comparing stator insulation systems under impact loading.

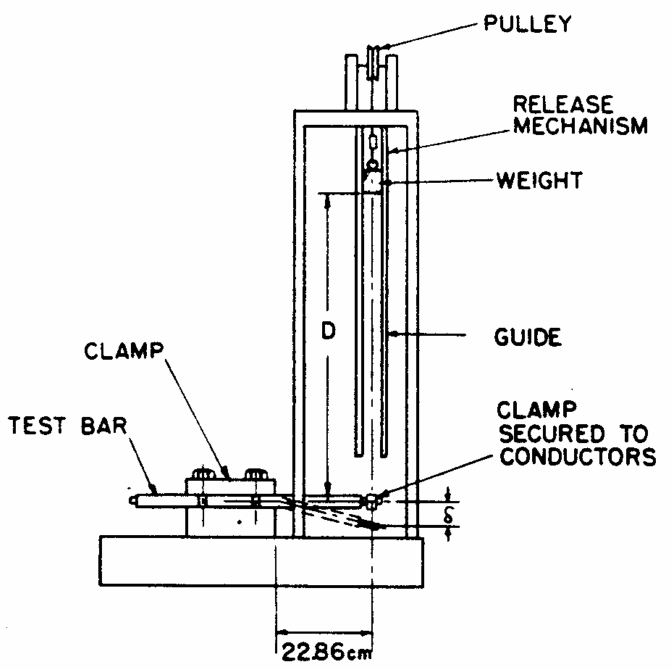

Figure 2—Apparatus for impact tests on stator conductor bar specimens loaded as a cantilever

7.3 Vibration

Damaged stator winding insulation resulting from electrically induced vibration has been observed in large machines. Test facilities may be set up to reproduce the conditions that cause such damage. These tests often require large testing apparatus. The test described in this subclause is designed to be simple and easily controlled.

Figure 3 outlines a possible design of an apparatus for applying a controlled oscillating load to insulation specimens. The length of the apparatus and the number of vibrating heads used is variable. Adjustment of the static load on the specimen will make it possible to set up two conditions to a required level. The rubbing action producing abrasion of the specimen surface will be influenced by the surface condition of the vibrating beam while a variable compressive load along the length of the test bar can induce fatigue in the insulation. If desired, a test frequency of 100 Hz or higher may be used to accelerate the deteriorating action.

7.4 Interpretation of results

The damage to the insulation specimen will usually be visible. It is, however, advisable to use an electrical test to quantify the extent of the damage. Measurement of partial discharges may reveal signs of internal changes such as void or crack formation. An overvoltage test may be used to indicate complete failure. This may take the form of a withstand test, a voltage endurance test, or a breakdown test.

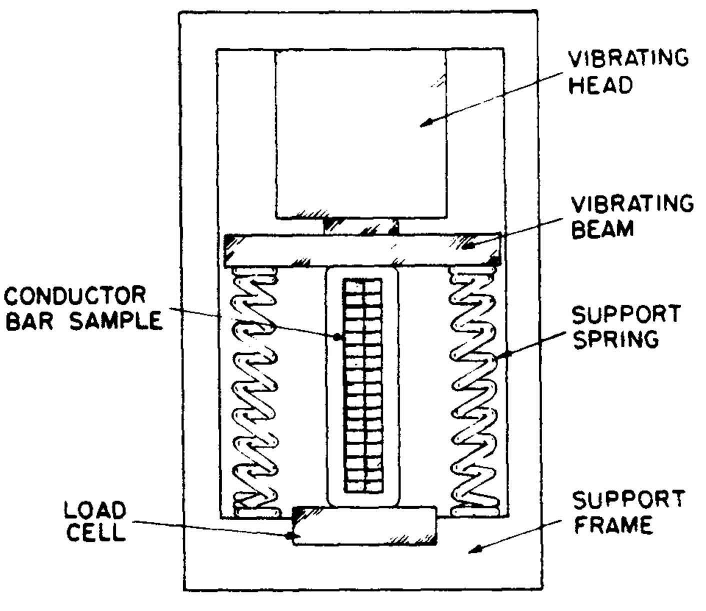

Figure 3—Apparatus for applying oscillating load on stator conductor bar specimens

Annex A

(informative)

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[11] The IEEE standards or products referred to in this annex are trademarks of the Institute of Electrical and Electronics Engineers, Inc.

[12] IEEE Std 56-1977 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181 (http://global.ihs.com/).

[13] IEEE Std 433-1974 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181 (http://global.ihs.com/).

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Annex B

(informative)

Glossary

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B17] should be referenced for terms not defined in this annex.

accelerated test: A functional test in which one or more factors of influence are increased in magnitude or frequency beyond normal service conditions so as to decrease the time needed for the test.

aging: An irreversible change in the properties of the insulation system due to the action of one or more aging factors.

aging factor: A factor of influence that causes an irreversible change (i.e., deterioration) in the insulation system. For this guide, the primary aging factors are electrical, thermal, mechanical, and environmental stresses.

diagnostic test: A periodic application of an evaluation test or measurement to the test specimen to determine whether the end point has been reached.

electric strength: A measure of the ability of an insulation to withstand electric stress (voltage) without failure.

end point: The condition at which a specimen has failed using electric breakdown, loss of mechanical strength, or other criterion or combination of criteria.

functional test: A means of evaluation in which an insulating material, insulation system, or electric equipment is exposed to factors of influence that simulate or are characteristic of actual service conditions.

pre-aged specimen: A specimen that has been subjected to one or more aging factors prior to functional testing.

service life (design life): The length of time that a component or apparatus is expected to perform satisfactorily and reliably under normal operating conditions and with manufacturer's recommended maintenance.

Annex C

(normative)

Step-by-step method of voltage application

Example

During a 1 h test using 5 kV steps, the specimen fails after 42 min at 65 kV.

Determine the equivalent 1 h breakdown voltage as follows:

a) Percent of time step held at breakdown voltage equals 42 min/60 min = 0.70 × 100% = 70%.
b) From the table below, the percent of voltage step to subtract from the breakdown voltage is 20%.
c) 20%of the voltage step equals 0.2 kV × 5 kV = 1 kV.
d) The equivalent 1 h breakdown voltage is 65 kV − 1 kV = 64 kV.

Table C.1—Equivalent breakdown voltage determined from step-by-step method of voltage application

Percent of time step held at breakdown voltage	Percent of voltage step to subtract from breakdown voltage
0–9	100
10–22	80
23–40	60
41–65	40
66–99	20