

IEEE Guide for Insulation Maintenance of Electric Machines

IEEE Power and Energy Society

Sponsored by the
Electric Machinery Committee



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USA

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IEEE Guide for Insulation Maintenance of Electric Machines

Sponsor

Electric Machinery Committee
of the
IEEE Power and Energy Society

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Abstract: This insulation maintenance guide is applicable to rotating electric machines rated from 35 kVA and higher. The procedures detailed herein may also be useful for insulation maintenance of other types of machines.

Keywords: aging mechanisms, alternating, armature, brush, commutator, core, corona, current, distribution factor, EL CID, electric, epoxy, field, flux, Global VPI, groundwall, IEEE 56™, insulation, ionization, ionizing radiation, machines, maintenance, mica, partial discharge, pitch factor, power-factor, recurrent surge oscillography, reliability, resistance temperature detector, rotating, RSO, RTD, semiconducting stress control coating, service, stator, testing, thermal cycling, thermal deterioration

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Introduction

This introduction is not part of IEEE Std 56-2016, IEEE Guide for Insulation Maintenance of Electric Machines.

This guide represents the merger of the following two standards:

- IEEE Std 432TM-1992, IEEE Guide for Insulation Maintenance for Rotating Electrical Machinery (5 HP to less than 10 000 HP).
- IEEE Std 56TM-1990, IEEE Guide for Insulation Maintenance of Large Alternating-Current Rotating Machinery 10 000 kVA and Larger.

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1. Overview

Rotating electric machines are complex structures that are subjected to various levels of stresses and environmental factors and therefore require maintenance. This guide provides an authoritative overview of insulation systems and the various tests and inspections employed for maintenance of them.

1.1 Scope

This insulation maintenance guide is applicable to rotating electric machines rated from 35 kVA and higher. The procedures detailed herein may also be useful for insulation maintenance of other types of machines.

1.2 Purpose

The purpose of this guide is to present information necessary to permit an effective evaluation of the insulation systems of ~~large alternating current~~ rotating electrical machines. Such an evaluation can serve as a guide to the degree of maintenance or replacement ~~which~~ as might be deemed necessary, and also offer some indication of the future service reliability of the equipment under consideration.

2. Normative references

9.1 IEEE Standards

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 60034-27, Off-line partial discharge measurements on the stator winding insulation of rotating electrical machines.¹

IEEE Std 4TM, IEEE Standard Techniques for High-Voltage Testing.^{2, 3}

IEEE Std 43TM 1974, IEEE Recommended Practice for Testing Insulation Resistance of ~~Rotating~~ Electric Machinery.

IEEE Std 62.2TM, IEEE Guide for Field Testing of Electric Power Apparatus Insulation—Electrical Machinery.

IEEE Std 95TM 1976, IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage.

IEEE Std 115TM 1965, IEEE Standard Test Procedure for Synchronous Machines.

¹IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembe, 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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IEEE Std 118TM-1949, [IEEE Standard](#) Master Test Code for Resistance Measurement ([Withdrawn](#)).⁴

IEEE Std 119TM-1974, [IEEE](#) Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus ([Withdrawn](#)).

IEEE Std 286TM-1975, [IEEE](#) Recommended Practice for Measurement of Power-Factor Tip-Up of ~~Rotating~~[Electric](#) Machinery Stator Coil Insulation.

[IEEE Std 334TM, IEEE Standard for Qualifying Continuous Duty Class 1E Motors for Nuclear Power Generating Stations.](#)

IEEE Std 433TM-1974, [IEEE](#) Recommended Practice for Insulation Testing of Large AC ~~Rotating~~[Electric](#) Machinery with High Voltage at Very Low Frequency.

[IEEE Std 510TM, IEEE Recommended Practice for Safety in High Voltage and High Power Testing \(Withdrawn\).](#)

IEEE Std 522TM, [IEEE](#) Guide for Testing Turn-to-Turn Insulation on Form-Wound Stator Coils for ~~Alternating-Current Rotating Machinery~~ [Electric Machines](#).

[IEEE Std 1129TM, IEEE Guide for Online Monitoring of Large Synchronous Generators \(10 MVA and Above\).](#)

⁴[This standard has been withdrawn. Withdrawn standards can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. \(303\) 792-2181 \(<http://global.ihs.com/>\).](#)

IEEE Std 1434™, IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery.

IEEE Std 1799™, IEEE Recommended Practice for Quality Control Testing of External Discharges on Stator Coils, Bars, and Windings.

IEEE Std C50.12™, IEEE Standard for Salient-Pole 50 Hz and 60 Hz Synchronous Generators and Generator/Motors for Hydraulic Turbine Applications Rated 5 MVA and Above.

IEEE Std C50.13™, IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz Synchronous Generators Rated 10 MVA and Above.

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

~~IEEE Std 51-1955, Guiding Principles for Dielectric Tests.~~

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

~~IEEE Std 100-1972, Dictionary of Electrical & Electronics Terms (ANSI C42.100-1972).~~

~~IEEE Std 432-1976, Guide for Insulation Maintenance for Rotating Electrical Machinery (5 HP to less than 10 000 HP).~~

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary: Glossary of Terms and Definitions*⁵ should be consulted for terms not defined in this clause.

discharge detector (ionization or corona detector): An instrument that can be connected in or across an energized insulation circuit to detect current or voltage pulses produced by electric discharges within the circuit.

high flux test: The high flux test, commonly known as the loop test, ring test, or full flux test, is a test method developed for evaluating laminated magnetic cores to detect shorting between the laminations. The detection method is accomplished by applying a high-energy flux density magnetic field at approximately the rated peak no load flux to the core and then evaluating if shorts have created a local temperature rise that could lead to detrimental heating during operation of the machine.

ionizing radiation: Particles or photons of sufficient energy to produce ionization in interactions with matter.

⁵*IEEE Standards Dictionary: Glossary of Terms and Definitions* is available at <http://shop.ieee.org>.

low-energy flux test: The low-energy flux test, commonly known as the EL CID test, is a test method developed for evaluating laminated magnetic cores to detect shorting between the laminations. The detection method is accomplished by applying a low flux density magnetic field to the core and then evaluating if shorts have created a circulating current loop that could lead to detrimental heating during operation of the machine.

power factor (PF): The cosine of the dielectric phase angle or the sine of the dielectric loss angle when tested under a sinusoidal voltage. The ratio of the power dissipated in the insulation, in watts, to the product of the effective voltage and current in volt-amperes, when tested under a sinusoidal voltage and prescribed conditions. The insulation power factor is equal to the cosine of the phase angle between the voltage and the resulting current when both the voltage and current are sinusoidal.

resistance temperature detector (RTD) (resistance thermometer resistor) (resistance thermometer detector): A resistor made of some material for which the electrical resistivity is a known function of the temperature and that is intended for use with a resistance thermometer. It is usually in such a form that it can be placed in the region where the temperature is to be determined.

semiconducting 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.

stator bar: A unit of winding on the stator of a machine. Two single-turn stator bars make one turn in the stator winding.

stator coil: A unit of a winding on the stator of a machine comprising of one or more (for multi-turn coils) turns in the winding.

stator core: The stationary magnetic circuit of an electric machine. It is commonly an assembly of laminations of magnetic steel, ready for winding.

stator: The portion that includes and supports the stationary active parts. The stator includes the stationary portions of the magnetic circuit and the associated winding and leads. It may, depending on the design, include a frame or shell, core, winding supports, ventilation circuits, coolers, and temperature detectors. A base, if provided, is not ordinarily considered to be part of the stator.

stress control coating: The paint or tape on the outside of the groundwall insulation that extends several centimeters beyond the semiconducting 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 end-turn. The stress control coating overlaps the semiconducting slot coating to provide electrical contact between them.

4. Safety

Testing and maintenance activities should be conducted and supervised by qualified personnel, and adequate safety precautions should be taken to avoid injury to personnel and damage to property.

It is not the intent of this document to prescribe safety and health requirements. Before starting any work, the relevant laws, regulatory standards, manufacturer instructions, and company policies should be consulted.

4.1 General

Prior to performing any test, inspection, or servicing of an electric machine where the unexpected energizing, start up, or release of kinetic or stored energy could occur and cause injury or damage, the apparatus shall be de-energized, isolated, blocked, and secured to control hazardous energy. Personnel and equipment shall not be considered protected until the appropriate safety procedures have been implemented. Safety procedures may involve the use of locking devices, warning tags, physical barriers, safety tape, caution signs, and/or observers as necessary to restrict access to the equipment being maintained. There should be a meeting of all personnel involved in or affected by the maintenance activities. Test and inspection procedures should be discussed so there is a clear understanding of all aspects of the work to be performed. Particular emphasis should be placed on personnel and equipment hazards, and the safety precautions associated with these hazards. In addition, details of the maintenance activities should be discussed to help ensure the successful completion of the planned tasks. Responsibilities for the various duties involved in performing the work should be assigned and documented.

4.2 Machine rotation

Some test and inspection procedures are performed with the machine rotating slowly and with cover plates, guards, and end-shields removed. In the case of hydrogenerators under test, the machine may be operated at rated speed or at over speed with its covers removed. These tests present mechanical and electrical hazards, and appropriate procedures are required to prevent injury to personnel and damage to equipment.

4.3 Solvents

Persons who carry out cleaning using solvents shall be instructed on the safe storage, use, and emergency actions related to the solvents used. Manufacturer's recommendations, local procedures, and safety regulations should be followed to help ensure the proper use of personal protective equipment (PPE) and the correct handling of waste materials. There are suitable non-toxic solvents that can be used for cleaning the windings/machines in most cases.

4.4 Asbestos, lead, and other hazardous materials

Operators should be aware that older machines may contain asbestos, polychlorinated biphenyls (PCB), or lead products that could pose a threat to worker health and safety if disturbed. Electrical apparatus that has been subjected to extreme overheating or other unusual conditions may be contaminated with dangerous or toxic substances. Chemical sampling and testing may be warranted to determine the presence of hazardous materials. Clean up or abatement activities may be necessary and workers should take special precautions, including the use of PPE.

2. — Scope

~~This insulation maintenance guide is applicable to rotating electric machines rated from 35 kVA and higher. The procedures detailed herein may also be useful for insulation maintenance of other types of machines.~~

5. Significance of maintenance

Data obtained from online monitoring, regular inspection, and testing programs can provide an evaluation of the present condition of the equipment, give some indication of long-term trends, and indicate probable need for future repair or replacement. ~~Rotating electrical machines are complex structures which are subjected to mechanical, electrical, and thermal stresses of varying magnitude. Of the various components,~~ The insulation systems are the most susceptible to aging or damage due to these stresses. The service life of an ~~electrical~~electric machine will, therefore, largely depend on the serviceability of the insulation systems.

~~Where reliability is of concern, adequate inspection and testing programs are advocated to assure that the equipment is maintained in satisfactory condition to minimize the possibility of in-service failure.~~

~~The experience and data obtained from regular maintenance inspection and testing programs can, in addition to providing an evaluation of the present condition of the equipment, give some indication of long-term trends and probable need for future repair or replacement.~~

The extent ~~to which~~ of a maintenance program ~~is pursued~~ will depend largely on the ~~operator's~~operator's own experience and ~~philosophy~~ policy, but should also take into account the importance of service reliability ~~of~~ for the equipment. Where high service reliability is required, a regular maintenance program involving periodic disassembly and knowledgeable visual examination of the equipment, together with the application of electrical tests of proven significance, is strongly recommended. The size and age of the machine will relate to the applicability of the individual tests and inspections.

It should be recognized that ~~some~~ over-potential tests ~~may be damaging to~~ can damage insulation that is contaminated or in marginal condition. Where there is uncertainty of the condition of the insulation system, refer to Clause 9 for additional information. Consultation with the manufacturer is recommended. ~~This is implicit in~~ for setting up ~~any~~ an appropriate maintenance-testing program.

~~4. Service Conditions Reducing Insulation Life~~

~~As has been stated, electrical machines and their insulation systems are subjected to mechanical, electrical, and thermal stresses which give rise to many deteriorating influences, the most significant of which are the following:~~

~~4.1 Thermal Aging~~

~~Gradual aging caused by temperatures due to normal operating loads.~~

~~4.2 Overtemperature~~

~~Unusually high temperature from causes such as overload, high ambient temperature, restricted ventilation, and loss of cooling liquid.~~

4.3 Overvoltage

Unusually high voltage such as from switching or lightning surges.

4.4 Contamination

This deteriorates electrical insulation by actually conducting current over insulated surfaces, or by attacking the material reducing its electrical insulating quality or its physical strength, or by thermally insulating the material forcing it to operate at higher than normal temperatures. Included here are:

Wetness or extreme humidity

Oil or grease

Conducting dusts and particles

Nonconducting dusts and particles

Chemicals of industry

4.5 Physical Damage

~~This contributes to electrical insulation failure by opening leakage paths through the insulation.~~

~~Included here are:~~

~~Physical shock~~

~~Vibration~~

~~Overspeed~~

~~Unusual electromagnetic forces~~

~~Erosion by foreign matter~~

~~Damage by foreign objects~~

~~Thermal cycling~~

4.6 Partial Discharge (Corona) Effects

~~Partial discharges which may occur at higher operating voltages may be accompanied by several undesirable effects such as chemical action, heating, and ionic bombardment.~~

6. Insulation systems in general use

5.1 Insulated Parts

Insulation is present in various machine components, but the complexity of the ~~structure~~ [subject](#) is such that only a general description can be given here. ~~However, detailed information on the structure of insulation systems and modes of insulation failure are important to evaluation.~~

6.1 Insulating materials

Electrical insulation uses many constituent insulating materials in various combinations that result in various thermal ratings. Some of the material can be found in higher or lower thermal classes depending on the resultant composite insulation system. Some common insulating materials applied to electric machines have the following thermal classifications:

- a) Class 105 (formerly Class A): impregnated cotton, silk, cellulose-based paper, linen (cambric).
- b) Class 130 (formerly Class B): mica, glass fiber, asbestos, etc. Typical bonding materials are shellac, asphalt varnish and some polyester resins. Also polyester terephthalate (PET) films and various laminated papers.
- c) Class 155 (formerly Class F): mica, glass fiber, PET, asbestos, etc. Bonding materials are usually epoxy, epoxy-polyester or acrylic resins.
- d) Class 180 (formerly Class H): silicone elastomer, mica, glass fiber, asbestos, etc. Bonding materials may consist of silicone resins.

Mica is a vital component in most insulation for high-voltage electric machines because it has good dielectric strength at high temperatures and is resistant to partial discharges. Muscovite and phlogopite are the two forms of mica that are most commonly used for electrical insulation.

Originally mica was used in the form of large flakes, or splittings. When applied in this way it is difficult to exclude all voids, and some problems with delaminations may occur. Mica is also used in the form of mica paper where small flakelettes of mica are deposited on and bonded to a backing tape. With mica paper it is easier to produce an insulating layer with a very low void fraction. However, mica paper is less resistant to partial discharges than is large flake mica.

Materials bonded with shellac or with asphalt varnish are termed “thermoplastic”. Materials bonded with polyester or epoxy resin are termed “thermosetting”. Further information on thermosetting resins will be found in Annex B.

When mica and glass fibers are bonded together with varnish or resin they form a composite insulation system. Such a system typically has good thermal, electrical, and mechanical properties.

WARNING

Asbestos may be present in slot packing materials, armor tape and strand insulation of many older windings. Some slot packing materials and varnished cambric may contain polychlorinated biphenyls (PCBs). Appropriate workplace safety and environmental regulations should be followed when examining, disturbing or disposing of these materials.

6.2 Armature winding insulation

5.1.1 Stator Winding.

The armature windings of ac machines are typically stationary and are therefore known as stator windings. The armature windings of dc machines are rotating. In addition, dc machine rotating elements normally require various commutator insulations, banding, and other specialized supporting materials.

The ~~stator~~ armature winding with its associated leads is the main current carrying winding of the machine. The coils of the ~~stator~~ armature winding have strands ~~and~~, ground insulation and may have turn insulation. Wedges, blocks, and other insulated mechanical supports are a part of the ~~stator~~ armature winding assembly.

The insulation systems listed in 6.2.1 through 6.2.9 have been used for armature windings.

5.1.2 Rotor Winding.

~~The rotors of ac machines are either salient pole or cylindrical type. In all cases, they have turn and ground insulation, insulated mechanical supports, and lead insulation and may have collector rings with insulation.~~

5.1.3 Brush Rigging.

~~Machines with collector rings will have insulated brush rigging.~~

5.1.4 Core Assembly.

~~The principal insulation components in this assembly are the insulation between laminations in the core and insulation on through bolts (when used).~~

5.1.5 Other Parts.

~~Insulation is sometimes used on bearings and other mechanical parts such as hydrogen seals, oil seals, and piping. Temperature sensors may be applied, and these usually incorporate insulation. Refer to the manufacturer's instruction book.~~

6.2.1 Strand insulation

5.2 ~~Stator-Winding-Insulation~~

The individual strands of ~~stator~~ armature coil conductors are usually insulated ~~with~~ . Strand insulation can be made up of organic resin enamels, polymeric films, resin bonded fibers ~~with resins,~~ ~~or mica in various forms bonded with resins. Fibers may be~~ (such ~~materials~~ as paper, cotton, asbestos, glass, polyester, or combinations thereof) or resin bonded mica.

In the 1920s cotton was commonly used as the insulation on individual copper strands. By the 1950s asbestos was in use as strand insulation because of its higher temperature classification. By the 1970s polyester glass fiber was commonly used as strand insulation. Some manufacturers alternate polyester glass fiber insulated strands with strands that have an enamel coating.

6.2.2 Turn insulation ~~(Conductor)~~.

In a coil with more than one turn, groups of strands forming a single-turn (conductor) may be held together and insulated. Individual strand insulation, as described in ~~Section-5~~ 6.2.1, may also serve as turn insulation.

Where dedicated turn insulation is provided for multi-turn coils it usually involves similar materials to those in the groundwall insulation in the slot section.

6.2.3 Groundwall insulation

Groundwall insulation is ~~generally defined as that insulation~~ the material intended to insulate the current-carrying components (~~such as e.g.,~~ the coils, the ~~collector~~ circuit rings, and connections ~~thereto~~) from one another and from the non-current-carrying components, which are usually ~~considered to be~~ grounded (such as the core iron, the ~~shaft~~ frame, and other structural members).

Groundwall insulation takes ~~on many~~ different forms depending on the type of machine and the manufacturer's practices. Groundwall insulation is generally a dry-type, multi-layered system ~~comprising~~ comprised of various bonded and filled insulating materials ~~bonded and filled~~. Mica ~~or micaceous-based~~ products are generally preferred in high-voltage machines for at least a part of the groundwall insulation system. Typical insulation systems in use are as follows:

- a) Phenolic Resins (Class 105 Insulation): Phenol formaldehyde, phenol urea, and phenol melamine resins are synthetic polymers often combined with cotton or glass fabrics to produce fiber reinforced composites for use in structural and electrical insulation applications. These materials are normally used for lower voltage and lower thermal classification machines.
- b) Varnished Cambric (Class 105 Insulation): Due to the absence of mica, this insulation system was usually restricted to windings rated 2300 V and below. Heat transfer is relatively poor as is its resistance to moisture and oil. A typical temperature rise rating for such windings is 50 °C.

- c) Shellac Micafolium (Class 130 Insulation): In this system mica flakes are bonded together by shellac to form sheets. These sheets are wrapped and hot pressed around the slot section of the coil. The end-windings are insulated with tape, such as asphalt-mica, or sometimes only with varnished cambric. Due to the evaporation of the volatiles in the shellac this system may have a high void content and is thus susceptible to partial discharge damage as well as to reduced heat transfer.
- d) Asphalt Micafolium (Class 130 Insulation): As above, except that asphalt is substituted for shellac in the slot section.
- e) Asphalt Bonded Mica Tape (Class 130 Insulation): The entire coil is insulated with asphalt-bonded half-lapped mica tape. The mica flakes are bonded together with asphalt and attached to a paper tape. By the 1960s some manufacturers added a polyester terephthalate film (PET film such as Mylar®⁶) tape to allow greater tension to be used during the taping operation. It was common to apply asphalt varnish as the coil was being taped. Some manufacturers used an autoclave in which vacuum was drawn to remove volatiles, followed by flooding of the tank with hot asphalt and application of pressure in order to consolidate the layers of asphalt mica tape. Prior to installation in the stator core, it was common to heat the coils to render them flexible and thus achieve a better fit in the slot. Lift coils had to be heated to facilitate bending at the knuckle. Asphalt mica stator coils can be susceptible to delamination or “puffing” as a result of overload, poor ventilation, or the use of unsuitable asphalt varnish. The asphalt bonded mica tape insulation system is also vulnerable to tape separation near the end of the stator core as a result of thermal cycling. This is especially true of windings in long cores such as turbo alternators.

⁶Mylar is a registered trademark of Dupont Teijin Films.

- f) Polyester Bonded Mica Tape (VPI) (Typically Class 130 Insulation): This system was first introduced in North America in the early 1950s. At that time it involved exclusively the use of large flake mica although several advances in both materials and processing technologies have improved the performance and reliability since it was introduced. In the vacuum pressure impregnation (VPI) process the coils or bars are placed in an autoclave and subjected to a high vacuum for drying purposes. The tank is then flooded with polyester resin and pressure is applied to achieve the desired impregnation. Following removal from the tank the coils are cured. There are advanced polyester systems up to Class 155.
- g) Epoxy Bonded Mica Tape (VPI) (Typically Class 155 Insulation): It has become common to use epoxy in place of polyester resin in VPI operations in order to obtain improved bonding characteristics and a higher temperature classification. This impregnation process is used for individual stator coils or bars that are hot pressed in molds, to cure the groundwall bonding resin, prior to inserting them into the stator slots. One impregnating epoxy resin that has been used in a VPI process is a catalyzed blend of bisphenol-A resin with a hardener. Once the catalyst has been added the resin must be refrigerated in order to reduce reactivity. There are advanced epoxy-based systems up to Class 180.
- h) Epoxy Polyester Blend or Hybrid Systems (VPI) (Typically Class 155 Insulation): Some modern insulations systems use a blend of epoxy and polyester resins to achieve a mix of the elasticity and strength attributes of both base resin systems.

- i) Global VPI (Class 155 up to Class 180 Insulation): The coils or bars are insulated with mica tape over which are applied the semiconducting slot armor tape and the stress control tape on the end arms. The coils or bars are installed in an unbonded state in the stator core. The entire core and winding is then placed in an autoclave for impregnation with resin following which the resin is cured. Global VPI resin choices include epoxy, polyester, polyesterimide, silicone, and combinations of these materials. To maintain the success of this process on longer machines some manufacturers utilize a slip plane between the core and coil surface to allow for the longitudinal expansion and contraction of the copper with respect to the core.

- j) Epoxy Bonded Mica Tape (Resin Rich) (Class 155 Insulation): This system involves a mica paper formulation in which the mica paper or flakes are deposited on a glass fiber backing tape. An uncured (B stage) epoxy resin is applied during the manufacture of the tape. A polyester (typically PET) film or fabric layer may be included to make it easier to handle the tape during its application to coils or bars. Once the bars or coils have been insulated, the B stage resin is cured under elevated temperature and pressure in one of the following two ways:
 - 1) In the heated press method, mold angles are applied to the slot section of the coil or bar prior to insertion in the heated press. The rate of temperature and pressure increase is critical in the bonding process. Additional heaters are used with splints and shrink tape to cure the tape on the end arms.

 - 2) An autoclave process is used by some manufacturers. This involves the following three major steps:
 - High vacuum to remove moisture, volatiles and trapped air.

- Elevated temperature at reduced pressure to allow the B stage resin to flow to a limited extent.
 - High temperature and high pressure while the resin cures.
- k) Silicone Rubber (Class 180 Insulation): Silicone rubber is a material that is suitable for use at high temperatures. When used as the groundwall insulation of a stator coil it usually has a fiberglass backing. In the absence of mica it is commonly restricted to lower voltages (e.g., 4160 V and below). A disadvantage of silicone rubber is its vulnerability to mechanical damage.
- l) Varnish Dip and Bake (Class 130 Insulation up to Class 180 Insulation): Especially at lower voltages (2300 V and below) and for small sized stators, such as some motors and random wound designs, the varnish dip/oven bake process is common. In this case the stator coils are insulated with materials including enamel insulated conductors with a variety of films, aramid papers, mica tapes and laminates as ground wall and phase insulation. Following this, the coils are installed in the stator core and connected together with all applicable lashings and bracing. The varnish or resin is then applied by dipping, often in automated equipment or by alternate methods such as trickling; or in some cases as a B-stage coating on the conductors and insulators. Common impregnants include polyesters and epoxies in a variety of evaporative formulations utilizing aromatic solvents or water as the carrier or with a catalyst as reactive polymeric cure. There are many curing schemes as well including UV light reactive materials, room temperature catalysts, induction or resistance heating, and traditional/automated ovens.

6.2.4 Semiconducting slot coating

5.2.4 Insulation Grading System.

The surface of slot portions of stator coils and bars, including several ~~inches~~centimeters of the coil beyond the core, is normally semiconducting. The semiconducting characteristic is accomplished by the application of ~~conducting~~semiconducting varnish over the armor tape (if any) or by the use of semiconducting armor tapes. These treatments are often referred to as conductive and are generally applied to machines with rated voltage of 4 kV and above.

6.2.5 Stress control coating

Due to the semi-conducting slot coating, the surface of the stator coils and bars just outside of the core is at ground potential. The surface of the end turn insulation, however, is typically not at ground potential. In order to linearize the electric field distribution along the coil or bar end turn a stress control coating is applied. This coating can be made from varnishes or tapes that have a non-linear resistance characteristic through the use of silicon carbide. These stress control coatings are often referred to as grading paint or tape and are generally applied to stator coils and bars insulated with thermosetting materials in machines with rated voltage of 6 kV and above. Such coatings are less necessary for thermoplastic insulation systems which operate at a lower electric stress.

6.2.6 Stator slot tightening systems

Various systems are used to secure the stator winding in the slot to achieve electrical contact and thermal contact to the core. These are required to maintain this contact when subjected to the operational forces, thermal mechanical forces, and material shrinkage or creep. These include side packing and top packing in the form of flat and ripple spring materials. Other systems also exist. With globally vacuum pressure impregnated insulation systems, the coils are integrally sealed in the core and may require slip layers for control of unmatched thermal expansion of various slot contents. If the stator coils or bars have semiconducting slot coatings, the slot side packing should also be semiconducting.

6.2.7 **Support insulation**

Supports may be nonmetallic or metallic in design. Nonmetallic supports include blocks, spacers, ties, slot wedges, slot fillers, etc. Nonmetallic supports are made of various ~~such as~~ materials including wood, molded parts, ~~or~~ compressed laminates of cotton, asbestos, glass, or synthetic fibers. ~~Where necessary, metallic supports are insulated,~~ and felt pads impregnated with various types of bonding agents including phenolic, polyester, and epoxy resins. These materials have a range of thermal classifications as well as different physical and electrical properties. Metallic supports such as the surge (bull) ring and its supports are insulated where necessary.

6.2.8 Circuit ring (also known as parallel ring) insulation

The windings of a machine associated with each phase and pole start and finish at physical locations around the machine which are determined based on the physical location of the phase with respect to other phases in the circumference of the machine. Various winding designs can affect these start-and-finish locations. The main leads of the machine are located generally together at one location; therefore, connections must be provided between phase groups and from phase groups to the leads. These rings are typically circumferential and are typically located behind the winding, usually on one end of the machine. These rings complete the electrical circuits of the phases and often provide multiple parallels between phase groups. The rings are usually physically parallel to one another; therefore, they are often referred to as circuit rings, parallel rings, or connection rings.

The rings are typically made of highly conductive copper either in bar, wire, or tubular form. The current carrying capability depends on the machine size, rating and the arrangement of the phase groups into various parallel circuits. The voltage difference between adjacent rings and to ground also varies depending on size, rating and circuit arrangements. In many cases some adjacent rings in the machine will have a voltage between them that equals the line-to-line operating voltage of the machine.

There are various approaches taken to insulate between the circuit rings. Typically the insulation is the same materials as used to insulate the armature windings. In some cases the circuit rings have a semiconducting outer-corona-protection (OCP) layer at their surface with gradients near termination points—this allows the rings to be placed closer together. In many cases the rings do not have any OCP layer; therefore, the circuit rings support mechanisms must be carefully configured with materials and spaces provided to minimize surface partial discharge.

Design considerations for circuit rings include addressing the voltages between rings as well as how they are cooled, and how they react to eddy currents due to current flow within the conductor as well as proximity effects of other rings.

Whether circuit rings consist of insulated wires or copper bars, maintenance inspection should include visual inspection to look for indications of overheating, dusting from looseness, deterioration of the insulation, and deterioration of surface coatings. Typically the circuit rings are tested for appropriate insulation condition as part of the winding high potential tests.

6.2.9 Commutator insulation

A commutator is a cylindrical assembly of wedge-shaped copper segments separated from each other and ground by insulation that is usually mica-based. This structure is mechanically locked together by various techniques including V-grooves, cones and support rings at commutator bar ends, steel shrink rings over ring insulation on the commutator surface, and highly tensioned fiberglass bands applied into grooves in the commutator surface. Small-size units are often compression molded with a high-strength molding compound.

6.3 Wound rotor windings (three-phase induction machines)

The rotating secondary windings of wound rotor ac induction machines are similar to armature windings. The three-phase winding, with its associated leads and collector rings is the secondary current carrying winding of the machine, but the current may be higher than the stator current. The voltage is usually less than 3000 V, but there is no real limit. The coils have ground insulation and may have turn insulation. Wedges, blocks, and other insulated mechanical supports are a part of the wound rotor winding assembly. They also have banding or retaining rings because of the centripetal forces. The coils of the winding may be constructed of insulated rectangular copper conductors wound with the long edge radial in partially closed slots or may be constructed with strands similar to an armature winding in an open slot.

6.3.1 Partially closed slots—strap or bar windings (generally used on high-speed machines)

The straps may be half straps or open ended full coils. There are usually two to four straps inserted radially in each partially closed slot. Each strap is insulated with insulation appropriate to the secondary voltage, usually mica. This insulation may also serve as the ground insulation.

6.3.2 Open or semi-enclosed slots

Coils made of copper wire(s) wound in loops or bars.

6.3.3 Strand (wire) insulation

In wound rotors, the conductors can be wound in loops as full coils or in bars (as half-coils). Strand insulation can be made up of enamels, polymeric films, resin bonded fibers (such as paper, cotton, asbestos, glass, polyester, or combinations thereof) or resin bonded mica. Aramid paper can be used in high temperature machines. The turn voltages are generally not high enough to require mica insulation or dedicated turn insulation.

6.3.4 Groundwall insulation

Sometimes wound-rotor groundwall insulation is similar to those listed in 6.2.3. However, usually slot liners are used to provide ground insulation between the rotor winding and core slots. Common slot liner materials are aramid paper (such as Nomex®⁷) and polyester-glass-polyester or polyester-glass laminates (using films such as Mylar®).⁸

⁷Nomex is a registered trademark of E. I. du Pont de Nemours and Company.

⁸Equivalent products may be used if they can be shown to lead to the same results.

6.3.5 Winding support wedges

Since there are high centrifugal forces imposed on the rotor winding during operation, substantial slot wedges are required to retain the winding in rotating cores. For this purpose, polyester or epoxy glass composite wedges are used in modern wound-rotor induction motors, while phenolic cotton composite wedges were commonly used in older motors.

6.3.6 Collector rings

There are three collector rings mounted on a steel hub with insulation to separate the rings from the hub. This insulation may be mica or other materials applied oversize, then turned down to size to allow for a shrink fit of the rings. The three rings are separated from one another by a distance dependent on the secondary three-phase voltage. A track-resistant compound is usually applied over all insulating surfaces of the collector.

6.4 Field winding insulation

6.4.1 Field windings

The field windings of ac machines are normally rotating and can be either salient pole or cylindrical type. The field coils of dc machines are stationary and are constructed in a similar fashion to ac salient pole rotating field coils, except that they need not be built to withstand the effect of rotational forces. Field coils for dc machines are usually a complex assembly of exciting and commutating coils, each fitted over and insulated from a pole piece. Some coils contain multiple windings.

In all cases, field windings have turn and ground insulation, insulated mechanical supports, and lead insulation. In addition, rotors for ac machines may have collector ring insulation, retaining ring insulation, and banding insulation.

~~5.3 Rotor Winding Insulation~~

6.4.2 Turn (conductor) insulation

Turn insulation on wire-wound field coils usually incorporates a thin insulating layer on the strand itself: ~~for example~~ Various materials such as asbestos, cotton, fiberglass, papers, micas, and synthetic materials have been used.

Turn insulation on strap-wound coils ~~of both salient pole and cylindrical type rotors~~ usually incorporates various forms of tape or strip material with resin bonding.

6.4.3 Ground insulation

A variety of organic and inorganic materials are used for ~~Various types of~~ ground insulation ~~are used~~ on the ~~rotating~~ field coils of ~~synchronous rotating~~ machines ~~(salient pole or cylindrical type) and on the wound rotor induction~~. Some early machines ~~A variety of organic and inorganic materials are used~~ may have used wood and cambric materials, which may have been replaced in later machines with phenolic laminates and sheet mica. Mica tapes were also used. Today common materials are mica laminates, glass laminates, and aramid paper.

6.4.4 Collector insulation

The insulation used on collector rings and leads must be adequate both for support and electrical creepage to the grounded shaft. The insulation usually consists of laminated fibers or mica suitably bonded or impregnated.

6.4.5 Brush rigging insulation

The insulated components on brush riggings are generally ~~molded~~ made from molding compounds, ~~laminates~~ laminated boards, or tubes made from paper, cotton, or glass ~~synthetic~~ fibers suitably bonded and impregnated. Moisture-resistant surfaces are very important for these components.

6.5 Core and frame-assembly insulation

6.5.1 Stator core interlaminar insulation (core plate insulation)

Stator cores are built up ~~from~~ with thin steel laminations insulated from ~~one another~~ each other to reduce core losses. ~~A~~ Laminations may be coated with a variety of thin insulating ~~films are used~~ coatings, such as varnish, silicates (water- glass ~~chemical deposits~~), oxides, ceramics and coatings that are combinations of organic and inorganic materials. On very small machines or ~~chemical treatments~~ machines where the volts per layer in the stator core are low, iron oxides produced by appropriate annealing processes are often used. On large machines with higher flux, where the volts per layer are higher, the standard practice is to de-burr and recoat the laminations.

6.5.2 Insulation punchings

In some designs, where deemed necessary, pieces of thin insulation sheet are cut to the shape of the punchings and are used to supplement the interlaminar insulation. These layers are also sometimes used as backing for ventilation layers where there are spot welded or riveted vent fingers. Typically the materials used are glass epoxy laminates or aramid fiber papers due to the compressive creep requirements. Older machines with lower thermal classification have used cellulose or cotton paper insulation punchings.

6.5.3 Core tightening through bolt insulation

The core tightening through bolts are insulated from ground ~~throughout~~ along their length with insulating materials suitably bonded. Bolt-end hardware, such as nuts and washers, must also be insulated from ground. Key bars or bolts, used at the outer diameter of the core for tightening, usually require no insulation. Typically the materials used are glass epoxy composites or aramid fiber composites for these insulating components; however, epoxy mica is sometimes used. In some newer designs, some rods, bolts, nuts and other mechanical components are fully manufactured of non-conductive glass composite materials.

6.5.4 Other insulating parts

Insulation is sometimes used on bearings or bearing brackets to eliminate shaft currents. Insulation is also used to isolate temperature-measuring devices such as thermocouples (TCs), resistance temperature detectors (RTDs), and thermistors.

7. Service conditions affecting insulation life

Electric machines and their insulation systems are subjected to mechanical, electrical, thermal and environmental stresses that give rise to many deteriorating influences. The degradation rate of electrical insulation systems is substantially greater when these stresses act simultaneously than when they are sequentially applied (Bartnikas and Morin [B8]). A thermal stress applied independently prior to application of electrical stress is appreciably less deleterious than when the two stresses act simultaneously (Bartnikas and Morin [B8]). The synergistic effects of environmental stresses are more difficult to ascertain. An insulation system operating in the presence of nuclear radiation may, in some cases, have a prolonged life expectancy. For example, polymeric based insulating systems operating in the presence of ionizing radiation may exhibit initially a prolonged life due to radiation induced cross linking of the polymers (Campbell [B13]).

7.1 Aging mechanisms

No machine insulation system that is economically produced is expected to last forever. The thermal, mechanical, electrical, and environmental stresses will gradually reduce the electrical and mechanical strength of the insulating materials. At some point, the materials will have aged significantly. In such a case, the insulation breaks down or cracks under the normal operating voltages or as a result of a transient electrical or mechanical situation (e.g., from lightning or switching voltage surges, motor switch-on in-rush current or current transients from faults in the power system that cause large electromagnetic impulses or rapid load changes). If the insulation breakdown occurs in the stator groundwall or turn insulation, this will rapidly lead to high-power frequency fault currents and circuit breaker operation. Failure of the strand insulation in stators, or the turn insulation (and to a limited degree, the ground insulation) in rotors will not result in motor or generator failure. However, performance will be adversely affected since the magnetic field intensities will be weaker and non-symmetrical, leading to vibration; or the efficiency of the machine will be reduced due to circulating currents. The circulating currents will cause additional heating that will accelerate insulation aging processes.

Additional failure processes can occur due to on-off cycling of motors or load cycling of generators. Such cycling leads to large and sometimes rapid swings in winding temperatures, and to a lesser extent core temperatures. Such temperature swings can lead to different thermally induced growth among the different winding components, developing shear stresses between the components.

The single and multi-stress interactions, together with load cycling, yield about 20 different identifiable failure processes in stator windings, and about 10 mechanisms in rotor windings. Which process will occur in a specific machine and how quickly the failure will occur will depend on the following: