MACHINE INSULATION

This article describes the application of the electrical insulation to electrical motors and generators. Initially an overview of the application of electrical insulation in machines is presented, followed by a more detailed discussion of the design of the insulation systems used in the various types of machines, how the insulated windings are made, and how they deteriorate and fail. Finally, a review is presented of the methods available to evaluate the condition of the insulation in motors and generators. Although the following will concentrate on ac motors and generators, much of the insulation aspects for dc machines is similar to the situation for integral horsepower motors rated 1000 V or less.

TYPES OF ROTATING MACHINES

Since the invention of the first motors and generators in the late 1800s, a wide variety of rotating machines have been conceived and commercially produced.

Generators. The most common types of generators, which convert mechanical energy to electrical energy, are synchronous generators. In the synchronous generator, a dc current from a few volts to as high as 1000 V is passed through a “field” winding mounted on a rotor. The rotor is most often spun by either a turbine driven by falling water or steam, or an engine (diesel or combustion turbine type). The current through the winding creates a magnetic field that interacts with the stator (or armature) winding, which is stationary. The rotating dc field induces an ac current in the stator winding. The frequency, voltage, and current developed in the stator winding depend on the electrical characteristics of the rotor and stator windings, as well as the rotational speed of the rotor.

Synchronous generators have been manufactured with output ratings from less than 1 W up to 2000 MW and with voltages from 100 V to 30 kV. There are two basic types of synchronous generators, classified according to the rotor design: round-rotor generators (also called turbine generators, and usually driven by engines or steam combustion turbines) and salient-pole generators (most often employed as hydrogenerators, i.e., falling water drives a turbine). In general, round rotors are used on generators with a rotor speed of 600 revolutions/min or more, whereas salient-pole rotors are used in applications with rotor speeds less than 1000 revolutions/min.

Motors. There are a wide variety of motors, both ac and dc. However, by far the most commercially important motors today are of the squirrel-cage induction (SCI) rotor type, which can have ratings from 1 HP (about 700 W) to 40,000 HP (about 30 MW), and voltages from 100 V to 13.8 kV and higher. In the SCI motor, an ac current is fed to the stator (armature) winding, creating a magnetic field, which induces some current in the rotor winding. The reaction of the resulting rotor magnetic field against the stator’s field, causes the rotor to spin. In the SCI motor, the actual mechanical rotation speed is slightly slower than the rotational speed of the magnetic field. Note that no current is directly input to the SCI rotor, and that the rotor winding consists of uninsulated conductors around the periphery of the rotor.

Finally, the inverter-fed drive (IFD) in combination with a conventional SCI motor has become very popular in the 1990s, because the IFD enables considerable electric energy savings in applications where a constant full load output is not required. As described later, the IFD can pose special hazards for SCI motors.

ROLE OF ELECTRICAL INSULATION

The preceding discussion makes repeated references to the rotor and stator windings in rotating machines. These windings usually consist of copper or aluminum conductors embedded in or wound around a magnetic or nonmagnetic steel core. Since the core is usually at ground potential, whereas the conductors are at a nonzero ac or dc voltage, electrical insulation is needed to isolate the conductors from ground, to ensure that the currents flow along the desired paths. The electrical insulation is a passive component in a rotor or stator winding. However, without its presence, electrical shorts occur that disturb the magnetic fields, impairing proper machine operation; allow circulating currents to flow, increasing losses; and/or enable very large fault currents to flow that can melt the steel core and conductors.

Most of the electrical insulation in modern machines is based on organic compounds such as enamels, films, polyester, or epoxy. Such organic insulation materials have low mechanical strength and low melting temperatures, in comparison with steel and copper. As a result, motor and generator winding designers must limit the winding operating temperatures and the mechanical forces to levels within the capability of the insulating materials. In practice, the expected operating life of a winding is fundamentally based on the capabilities of the insulation. In fact, almost all winding failures result from deterioration of the insulation, rather than problems with the conductors or stator core. In a study of 7500 motor failures in electric utility applications, 37% of the failures were attributed to stator winding problems, which in turn were caused by insulation deterioration (1). Thus the electrical insulation is of critical concern for the effective operation of motors and generators.

STATOR-WINDING INSULATION SYSTEMS

Stator windings of the same ratings (watts, voltage) are essentially the same for both motors and generators, and thus no distinction will be made between motor or generator stator windings.

Stator windings consist of parallel paths of series connected insulated copper conductors formed into coils. The

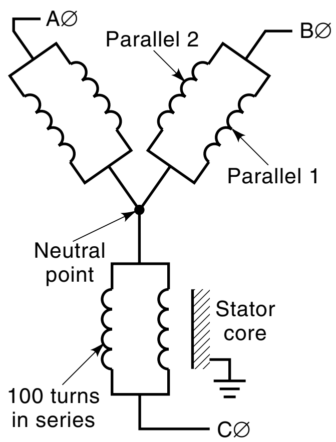

Figure 1. Schematic of a wye-connected stator with two parallels per phase.

coils have a certain number of loops or turns. Figure 1 shows the electrical schematic of a wye-connected three-phase stator winding consisting of 100 turns between the phase terminal and the neutral point. If the stator winding is rated 440 V (phase-to-phase), the terminal phase-to-ground operating voltage is approximately 260 V. The potential difference between two sequential turns in the same phase is 2.6 V.

There are two major classifications of stator windings according to how the turns in the winding are physically configured: random wound and form wound. Random-wound stators consist of insulated copper conductors (magnet wire) which are continuously wound (by hand or by a winding machine) through the stator core slots to form a coil (Fig. 2). Each turn (loop) of magnet wire (i.e., insulated conductor) can be randomly placed against any other turn of magnet wire in the coil, independent of the voltage level of the turn. Since a turn that is connected to the phase terminal can be adjacent to a turn that is operating at low voltage (i.e., at the neutral point), random-wound stators usually operate at voltages less than 1000 V.

In contrast, form-wound stators are usually intended for machines operating at 1000 V and above. Such windings are made from coils that have been preformed prior to insertion in the slots in the stator core. Usually each coil can have from 2 to 12 turns, and several coils are connected in series to create the proper number of turns between the phase terminal and ground (or neutral)—see Fig. 1. Wire used in form-wound stators is usually rectangular in cross-section. Careful design and manufacturing are used to ensure that each turn in a coil is adjacent to another turn with the smallest possible voltage difference. By minimizing the voltage between adjacent turns, thinner insulation is needed to separate the turns. For example, in a 4160 V stator winding (2400 V line-to-ground), the winding may have ten coils connected in series, with each coil consisting of ten turns, yielding 100 turns between the phase terminal and neutral. The maximum voltage between adjacent turns is 24 V. If the stator were of a random wound type, there might be 2400 V across adjacent turns, which would require much thicker magnet wire insulation.

Figure 3 is a photograph of a diamond-shaped, form-wound multiturn coil being inserted in a stator slot. For stators of machines larger than approximately 50 MW, the form-wound coil is large enough that there are difficulties in inserting both legs of the coil in the stator slots without risking mechanical damage to the coil during the insertion process. Thus, most large generators today are made not from multiturn coils, but rather from "half-turn" coils, often referred to as Roebel bars. With a Roebel-bar construction, only one half of a "coil" is inserted into the slot at a time, which is considerably easier than inserting two sides of a coil in two slots simultaneously. With the Roebel-bar approach, electrical connections are needed at both ends of the bar to make the "coils." Roebel windings also incorporate an arrangement that physically transposes the copper strands in the bar. Each strand is braided through the bar in such a manner that each strand occupies every position in the cross section at some point throughout the length of the bar. This method is used to control circulating currents due to nonuniform magnetic fields. Special insulation material and processes are required to prevent strand shorts at cross-over points and to smooth out uneven surfaces.

To ensure that appropriate magnetic fields are created, to minimize electrical losses and to prevent short circuits, several types of insulation components are required in stator windings. The components are the strand, turn, and

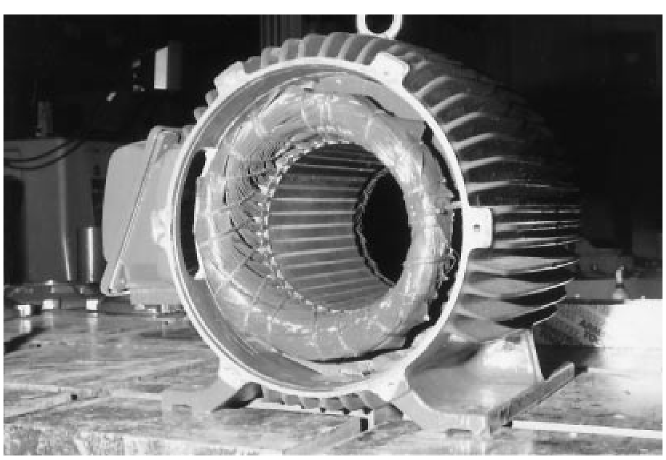

Figure 2. Photograph of a random-wound stator.

Figure 3. Photograph of a complete form-wound stator.

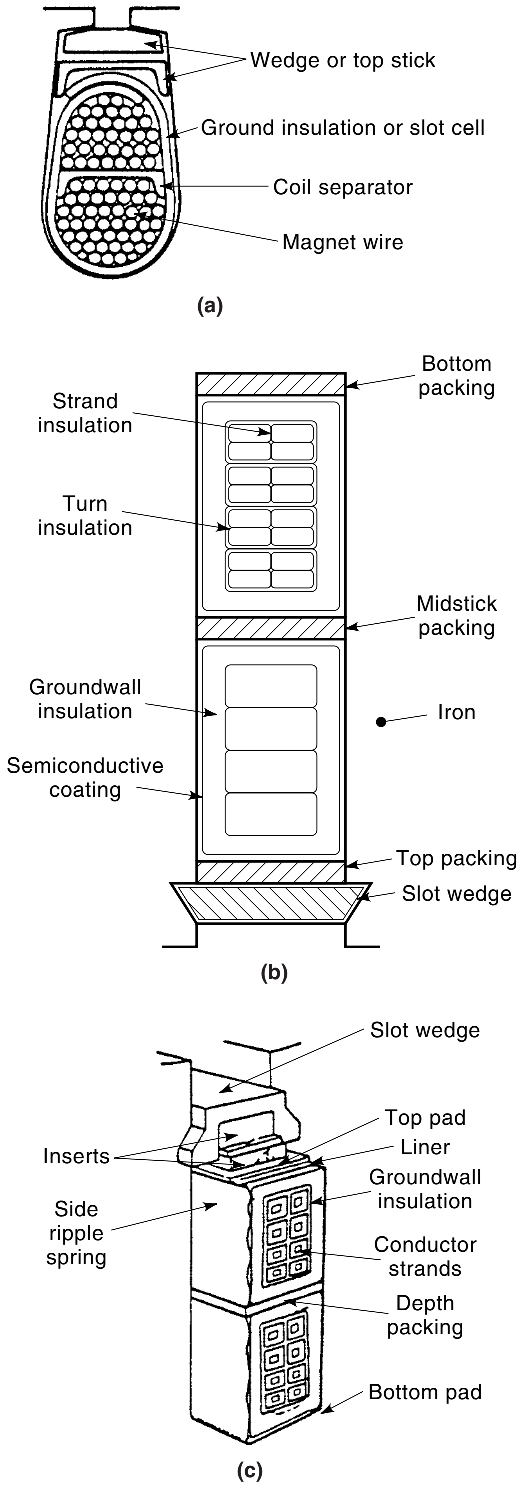

Figure 4. (a) Cross section of a slot containing random-wound coils. (b) Cross section of two multiturn form-wound coils in a slot. (c) Cross section of two direct water-cooled Roebel bars in a slot.

groundwall insulation. Figures 4(a) to 4(c) show the different insulation components in the cross section of a random-wound multiturn coil, a form-wound multiturn coil, and a Roebel bar (DuPont), respectively, in a stator slot. The purpose of each insulation component is discussed later. The strand and turn insulation is very thin, since the voltages involved are quite low. For form-wound stators rated 1000 V and above, the groundwall may be several millimeters thick to withstand this high voltage. Note from Fig. 4(c) that there is no turn insulation in a Roebel bar, since the ground insulation is effectively the turn insulation. In modern random-wound stators, the insulation is a synthetic polymer (typically polyamide-imide) film that is bonded to the copper conductor. Random-wound stators rated more than 120 V may also have thin sheets of flexible insulation (Nomex or similar) to provide additional insulation between the turns and the stator core or between the coils in different phases.

For form-wound machines, the strand and turn insulation is often the polymer film, overcoated with Dacron and fiberglass tape, which is heat fused to the conductor. A separate groundwall insulation in the form wound bar or coil is usually made from layers of tape consisting of small bits of mica, bonded to the Dacron and/or fiberglass. The tape layers are then bonded together, as well as to the conductors, with epoxy. Such an insulation system is often referred to as an epoxy–mica system. More details on the materials and manufacturing processes are presented later.

ROTOR-WINDING INSULATION SYSTEMS

The most common type of motor uses a squirrel-cage induction rotor. Since there is no insulation on the conductors that form the rotor winding, SCI rotors will not be discussed further. Most generators have insulated rotor (field) windings. The field windings consists of multiple turns of copper conductors embedded in the rotor body (round-rotor design, Fig. 5), or conductors coiled around a laminated steel field pole (salient-pole design, Fig. 6). The rotor windings usually operate at low dc voltages, with about 1000 V being the highest operating voltage in a very large generator. Thus, the ground insulation is relatively thin in comparison with the stator winding insulation. The voltage between turns is usually a few tens of volts; thus the turn insulation can be relatively thin. In large generators, the field winding may have currents of thousands of amps, therefore a large copper cross section is needed. However, since the current is dc, there is often no need to break up the cross-sectional area into strands in order to minimize losses.

On smaller machines, the rotor windings are usually wound with magnet wire, that is, copper wire coated with a polymer film. For modern machines rated more than a few megawatts, the copper conductors are often bare, with aramid paper or epoxy–glass laminate [National Electrical Manufacturers Association (NEMA) material grades G-10 or G-11] strips used to separate the turns from one another and from ground. These are discussed in more detail later.

INSULATION SYSTEM REQUIREMENTS

The insulation in rotor and stator windings are exposed to the following stresses:

- High temperatures, primarily from the conductor current (I^2R) losses.
- High mechanical forces. In the stator, these are primarily from the Lorenz magnetic field forces that are propor-

tional to the conductor current squared. In a stator operated with 60 Hz current, the stator current creates a 120 Hz vibrating magnetic force on the conductors. In addition, during motor start-up or a generator out-of-phase synchronization event, the high stator in-rush current creates a very high mechanical impulse force. On the rotor, the insulation is exposed to a very high centrifugal force due to the high rotational speed at the rotor surface.

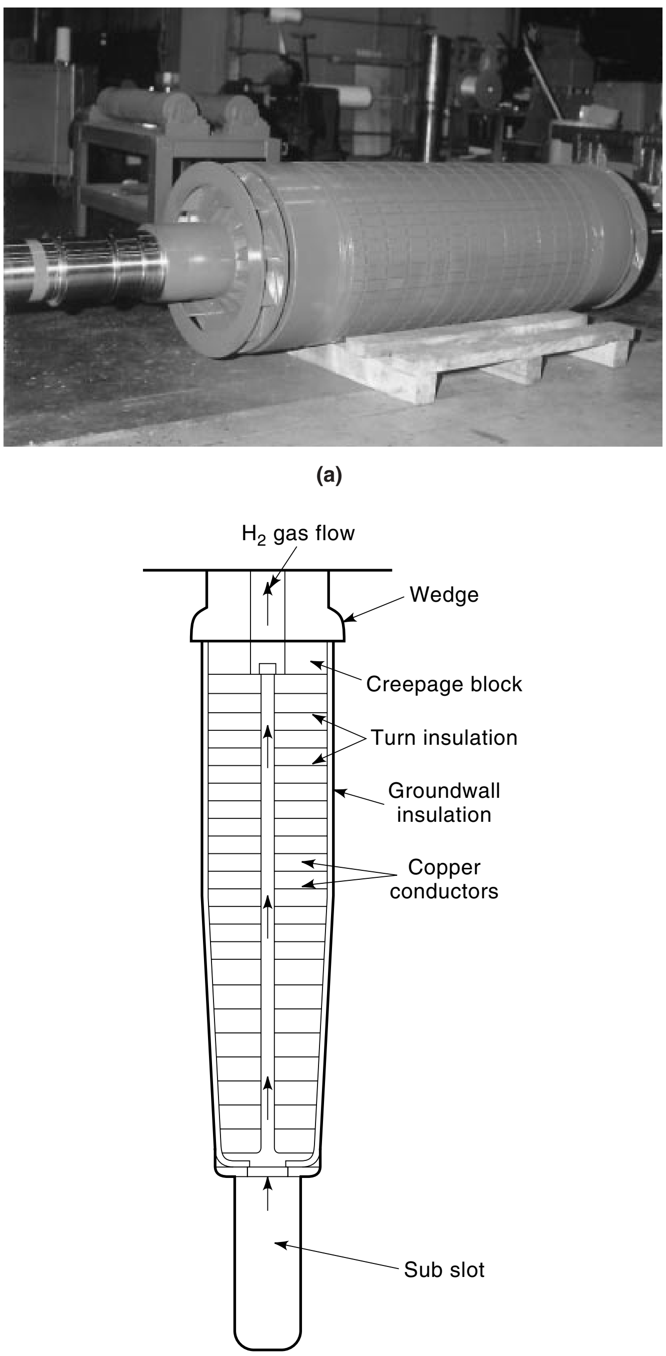

Figure 5. (a) Photograph of a round rotor. (b) Cross section of a round-rotor slot of a direct hydrogen-cooled rotor.

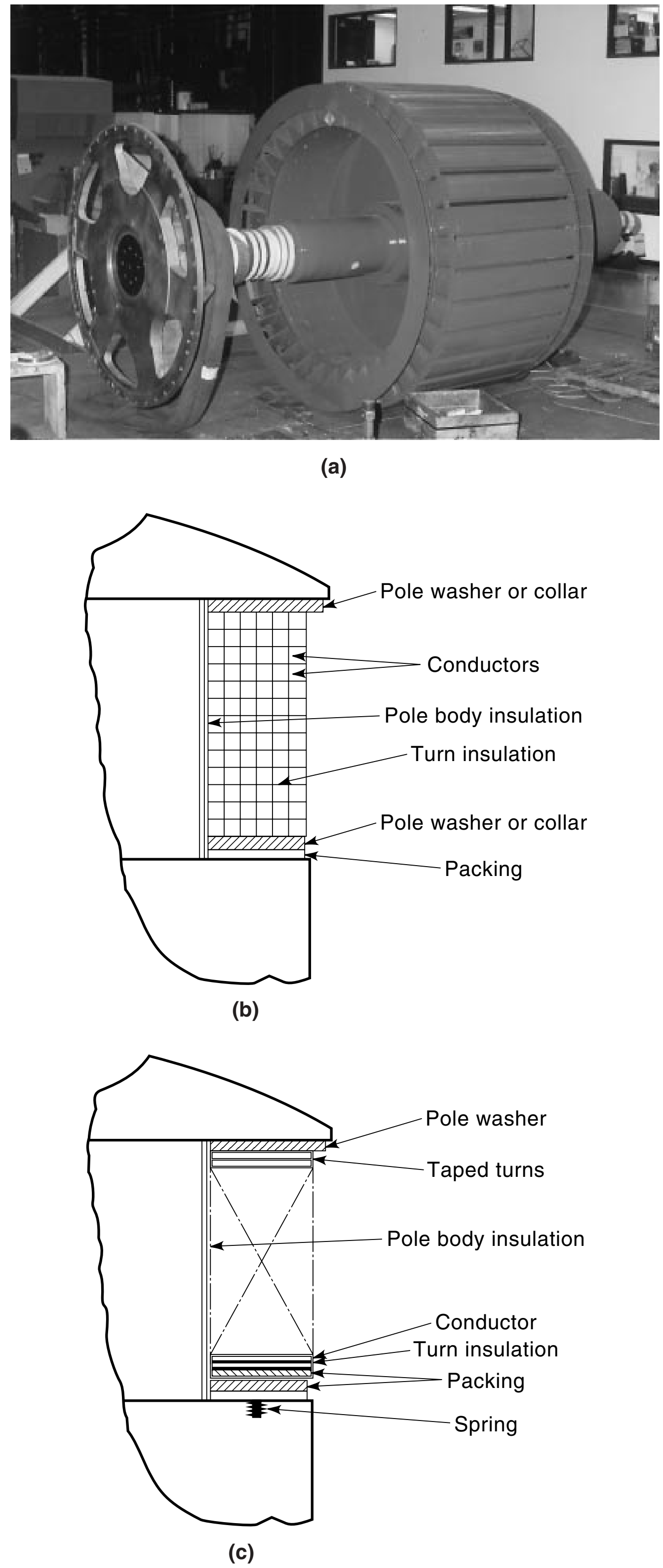

Figure 6. (a) Photograph of a salient-pole hydrogenerator rotor. (b) Cross section of a strip-on-edge field pole. (c) Cross section of a multilayer field pole.

- High voltages, either from normal operation on machines rated 1000 V and above, or from electrical transients due to lightning or switching events from the supply system.
- Harsh environments that may contain oil, moisture, radiation, and abrasive materials in the cooling air stream flowing over the windings.

All of these stresses can cause gradual or catastrophic degradation of the insulation materials. Machine manufacturers have to design the machine to limit the thermal, mechanical, and electrical stresses to levels that the insulation can withstand for the design life of the machine. This requires the designers to evaluate the capabilities of the insulation materials. This evaluation is done using accelerated aging tests to simulate the aging process an insulation may see in 30 years, but with higher stress levels so that aging occurs in weeks or months. (See the articles on INSULATION AGING TESTING and INSULATION TESTING.) Many standard test procedures have been developed to evaluate the thermal, mechanical, electrical, and environmental capabilities of insulating materials and systems used in motors and generators. Table 1 identifies some of the key Institution of Electronic and Electrical Engineers (IEEE) and International Electrotechnical Commission (IEC) insulation standards for rotating machines.

With regard to the critical requirement of thermal capability, all the insulation materials used in motors and generators are assigned a temperature at which they are expected to operate with a low risk of failure for 20,000 h (about three years). Materials are grouped into classes; see Table 2. Most of the materials used in modern random wound stators have a class 180 (or class H) capability. Most of the materials used in modern form-wound stators and generator rotors, including epoxy–mica insulation, have a class 155 (or class F) rating. It is important to note that operating these materials at the class temperature (say 155°C) for more than three years implies that insulation failure is likely. That is why manufacturers usually design the machine to have an operating temperature for the insulation system that is significantly lower than the thermal class.

Unfortunately, although there are standard test procedures to evaluate electrical and mechanical capability for the insulation materials (see Table 1 for a selection), there is no accepted classification of materials for electrical and mechanical capability for rotating machine application. Thus, machine designers are left to judge the suitability of a particular material for a specific application.

Table 1. Insulation Material and System Standards

Standard	Purpose
IEEE 1	General principles for determining thermal capability
IEEE 117	Classification of insulation for ac random windings
IEEE 275	Classification of thermal capability of ac form-wound stator coils
IEEE 304	Classification of thermal capability of dc windings
IEEE 429	Classification of thermal capability of ac windings sealed against moisture
IEEE 434	Evaluation of functional capability of ac form-wound windings
IEEE 792	Evaluation of impulse voltage capability of ac form-wound coils
IEEE 1043	Evaluation of form-wound coil insulation to withstand long term 50 (60) Hz voltage stress
IEEE 1107	Classification of thermal capability of ac random-wound windings sealed against moisture
IEEE 1310	Evaluation of ac form-wound coils to resist thermal cycling
NEMA MW1000	Classification of magnet-wire insulation
IEC 60034	Classification of rotating-machine insulation systems (multiple parts)
IEC 60216	Thermal classification of insulating materials (multiple parts)
IEC 61033	Evaluation of bonding strength of enamel to magnet wire

Table 2. Material Thermal Classification

Class	Temperature Index[a] (°C)
A	105
B	130
F	155
H	180

[a] Maximum operating temperature at the conductor for average life of 20,000 h.

WINDING LIFE

No insulation system that is economically produced is expected to last forever. The thermal, mechanical, electrical, and environmental stresses described previously 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 (e.g., lightning or switching voltage surges) or mechanical (from motor switch-on in-rush current or current transients from faults in the power system, which cause large magnetic field impulses) situation. 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 (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 nonsymmetrical, leading to vibration, or the efficiency of the machine will be reduced due to circulating currents.

Different stresses combine in different ways to yield a wide variety of specific failure mechanisms in both the rotor and stator windings. Some mechanisms are due to pure thermal stress. For example, in windings that are operated at high temperatures for long periods of time, the insulation oxidizes, making it brittle and subject to mechanical failure. Similarly, insulation abrasion can occur as a result of the magnetically induced forces causing the winding to rub against the stator core, until the insulation is thin enough to puncture. Although relatively unusual, pure electrical failure can occur on stators operating above 6 kV, since partial discharges (small electrical sparks, sometimes referred to as *corona*) occur, which eventually bore a hole through the organic insulation, causing a short circuit. Finally, partly conductive pollution (for example, oil mixing with dirt) can lead to small currents flowing over the insulation surface in the endwinding, leading to electrical tracking.

In addition to these single-stress deterioration processes, the stresses can combine to lead to more complicated deterioration mechanisms. Long-term operation at moderately high stator winding temperatures can lead to groundwall-insulation delamination, that is, the mica-tape layers debond, allowing air gaps to occur within the groundwall. If the stator is operating above 6 kV, there may be sufficient electrical stress within these air gaps, causing electric breakdown of the air, i.e., sparks occur between the tape layers. The sparks (called partial discharges) break the carbon–hydrogen bonds in the polymeric components, eventually boring a hole through the groundwall, leading to failure. Thus, the combination of thermal and electrical stresses result in failure. There are several multistress failure mechanisms as such. Theoretical descriptions of the aging models are presented in INSULATION AGING TESTING.

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. Such temperature swings can lead to different thermally induced growth among the different winding components, developing shear stresses between the components. For example, when a large generator goes from no load to full load in a few minutes, the stator winding copper temperature goes from a low temperature to a high temperature, and the copper grows axially along the slot. The insulation temperature is lower, and modern epoxy–mica has a lower coefficient of thermal expansion than copper, causing the groundwall insulation to experience a much smaller axial growth. Since the copper expands more than the groundwall, a shear stress develops between the conductor and the insulation. With a sufficient number of load cycles, the groundwall may debond away from the conductors, creating an air gap, leading to failure from partial discharges.

The single- and multistress interactions, together with load cycling, yield about 20 different identifiable failure processes in stator windings, and about 10 mechanisms in rotor windings. See Tables 3 and 4 for a summary of the main failure processes. Which process will occur in a specific machine and how quickly the failure will occur will depend on:

- The design stress levels (i.e., operating temperatures, mechanical stress, etc.) the machine designer employed, and how close these levels are to the insulation material capabilities.
- How well the windings were manufactured and assembled.
- The operating environment the user provides, that is, is the machine run at constant load or cycled, is it overloaded; are oil, moisture, or abrasive particles present?
- How well the user maintains the windings, that is, keeping them clean, keeping them tight to prevent vibration, etc.

Knowing which deterioration processes is occurring is important, since any winding maintenance to extend winding life should directly address the processes. For example, cleaning a winding may slow the electrical tracking process and lower the winding operating temperature (since winding cooling will be more effective), but such cleaning is not likely to slow down an insulation abrasion process if coils are loose in a stator slot. Other maintenance is required if the coils are loose. Thus the maintenance should be appropriate for the deterioration processes occurring.

Determining which deterioration processes are occurring requires tests on the windings and sometimes a visual inspection of the winding. This topic will be discussed later.

FORM-WOUND STATOR WINDINGS

Due to the complexity of the subject and its commercial importance, a more extensive description of the design, manufacture, and aging of form-wound stator windings in large motors and generators, follows. The insulation systems in other commercially important winding types is detailed later.

Form-wound stator windings are used in motors and generators rated 2300 V and above, corresponding roughly to motors rated a few hundred HP and above, and generators of 1 MW and above. Such stator windings usually consist of strand, turn, and groundwall insulation components, as well as wedging, bracing, and blocking materials to prevent winding vibration and movement. In addition, for stators rated 6 kV and above, an additional component is normally present: electrical stress control coatings. Finally, in very large electrical generators, often in machines rated a few hundred megawatts and above, the copper conductors are directly cooled with hydrogen gas or water. This cooling medium must be considered an insulation system component. The following addresses each of these components.

Strand Insulation

The strand insulation materials used in form-wound coils and bars are usually the same as the turn insulation used in stator windings rated 1000 V or less. Thus the following discussion, which primarily discusses *magnet-wire* insulation, is relevant to random-wound windings and rotor windings as well.

In form-wound coils and bars, the required ampacity of the conductors is such that a large copper or aluminum cross section is required. It is difficult to form a single large conductor into the coil shape mechanically. Thus, most stators rated more than a few hundred horsepower will have the turn composed from two or more strands (or subconductors) in order to make it easier to form the coil or bar. (Recall that a wire rope is much more flexible than a steel bar of the same cross section.) There are also several electrical advantages to making a turn from two or more strands. A single large conductor carrying 50 or 60 Hz current will experience electrical skin-effect losses, which are minimized by using smaller conductor cross sections. Another factor is that the magnetic field intensity is not uniform from one edge of the conductor to the opposite edge. The nonuniform magnetic field induces different potentials in different parts of the conductor, which leads to a circulating current and thus electrical losses. Finally, in a practical motor and generator, there are some axial magnetic fields, especially in the end windings (the portions of the coils

Table 3. Common Stator-Winding-Insulation Deterioration Mechanisms

Mechanisms	Description	Root Causes	Susceptible Insulation Types	Relative Speed	Best Test
Thermal	Long-term operation at high temperature, leading to embrittlement and insulation delamination	Overloading, blocked cooling, unbalanced voltage, frequent starting	All	Slow	Visual, PD, tip-up
Load cycling	Rapid, frequent on–off cycling leading to delamination	0% to 100% load changes in less than 15 min	FW,[a] asphaltic mica, polyester mica splitting	Moderate	PD, tip-up, visual
Poor impregnation	Voids in insulation leading to PD	Lack of penetration of mica tapes, by epoxy, or polyester	FW, polyester, and epoxy	Moderate	PD
Internal water leaks	Saturation of insulation by water from cracks in hollow copper conductors	Water fittings in direct-water-cooled windings	FW, epoxy-mica	Slow	Pressure decay, capacitance map
Loose windings in slot	Abrasion of insulation due to movement in slot	Insulation shrinkage over years, oil contamination	FW, RW,[a] epoxy-mica	Fast	Wedge tightness, visual, PD
Electrical slot discharge	Partial discharge attack where semiconductive coating missing	Poorly made semiconductive coating	FW, epoxy-mica	Slow	Visual, PD, ozone
Contamination	Surface discharges or sparking in end windings due to partly conductive pollution	Poor maintenance	All	Slow	Insulation resistance, visual, PD
End-winding vibration	100/120 Hz vibration of coils leading to insulation abrasion, cracking	Poor design, oil contamination	All	Moderate	Visual
Electrical surges	Puncture of turn insulation by high-voltage pulses	Voltages developed by motor switch-on or inverter-fed drives combined with poor or aged turn insulation	RW, FW, multiturn coils	Slow	Surge comparison

[a] RW denotes random wound, FW denotes form wound.

beyond the stator core). These axial fields lead to circulating currents around the periphery of the copper conductors. The smaller the conductor cross-sectional area, the smaller are the induced currents and thus the lower the power (I^2R) losses. By fabricating the required conductor cross-sectional area from two or more strands that are insulated from one another, the stator electrical losses from skin effect and axial magnetic fields are minimized, that is, the stator winding efficiency is increased.

The voltage from strand to strand in a form-wound coil or bar is very low, typically less than 1 V. Thus, the strand insulation is very thin, which is very desirable, since this allows

Table 4. Common Rotor-Winding-Insulation Deterioration Mechanisms

Mechanism	Description	Root Cause	Relative Speed
Thermal	Long-term operation at high temperature leading to embrittlement, insulation distortion	Overloading, blocked cooling, negative-sequence currents	Slow
Load cycling	Rapid, frequent load changes, leading to relative movement, abrasion	Different coefficients of thermal expansion	Moderate
Centrifugal	Crushed, cracked insulation due to high rpm	Poor design, manufacture	Moderate
Contamination	Shorts due to partly conductive contamination	Oil, moisture, or metallic particles due to poor operation or maintenance	Slow
Abrasion	Erosion of insulation due to abrasive material (e.g., sand) in cooling air	Misapplication, poor maintenance	Moderate
Chemical attack	Softening or weakening of insulation due to corrosive chemicals in cooling air	Misapplication	Moderate

more copper to be used within the slot, maximizing the ratings for a given stator frame size.

Many different types of strand insulation materials have been used over the years in magnet wire (2). The first were oleoresinous enamels, composed of natural resins and drying oils. These materials proved unsuitable for high-mechanical-stress applications in rotating machines because they were weak and subject to degradation of mechanical properties due to thermal aging. Polyvinyl acetal (PVA) enamels were then introduced in the late 1930s. This material was vastly superior to the oleoresinous types and in many ways changed the face of the magnet wire industry. It had good dielectric strength, toughness, flexibility, adhesion, and heat shock resistance. Since PVA had a good capacity for physical abuse, it could be rolled into a tight loop without damage or significant impairment of its electrical properties. However, this material could not safely operate at temperatures above 100°C. During the mid-1950s polyester enamel was introduced. Although this material had exceptional thermal endurance, a thermal class of 155°C, good dielectric strength, and tolerable resistance to abrasion, it became unpopular because its heat-shock-withstand capabilities were not nearly as good as those of PVA. Consequently, when windings were processed and baked in the same manner as those with PVA enamel, failures were experienced due to heat shock. A modern polyester (Mylar, from DuPont) was introduced in the 1950s that could operate at a higher temperature (class 155); however, it was still limited in its ability to resist heat shock. The shortcomings of polyester enamel were overcome when magnet-wire manufacturers started overcoating it with other enamels, such as polyimide, which have good heat-shock capabilities.

Almost coincident with the development work on polyester enamels was the development by DuPont of a range of aromatic polyimides (Kapton). Although these had relatively poor resistance to abrasion, they had exceptional resistance to heat shock, solvents, and cut-through, and had exceptional burnout resistance in that they could be operated continuously at temperatures up to 220°C. Being strong in areas where polyesters were weak, the polyimide development prompted further work that culminated in the production of a polyester/polyimide enamel, that is, a polyester enamel overcoated with polyimide. This gave the polyester enamel the required heat-shock capability and a thermal class of 180°C.

Amide-imide enamel was developed during the mid-1960s by the Anaconda Company and was intended to replace many of the older types of enamels. Despite the fact that this material had good thermal and winding properties, it was not generally used on its own. However, it was found that, like polyimide, it could enhance the properties of other enamels, such as polyester and polyester-imide, if it was used as a top coat. That is, it enhanced windability, resistance to burnout, cut-through, and solvent resistance and increased the operating temperatures of these materials to 200°C. Nowadays, polyester with a polyamide-imide overcoat is the most common magnet-wire insulation material in use.

Since the 1980s, General Electric Corp. and now other manufacturers have been adding inorganic fillers such as alumina to the outer film layers of the magnet wire (3,4). Such fillers with appropriate particle sizes improve the thermal conductivity of the insulation, reducing winding temperatures. Of importance to motors driven by IFDs, the oxides also confer greater resistance to partial discharges (corona), which have been found to occur even in 440 V motor stators as a result of the voltage surges produced by such drives (4,5).

For machines operating at 2300 V and above, winding manufacturers have found it prudent to overcoat the enamel film of magnet wire either with fiberglass or woven polyester (Dacron being the DuPont trade name) and glass fibers (DuPont, trade name: Daglas), which are thermally fused over the magnet-wire enamel. The Daglas material is less susceptible to damage when the wire is bent or formed and helps maintain physical separation between the strands

In stators rated greater than 6 kV, the risk of partial discharges occurring is very high. To maximize the ability to resist deterioration by partial discharges, the strand insulation is often upgraded by overcoating it with a mica-paper tape. Mica-paper tape consists of small mica platelets that are electrostatically held or bonded by a polymer to a backing tape, most commonly made from a woven glass fabric or Mylar. Mica is used since it is almost completely resistant to deterioration caused by the partial discharges. In addition, mica can operate at very high temperatures. The backing tape is needed to provide mechanical stability to the mica, since mica is easily damaged by mechanical stress. Mica-paper tape is most often used as a strand insulation when the strand insulation is upgraded to serve also as the turn insulation in high-voltage multiturn coils.

As mentioned previously, failure of the strand insulation (when it does not also serve as the turn insulation), will normally not result in immediate failure. Instead, there will be larger circulating currents (especially in transposed Roebel bars), which reduce efficiency and raise operating temperatures.

Turn Insulation

Half-turn Roebel bars do not require turn insulation. For multiturn form wound coils, the turn insulation must withstand 50 or 60 Hz voltages from a few volts in small motors to 200 V in large generators. In addition, the turn insulation must be able to withstand from a few hundred volts to the many thousands of volts that can briefly occur during voltage transients. For example, when a motor is switched on, a voltage up to several times the normal line-to-ground voltage with a rise time of about 200 ns can impinge on the stator winding, due to transmission-line propagation effects among the breaker, the power cable, and the stator windings (6). The fast-rise-time nature of the voltage surge can lead to a nonuniform distribution of the voltage through the stator winding, and up to 40% of the voltage that is applied to the stator winding can be dropped across the first turn in the coil connected to the phase terminal (6). If the turn insulation thickness is insufficient or the turn insulation has degraded due to thermal, mechanical, or electrical (i.e., partial discharge) aging, then the turn insulation can fail. Failure of the turn insulation causes a very high current to flow through the affected turn and the associated short circuit, which melts the copper conductor, and eventually the groundwall insulation. Once the groundwall has melted, a stator-winding ground fault occurs and the motor fails. Thus, failure of the turn insulation leads to stator-winding failure, usually within minutes or days.

In modern multiturn form-wound coils rated greater than 1000 V but less than approximately 6 kV, the most common turn insulation is made from polyamide-imide film often overcoated with fused Daglas fibers. Earlier turn insulations may have included asbestos. For machines rated approximately 6 kV and above, it is now common to use magnet wire with one or two layers of half-lapped or butt-lapped mica-paper tape as the turn insulation, since this confers greater partial discharge resistance, as well as improves the ability to withstand switching surges.

Groundwall Insulation

The groundwall insulation in a form-wound coil or bar is usually composed of many layers of insulation tapes over the strand or turn insulation, since the voltage across the groundwall can be up to 18 kV line-to-ground in the highest rated large steam turbine generators. Failure of the groundwall results in a phase-to-ground fault, which will trigger circuit-breaker operation.

The groundwall-insulation systems employed from the 1930s to the 1950s (and later in some countries) were made from mica splittings (thin layers of mica flakes up to several centimeters in diameter) backed onto cotton tapes and impregnated with shellac or asphalt (called bitumen in some countries). As mentioned previously, mica was employed because of its high melting temperature and its excellent ability to resist partial discharges. The cotton tape (which was eventually replaced by fiberglass or Daglas) gave mechanical stability to the mica. The tapes (or sometimes sheets) were bonded together with shellac or asphalt. It was important to bond the tape layers together and exclude air pockets since

- This improved the conduction of heat from the I^2R losses in the copper conductors (heat source) to the stator core (the heat sink).
- A well-bonded groundwall would hold the copper conductors still. If the groundwall was not well bonded, the copper conductors would be free to move relative to one another (driven by the currents in each strand creating a magnetic field that would react against the other magnetic fields), leading to abrasion of the strand and/or turn insulation.
- Partial discharges (PDs) would occur if an air pocket existed in the groundwall in a coil or bar connected to the phase terminal (and thus operating at the highest ac voltage). For a stator operating at 6 kV or above, sufficient voltage will appear across the air gap (due to a capacitive-voltage division effect) that the air will break down, that is, a spark will occur in the air gap. (The electric strength of air is about 1% of the electric strength of solid insulation.) The spark or discharge consists of electrons and ions that bombard the tape layers on either side of the air gap, and any organic materials present will decompose into carbon. A well-bonded groundwall will have few significant air gaps, and thus there is no place for the PD to occur, preventing degradation of the organic parts of the insulation.

The limitation of the early *thermoplastic* groundwall materials was the relatively low temperature at which the shellac or asphalt would lose its ability to "glue" the mica-tape layers together. The bonding materials would soften and flow when the operating temperatures exceeded about 90°C, depending on the formulations. This effectively limited such insulation to class B (i.e., class 130) operation.

In the early 1950s synthetic thermosetting bonding materials such as polyester and epoxy were starting to replace asphalt. At that time polyesters were much more popular than epoxies because solventless forms of polyester had been developed that could directly replace the asphaltic bonding compounds being used in a vacuum-pressure impregnation (VPI) process (discussed later). The new polyesters did not expand appreciably in comparison to thermoplastic systems, retained good mechanical strength when heated, and had very low viscosities in the uncured state. In fact, they flowed so easily through the tape layers that difficulties were experienced in retaining the polyester until it was polymerized by heating.

The first major manufacturer to introduce a thermosetting synthetic resin bonded groundwall insulation system was Westinghouse with its Thermalastic system, initially developed for turbine generators (7). This was a continuous tape system consisting of large mica flakes sandwiched between two layers of a backing material and vacuum-pressure impregnated with a thermosetting polyester resin and cured prior to winding in the core. With the VPI process, dry (green) tapes are applied to the coil or bar and then the bar or coil is placed in a chamber where a vacuum is pulled in order to remove trapped air between the tape layers. The chamber is then filled with polyester (and now epoxy or occasionally other compounds) under pressure to impregnate the tape. Once the resin has impregnated all the tape layers, the coils are removed from the resin bath and heat is applied to cure the resin, usually at the same time that mechanical pressure is applied to the coils to hold the tape layers together, in order to shrink any air bubbles that may still be trapped between the layers. There are now many variations of this process. Turbine generators using coils and bars made with the polyester VPI process were manufactured with this system in 1949, and by the early 1950s it was also being used in large motors and hydrogenerators.

General Electric closely followed Westinghouse with its Micapal system for turbine generators (8), using thermosetting epoxy resin as a bonding agent. The development of this system produced two important components of groundwall insulation that are still being used today:

- The introduction of mica paper (previously discussed)
- Application of a thermosetting synthetic epoxy resin bonding material that remained stable at high temperatures

From these materials a groundwall insulation was developed consisting mainly of half-lapped layers of mica-paper tape, with a few layers of mica-flake tape material interspersed between them. Another important feature of this system was that the epoxy bonding resin was impregnated into the tapes prior to their application. (The early epoxies were too viscous to penetrate many layers of tape with the VPI process.) The epoxy resin was then cured by placing the coils in an autoclave and applying heat and pressure. This tape is now commonly known as a *resin-rich* or *B stage* tape [the B referring to the A and B (or resin and hardener) parts of the epoxy that have been mixed]. The manufacturing process is called the resin-rich or *press-cure* process, to distinguish it from the VPI process. The first large generator using the Micapal system was put into service in 1954.

Since the early 1950s, major improvements have been made in the development of high-voltage groundwall insulation. This improved the quality of mica paper and backing materials, the mechanical properties of the resin and the processes by which the synthetic binder is applied and cured.

One significant advancement was the introduction of a global VPI (also called the post-VPI) process for small- and medium-sized stators. In this process the coils were insulated with dry mica paper tapes. With the “green” coils still flexible, the coils were inserted in the stator core slots and all connections between coils were made. Then, the entire stator core was inserted in a large tank, where a vacuum was drawn to extract trapped air between the tape layers. The tank was then filled with resin (epoxy or polyester) under pressure to impregnate the coils, and the excess resin was drained away. Heat was then applied by placing the stator in an oven to cure the resin. The advantage of the global VPI process is that all coils are impregnated at the same time, greatly increasing throughput; there is less chance of damaging the coils during insertion in the slot (since they are still flexible); and the stator winding is very mechanically sound. Since the 1960s when this process was introduced, the size of the stators that can undergo global VPI has grown steadily. In the early 1990s Siemens and ABB began producing generator stators rated up to 300 MVA using this process.

Recently epoxy resins have almost exclusively been used as the bonding agent by stator-winding manufacturers, because they were found to be superior to polyesters in mechanical properties and resistant to moisture and chemical attack. Also, epoxies do not shrink as much after curing. Solventless grades of epoxy, suitable for use in a VPI process, are now widely available. However, many rewind shops still prefer polyester since it is less expensive, and fewer health and safety precautions are needed in its use. In the mid-1980s, polyester-imide VPI resins were introduced in Europe for class H (class 180) windings.

Stator Electrical Discharge Control

As soon as early machine conductor-to-ground ac rms voltages reached values in the order of 3000 V to 4000 V, ground insulation failures occurred due to slot and stator-core end region PD. It was found that these discharges were apparently “eating” holes, or even grooves, through the groundwall from the outside. This effect was most pronounced at the sharp edges formed by stator-core cooling ducts and at the ends of the stator core. At this time, the high discharge resistance of mica was appreciated, since the coils with mica wrappers experienced relatively little deterioration.

The cause of the PD problem is that with resin-rich and VPI coils, there will always be an air gap along some portion of the coil or bar between the surface of the coil and the grounded stator core. In coils or bars connected to the phase terminals of stators rated greater than 6 kV, a capacitive-voltage divider effect will ensure that there is sufficient voltage across the air gap to ensure that the air will break down, that is, a spark will occur between the core and the coil surface. As discussed before, this discharge (which is called *partial* since the remaining epoxy mica-tape layers still prevent a complete phase-to-ground breakdown) will gradually carbonize the organic portions of the groundwall, leading to eventual failure.

The problem of PD occurring on the surface of the coils in the slot area (sometimes called slot discharge) was prevented by coating the surface of the coil or bar with a carbon-loaded tape or paint. This coating has a surface resistance ranging from 500 to 10,000 Ω per square and is expected to be in electrical contact with the core all along the length of the slot. Therefore, any air gap between the surface of the coil or bar and the core has no potential across it (the air-gap capacitance is shorted out), preventing the slot discharge.

At the ends of the carbon-loaded coatings at the slot ends, PD occurs from the sharp edges at the end of the coating. Earlier, this problem was solved by applying electric stress grading materials, such as asbestos impregnated with high-resistance materials, or by embedding metal foil shielding layers into the coil groundwall at the ends of the coil straights. More recently, a type of paint containing a nonlinear resistance material such as silicon carbide has been used to relieve the electric stress at the slot exits. Such materials reduce the electric stress and effectively “terminate” each end of the coil or bar, much like a high-voltage cable termination.

Mechanical Support

Tremendous mechanical forces induced by the magnetic fields act upon the coils or bars in the stator slots. Analysis shows that within the stator slot, there is a net force that occurs primarily in the radial direction (i.e., up and down in the slot), at twice the power frequency. In addition, about 10% of the vibrating force is circumferential (i.e., sideways) in direction (9). The greatest mechanical force acts on the top bar or coil, tending to push the coil or bar to the bottom of the slot. The forces can amount from 1 or so kg/cm of slot length in a small generator, to 25 kg to 50 kg per cm length of slot in large turbine generators.

In addition, there are large magnetic forces acting on the coils and bars outside of the slots (the end windings or end arms) as the magnetic fields from adjacent coils and bars interact. Again, the vibration is at 100 (120) Hz for 50 (60) Hz current, respectively. These forces can increase dramatically during current surges, for example, from motor starting, since the forces are proportional to the square of the current. With a five-times greater motor start in-rush current, the mechanical force will be 25 times higher than normal, which can crack inadequately supported coils and bars.

The coils and bars need to be restrained against these continuous vibration and the transient forces. Elaborate systems consisting of depth packing, wedges, and side packing are used to fix the coils in the slot. Systems involving the use of ripple springs (either under the wedges or on the side) have been in use since the 1960s to take up the slack that sometimes develops as the insulating materials shrink just after manufacture or with long-term operation at high temperature. All these materials tend to be made from epoxy glass laminates or materials closely allied to them. More recently, resilient materials such as silicone rubber have been used to enable a “zero-clearance” fit between the bar or coil surface and the core (10). Usually, such materials are partly conductive.

In the endwinding, insulating spacer blocks are used to keep the coil or bars from coming too close. Bull rings (usually made of fiberglass or nonmagnetic stainless steel) and lashing (epoxy or polyester-impregnated cords) are used to prevent relative movement. In some applications bracing rings can be made in place using glass or polyester cord, which may be pre- or postimpregnated with resin. The endwindings are essentially cantilevered beams subject to enormous forces, especially in the case of large two-pole turbine generators that have very long endwindings. The endwinding support system can become very elaborate, since metallic parts cannot be used due to the presence of high voltage, and one has to allow for the axial expansion of the winding as the load increases (11).

Direct Stator Winding Cooling

For turbine generators rated more than about 100 MW or hydrogenerators rated more than about 500 MW, it is common to cool the high-voltage copper conductors in the Roebel bars directly. Since the copper conductors are at high voltage, the cooling medium must be able to withstand the voltages as it traverses the cooling circuit. Some stators, principally those rated from 100 MW to 600 MW made by Westinghouse, Siemens, and Mitsubishi, are directly cooled with high-pressure hydrogen gas. Usually stainless-steel tubes run the length of the bar, immediately adjacent to the high-voltage copper conductors. Since hydrogen has to flow through these tubes at the end of the bars, the metallic tubes are exposed, that is, protrude through the groundwall insulation. If the winding gets coated with partly conductive films such as dirty oil, then electrical tracking to ground or to another phase can occur. To limit this possibility, very long surface "creepage" distances must be present.

Direct water cooling is also very common in large generators. The water is introduced to one end of the bar, usually by means of a polytetrafluoroethylene (PTFE) (DuPont trade name: Teflon) hose, connected to a grounded water pipe system. The water flows down the bar in hollow copper tubes, which also serve as the high-voltage conductors, and pass out the other end, again by a Teflon hose. Since the conductors are at high voltage and the water has to pass to ground potential for removing the heat, the water must be insulating, that is, demineralized and deionized. Thus, water and the Teflon hoses are part of the insulation system.

Failure Mechanisms

A detailed description of the failure mechanisms for form-wound stator-insulation systems and the associated repair procedures is beyond the scope of this article. A summary listing of the various failure processes is shown in Table 3, with more extensive descriptions in Ref. 12. It is apparent that there are many different failure processes.

The most common failure mechanism of stator windings is probably due to the long-term operation of the insulation at relatively high operating temperatures. The high temperatures come from

- Overloading of the motor or generator
- Deterioration of the cooling system (from blockage of the cooling ducts, etc., which normally just requires cleaning to reverse)
- Poor cooling system design [which may require an upgrade in the capability of the cooling system (13)]
- Unbalanced phase voltages, especially in motors, which leads to negative sequence currents (corrected by ensuring that the three phases in the power system supply are all equally loaded)

Operation at high temperature essentially oxidizes the organic compounds in the insulation, making the insulation brittle or causing the debonding of the mica-paper tape layers. The result is reduced mechanical strength and, in medium- and high-voltage stators, the occurrence of PD, which leads in insulation puncture.

Another important failure mechanism in nonglobal VPI windings is the eventual abrasion of the groundwall insulation due to coil or bar looseness in the slot. Looseness occurs because organic insulation materials shrink over the years, and the effectiveness of the ripple springs and wedging decreases, especially in the presence of oil. Loose coils and bars in the slots vibrate against the laminated steel stator core, abrading the insulation. When about one-third of the groundwall has been abraded, a ground fault occurs. This mechanism is most prominent with epoxy–mica paper windings, since epoxy does not expand to fill the slot when it is brought up to operating temperature. The mechanism can be slowed by rewedging, replacing ripple springs and/or packing materials, and sometimes by injecting of carbon-loaded silicon rubbers or epoxies into the slots to replace material that has been abraded and to fix the coils or bars.

The third most important failure mechanism is electrical tracking due to partly conductive pollution over the endwindings of the stator. As discussed previously, this allows small power-frequency currents to flow between coils operating at different voltages. Since there will be some portions of the current path that will have higher resistance, relatively high voltages will appear at discontinuities, leading to sparks or discharges. The sparks degrade the organic parts of the insulation, leading to carbon tracks over the insulation surfaces. After many years, the tracks can lead to phase to phase or phase to ground faults. The mechanism is slowed by cleaning the windings to remove any conductive films.

Finally, an important failure mechanism for large two- and four-pole turbine generators occurs as a result of endwinding vibration. Such large machines have endwindings that can be 2 m or more long. This long endwinding can be very difficult to support physically, allowing relative movement of the bars against one another, or fatiguing of the insulation at the slot exit, driven by the 100 (120) Hz magnetic forces. The relative movement gives rise to insulation abrasion (*greasing*) and insulation cracking. The only effective fix is to improve the endwinding support system and replace any loose blocking, bracing, and lashing. Many other less common failure processes are identified in Table 3.

RANDOM-WOUND STATOR WINDINGS

Random-wound stators are most commonly used in motors and generators below about 1000 V. They are much less complicated than form-wound stators and experience fewer failure mechanisms.

Magnet-Wire Insulation

Magnet wire, that is, copper or aluminum conductors with insulating enamels or films bonded to the conductors, is formed into coils, usually by coiling machines. The insulation materials used over the years are discussed in a previous section entitled "Strand Insulation." The most common magnet wire for random-wound stators in use today is a round copper wire insulated with a polyamide-imide insulation (class 220°C) or polyester with a polyamide-imide overcoat. The insulation thickness is usually from 0.05 mm to about 0.1 mm. The most common standard covering magnet wires is NEMA standard MW1000. The insulation on the magnet wire serves as the coil-turn insulation. Failure of the magnet-wire insulation normally yields a turn-to-turn short or turn-to-ground short circuit, which normally leads to rapid stator winding failure due to high circulating currents melting the copper conductor.

With the introduction of IFDs, even motors rated as low as 440 V have been observed to have the white powder associated with partial discharge deterioration on the turns connected to the phase terminals. Thus new magnet wires have been introduced that contain metal oxides to impart PD resistance to the normal organic insulation (3,4). These filler materials are expected to increase the life of windings subject to voltage surges from IFDs.

Phase and Ground Insulation

Figure 5(a) shows the cross section of a random-wound stator in the stator slot. As with form-wound machines, typically there are two coils, often from different phases, in the same slot. Thus *phase* insulation is often used to separate the two coils. The most common phase insulation are *papers* made from the synthetic material *aramid,* sold under the DuPont tradename Nomex. Nomex has a 220°C thermal classification, is resistant to chemical attack, and has excellent tear resistance. Depending on the voltage class, the paper may be from 0.1 mm to 0.5 mm thick.

The same aramid material is used as a slot liner to provide extra ground insulation between the coils and the stator slot. Similarly, this material is often used between coils in different phases in the end winding.

Wedging

As with form-wound machines, the coils need to be secure in the slot to prevent relative movement of coils and turns against one another, or between the coils and the laminated stator slot. An important component to achieve this is the wedges [Fig. 5(a)]. Modern wedges are made from epoxy glass laminates (NEMA G10 or G11) material, which have a 155°C or 180°C thermal classification.

Varnish Treatment and Impregnation

Most random-wound stators are coated with a varnish or resin after the coils have been inserted in the slot. This coating imparts resistance to moisture and contamination (which lead to electrical tracking) and improves the electrical breakdown strength of the windings. Since the NEMA MW1000 specifications for magnet wire do allow a certain number of pinholes in the insulation per length of wire, the varnish or resin make sure that partly conductive films cannot lead to turn to turn faults. In addition, the varnish or resin will improve the transmission of heat from the copper to the stator core, since the number of air pockets are reduced. As IFDs permeate the market, the voltage surges they create can lead to destructive PDs in any air pockets. Thus filling of the air pockets with varnish or epoxy is becoming more critical, since PDs can only occur if air pockets exist.

The materials used for varnish or resins follow the same progression over the years as impregnates for form-wound stator coils (see the section entitled "Groundwall Insulation"). Today, acrylic, polyamide, and polyimide are used as varnishes, and solventless polyesters and epoxies are used as resins. The varnishes are usually applied by dipping the stator in a tank of varnish and then heat-curing the stator (referred to as a "dip-and-bake" process). For better impregnation to minimize the possibility of air pockets within the winding (to improve heat transfer and eliminate partial discharges), a VPI process using a solventless epoxy or polyester is preferred.

Recently, trickle coating processes have been introduced for small stators. In this case, rapid curing resins are trickled or poured slowly on the preheated endwindings while the stator is rotated. The resin cures at low or ambient temperatures. This process offers significant processing speed and increased resin thickness in appropriate applications.

During the 1990s, there has been a trend away from solvent-based varnishes toward solventless resins, even for dip-and-bake applications. Originally this was to comply with environmental regulations. However, solventless resins tend to produce few voids and have improved heat transfer.

Failure Mechanisms

Many of the deterioration processes listed in Table 3 for form-wound machines are relevant to random-wound machines. The most common failure processes for random-wound stators are as follows:

- Oxidation of the insulation due to long-term operation at high temperatures. This makes the insulation brittle so that during motor starting, the insulation is easily cracked, leading to short circuits if moisture or partly conductive contamination is present. Making sure that the cooling system is effective (usually by cleaning the machine) and making sure a motor is not started too frequently or overloaded are the best ways to slow thermal deterioration. In addition, motor users should make sure there is no more than 1% or so difference in the voltages between phases.
- Electrical tracking due to partly conductive contamination. Contamination may be due to moisture or dirt mixing with oil or other liquids. Winding cleaning is the best repair, possibly followed by a dip and bake with a varnish or resin (see preceding section).
- For motors using an IFD, partial discharges from the high-voltage spikes, which such drives produce. There is little that can be done to slow this process, except to rewind with a partial-discharge-resistant magnet wire and impregnate using the VPI process or install filters between the IFD and the motor.

Many other failure processes can also occur, but usually with less probability.

ROTOR WINDINGS

This section discusses only rotor-winding insulation systems for salient-pole and round-rotor windings, most commonly found on synchronous machines (motors and generators).

Round Rotors

Figure 6(a) shows a photograph of a round rotor as used in a turbine generator spinning at 3600 revolutions/min. Copper conductors forming the field winding are embedded in a nonmagnetic steel slot, with epoxy glass laminates serving as the ground and turn insulation [Fig. 6(b)]. Often the copper conductors are bare strips of copper, rather than being insulated as in a magnet wire. Outside the slots (i.e., in the endwinding) the copper goes through a right-angle bend and traverses to the other slot required to make a pole. Insulation is also required here to isolate the turns from one another and to isolate the turns from the grounded-retaining ring (now usually made of stainless steel), which ensures that the end windings remain in place when the rotor is spinning.

The stresses that the rotor winding insulation are exposed to are different from those in the stator winding (see the section entitled "Insulation System Requirements") and include:

- Thermal stress from the I^2R dc current losses in the field winding
- Centrifugal force from the high rotational speed of the rotor
- Relatively low electrical stress, since the field winding rarely operates at more than 1000 V dc
- Oil, moisture, and abrasive materials that may be present in the air gap, which can cause electrical tracking between the turns or to ground
- Expansion and contraction of the copper conductors every time the machine is turned on and off, where the copper movement leads to abrasion of the insulation and/or distortion of the copper conductors in the endwinding

In rotors for machines larger than about 100 MVA, the rotors are often directly cooled by air or hydrogen gas to extract the I^2R losses directly from the rotor winding. The cooling channels can sometimes become blocked by debris or from the insulation slipping or ratcheting under the load cycling forces. (Hydrogen cooling is used on larger generators since hydrogen creates less windage loss than air, thus improving the efficiency of the generator.)

Older round rotors used asbestos strips or mica backed with asbestos as the slot and turn insulation. Such materials had very high thermal capability. Most modern machines use polyester or epoxy strips reinforced with fiberglass (NEMA G10 or G11) as the insulation.

The failure of the rotor insulation does not result in immediate failure of the machine. Since the entire rotor winding is usually isolated from ground (i.e., the potential of the rotor body), one rotor ground fault can occur with no impact on machine operation. However, if a second ground fault then occurs, and if the two ground locations are widely separated, then heavy currents will flow, usually damaging the rotor body. Turn-to-turn short circuits do not result in machine failure. The only consequence of a small number of turn short circuits are that the dc field is not as strong (requiring more excitation current for the same load), the magnetic field may be unsymmetrical (leading to vibration), and the currents in some slots will be higher than others, leading to *thermal bends,* which again can increase bearing vibration. Turn short circuits, however, can imply that a ground fault may occur in the future, especially if the number of turn short circuits is increasing with time.

Salient-Pole Rotors

In salient-pole rotors, the field winding is made from insulated or uninsulated copper conductors that are formed around the periphery of a laminated steel pole (Fig. 6). There are two basic construction types:

- The strip-on-edge type, which is used in most hydrogenerators and higher-speed synchronous motors and standby generators [Fig. 6(b)]. This construction consists of coils made from wide copper strips joined at the corners or from a continuous strip bent at the corners, as illustrated in Fig. 6(b). This type is used because it is mechanically strong and can be easily braced against the centrifugal forces imposed in high-speed machines (up to 900 revolutions/min) and large-diameter slow-speed machines. In modern rotors of this type, the turns are insulated from one another by Nomex paper bonded to the copper strips by epoxy and hot pressed to consolidate the winding prior to insertion on the pole.
- The wire-wound, multilayer type, which is used in small hydrogenerators and medium- and slow-speed synchronous motors and standby generators [Fig. 6(c)]. This construction uses preinsulated magnet wire that can be directly wound into the required coil configuration. This configuration is used where possible because manufacturing costs are significantly lower than those for the strip-on-edge type. These coils can either be wound directly onto the pole or be preformed before fitting. The magnet wire insulation may be variations on the amide-imide films discussed in the section entitled "Strand Insulation.". For larger rotors, the magnet wire is often overcoated with a fiberglass or Daglas tape to add physical bulk and greater mechanical strength.

To isolate the strip on edge or the multilayer coils from the grounded pole, modern machines now mainly use epoxy glass laminates.

As with round rotors, one ground fault can be tolerated, and a large number of turn-to-turn faults can be tolerated before machine failure. However, any short circuits should be investigated.

WINDING TESTING AND MONITORING

The deterioration processes of the electrical insulation that ultimately lead to motor and generator failure normally take many years or decades to play out. That is, many years before failure, it is often possible to detect that deterioration is occurring. If a deterioration process is discovered, it is often pos-

Table 5. Common Off-Line Stator Winding Tests

Name	Description	Performance Difficulty	Effectiveness	Relevant Standard
Insulation resistance	Apply dc voltage for 1 min to measure leakage of current-rated voltage	Easy	Only finds contamination or short circuits	IEEE 43
Polarization index	Ratio of 1 min and 10 minute IR	Easy	Only finds contamination or short circuits	IEEE 43
Dc high potential	Apply high dc voltage for 1 min	Easy	Only finds serious defects	IEEE 95
Ac high potential	Apply high ac voltage for 1 min	Moderate, due to large transformer needed	More effective than dc high potential	
Capacitance	Apply low or high voltage to measure winding capacitance to ground	Moderate	Moderately effective to find thermal or water leak problems	
Dissipation (power) factor	Apply low or high voltage to measure insulation loss	Moderate	Moderately effective to find thermal or water leak problems	
Power factor tip-up	Differences in insulation loss from high to low voltage	Moderate	Effective to find widespread thermal or contamination problems in FW	IEEE 286
Off-line partial discharge	Directly detect PD pulse voltages at rated voltage	Difficult	Finds most problems except end winding vibration, for FW only	IEE 270
Surge comparison	Apply simulated voltage surge	Difficult to determine if puncture occurred in FW	Effective for finding turn insulation problems in RW and multiturn FW	IEEE 522
Blackout	Apply high ac voltage and look for discharges with lights out	Moderate	Effective for contamination problems in end winding	
Wedge tightness	"Hammer" wedges to see if loose	Moderate	Effective to find loose windings in FW	
Side clearance	Insert "feeler gauges" down side of slot	Easy, after wedges removed	Effective to find loose windings in FW	

[a] FW is form-wound winding; RW is random-wound winding.

sible to repair the deterioration or reduce the rate of deterioration (thus delaying failure) by maintenance or changes in machine operation. These actions lead to a longer winding life and delay rewinding. In addition, the risk of an in-service failure and the consequential damage that may occur is reduced.

The key to long winding life is to detect any deterioration mechanism that may be occurring as soon as possible. This will allow repairs, maintenance, and/or operation changes at an early stage in the failure process, increasing the overall life of the windings. Experience has shown that *predictive maintenance* (also called *condition-based* maintenance), where repairs or corrective action is taken if and only if deterioration has been detected, can be very economically applied to rotating machine windings.

Over the past decades, several tests and monitors have been developed to allow machine users to detect deterioration in the early stages, enabling predictive maintenance. As used here, tests will refer to measurements taken while the motor or generator has been shut down (i.e., off-line tests). Monitoring (sometimes known as on-line testing) will refer to measurements taken during normal operation of the machine. The definitive means of assessing the condition of the winding insulation is a visual inspection by a knowledgeable expert. Unfortunately, a good inspection requires a long machine shutdown and disassembly of the machine. Thus inspections are the most invasive means of determining if maintenance is required.

A detailed description of all the tests and monitors used in rotor and stator winding evaluation is beyond the scope of this article. Additional information is presented in INSULATION TESTING. As a summary, Tables 5 and 6 present the main off-line tests that are currently in use to evaluate stator and rotor windings, respectively. Table 7 presents the on-line monitoring that can detect rotor- and stator-winding problems during normal motor and generator operation.

In reality, it is not practical to employ all the tests shown in Tables 5 to 7, since the testing and monitoring costs would be too high, and in the case of testing, the machine would be out of service more than is necessary. Instead, to ensure long winding insulation life, one needs, as a minimum, to do the following:

- Ensure that a new winding is subjected to the appropriate commissioning tests and meet the minimum conditions. The commissioning tests usually include an insulation resistance test and a high potential or "hipot" test (with the winding sometimes sprayed or immersed in water). For form-wound machines, a power factor test and tip-up test are also often required.
- Monitor the winding temperatures and bearing vibration (since the latter is a good indication of rotor-winding problems). In addition, for machines rated 4 kV or above, monitor the in-service partial discharge activity. Although beyond the scope of this article, monitor the sta-

Table 6. Common Off-Line Rotor Winding Tests

Name	Description	Performance Difficulty	Types of Winding	Effectiveness
Insulation resistance	Apply dc voltage for 1 min to measure leakage current	Easy	All	Only finds contamination or short circuits
Polarization index	Ratio of 1 min and 10 min IR	Easy	All	Only finds contamination or short circuits
Dc high potential	Apply high-voltage dc voltage for 1 min	Easy	All	Only finds serious defects
Ac high potential	Apply high ac voltage for 1 min	Moderate, due to large transformer needed	All	More effective than dc high potential
Open circuit	Measure generator output voltage a function of field current to find short-circuited turns	Moderate	All	Effective only for generators, needs measurement when rotor OK
Impedance test	Apply 50 (60) Hz current and measure V/I at different speeds to find turn short circuits	Moderate	All rotors with slip rings	
Pole drop	Apply 50 (60) Hz current and measure voltage drop across each pole to find poles with turn short circuits	Easy	SPR[a]	Only finds short circuits that occur when rotor stopped
Surge voltage	Find turn and ground faults by measuring discontinuities in surge impedance	Difficult	RR[a]	Effective if close to dead short circuit

[a] RR is round rotor; SPR is salient-pole rotor.

tor currents in squirrel-cage induction motors, since this will detect broken rotor bars.

- Usually about once per year, take a short machine shutdown where at least one dc test (usually the insulation resistance or polarization test) and one ac test is performed. For random-wound machines, the ac test is usually the capacitance or dissipation factor test. For form-wound machines rated 4 kV and above, the partial discharge test is the best indicator of stator problems. In addition, since end-winding vibration problems are not

Table 7. Common On-Line Monitors for Rotor and Stator Windings

Name	Description	Applicability	Performance Difficulty and Cost	Effectiveness
Temperature	RTDs thermocouplers in stator, V/I measurement on rotor	All machines	Easy; inexpensive	Very effective to find widespread thermal problems
Bearing vibration	Accelerometers measure bearing vibration	All machines	Moderate; inexpensive	Finds rotor winding turn faults
Ozone	Measures O_3 concentration	Stators > 6 kV	Moderate; inexpensive	Finds stators with advanced deterioration by surface PD
Condition (particulate) monitors	Measure “smoke” in hydrogen-gas stream	Hydrogen-cooled generators	Moderate; very expensive	Finds very overheated (burnt) insulation
Conventional on-line PD	Expert measures PD from capacitors or RF current transformers	Stators > 4 kV	Great expertise; moderate	Effective for finding most problems
PDA or TGA[a]	On-line PD test using permanently installed sensors and noise-canceling instrumentation	Stators > 4 kV	Easy; moderate	Effective for finding most problems
End-winding vibration	Use optical sensors to measure end-winding vibration	Normally two and four pole generators	Moderate; very expensive	Effective for finding endwinding vibration

[a] Partial Discharge Analyzer or Turbine Generator Analyzer Test, respectively (14).

easily detected with electrical tests, a quick visual inspection of the stator end windings for cracks, abrasion, and greasing (a black sludge at interfaces) is useful.

With the strategy just outlined, it is likely that most problems that can result in winding-insulation failure in the next few years can be identified, allowing corrective action.

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