CHAPTER 1

ROTATING MACHINE INSULATION SYSTEMS

Since electrical motors and generators were invented, a vast range of electrical machine types have been created. In many cases, different companies called the same type of machine or the same component by completely different names. Therefore, to avoid confusion, before a detailed description of motor and generator insulation systems can be given, it is prudent to identify and describe the types of electrical machines that are discussed in this book. The main components in a machine, as well as the winding subcomponents, are identified and their purposes described.

Although this book concentrates on machines rated at 1 kW or more, much of the information on insulation system design, failure, and testing can be applied to smaller machines, linear motors, servomotors, etc. However, these latter machine types will not be discussed explicitly.

1.1 TYPES OF ROTATING MACHINES

Electrical machines rated at about 1 HP or 1 kW and above are classified into two broad categories: (i) motors, which convert electrical energy into mechanical energy (usually rotating torque) and (ii) generators (also called alternators), which convert mechanical energy into electrical energy. In addition, there is another machine called a synchronous condenser that is a specialized generator/motor generating reactive power. Consult any general book on electrical machines for a more extensive description of machines and how they work [1,2]. An excellent book that focuses on all aspects of turbogenerators has been written by Klempner and Kerszenbaum [3].

Motors or generators can be either AC or DC, that is, they can use/produce alternating current or direct current. In a motor, the DC machine has the advantage that its output rotational speed can be easily changed. Thus, DC motors and generators were widely used in industry in the past. However, with variable-speed motors now easily made by combining an AC motor with an electronic "inverter-fed drive" (IFD), DC motors in the hundreds of kilowatt range and above are becoming less common.

Machines are also classified according to the type of cooling used. They can be directly or indirectly cooled, using air, hydrogen, and/or water as a cooling medium.

Electrical Insulation for Rotating Machines: Design, Evaluation, Aging, Testing, and Repair, Second Edition. Greg C. Stone, Ian Culbert, Edward A. Boulter, and Hussein Dhirani.

This book concentrates on AC induction and synchronous motors, as well as synchronous and induction generators. Other types of machines exist; however, these motors and generators constitute the vast majority of electrical machines rated more than 1 kW presently used around the world.

1.1.1 AC Motors

Nearly all AC motors have a single-phase (for motors less than about 1 kW) or three-phase stator winding through which the input current flows. For AC motors, the stator is also called the *armature*. AC motors are usually classified according to the type of rotor winding. The rotor winding is also known as a *field winding* in synchronous machines. A discussion of each type of AC motor follows.

Squirrel Cage Induction (SCI) Motor The SCI motor (Figure 1.1) is by far the most common type of motor made, with millions manufactured each year. The rotor produces a magnetic field by transformer-like AC induction from the stator (armature) winding. The squirrel cage induction motor (Figure 1.1) can range in size from a fraction of a horsepower (<1 kW) to many tens of thousands of horsepower (>60 MW). The predominance of the SCI motor is attributed to the simplicity and ruggedness of the rotor. SCI rotors normally do not use any electrical insulation. In an SCI motor, the speed of the rotor is usually 1% or so slower than the “synchronous” speed of the rotating magnetic field in the air gap created by the stator winding. Thus, the rotor speed “slips” behind the speed of the air gap magnetic flux [1,2]. The SCI motor is used for almost every conceivable application, including fluid pumping, fans, conveyor systems, grinding, mixing, gas compression, and power tool operation.

Wound Rotor Induction Motor The rotor is wound with insulated wire and the leads are brought off the rotor via slip rings. In operation, a current is induced into the rotor from the stator, just as for an SCI motor. However, in the wound rotor machine, it is possible to limit the current in the rotor winding by means of an external resistance or slip-energy recovery system. This permits some control of the rotor speed. Wound rotor induction motors are relatively rare because of the extra maintenance required for the slip rings. IFDs with SCI motors now tend to be preferred for variable-speed applications as they are often a more reliable, cheaper alternative.

Synchronous Motor This motor has a direct current flowing through the rotor (field) winding. The current creates a DC magnetic field, which interacts with the rotating magnetic field from the stator, causing the rotor to spin. The speed of the rotor is exactly related to the frequency of the AC current supplied to the stator winding (50 or 60 Hz). There is no “slip.” The speed of the rotor depends on the number of rotor pole pairs (a pole pair contains one north pole and one south pole) times the AC frequency. There are two main ways of obtaining a DC current in the rotor. The oldest method, is to feed current onto the rotor by means of two slip rings (one positive, one negative). Alternatively, the “brushless exciter” method, by most manufacturers, uses a DC winding mounted on the stator to induce a current in an auxiliary three-phase

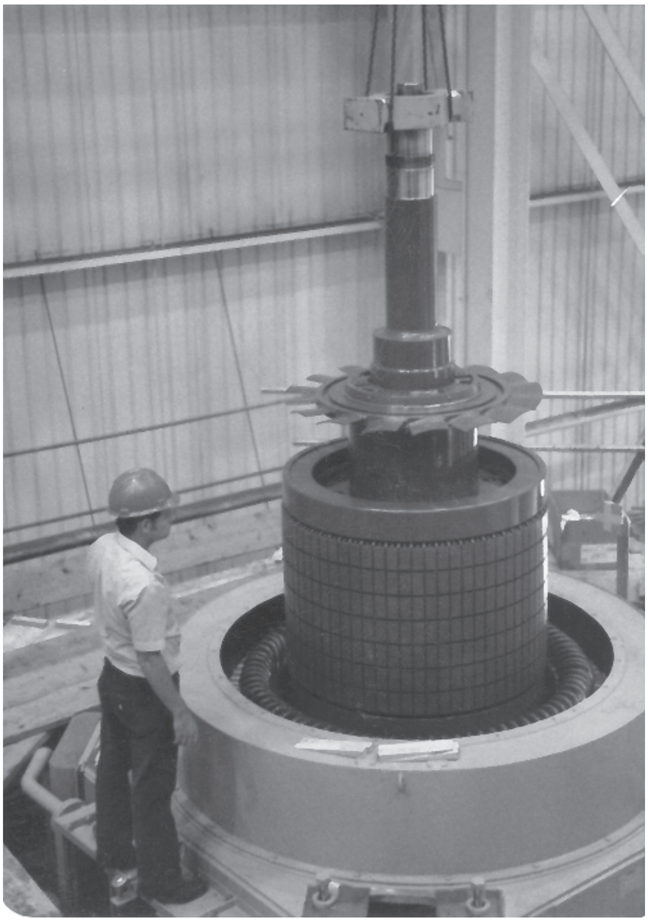


Figure 1.1 Photograph of an SCI rotor being lowered into the squirrel cage induction motor stator.

winding mounted on the rotor to generate AC current, which is rectified (by "rotating" diodes) to DC. Synchronous motors require a small "pony" motor to run the rotor up to near synchronous speed. Alternatively, an SCI type of winding on the rotor can be used to drive the motor up to speed, before DC current is permitted to flow in the main rotor winding. This winding is referred to as an *amortisseur* or *damper winding*. Because of the more complicated rotor and additional components, synchronous motors tend to be restricted to very large motors today (>10 MW) or very slow speed motors. The advantage of a synchronous motor is that it usually requires less "inrush" current on startup in comparison to an SCI motor, and the speed is more constant. In addition, the operating energy costs are lower as, by adjusting the rotor DC current, one can improve the power factor of the motor, reducing the need for reactive power and the associated AC supply current. Refer to Section 1.1.2 for further subdivision of the types of synchronous motor rotors. Two-pole synchronous motors use round rotors, as described in Section 1.1.2.

1.1.2 Synchronous Generators

Although induction generators do exist (Section 1.1.3), particularly in wind turbine generators, they are relatively rare compared to synchronous generators. Virtually all generators used by electrical utilities are of the synchronous type. In synchronous generators, DC current flows through the rotor (field) winding, which creates a magnetic field from the rotor. At the same time, the rotor is spun by a steam turbine (using fossil or nuclear fuel), gas turbine, diesel engine, or hydroelectric turbine. The spinning DC field from the rotor induces current to flow in the stator (armature) winding. As for motors, the following types of synchronous generators are determined by the design of the rotor, which is primarily a function of the speed of the driving turbine.

Round Rotor Generators Also known as cylindrical rotor machines, round rotors (Figure 1.2) are most common in high speed machines, that is, machines in which the rotor revolves at about 1000 rpm or more. Where the electrical system operates at 60 Hz, the rotor speed is usually either 1800 or 3600 rpm. The relatively smooth surface of the rotor reduces "windage" losses, that is, the energy lost to moving the air (or other gas) around in the air gap between the rotor and the stator—the fan effect. This loss can be substantial at high speeds in the presence of protuberances from the rotor surface, but these losses can be substantially reduced in large generators with pressurized hydrogen cooling. The smooth cylindrical shape also lends itself to a more robust structure under the high centrifugal forces that occur in high speed machines. Round rotor generators, sometimes called "turbogenerators," are usually driven by steam turbines or gas turbines (jet engines). Turbogenerators using round rotors have been made up to 2000 MVA (1000 MW is a typical load for a city of 500,000 people in an industrialized country). Such a machine may be 10 m in length and about 5 m in diameter, with a rotor on the order of 1.5 m in diameter. Such large turbogenerators almost always have a horizontally mounted rotor and are hydrogen-cooled (see Section 1.1.5).

Salient Pole Generators Salient pole generator rotors (Figure 1.3) usually have individual magnetic field pole windings that are mounted on solid or laminated magnetic steel poles that either are an integral part of or are mounted on the rotor shaft.

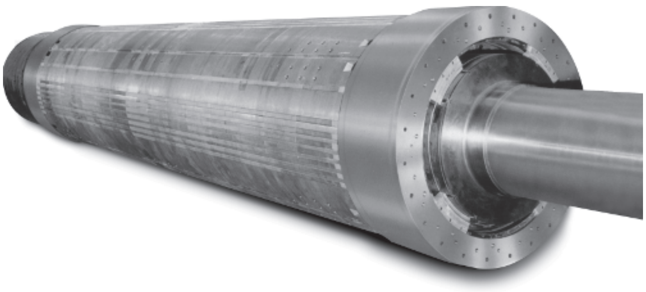


Figure 1.2 Photograph of a round rotor. The retaining rings are at each end of the rotor body.

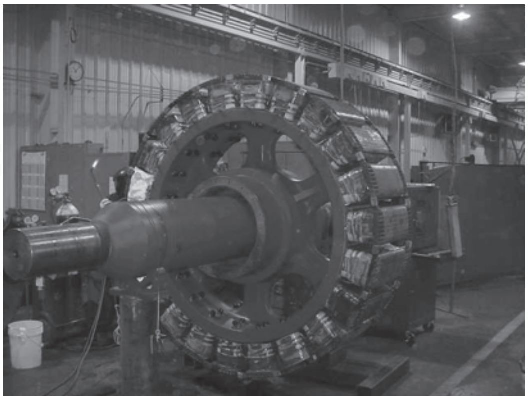


Figure 1.3 Photograph of a salient pole rotor for a large, low speed motor (Source: Photo courtesy Teco-Westinghouse).

In slower speed generators, the pole/winding assemblies are mounted on a rim that is fastened to the rotor shaft by a “spider”—a set of spokes. As the magnetic field poles protrude from the rim with spaces between the poles, the salient pole rotor creates considerable air turbulence in the air gap between the rotor and the stator as the rotor rotates, resulting in a relatively high windage loss. However, as this type of rotor is much less expensive to manufacture than a round rotor type, ratings can reach 50 MVA with rotational speeds up to 1800 rpm. Salient pole machines typically are used with hydraulic (hydro) turbines, which have a relatively low rpm (the higher is the penstock, i.e., the larger is the fall of the water, the faster will be the speed) and with steam or gas turbines where a speed reducing gearbox is used to match the turbine and generator speeds. To generate 50- or 60-Hz current in the stator, a large number of field poles are needed (recall that the generated AC frequency is the number of pole pairs times the rotor speed in revolutions per second). Fifty pole pairs are not uncommon on a hydrogenerator, compared to one or two pole pairs on a turbogenerator. Such a large number of pole pairs require a large rotor diameter in order to mount all the poles. Hydrogenerators are now being made up to about 1000 MVA in China. The rotor in a large hydrogenerator is almost always vertically mounted, and may be more than 15 m in diameter, but there are some horizontal applications for use with bulb hydraulic turbines for low head high flow application with ratings up to about 10 MVA.

Pump/Storage Motor Generator This is a special type of salient pole machine. It is used to pump water into an upper reservoir during times of low electricity demand. Then, at times of high demand for electricity, the water is allowed to flow from the upper reservoir to the lower reservoir, where the machine operates in reverse as a generator. The reversal of the machine from the pump to generate mode is commonly accomplished by changing the connections on the machine’s stator winding to reverse rotor direction. In a few cases, the pitch of the hydraulic turbine blades is changed. In the pump motor mode, the rotor can come up to speed using an SCI-type winding on the rotor (referred to as an *amortisseur* or *damper winding*), resulting in a large inrush current, or using a “pony” motor. If the former is used, the machine is often energized by an IFD that gradually increases the rotor speed by slowly increasing the AC frequency to the stator. As the speed is typically less than a few hundred rpm, the rotor is usually of the salient pole type. However, high speed pump storage generators may have a round rotor construction [4]. Pump storage units have been made up to 500 MVA.

1.1.3 Induction Generators

The induction generator differs from the synchronous generator in that the excitation is derived from the magnetizing current in the stator winding. Therefore, this type of generator must be connected to an existing power source to determine its operating voltage and frequency and to provide it with magnetizing volt-amperes. As this is an induction machine, it has to be driven at a super-synchronous speed to achieve a generating mode. This type of generator comes in two forms that can have the same type of stator winding, but which differ in rotor winding construction. One of these has a squirrel-cage rotor and the other has a three-phase wound rotor connected to slip rings for control of rotor currents and therefore performance. The squirrel cage type is used in some small hydrogenerator and wind turbine generator applications with ratings up to a few MVA. The wound rotor type has, until recently, been used extensively in wind turbine generator applications. When used with wind turbines, the wound rotor induction generator is configured with rectifier/inverters both in the rotor circuit and at the stator winding terminals as indicated in Figure 1.4. In this configuration, commonly known as the *doubly fed rotor concept* (for use in doubly fed induction generators or DFIGs), the output converter rectifies the generator output power and inverts it to match the connected power system voltage and frequency. The converter in the rotor circuit recovers the slip energy from the rotor to feed it back into the power supply and controls the rotor current. This slip recovery significantly improves the efficiency of the generator. Such generators are connected to the low speed wind turbine via a speed-increasing gearbox and have ratings up to around 3 MVA. The DFIG has also been used in large variable-speed pump storage generators.

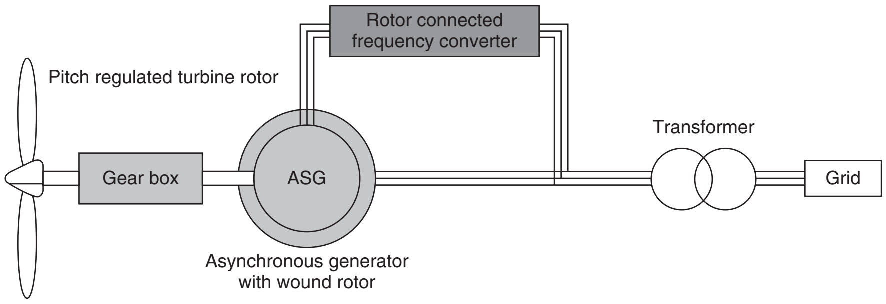


Figure 1.4 Wound rotor induction generator doubly fed configuration [5].

1.1.4 Permanent Magnet (PM) Synchronous Motors and Generators

There has been significant recent development on permanent magnet (PM) machines [6]. The major efforts in this regard were to employ PM materials such as neodymium iron boron (NdFeB) for the rotor field poles that produce much higher flux densities than conventional permanent magnet rotors. Standard induction motors are not particularly well suited for low speed operation, as their efficiency drops with the reduction in speed. They also may be unable to deliver sufficient smooth torque at low speeds. The use of a gearbox is the traditional mechanical solution for this challenge. However, the gearbox is a complicated piece of machinery that takes up space, reduces efficiency, and needs both maintenance and significant quantities of oil. Elimination of the gearbox via the use of these new PM motor/drive configurations saves space and installation costs, energy, and maintenance, and provides more flexibility in production line and facility design. The PM AC motor also delivers high torque at low speed—a benefit traditionally associated with DC motors—and, in doing so, also eliminates the necessity of a DC motor and the associated brush replacement and maintenance. There are many applications for this type of motor in conjunction with inverters, which include electric car, steel rolling mill, and paper machine drives. In addition, larger versions are used in other industrial and marine applications that require precise speed and torque control.

The PM synchronous generator has basically the same advantages and construction as the motor. It is now being widely used in wind turbine generator applications because its construction is much simpler and efficiency much better than a wound rotor induction motor.

1.1.5 Classification by Cooling

Another important means of classifying machines is by the type of cooling medium they use: water, air, and/or hydrogen gas. One of the main heat sources in electrical machines is the DC or AC current flowing through the stator and rotor windings. These are usually called *I^2R losses*, as the heat generated is proportional to the current squared times the resistance of the conductors (almost always copper in stator windings, but sometimes aluminum in SCI rotors). There are other sources of heat: magnetic core losses, windage losses, and eddy current losses. All these losses cause the temperature of the windings to rise. Unless this heat is removed, the winding insulation deteriorates because of the high temperature and the machine fails because of a short circuit. References 7 and 8 are general rotating machine standards that discuss the types of cooling in use.

Indirect Air Cooling Motors and modern generators rated less than about 100 MVA are almost always cooled by air flowing over the rotor and stator. This is called *indirect cooling* as the winding conductors are not directly in contact with the cooling air because of the presence of electrical insulation on the windings. The air itself may be continuously drawn in from the environment, that is, not recirculated. Such machines are termed open-ventilated machines, although there may be some effort to prevent particulates (sand, coal dust, pollution, etc.) and/or moisture from entering the machine using filtering and indirect paths for drawing in the air. These open-ventilated machines are referred to as weather-protected (WP) machines.

A second means of obtaining cool air is to totally enclose the machine and recirculate air via a heat exchanger. This is often needed for motors and generators that are exposed to the elements. The recirculated air is most often cooled by an air-to-water heat exchanger in large machines, or cooled by the outside air via radiating metal fins in small motors or a tube-type cooler in large ones. Either a separate blower motor or a fan mounted on the motor shaft circulates the air.

Although old, small generators may be open-ventilated, the vast majority of hydrogenerators have recirculated air flowing through the machine with the air often cooled by air-to-water heat exchangers. For turbogenerators rated up to a few hundred megawatts, recirculated air is now the most common form of cooling [9,10].

Indirect Hydrogen Cooling Almost all large turbogenerators use recirculated hydrogen as the cooling gas. This is because the smaller and lighter hydrogen molecule results in a lower windage loss, and hydrogen has better heat transfer than air. It is then cost effective to use hydrogen in spite of the extra expense involved, because of the small percentage gain in efficiency. The dividing line for when to use hydrogen cooling is constantly changing. There is now a definite trend to reserve hydrogen cooling for machines rated more than 300 MVA, whereas in the past, hydrogen cooling was sometimes used on steam and gas turbine generators as small as 50 MVA [9,10].

Directly Cooled Windings Generators are referred to as being indirectly or conventionally cooled if the windings are cooled by flowing air or hydrogen over the surface of the windings and through the core, where the heat created within the conductors must first pass through the insulation. Large generator stator and rotor windings are frequently "directly" cooled. In directly cooled windings, water or hydrogen is passed internally through the conductors or through the ducts immediately adjacent to the conductors. Direct water-cooled stator windings pass very pure water through hollow copper conductor strands, or through stainless steel tubes immediately adjacent to the copper conductors. As the cooling medium is directly in contact with the conductors, this very efficiently removes the heat developed by I^2R losses. With indirectly cooled machines, the heat from the I^2R losses must first be transmitted through the electrical insulation covering the conductors, which forms a significant thermal barrier. Although not quite as effective in removing heat, in direct hydrogen-cooled windings, the hydrogen is allowed to flow within hollow copper tubes or stainless steel tubes, just as in the water-cooled design. In both cases, special provisions must be taken to ensure that the direct water or hydrogen cooling does not introduce electrical insulation problems (see Sections 1.4.3 and 8.16). Recently, some Chinese manufacturers have been experimenting with direct cooling of hydrogenerator stators using a Freon type of liquid [11]. The advantage of using this type of coolant instead of water is that if leaks develop, the resulting gas is an excellent insulator, unlike water. Water leaks are an important failure mechanism in direct water-cooled windings (see Section 8.16).

Direct water cooling of hydrogenerator stator windings is applied to machines larger than about 500 MW. There are no direct hydrogen-cooled hydrogenerators. In the 1950s, turbogenerators as small as 100–150 MVA had direct hydrogen or direct water stator cooling. Modern turbogenerators normally only use direct cooling if they are larger than about 200 MVA.

Direct cooling of rotor windings in turbogenerators is common whenever hydrogen is present, or in air-cooled turbogenerators rated more than about 50 MVA. With the exception of machines made by ASEA, only the very largest turbo- and hydrogenerators use direct water cooling of the rotor.

1.2 WINDING COMPONENTS

The stator winding and rotor windings consist of several components, each with its own function. Furthermore, different types of machines have different components. Stator and rotor windings are discussed separately in the following sections.

1.2.1 Stator Winding

The three main components in a stator are the copper conductors (aluminum is rarely used), the stator core, and the insulation. The copper is a conduit for the stator winding current. In a generator, the stator output current is induced to flow in the copper conductors as a reaction to the rotating magnetic field from the rotor. In a motor, a current is introduced into the stator, creating a rotating magnetic field that forces the rotor to move. The copper conductors must have a cross section large enough to carry all the current required without overheating.

Figure 1.5 is the circuit diagram of a typical three-phase motor or generator stator winding. The diagram shows that each phase has one or more parallel paths for current flow. Multiple parallels are often necessary as a copper cross section large enough to carry the entire phase current may result in an uneconomic stator slot size. Each parallel consists of a number of coils connected in series. For most motors and small generators, each coil consists of a number of turns of copper conductors formed into a loop. The rationale for selecting the number of parallels, the number of coils in series, and the number of turns per coil in any particular machine is beyond the scope of this book. The reader is referred to any book on motors and generators, for example, References 1–3.

The stator core in a generator concentrates the magnetic field from the rotor on the copper conductors in the coils. The stator core consists of thin sheets of magnetic steel (referred to as *laminations*). The magnetic steel acts as a low reluctance (low magnetic impedance) path for the magnetic fields from the rotor to the stator, or vice versa for a motor. The steel core also prevents most of the stator winding magnetic field from escaping the ends of the stator core, which would cause currents to flow in adjacent conductive material. Chapter 6 contains more information on cores.

The final major component of a stator winding is the electrical insulation. Unlike copper conductors and magnetic steel, which are active components in making a motor or generator function, the insulation is passive; that is, it does not

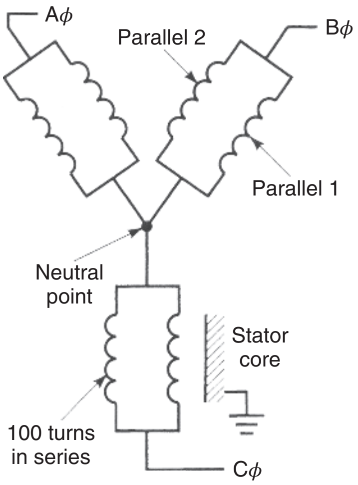


Figure 1.5 Schematic diagram for a three-phase, Y-connected stator winding, with two parallel circuits per phase.

help to produce a magnetic field or guide its path. Generator and motor designers would like nothing better than to eliminate the electrical insulation, as the insulation increases machine size and cost, and reduces efficiency, without helping to create any torque or current [12,13]. Insulation is “overhead,” with a primary purpose of preventing short circuits between the conductors or to ground. However, without the insulation, copper conductors would come in contact with one another or with the grounded stator core, causing the current to flow in undesired paths and preventing the proper operation of the machine. In addition, indirectly cooled machines require the insulation to be a thermal conductor, so that the copper conductors do not overheat. The insulation system must also hold the copper conductors tightly in place to prevent movement.

As will be discussed at length in Chapters 3 and 4, the stator winding insulation system contains organic materials as a primary constituent. In general, organic materials soften at a much lower temperature and have a much lower mechanical strength than copper or steel. Thus, the life of a stator winding is limited most often by the electrical insulation rather than by the conductors or the steel core. Furthermore, stator winding maintenance and testing almost always refers to testing and maintenance of the electrical insulation. Section 1.4 describes the different components of the stator winding insulation system and their purposes.

1.2.2 Insulated Rotor Windings

In many ways, the rotor winding has the same components as the stator, but with important changes. In all cases, copper, copper alloy, or aluminum conductors are present to act as a conduit for current flow. However, the steady state current flowing through the rotor winding is usually DC (in synchronous machines), or very low frequency AC (a few hertz) in induction machines. This lower frequency makes the need for a laminated rotor core less critical.

The conductors in rotor windings are often embedded in the laminated steel core or surround laminated magnetic steel. However, round rotors in large turbogenerators and high speed salient pole motors are usually made from forged magnetic steel, as laminated magnetic steel rotors cannot tolerate the high centrifugal forces.

Synchronous machine rotor windings, as well as wound rotor induction motors, contain electrical insulation to prevent short circuits between adjacent conductors or to the rotor body. As will be discussed in Chapters 3 and 5, the insulating materials used in rotor windings are largely composites of organic and inorganic materials, and thus have poor thermal and mechanical properties compared to copper, aluminum, or steel. The insulation then often determines the expected life of a rotor winding.

1.2.3 Squirrel Cage Induction Motor Rotor Windings

SCI rotor windings are unique in that they usually have no explicit electrical insulation on the rotor conductors. Instead, the copper, copper alloy, or aluminum conductors are directly installed in slots in the laminated steel rotor core with their ends being connected to shorting rings by brazed or welded joints. (Smaller SCI rotors may have the aluminum or copper conductors and shorting rings cast in place.) In normal operation, there are only a few volts induced on the rotor conductors, and the conductivity of the conductors is much higher than that of the steel core. Because the current normally flows only in the conductors, electrical insulation is not needed to force the current to flow in the right paths. Reference 14 describes the practical aspects of rotor design and operation in considerable detail.

The only time that significant voltage can appear on the rotor conductors is during motor starting. This is also the time that extremely heavy currents will flow in the rotor windings. Under some conditions during starting, the conductors make and break contact with the rotor core, leading to sparking. This is normally easily tolerated. However, some SCI motors operate in a flammable environment, and this rotor sparking may ignite an explosion. Therefore, some motor manufacturers do insulate the conductors from the rotor core to prevent the sparking [15]. Because such applications are rare, for the purposes of this book, we assume that the SCI rotor is not insulated.

Since SCI rotor windings are generally not insulated they are nominally beyond the scope of this book. However, for completeness, Chapter 12 does discuss such rotors, and Chapters 15 and 16 present some common tests and monitors for SCI rotor winding integrity.

1.3 TYPES OF STATOR WINDING CONSTRUCTION

Three basic types of stator winding structures are employed over the range from 1 kW to 2000 MW:

- Random-wound stators
- Form-wound stators using multi-turn coils
- Form-wound stators using Roebel bars

In general, random-wound stators are typically used for machines less than several hundred kilowatts. Form-wound coil windings are used in most large motors and many generators rated up to from 50 to 100 MVA. Roebel bar windings are generally used for large generators. Although each type of construction is described in the following sections, some machine manufacturers have made hybrids that do not easily fit into any of the above-mentioned categories: these are not discussed in this book.

1.3.1 Random-Wound Stators

Random-wound stators consist of round, insulated copper conductors (magnet wire or winding wire) that are wound continuously (by hand or by a winding machine) through slots in the stator core to form a coil (Figure 1.6). Figure 1.6 shows that most of the turns in the coils can be easily seen. Each turn (loop) of magnet wire could, in principle, be placed randomly against any other turn of magnet wire in the coil, independent of the voltage level of the turn, thus the term “random.” As 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. This effectively limits random-wound stators to machines less than several hundred kilowatts or horsepowers.

1.3.2 Form-Wound Stators — Coil Type

Form-wound stators are usually intended for machines operating at 1000 V and above. Such windings are made from insulated coils that have been preformed before insertion in the slots in the stator core (Figure 1.7). The preformed coil consists of a continuous loop of rectangular magnet wire shaped into a coil (sometimes referred to as a *diamond shape*), with additional insulation applied over the coil loops. Usually, each coil can have from 2 to 12 turns, and several coils are connected in series to

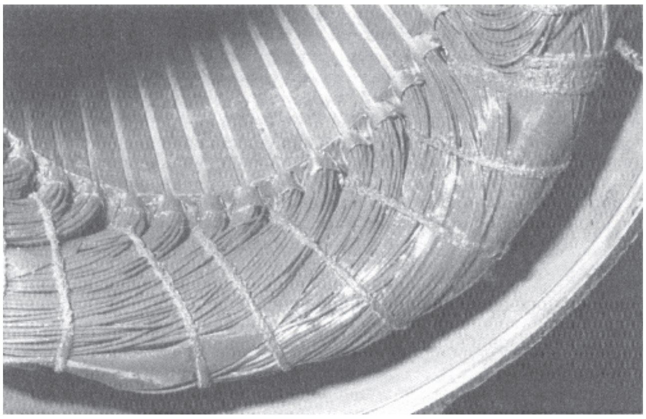


Figure 1.6 Photograph of the end winding and slots of a random-wound stator (Source: TECO-Westinghouse).

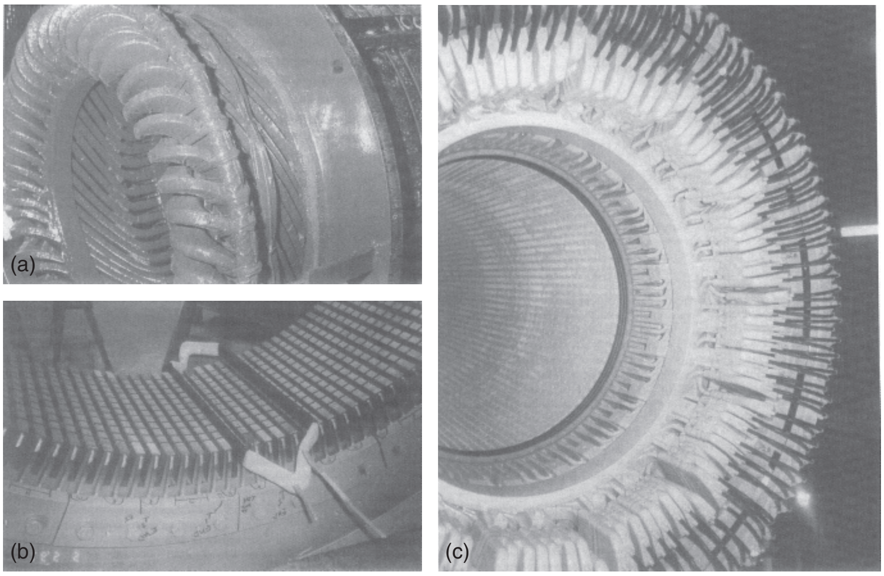


Figure 1.7 (a) Photograph of a form-wound motor stator winding (Source: TECO-Westinghouse). (b) A single form-wound coil being inserted into two slots. (c) Photo of a turbogenerator stator winding using Roebel bars.

create the proper number of poles and turns between the phase terminal and the ground (or neutral); see Figure 1.5. Careful design and manufacture 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 can be used to separate the turns. For example, in a 4160-volt stator winding (2400 V line-to-ground), the winding may have 10 coils connected in series, with each coil consisting of 10 turns, yielding 100 turns between the phase terminal and the neutral. The maximum voltage between the adjacent turns is 24 V. In contrast, if the stator were of a random-wound type, there might be up to 2400 V between the adjacent turns, as a phase-end turn may be adjacent to a neutral-end turn. This placement would require an unacceptably large magnet wire insulation thickness.

1.3.3 Form-Wound Stators — Roebel Bar Type

In large generators, the more the power output is, the larger and mechanically stiffer each coil usually is. In stators larger than about 50 MVA, the form-wound coil is large enough that there may be difficulties in inserting both legs of the coil in the narrow slots in the stator core without risking mechanical damage to the coil during the insertion process. Thus, most large generators today are not made from multi-turn 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 to make the “coils” are needed at both ends of the bar (Figure 1.7c).

1.4 FORM-WOUND STATOR WINDING INSULATION SYSTEM FEATURES

The stator winding insulation system contains several different components and features, which together ensure that electrical shorts do not occur, that the heat from the conductor I^2R losses is transmitted to a heat sink, and that the conductors do not vibrate in spite of the magnetic forces. The basic stator insulation system components are:

- Strand (or subconductor) insulation
- Turn insulation
- Groundwall (or ground or earth or mainwall) insulation

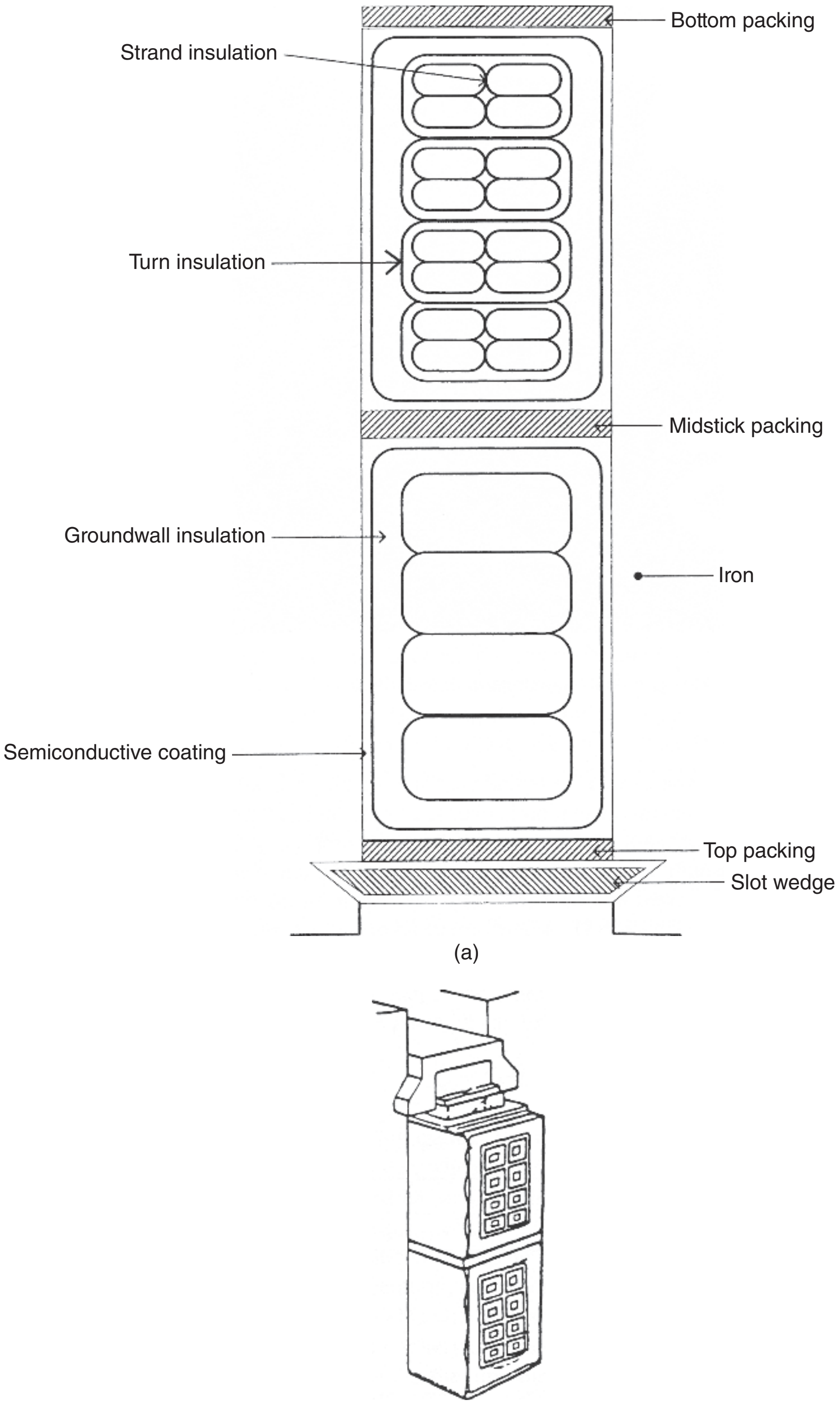
Figure 1.8 shows the cross sections of form-wound coils in a stator slot and identifies the above components. Note that the form-wound stator has two coils per slot; this is typical. In large generators, sometimes, the bottom bar may have a smaller copper cross section, to equalize the temperature of the top and bottom bars (there are fewer magnetic losses in a bottom bar). Figure 1.9 shows the cross section of a multi-turn coil. In addition to the main insulation components, the insulation system sometimes has high-voltage stress-relief coatings and endwinding support components (Sections 1.4.5 and 1.4.9).

The following sections describe the purpose of each of these components. The mechanical, thermal, electrical, and environmental stresses that the components are subjected to are also described. As these stresses also affect the insulation components in random-wound windings, occasional reference is made to random windings. Such windings are also discussed in Section 1.5.

1.4.1 Strand Insulation

There are both electrical and mechanical reasons for stranding a conductor in a form-wound coil or bar. From a mechanical point of view, a conductor that is big enough to carry the current needed in the coil or bar for a large machine will have a relatively large cross-sectional area. That is, a large conductor cross section is needed to achieve the desired ampacity. Such a large conductor is difficult to bend and form into the required coil/bar shape. A conductor formed from smaller strands (also called *subconductors*) is easier to bend into the required shape using coil-forming equipment than one large conductor.

From an electrical point of view, there are a few reasons to make strands and insulate them from one another. It is well known from electromagnetic theory that if a copper conductor has a large enough cross-sectional area, AC current will tend to flow on the periphery of the conductor. This is known as the *skin effect*. The skin effect gives rise to a skin depth through which most of the current flows. The skin



(a)

(b)

Figure 1.8 Cross sections of slots containing (a) form-wound multi-turn coils and (b) directly cooled Roebel bars.

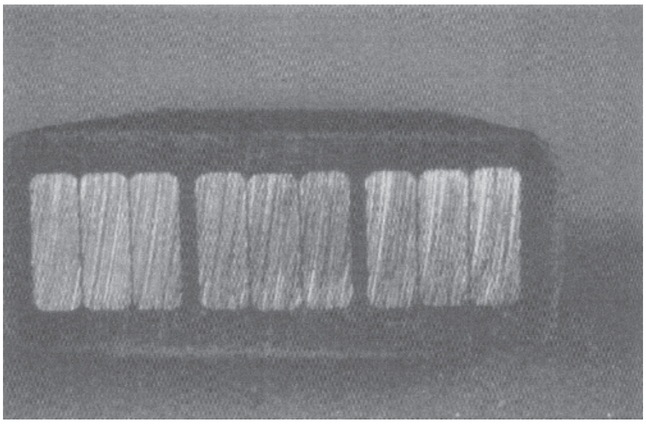


Figure 1.9 Cross section of a multi-turn coil with three turns and three strands per turn.

depth of copper is 8.5 mm at 60 Hz. If the conductor has a cross section such that the thickness is greater than 8.5 mm, there is a tendency for the current *not* to flow through the center of the conductor, which implies that the current is not making use of all the available copper cross sections. This is reflected as an effective AC resistance that is higher than the DC resistance. The higher AC resistance gives rise to a larger I^2R loss than if the same cross section had been made from strands that are insulated from one another to prevent the skin effect from occurring. That is, by making the required cross section from strands that are insulated from one another, all the copper cross sections are used for current flow, the skin effect is negated, and the losses are reduced.

In addition, eddy current losses occur in solid conductors of too large a cross section. In the slots, the main magnetic field is primarily radial, that is, perpendicular to the axial direction. There is also a small circumferential (rotor slot leakage) flux that can induce eddy currents to flow. In the end winding, an axial magnetic field is caused by the abrupt end of the rotor and stator core. This axial magnetic field can be substantial in synchronous machines that are under-excited. By Ampere's law, or the "right hand rule," this axial magnetic field will tend to cause a current to circulate within the cross section of the conductor (Figure 1.10). The larger the cross-sectional area is, the greater will be the magnetic flux that can be encircled by a path on the periphery of the conductor, and the larger will be the induced current. The result is a greater I^2R loss from this circulating current. By reducing the size of the conductors, there is a reduction in stray magnetic field losses, improving efficiency.

The electrical reasons for stranding require the strands to be insulated from one another. The voltage across the strands is less than a few volts; therefore, the strand insulation can be very thin. The strand insulation is subject to damage during the coil-manufacturing process, so it must have good mechanical properties. As the strand insulation is immediately adjacent to the copper conductors that are carrying the main stator current, which produces the I^2R loss, the strand insulation is exposed to the highest temperatures in the stator. Therefore, the strand insulation must have

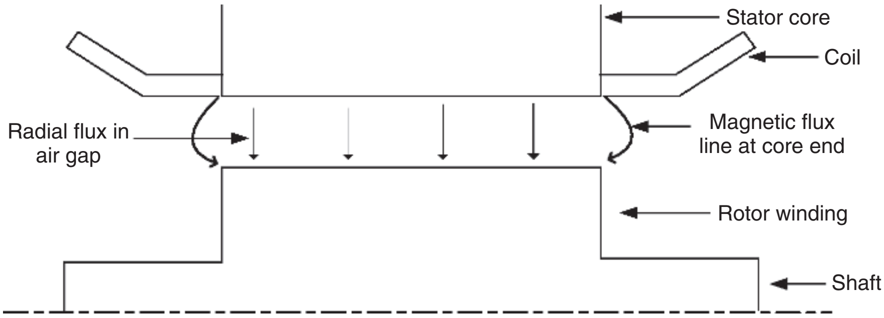


Figure 1.10 Side view of a generator showing the radial magnetic flux in the air gap and the bulging flux at the core end, which results in an axial flux.

good thermal properties. Section 3.8 describes in detail the strand insulation materials that are in use. Although manufacturers ensure that strand shorts are not present in a new coil, they may occur during service because of thermal or mechanical aging (see Chapter 8). A few strand shorts in form-wound coils/bars will not cause winding failure, but will increase the stator winding losses and cause local temperature increases because of circulating currents.

1.4.2 Turn Insulation

The purpose of the turn insulation in both random- and form-wound stators is to prevent shorts between the turns in a coil. If a turn short occurs, the shorted turn will appear as the secondary winding of an autotransformer. If, for example, the winding has 100 turns between the phase terminal and neutral (the "primary winding"), and if a dead short appears across one turn (the "secondary"), then 100 times normal current will flow in the shorted turn. This follows from the transformer law:

$$n_p I_p = n_s I_s \tag{1.1}$$

where n refers to the number of turns in the primary or secondary and I is the current in the primary or secondary. Consequently, a huge circulating current will flow in the faulted turn, rapidly overheating it. Usually, this high current will be followed quickly by a ground fault because of melted copper burning through any groundwall insulation. Reference 12 suggests that a ground fault will occur in 20–60 s in a low voltage motor, and almost immediately in a medium voltage stator. Clearly, effective turn insulation is needed for long stator winding life.

The power frequency voltage across the turn insulation in a random-wound machine can range up to the rated phase-to-phase voltage of the stator because, by definition, the turns are randomly placed in the slot and thus may be adjacent to a phase-end turn in another phase, although many motor manufacturers may insert extra insulating barriers between coils in the same slot but in different phases and between coils in different phases in the endwindings. As random winding is rarely used on machines rated more than 690 V (phase-to-phase), the turn insulation can be fairly thin. However, if a motor is subject to high voltage pulses, especially from modern

IFDs), interturn voltage stresses that far exceed the normal maximum of 690 Vac can result. These high voltage pulses give rise to failure mechanisms, as discussed in Section 8.10.

The power frequency voltage across adjacent turns in a form-wound multi-turn coil is well defined. Essentially, one can take the number of turns between the phase terminal and the neutral and divide it into the phase-ground voltage to get the voltage across each turn. For example, if a motor is rated 4160 Vrms (phase–phase), the phase–ground voltage is 2400 V. This will result in about 24 Vrms across each turn, if there are 100 turns between the phase end and neutral. This occurs because coil manufacturers take considerable trouble to ensure that the inductance of each coil is the same, and that the inductance of each turn within a coil is the same. As the inductive impedance (X_L) in ohms is:

$$X_L = 2\pi fL \tag{1.2}$$

where f is the frequency of the AC voltage and L the coil or turn inductance, the turns appear as impedances in a voltage divider, where the coil series impedances are equal. In general, the voltage across each turn will be between about 10 Vac (small form-wound motors) and 250 Vac (for large generator multi-turn coils).

The turn insulation in form-wound coils can be exposed to very high transient voltages associated with motor starts, inverter fed drive (IFD) operation, or lightning strikes. Such transient voltages may age or puncture the turn insulation. This is discussed in Sections 8.9 and 8.10. As described below, the turn insulation around the periphery of the copper conductors is also exposed to the rated AC phase–ground stress, as well as the turn–turn AC voltage and the phase coil-to-coil voltage.

Before about 1970, the strand and the turn insulations were separate components in form-wound multi-turn coils. Since that time, many stator manufacturers have combined the strand and turn insulations, although some users oppose this [16].

Figure 1.11 shows the strand insulation that is upgraded (usually with more thickness) to serve as both the strand and turn insulations. This eliminates a manufacturing step (i.e., the turn taping process) and increases the percentage of the slot cross section that can be filled with copper. However, some machine owners have found that in-service failures occur sooner in stators without a separate turn insulation component [16].

Both form-wound coils and random-wound stators are also exposed to mechanical and thermal stresses. The highest mechanical stresses for the turn insulation tend to occur in the coil-forming process, which requires the insulation-covered turns to be bent through large angles, which can stretch and crack the insulation. Steady state, magnetically induced mechanical vibration forces (at twice the power frequency) act on the turns during normal machine operation. In addition, very large transient magnetic forces act on the turns during motor starting or out-of-phase synchronization in generators. These are discussed in detail in Chapter 8. The result is the turn insulation that requires good mechanical strength.

The thermal stresses on the turn insulation are essentially the same as those described earlier for the strand insulation. The turn insulation is adjacent to the copper conductors, which are hot from the I^2R losses in the winding. The higher the melting

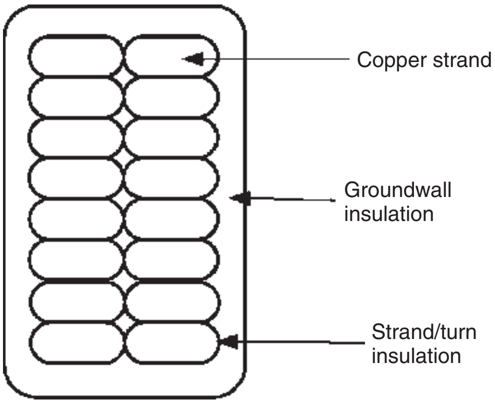


Figure 1.11 Diagram of the cross section of a coil where the turn insulation and the strand insulation are the same.

or decomposition temperature of the turn insulation is, the greater will be the design current that can flow through the stator.

In a Roebel bar winding, no turn insulation is used and there is only strand insulation. Thus, as will be discussed in Chapter 8, some failure mechanisms that can occur with multi-turn coils will not occur with Roebel bar stators.

1.4.3 Groundwall Insulation

Groundwall insulation (also called the *main wall insulation* outside of North America) is the component that separates the copper conductors from the grounded stator core. Its failure usually triggers a ground fault relay, taking the motor or generator off-line*. Thus, the stator groundwall insulation is critical to the proper operation of a motor or generator. For a long service life, the groundwall must meet the rigors of the electrical, thermal, and mechanical stresses that it is subject to.

Electrical Design The groundwall insulation in form-wound multi-turn coils and Roebel bars connected to the phase end of the winding will have the full rated phase–ground voltage across it. For example, a stator rated at 13.8 kV (phase–phase) will have a maximum of 8 kV ($13.8/\sqrt{3}$) between the copper conductors and the grounded stator core. This high voltage requires a substantial groundwall insulation thickness. The high groundwall voltage only occurs in the coils/bars connected to the phase terminals. The coils/bars connected to the neutral (in a wye-connected winding) have essentially no voltage across the groundwall during normal operation. Yet virtually all machines are designed to have the same insulation thickness for both phase- and neutral-end coils. If the coils all had different groundwall thicknesses, then, to take advantage of the smaller width of a neutral end bar or coil, the stator

---

*If the fault occurs electrically close to the neutral in a wye-connected winding with high impedance between the neutral and ground, some types of relays will not detect the ground fault. This allows a current to flow from the copper to the stator core, which may damage the stator core. Special third-harmonic ground fault relays or relays that inject a current into the stator are available to detect this type of condition [17].

slot would be narrower. All the slots would be of different sizes, and problems would occur when a neutral bar/coil had to be placed on top of a phase-end bar in the same slot. It is simply easier to make the stator core slots all the same size. An advantage to this design approach is that as all coils/bars have the same groundwall thickness, changing connections to reverse the line and neutral ends may extend the life of a winding. That is, the coils formerly at the neutral are now subjected to high voltage, and vice versa. Such a repair may be useful if purely electrical failure mechanisms, such as those described in Sections 8.5, 8.6, and 8.14, are occurring. Other aspects of the electrical design are discussed in Section 1.4.4.

Thermal Design The groundwall insulation in indirectly cooled form-wound machines is the main path for transmitting the heat from the copper conductors (heat source) to the stator core (heat sink). Thus, the groundwall insulation should have as low a thermal resistance as possible, to prevent high temperatures in the copper. Achieving a low thermal resistance requires the groundwall materials to have as high a thermal conductivity as possible, and for the groundwall to be free of voids. Such air voids block the flow of heat, in the same way that two layers of glass separated by a small air space inhibits the flow of heat through a window. Therefore, the insulation must be able to operate at high temperatures (in the copper) and be manufactured in such a way as to minimize the formation of air pockets within the groundwall. Recently, effort has been devoted to develop materials with a higher thermal conductivity than has been available in the past [18,19].

Mechanical Design There are large magnetic forces acting on the copper conductors. These magnetic forces are primarily the result of the two magnetic fields from the current flowing in the top and bottom coils/bars in each slot. These fields interact, exerting a force that makes the individual copper conductors and the entire coil or bar vibrate (primarily) up and down in the slot. The force, F, acting on the top coil at 120 Hz for a 60-Hz current in the radial direction for 1-meter length of coil is given by [20]:

$$F = \frac{cI^2}{d}\,\mathrm{kN/m} \tag{1.3}$$

where I is the rms current through the Roebel bar, or $I = nI_o$ with I_o being the rms coil current times the number of turns in the coil; d the width of the stator slot in meters; and $c = 0.96$. The force is expressed in kilonewton of force acting per meter length of coil/bar in the slot. The highest forces are when both coils/bars in the slot are in the same phase. If the current in a stator bar is:

$$I \quad = A \sin \omega t$$

where ω is $2\pi f$, f the 50- or 60-Hz power frequency, and t time, and then (1.3) becomes

$$F = \frac{cA^2(1 - \cos 2\omega t)}{(2d)}$$

Thus, with two coils/bars in the same phase, there is a net force to the bottom of the slot. Around this “DC” force is an oscillating force at twice the power frequency, that is, 100 or 120 Hz. There is also a 100- or 120-Hz force in the circumferential direction on the top bar/coil caused by the rotor's magnetic field interacting with the current in the stator coil/bar. This circumferential force is only about 10% of the radial force [20].

The groundwall insulation must also help to prevent the copper conductors from vibrating in response to these magnetic forces. If the groundwall were full of air pockets, the copper conductors might be free to vibrate. This would cause the conductors to bang against the remaining groundwall insulation, as well as allowing the copper strands and turns to vibrate against one another, leading to insulation abrasion. If an incompressible insulating mass exists between the copper and the coil surface, then the conductors cannot move.

1.4.4 Groundwall Partial Discharge Suppression

In form-wound bars and coils rated greater than about 4 kV, partial discharges (PDs) can occur within the groundwall insulation or between the surface of the coil or bar and the stator coil. These PDs, which are sometimes colloquially (but incorrectly) called corona[†], are the result of the high voltage electrical stress that occurs in the groundwall. If an air pocket (also called a *void* or a *delamination*) exists in the groundwall, the high electric stress may cause electrical breakdown of the air, resulting in a spark. The electrons and ions in the spark will degrade the insulation and, if not corrected, repeated discharges may eventually erode a hole through the groundwall, leading to failure. Therefore, efforts are needed to eliminate voids in the groundwall to prevent stator winding failure. In addition, a PD suppression system is needed to prevent PD in any air gaps between the surface of the coils/bars and the core. The following is a brief discussion of the physics of the PD process within voids in the groundwall. Section 1.4.5 discusses the requirement for a PD suppression system on coil and bar surfaces.

Electric breakdown of insulation is analogous to mechanical failure of a material. For example, the tensile strength of a material depends on the nature of the material (specifically, the strength of the material's chemical bonds) and the cross-sectional area of the material. Mechanical failure occurs when the chemical bonds rupture under the mechanical stress. Tensile stress (kPa) is defined in terms of force (weight) supported (in kilonewton or pounds) per unit cross-sectional area (m^2) or, in British units, pounds per square inch (psi). The larger the cross section is, the more will be the force a material (e.g., a steel wire) can support before it breaks. Different materials have vastly different tensile strengths. The tensile strength of steel exceeds that of copper, which, in turn, is hundreds of times greater than the tensile strength of paper.

Electric breakdown strength is also a property of an insulating material. Electric breakdown is not governed by voltage alone. Rather, it depends on the electric field, just as the tensile stress on a copper wire is not solely determined by the force it is

---

[†] According to the IEEE Dictionary (IEEE Standard 100-2000), corona is a form of PD [21]. The term corona is reserved for the visible PDs that can occur on bare metal conductors operating at high voltage, which ionize the surrounding air. As PD within the groundwall is not visible, it should not be termed corona.

supporting but by the force per cross-sectional area. Electric stress, E, in a parallel plate geometry is given by

$$E = \frac{V}{d}(\mathrm{kV/mm}) \tag{1.4}$$

where V is the voltage across the metal plates in kilovolts and d the distance between the plates in millimeter. Note that as for the tensile stress, there is an element of dimensionality. If the voltage is gradually increased across the metal plates, there will be a voltage at which electric breakdown occurs, that is, at which a spark will cross between the plates. Using Equation 1.4, one can then calculate the electric strength of the insulation material. Breakdown involves a process in which the negatively charged electrons orbiting the atoms within the insulation are ripped away from the molecules because they are attracted to the positive metal plate. This is called *ionization*. The electrons accelerate toward the positive metal plate under the electric field, and often collide with other atoms, ionizing these also. A cloud of positive ions is left behind that travels gradually to the negative metal plate. The electrons and ions create a conducting plasma that shorts the voltage difference between the two metal plates. The result is the electric breakdown of the insulation. Two examples of the electric breakdown of air are lightning and the static discharge from a person who has acquired a charge by walking across a carpet in a dry atmosphere and then reaches for a grounded doorknob.

Like mechanical (tensile) strength, each material has its own characteristic electric breakdown strength. For air at room temperature and one atmosphere (100 kPa) pressure, and in low humidity, the electric strength is about 3 kV/mm peak. The electric strength of gas insulation depends on the gas pressure and humidity. For example, the breakdown strength of air at 300 kPa is about 9 kV/mm, that is, for the same distance between the plates, the breakdown voltage is three times higher than at atmospheric pressure (100 kPa). This relationship is known as Paschen's law [22]. The breakdown strength of air and hydrogen is about the same. However, as hydrogen-cooled generators often operate at 300 kPa or more pressure, the breakdown strength of hydrogen under this pressure is 9 kV/mm. As we will see later, this allows hydrogen-cooled generators to operate at higher voltages than air-cooled machines, which operate at atmospheric pressure. The intrinsic breakdown strength of most solid insulating materials such as epoxy and polyester composites is on the order of 200 kV/mm. That is, solid materials used as stator winding insulation are almost 100 times stronger than air. More details on electric breakdown and the physics behind it are in Reference 22.

The presence of air (or hydrogen) pockets within the groundwall can lead to the electric breakdown of the gas filled pockets, a process called a *partial discharge (PD)*. To understand this process, consider the groundwall cross section in Figure 1.12. For electric breakdown to occur in the air pocket, there must be a high electric stress across it. Using a simple capacitive voltage divider circuit (Figure 1.12b), one can calculate, to a first approximation, the voltage across the air pocket.

The capacitance of the air pocket, to a first approximation, can be calculated assuming that it is a parallel plate capacitor, that is,

$$C_a = \frac{\epsilon A}{d_a} \tag{1.5}$$

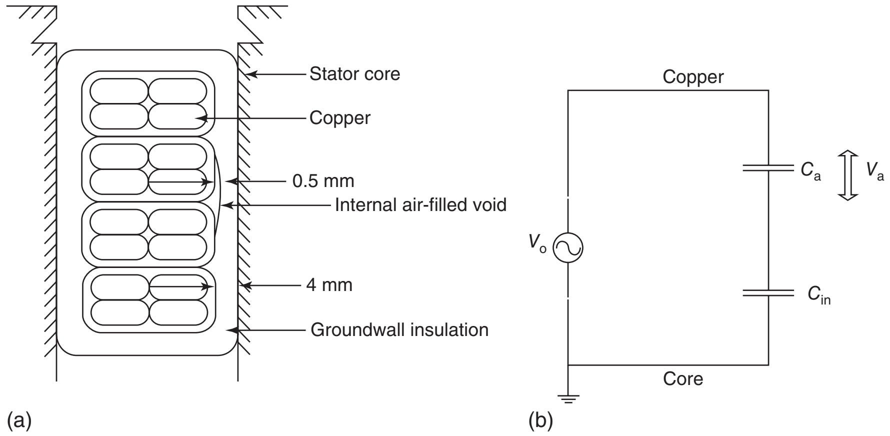


Figure 1.12 (a) Cross section of a coil with an air pocket next to the turn insulation. (b) An electrical equivalent circuit.

where ϵ is the permittivity of the insulating material, A the cross-sectional area of the void, and d_a the thickness of the void (0.5 mm in the example in Figure 1.12a). The permittivity is often represented as:

$$\epsilon = \epsilon_\mathrm{r}\epsilon_\mathrm{o} \tag{1.6}$$

where ϵ_r is called the *relative dielectric constant* and ϵ_o the permittivity of free space, equal to 8.85×10^{-12} F/m. The dielectric constant for air is 1.0. Thus, assuming a unity cross-sectional area, the capacitance of the air pocket in Figure 1.12a can be calculated.

The air pocket is in series with another capacitor, which represents the capacitance (C_in) of the solid insulating material. Using Equation 1.5, assuming a dielectric constant of 4, and assuming that the thickness of the insulation capacitor is 4 mm, the insulation capacitances can be calculated, to a first approximation.

Using simple circuit theory, the voltage across the air pocket can be calculated:

$$V_\mathrm{a} = \frac{C_\mathrm{in}}{C_\mathrm{a} + C_\mathrm{in}} V_\mathrm{o} \tag{1.7}$$

where V_o is the applied AC voltage (8 kV rms if the coil is at the phase terminal) and C_in the solid insulating material capacitance. Using the above equations, the dimensions in Figure 1.12a, recognizing that A and ϵ_o will cancel out, and assuming the dielectric constants are 1 and 4 for air and the insulation, respectively, one can calculate that the voltage across the air pocket is 33% of the applied voltage. For a V_o of 8 kV rms (rated phase–ground voltage for a phase-end coil in a 13.8-kV stator), the voltage across the air pocket is about 2.6 kV. Note that this is an approximate voltage across the void. A more precise calculation would use finite element electric field computation methods that are now readily available. From Equation 1.4, this voltage implies the electric stress within the air pocket is 5.2 kV/mm rms. This far exceeds the 3 kV/mm peak electric strength of the air, and thus electric breakdown will occur within the air. The resulting spark is called a *partial discharge*. The discharge is referred to as *partial* as the spark is only in the air pocket or void. The rest of the insulation is intact and can support the applied voltage. (A complete discharge is really a phase–ground breakdown, which would trigger the ground fault relay.) The above capacitive model for determining if PD will occur is approximate. In reality, finite element electric field calculations are needed to determine if PD will occur, and account for the nonuniform electric fields within the coil/bar cross section and different void shapes. For a more accurate analysis of the PD phenomena, see References 22 and 23.

As the intrinsic breakdown strength of typical solid groundwall insulation materials is about 200 kV/mm, there is practically no possibility of the solid groundwall insulation itself experiencing electrical breakdown. Rather, PD will occur only when there are gas-filled voids within the groundwall. These discharges are harmful to the groundwall, because repeated PD will eventually degrade the solid insulation by breaking the chemical bonds. The spark contains electrons and ions that bombard the insulation surfaces of the void. This bombardment can rupture the chemical bonds, especially in organic materials such as asphalt, polyester, and epoxy, all common groundwall insulation materials. Over the years, the constant impact from the electrons and ions will erode a hole (called an *electric tree*) through the groundwall, giving rise to a ground fault. The consequence of PD is discussed in greater detail in Chapter 8. The important conclusion is that air pockets within the groundwall of high voltage coils can lead to PD and eventual failure.

1.4.5 Groundwall Stress Relief Coatings for Conventional Stators

The stress relief coatings are important insulation system components in 50/60-Hz stator windings operating at 6 kV or above and IFD motor stators rated 3.3 kV and above (see Section 1.4.6). These coatings are present to prevent PDs from occurring on the surface of the stator bars or coils. They prevent PD from occurring in any air gap that might be present between the coil/bar surface and the stator core, or in the end winding near the end of the stator core.

Slot Semiconductive (Semicon) Coating The reason PD may occur between the coil and the core is similar to the reason PD can occur in air pockets within the groundwall. As coils and bars are fabricated outside of the stator core, they must be thinner in the narrow dimension than the width of the core's steel slots; otherwise, the coils/bars cannot be inserted into the slot. Thus, an air gap between the coil/bar surface and the core is inevitable[‡]. Figure 1.13a shows the gap that can occur in the slot, adjacent to the coil surface, as the coil is undersized. An equivalent circuit, only slightly different from the groundwall case, is shown in Figure 1.12b. As for the

---

[‡] As discussed in Chapter 3, one stator-manufacturing process called *global VPI* may fill in the gap with epoxy or polyester between the coil surface and the core, thus, in theory, eliminating the need for stress relief coatings. However, because of thermal cycling considerations (Section 8.2), machine manufacturers still use a semiconductive coating with global VPI stators.

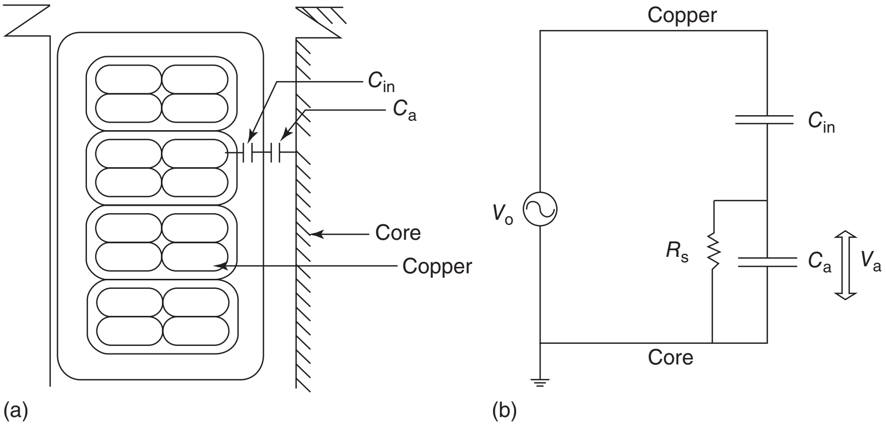


Figure 1.13 (a) Cross section (not to scale) of a coil in a slot where PD can occur at the surface of the coil and (b) the equivalent electrical circuit.

groundwall voids, a significant percentage of the copper voltage will appear across the air gap. If the electric stress in the air gap exceeds 3 kV/mm, PD will occur, at least in an air-cooled machine at atmospheric pressure. This PD will eventually erode a hole through the groundwall causing failure. Discharges on the coil/bar surface are sometimes referred to as *slot discharge*, as they can be seen in the slot. Under practical conditions, most stators rated 6 kV or more will experience this PD on the coil/bar surface. In addition to deteriorating the insulation, surface PD in air-cooled machines creates ozone. The ozone combines with nitrogen and humid air to create nitric acid (HNO_3) that poses a health hazard, and which can chemically attack organic materials and corrode metal; for example, in heat exchangers.

To prevent PD on the coil or bar surfaces, manufacturers have long been coating the coil/bar in the slot area with a partly conductive coating. The coating is usually a graphite-loaded paint or tape. This coating, often called a *semiconductive* or *semicon* coating (although this has nothing to do with semiconductors in the transistor sense), is likely to be in contact with the grounded stator core at many places along the length of the slot. With a sufficiently low resistance (schematically shown as Rs in Figure 1.13b), this coating is essentially at ground potential because of the contact with the core. Thus, the voltage across any air gap is zero. PD cannot occur in the air gap, because the electric stress will never exceed 3 kV/mm. The result is that semiconductive coatings with surface resistance from 0.3 to 10 kΩ per square prevent surface discharges in the slot. Note that the coating cannot be too conductive (i.e., a metalized coating), as this will short out the stator core laminations and/or lead to vibration sparking if the coils/bars are vibrating under the magnetic forces (see Section 8.8).

Semiconductive coatings on coils in the slot are not normally needed for stators rated less than 6 kV. Clearly, this is because it is unlikely that the critical threshold of 3 kV/mm (electric breakdown strength of air) will occur at this low operating voltage, even if a substantial gap occurs between the coil and the core. However, if the winding is to operate at high altitudes (generally higher than 1000 m) where the air pressure is lower, then semiconductive coatings may be needed for 3.3 and 4.1 kV windings as the lower pressure will result in a lower breakdown strength for the air.

Silicon Carbide Coating The low-resistance semiconductive slot coating usually extends only a few centimeters beyond each end of the slot (to the end of the pressure fingers clamping the stator core together)[§]; otherwise, the grounded surface would be brought too close to the connection of one coil/bar to another. Decades of experience shows that even a fully insulated connection between adjacent coils will be a weak spot that may prompt a future insulation failure if ground potential is nearby. In addition, as described in Chapters 3 and 4, it is often difficult to avoid air pockets in the insulation occurring in the end winding during manufacture. If a low-resistance semiconductive coating grounded the endwinding surface, such air pockets are likely to initiate PD as described earlier, eventually leading to failure.

The slot semiconductive coating cannot end abruptly a few centimeters outside the slot as the thin coating would give rise to a high, localized electric field. This field would exceed 3 kV/mm, and PD would occur at the end of the coating. Such PD would eventually destroy the insulation in the vicinity, leading to failure. The thin edge of the coating creates a very nonuniform electric field at the end of the slot coating as the electric stress depends strongly on the inverse of the radius. The smaller the radius is (i.e., the thinner the semiconductive coating is), the larger will be the electric field. For example, a needlepoint at voltage V with a radius r, and a distance d between the needle and a flat ground plane, will create a maximum electric field at the needle tip of approximately [24]:

$$E = \frac{2\,\mathrm{V}}{r \ln\left(\frac{4d}{r}\right)} \tag{1.8}$$

where ln is the natural logarithm. This shows that the radius is critical to the maximum electric field.

Thus, just as for high voltage cables, the end of the semiconductive coating must be "terminated." In the early days of high voltage rotating machines, the electric field just outside of the slot was made more uniform by embedding concentric floating metal foils of specific lengths within the volume of the groundwall, in the area where the semiconductive coating ends. This is the same principle used in high voltage condenser bushings in transformers [22]. However, when a unique material called *silicon carbide* became available, it superseded the bushing approach.

Silicon carbide is a special material that has an interesting property: as the electric stress increases in this material, its resistance decreases. That is, it is not "ohmic." In the past, silicon carbide was used in high-voltage surge arrestors to divert high-voltage surges due to lightning strikes to ground (i.e., it has a low resistance

---

[§] Some manufacturers of very high voltage stator windings may use a high resistance (usually megohms per square) over the entire end winding to control the electrical stress more closely, reducing the probability of flashover during an AC hipot test (Section 15.6). As the coating is high resistance, the further a point is away from the core is, the higher the point will be above ground potential. At the connection to the next coil or bar, the voltage of the coating is assumed to be at the same potential as the voltage of the copper underneath the insulation.

state), whereas being fully insulating during normal operating voltage of a transmission line. When applied to stator coils and bars, the silicon carbide has a very low resistance in the high-stress region at the end of the slot semiconductive coating, and dramatically increases its resistance further along the end winding from the core. This varying resistance makes the electric field at the end of the semiconductive coating more uniform. Figure 1.14a shows an equivalent circuit of the groundwall insulation capacitance and the variable resistance of the silicone carbide coating. R1, closest to the semiconductive coating, has a much lower resistance than say R5, which is farther from the core. The silicon carbide particle density and size are adjusted to make the voltage drop from the groundwall capacitive current across each resistance about the same. Usually, the stress is reduced to below the critical 3 kV/mm (in air) that would initiate PD.

Silicon carbide particles are usually mixed into a paint base, or incorporated into a tape that is applied to the coil/bar surface. The length of the silicon carbide surface coating depends on the voltage rating and the silicone carbide particle size, but 10–20 cm is usual. In Figure 1.7b, the black tape in the middle of the coil is the slot semiconductive coating, whereas the short gray areas at the end of the semiconductive coating are the silicon carbide coatings (not visible owing to a surface paint). The silicon carbide coating is also called the *gradient coating* or the *OCP (outer corona protection coating)*. Further information on stress control coatings can be found in References 25 and 26.

1.4.6 Surface Stress Relief Coatings for Inverter-Fed Stators

SCI motors with form-wound stators rated up to 13.8 kV are now being supplied from inverters for the purpose of speed control. One of the most common types of inverter is called the *voltage source*, *pulse width-modulated (PWM) inverter*. Such invertors use very short risetime electronic switching devices (IGBTs or ICBTs) that are switched on and off at a rate of several kilohertz. As described in more detail in Sections 8.9 and 8.10, the short risetime impulses from the inverter may cause the impulse voltage from the inverter to as much as double because of transmission line effects (reflections) as the impulse travels along the power cable from the inverter to the motor stator winding [27,28]. The result is the peak voltage at the stator winding fed by an inverter will be much higher than the peak voltage in an AC sinusoidal motor, for the same nominal (rms) voltage rating. As electric breakdown and PD are caused by the peak voltage (not the rms or effective voltage), the stress is much more likely to reach the critical 3 kV/mm electric stress in any air gap between the surface of the coil and the stator core, if there is no semiconductive coating on the coil. As a result, most motors rated 3.3 and 4.1 kV intended for inverter duty operation from a voltage source PWM drive should have semiconductive coatings in the slot portion of the coil.

Stator windings fed from a PWM voltage source inverter normally also require some modification of the silicon carbide coatings. The higher frequency current, both from the IFD switching rate and from the short risetimes (which have Fourier frequencies up to 1 MHz), greatly increases the capacitive currents that flow through the groundwall. As a minimum, an inverter switching speed of 2 kHz will result in

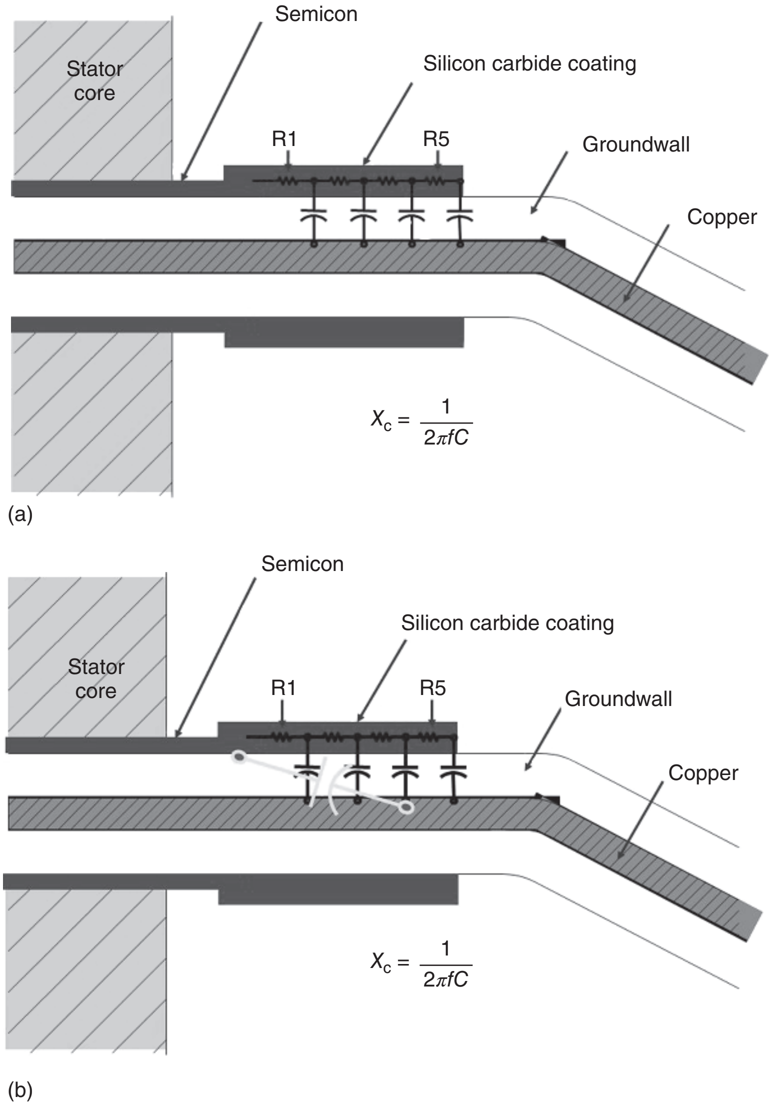


Figure 1.14 (a) Model of the groundwall capacitance and the silicon carbide coating to create a uniform axial stress at the end of the semiconductive coating in 50/60-Hz applications. (b) Model where the groundwall capacitive impedance is low compared to the semiconductive coating and silicon carbide coating impedances. This is the case for inverter-fed windings.

capacitive currents that are 2000/60 or about 33 times higher than a 60-Hz machine. This higher current flows through the silicon carbide coating (Figure 1.14a) and will greatly increase the I^2R heating in the silicon carbide. Measurements have shown that the I^2R loss can increase the local temperature of the coating by 40°C or more if a conventional silicon carbide coating intended for 50/60-Hz machines is used [27–29].

To reduce the temperature, the silicon carbide coating must be designed to have a significantly lower resistance than the coatings used in 50/60-Hz stators.

Significantly lower resistance is also needed to ensure that the capacitive currents actually flow through the silicon carbide. Sharifi [28] has shown, using analytical techniques and thermography, that with PD suppression coatings designed for 50/60-Hz application, the semiconductive coating and silicon carbide resistances can be so large compared to the capacitive impedance, and that the high capacitive currents are shunted directly to the stator core (Figure 1.14b). Thus, the coatings can rapidly degrade, leading to surface PD (and ozone). Wheeler suggests that the voltage across the silicon carbide coating should be less than 600 V/mm along the length of the coating [29]. Thus, not only must the stator designer use lower resistance silicon carbide materials, it is also advisable that the resistance of the semiconductive coating just outside of the slot also be lower than for a 50/60-Hz machine. Many innovations are being made by machine designers to ensure that the PD suppression coatings are effective, yet do not cause too much of an increase in local temperature. These include the use of much lower resistances of semiconductive coatings outside of the slot, lower resistance silicon carbide coatings, silicon carbide coatings of different properties near and far from the semicon interface, the use of metal-oxide nonlinear materials in place of silicon carbide, and multi-level connections between the semicon coating and the stress relief coating to reduce the resistance of the junction. The optimum design for the PD suppression coatings in PWM voltage source inverter-fed motors is not yet clear.

1.4.7 Conductor Shields

Form-wound coils and bars sometimes use a conductor shield (also called *inner conductor shield* or *inner corona protection (ICP)* coating) applied over the consolidated copper conductor stack in the slot area [30,31]. As with the surface coatings, the purpose of this shield is to reduce the probability of PD occurring, in this case near the copper conductors. During manufacturing of the coils and bars, an insulating material is often wrapped around the copper stack to consolidate the stack and force the copper cross section into a rectangular shape. Experience has shown that it is likely that some small voids will occur next to the rounded edges of the copper strands or at the transposition insulation (Section 1.4.10) in the consolidated stack. Voids tend to be likely here as the conductor stack consolidation process must necessarily be done in air, and thus the high pressures that can be applied in the groundwall impregnation process to reduce void sizes are not possible. In addition, it is possible that the surface of the copper will have imperfections that may cause some of the copper to have a sharp burr that extends from the copper increasing the local electric field. Finally, rapid variations in the stator current may lead to shear stresses between the copper and the groundwall – leading to voids between the copper and the immediately adjacent groundwall insulation (Section 8.2). The voids or copper burrs may lead to PD in the finished coils/bars adjacent to the copper.

To allow for these inevitable imperfections, the insulation system designer may use a lower design electric stress to make sure that such imperfections do not lead to PD in operation. This approach is often used on stator windings rated up to 15 kV or so. Alternatively, such imperfections can be compensated for using a conductive material over the consolidated stack that is close to the same potential as the copper conductors. Any imperfections between the copper and the shield will thus have little or no electric stress across it, thereby preventing PD and its consequent effects on insulation life. The use of conductor shields tends to be more likely on windings rated greater than 15 kV.

Today, conductor shields are usually made from a graphite-loaded tape that is placed as "caps" at the top and bottom of the consolidated stack (i.e., the narrow sides of the copper) or they may be wrapped helically over the entire circumference of the consolidated conductor stack for the length of the slot (and of course underneath the groundwall insulation). In most cases, the graphite layer must be electrically bonded to one of the copper strands, to ensure that the shield is at the same voltage as the copper, and to lower the dissipation factor [30]. Manufacturers sometimes make no intentional galvanic connection between the shield and the copper. Instead, they rely on the very high capacitance between the copper and the shield (as the insulation between these layers is very thin) to ensure that the copper and the shield are close to the same voltage.

A few manufacturers use a very thin metallic foil as the conductor shield on their high voltage coils/bars. If the connection between the foil and the copper is not good, large arcs can occur, which may corrupt PD measurements (Sections 15.12 and 16.4).

1.4.8 Mechanical Support in the Slot

The coils and bars are subject to large magnetically induced forces during normal motor or generator operation, as described in Equation 1.3 and References 2 and 20. These forces are at twice the AC line frequency. Furthermore, if a phase–phase fault occurs near the machine terminals, the transient fault current can be 10 times the rated current [32], which, due to the I^2 component in Equation 1.3, causes a magnetic force as much as 100 times larger than that occurring during normal operation. The coils must be restrained from moving under these steady state and transient mechanical forces. If the coils become loose, then any relative movement that occurs between conductors or coils in the slot or the endwinding will lead to abrasion of the insulation or fatigue cracking of the insulation. Both are obviously undesirable, as they can lead to shorts.

Within the stator slot, the restraint of the coil or bar is accomplished by several means. Often, more than one method is used. As shown in the slot cross sections in Figure 1.8, fundamentally, both random- and form-wound slots are filled as much as possible with conductors and insulation, and then the slot is closed off with a nonconductive and usually nonmagnetic wedge. Filling the slot as much as possible reduces the probability that the coils/bars will become loose. A slot wedge is an essential component to keep the coils and bars in the stator slot. The slot wedge is usually made from an insulating material (nowadays an epoxy glass laminate, usually a NEMA G10 or G11 material) and is critical to restricting movement. Wedges tend to be about 10–20 cm long to make it easier to install them, rather than being a single part that is the length of the slot. Originally, wedges were of a simple "flat" design, held in place

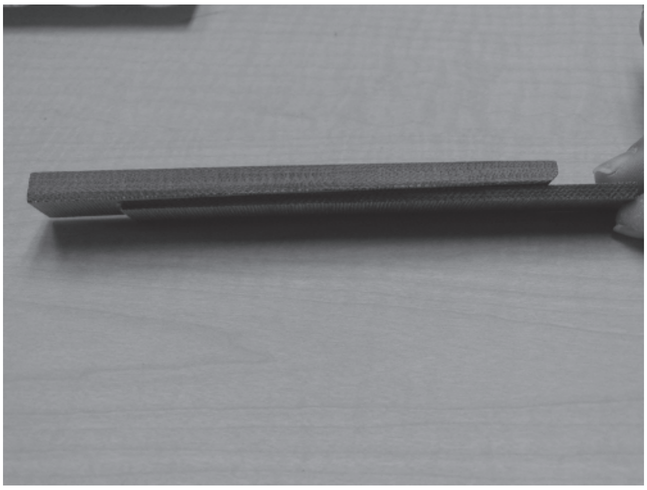


Figure 1.15 Side view of a two-part wedge, where a tapered slider is pushed under the wedge to increase radial pressure on the coils.

by dovetail grooves in the stator slot (Figure 1.8). Some insulation filler strips (also known as *sticks*, *midsticks*, *depth packing*, or *side packing*) are also inserted to take up any extra space in the slot, either under the wedge or on the side of the slots. In machines rated at more than 6 kV, often the filler strips have been filled with graphite to make them semiconductive. This ensures that the semiconductive coating on the coils/bars is grounded to the core via the filler strips, preventing slot discharge.

For large machines, in this context those rated above approximately 20 MW, many manufacturers use a more sophisticated wedge that has two parts (Figures 1.8b and 1.15). The two-part wedge has a tapered slider that is pushed between the main wedge and the coils/bars. This creates a slight spring action in the radial direction that can keep pressure on the coils, even if the slot contents shrink slightly over time.

As an alternative to the two-part wedge (or sometimes as an addition), large machines may use “ripple springs.” The ripple spring is a laminated material, sometimes filled with graphite to make it partly conductive (Figure 1.16). The waves in the ripple spring are normally flattened during installation. If the slot contents shrink or creep over time, the ripple spring expands, taking up the new space and holding the coils/bars tight. Ripple springs under a wedge are usually nonconductive. Side ripple springs (between the side of a coil and the core) must be semiconductive.

Other technologies have also been developed to keep coils and bars tight within the slot in large machines. Coils and bars have been manufactured with a compliant semiconductive compound bonded to the surface of the coils/bars, outside of the semiconductive slot coating [33]. As the silicone rubber is compliant, the coils are made to a zero-clearance fit and gradually forced into the slots with hydraulic jacks. If the slot contents shrink over time, the silicone rubber expands to fill the new space. At least some of the silicone rubber must be loaded with graphite to ensure that the semiconductive coating is grounded. Other designs use a U-shaped graphite-loaded hollow tube that is placed in the slot. After wedging (and perhaps after some thermal cycling

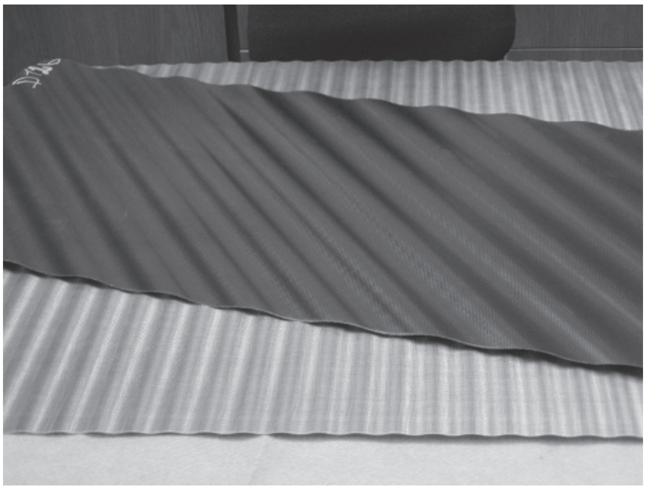


Figure 1.16 Photograph of semiconductive ripple spring material lying on top of nonconductive ripple sprint material (Source: Von Roll).

to compact the slot contents), the hollow tube is filled with an insulating material (often silicon rubber) under pressure, to take up any remaining space.

Another way to ensure that the coils/bars do not become loose is to glue the coils/bars into the slot. This is very common for motor stators, and a few manufacturers have used it on high speed generators rated up to about 300 MVA [34,35]. For form-wound machines (and now even some critical random-wound stators and rotors), a process called *global vacuum pressure impregnation (GVPI)* is used. The latter uses epoxy or polyester as the glue. These processes are described in detail in Chapters 3 and 4. The result is coils or bars that do not move in the slot.

Although most stator wedges are made from an insulating material (usually an epoxy-glass laminate), in some applications, designers will use magnetic wedges because of the better coupling of the magnetic field between the rotor and the stator. Magnetic wedges will improve the efficiency of the motor or generator, and thus all other things being equal can result in a smaller stator for the same rating, or a higher rating for the same size of stator without magnetic wedges. The magnetic wedges are made from iron powder or ferrite powder mixed into an organic base material such as epoxy. The wedges may be preformed and slid into the slot dovetail, or may be a thixotropic putty that is molded into the slot and later cured. In the latter, a conventional nonmagnetic wedge may physically secure the coils in the slot [36]. As discussed in Sections 8.4 and 8.11, magnetic wedges on their own are much less robust than insulating wedges, and their disintegration can contaminate the windings or accelerate winding looseness.

1.4.9 Mechanical Support in the End winding

The principle purpose of the endwinding (also called the *end turn*, *endarm*, or *overhang*) is to allow the bars in two slots separated by some distance (or the coil legs that must also be in different slots) to be connected together. In addition, the end winding area facilitates safe electrical connections between coils/bars that are in series and to make safe connections to other parallels. As discussed earlier, for machines rated at 1000 V or more, these connections must be made well away from the grounded stator core, to prevent eventual problems with insulation failure at the insulated connection points. Generally, the higher the voltage rating is, the longer will be the "creepage distance" between the core and the connections. For geometric reasons, high speed machines also tend to have long endwindings. On large two-pole generators, the endwindings can extend up to 2 m beyond the core.

These end windings must be supported to prevent movement. If not suppressed, end winding vibration will occur because the stator winding currents in each coil/bar will create a magnetic field that will interact with the fields produced by adjacent bars/coils. The resulting force vectors can be quite complicated [32,37,38]. However, both radial and circumferential (also called *tangential*) vibrating forces occur at twice AC line frequency (Figure 1.17). As the end winding coils and bars in large machines are essentially cantilevered beams supported by the stator core, once per rotor revolution mechanical forces may also appear on the end windings coupled from the bearings to the machine frame and then to the stator core [38]. These end winding vibration forces can lead to fatigue cracking of the insulation and sometimes even the conductors, at the core end or at the connections. In addition, if the coils/bars are free to vibrate relative to one another, this relative movement can lead to insulation abrasion (fretting) in the end winding. If the machine is expected to see many system disturbances, or a motor is to be frequently started, the high in-rush currents will create even larger transient forces, which must be accommodated. For example, a phase–phase fault in a generator can increase the current by 10 times, resulting in a magnetic force up to 100 times the normal force [32,38]. Motor starting may cause an in-rush current of 5 or 6 times normal, resulting in a 25–36-fold increase in magnetic forces.

End windings can be supported against the vibratory rotational and magnetic forces in many ways. In random-wound machines, the coil endwindings are

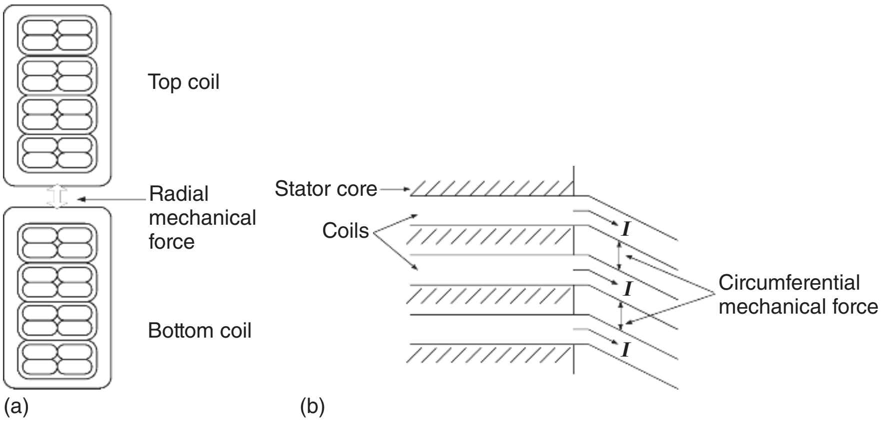


Figure 1.17 Schematics showing the magnetically induced mechanical forces occurring (a) between the top and bottom layers of coils in the end winding (b) between adjacent coils.

essentially right up against the core. With the short extensions and low currents involved, the normal “glues” that impregnate such windings, together with modest insulation tapes or cords (Figure 1.6) around the coil endwindings, are often adequate to support the end winding.

For the form-wound machines, which always have a significant end winding structure, there is almost always one or more “support rings” or “bracing rings” of some sort (Figures 1.7). The ring can be made of steel, which is usually insulated; or polyester or epoxy fiberglass laminate, or fiberglass rope (which is impregnated with stage B epoxy or is dry and then impregnated during a global VPI process). This ring is placed either inside the coil/bar layers (i.e., closer to the rotor than the coils/bars) or radially outside of the coils or bars. Each coil/bar is lashed to the ring. Large machines expecting many starts and stops may have more than one support ring and large generators usually have both inner and outer end winding support rings. The ring tends to prevent coil/bar movement in the radial direction. Insulating blocks a few centimeters in length, placed between adjacent coils, provide circumferential support. One or more rows of such blocking may be present in each endwinding (Figure 1.7a).

Support against the radial magnetic forces comes mainly from insulating blocking that is placed between the bottom (i.e., coils/bars furthest from the rotor) and top layers of coils/bars in the endwinding. The hoop strength of the support ring also helps to ensure that the coils/bars do not move radially.

Most of the endwinding blocking materials, as well as any cords/ropes that may be used to bind coils/bars to one another and to the support rings, are made from insulating material that will bond to other components. For stators that are entirely impregnated, for example, in the global VPI process (Section 3.10.4), the end windings are less likely to suffer from relative movement.

Another consideration in end winding design, especially for large two- and four-pole generators, is the growth of the coils in the slot and the end winding because of high operating temperatures. As a stator goes from no load to full load, the copper conductors heat and, owing to the coefficient of thermal expansion, the bars grow in length. The end winding support system must be able to compensate for this growth; otherwise, the support system and even the bars can become distorted. Accomplishing this tends to be somewhat of an art. See Reference 38 and 39 for more information on methods of allowing for axial expansion in large turbogenerators.

1.4.10 Transposition Insulation

The final stator winding insulation component considered in this chapter is the transposition insulation component. Transpositions occur only in form-wound machines. Multi-turn coils may have what may be called an *internal transposition* of the copper conductors (often called an *inverted* or *twisted turn*). Roebel bars (half-turn coils) always have a transposition. Usually, extra insulation is needed in the vicinity of the transposition to ensure that strand shorts do not occur.

The need for transpositions of the copper strands will be briefly explained first for Roebel bars. The reader is encouraged to refer to Reference 2 for more comprehensive explanations. Magnetic flux leaking across the stator slots is higher near the rotor side of the bar in a generator than at the bottom of the same bar (i.e., furthest from the rotor). Consequently, if the strands in a half-turn coil were always in the same position within the bar, throughout the length of the bar, the strands closer to the rotor would have a greater induced voltage on them than strands furthest from the rotor. In a Roebel bar arrangement, all the strands are normally braised together at each end of the bar. If strands are connected together that have a potential difference induced by the different flux levels, then, by Ohm's law, an axial current will be forced to flow up and down the bar. As the resistance of the copper is low, the circulating current flow will be substantial. This will significantly increase the I^2R loss, which reduces efficiency and increases the temperature of the copper.

In a Roebel transposition, each copper strand is placed into every possible position in the bar as the strand moves along the length of the bar. That is, a strand that is initially in the top left position (Figure 1.18a), after several centimeters along the bar, will be shifted one position lower on the left. The same strand will then be forced another position lower (i.e., two strand positions from the top) a few centimeters further along the bar. About half way along the bar, the strand will be in the bottom position on the left. Then, the strand is shifted from the left side of the conductor stack to the right side, and gradually moves up to the top right position in the other half of the bar. Eventually, it reaches its original position. This is called a 360° transposition. If this 360° transposition is done in the stator core, where the magnetic flux is the highest, then a single strand will have been in each radial position for the same distance along the slot. The total induced voltage on this strand will then be the same as the induced voltage on all the other strands that were transposed. Thus, one can safely connect all the strands together at both ends of the bar and not give rise to axial circulating currents.

There are many different ways to accomplish the movement of the strands into all radial positions. Besides the approach described earlier, another popular way is to

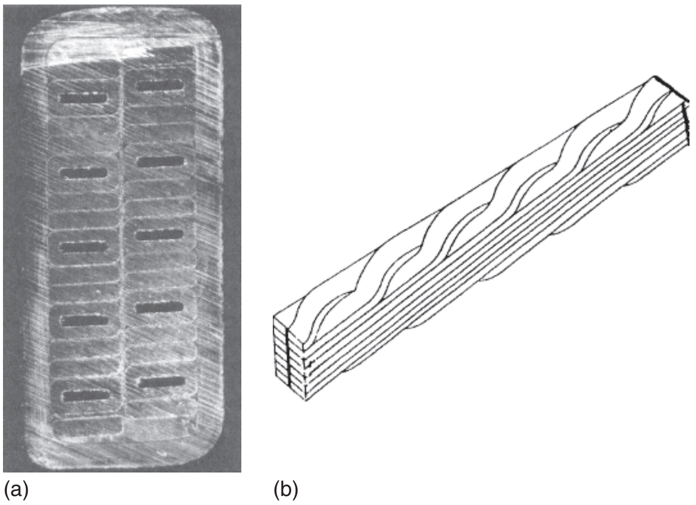

(a) (b)

Figure 1.18 (a) Photo of cross section of a water-cooled Roebel bar with transpositions. (b) Side view showing one way of transposing insulated strands in stator bar.

have the strands move back and forth between the left and right (Figure 1.18b) as it moves from top to bottom. In addition, some manufacturers prefer 540° or even 720° transpositions. Transposing can also occur in the endwinding, as stray magnetic fields are present there. The purpose of the transposition is to improve stator winding efficiency and reduce operating temperature. The mechanical process of shifting strands from one position to another is called *Roebelling*, after the inventor of the original equipment that makes the transpositions.

As discussed earlier, the copper strands have their own insulation layer. As the difference in magnetic flux between the top and bottom positions is not great, the potential difference between the strands is less than a few volts. Thus, normal strand insulation is sufficient to insulate the strands from one another. However, in the vicinity where a copper strand is shifted from one position to another, an air pocket can occur. Extra insulation (often a putty) is needed in these areas to eliminate the air gap and thus any consequent PD. Although all bar manufacturers ensure that strand shorts are not present in new bars, such shorts can occur as a result of in-service aging. A few strand shorts are easily tolerated, especially if they are close to one another.

Most multi-turn coils do not use Roebel transpositions, that is, shifting of strand positions continuously along the slot, because the distance between the top strand in a turn (i.e., the strand closest to the rotor) and the bottom strand in a turn is usually much shorter than occurs in a Roebel bar. Thus, the difference in magnetic flux between the top and bottom strands is much smaller, and the potential difference is much smaller. However, to improve efficiency, many coils have an inverted turn in the knuckle region of the coil (the end that is opposite to the connection end). What effectively happens here is the strand bundle in the turn is rotated through 180°. Thus, the strand that was in the bottom position in one leg of the coil is in the top position of the other leg of the coil. This approximately balances out the induced voltage on each strand in the turn. Alternatively, some manufacturers accomplish a transposition over several coils by more laborious connection arrangements outside of the coil.

1.5 RANDOM-WOUND STATOR WINDING INSULATION SYSTEM FEATURES

Figure 1.19a shows the cross section of a slot in a random-wound stator. Normally, the copper conductors have a circular cross section in smaller stators. The thermal and mechanical stresses in random-wound stators are similar to those in form-wound stators. Random windings have ground and turn insulation. Note that Figure 1.19a could also be the cross section of a wound rotor slot, as used in wound rotor induction motors (Section 1.6.3) and doubly fed generators (Section 1.1.3). The magnet wire insulation serves as both the turn insulation and as one of the components of the ground insulation. The turn insulation is designed to withstand the full phase–phase applied voltage, usually a maximum of 690 Vac.

In most stators rated at more than 250 V, the slots usually also have sheets of insulating material lining the slots, to provide additional ground insulation (Figure 1.19a). They may also have sheets of insulating material separating coils in different phases. Such insulating materials are discussed in Section 3.7. The thermal

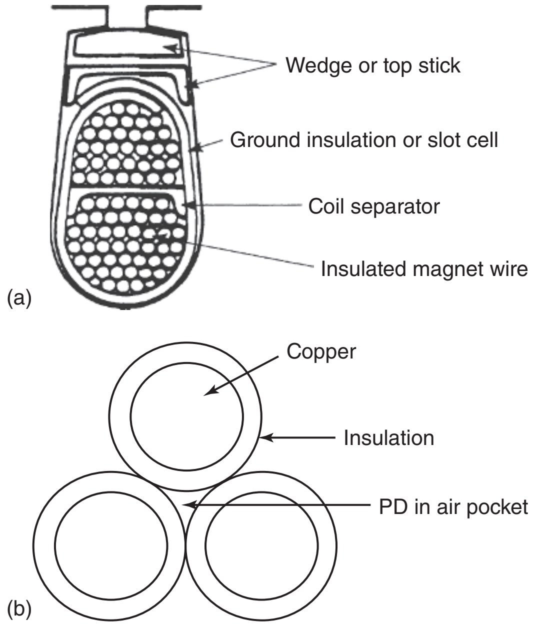


Figure 1.19 (a) The cross section of a random winding in a stator slot and (b) a schematic of (a) where PD can occur between turns in IFD motors.

capability of the liners and separators is less stringent than required of the turn insulation, as the liners are not in immediate contact with the copper conductors. Mechanically, however, the liners must have excellent abrasion resistance to withstand the magnetic forces, which cause the turns to vibrate (Section 1.4.3), and good tear resistance to withstand the manufacturing operation.

The stator winding is usually impregnated with a liquid resin or a varnish (Section 3.4). This is primarily to hold the windings tight within the slot against the twice frequency magnetic forces, so that insulation abrasion will not occur in service. The resin also reduces the amount of air in the slot. This, in turn, will aid in heat transfer from the copper conductors to the stator core. Unlike form-wound coils, with conventional random windings (see Section 1.5.1 for inverter duty motors), the insulation does not have to be void-free to suppress PD, owing to the low voltage on the winding. The most common method for impregnating the resin within the winding is simply to dip the entire stator into a tank full of liquid resin, allow time for impregnation, and then move the stator to an oven for curing (often called the dip-and-bake process). Trickle impregnation and other variations are also sometimes used to introduce the resin into the slots. The best, but most expensive, impregnation method is the GVPI method, as described in Section 3.10.4.

1.5.1 Partial Discharge Suppression in Inverter-Fed Random Windings

With the widespread application of voltage source, PWM variable-speed drives in the late 1980s even low voltage random-wound stator windings started to suffer from PD-related failures. PD has always been an issue with form-wound machines

(Section 1.4.3), but PD causing random-wound stator winding failures (and indeed wound rotor winding failures in DFIGs) was unexpected. The PD was occurring between turns, and sometimes between the turns and the stator slot in voids. Figure 1.19b shows a diagram of a void between turns in the slot, which was not fully impregnated with resin. As described in Sections 8.9 and 8.10, voltage surges from a voltage source PWM inverter will result in a significant portion of the terminal voltage across a pair of turns. Similar to the description in Section 1.4.3, this relatively high voltage will cause breakdown of the air in any void between the turns, which is a PD. The PD will gradually erode the magnet wire insulation and result in a turn-to-turn fault, which rapidly morphs into a ground fault. As the magnet wire insulation has little PD resistance, it has been found prudent to require such inverter-fed motors to be PD free at the operating voltage of the inverter. Effectively, inverter duty random-wound windings need better impregnation by resin than is needed for conventional stators. Thus, such stators often are made with the trickle impregnation or GVPI processes. This is discussed in further detail in Section 8.10 and IEC 60034-18-41.

1.6 ROTOR WINDING INSULATION SYSTEM COMPONENTS

Electrical insulation is present on the salient pole and round rotor types of synchronous motors and generators, as well as wound rotor induction motors and generators (the latter being widely used in wind turbines). Synchronous machine rotor windings have turn-to-turn insulation and slot (ground) insulation. The rotor windings in synchronous motors and generators are subject to relatively low DC voltage, unlike the high AC voltage on the stator. Even in very large turbogenerators, the rotor voltage is usually less than 600 Vdc. This low voltage implies that the turn and ground insulation can be relatively thin. As the voltage is DC, there is no need for strand insulation,[¶] because the skin effect is not present under DC voltage. If the DC is provided by static excitation systems, that is, DC created from thyristor operation, some high spike-type voltages may be superimposed on the DC. This is an additional stress that can cause PD [40]. In addition to the steady state DC voltage, voltage transients up to five times operating voltage will occasionally be imposed on the rotor winding when power system events occur such as phase-to-ground faults, energizing a generator with the rotor at standstill, and so on [41].

The other stresses on the rotor insulation include temperature and centrifugal forces. As with the current through the stator winding, the DC current through the rotor winding copper conductors creates considerable I^2R losses, leading to copper heating. The adjacent turn and ground insulation must be able to withstand these high temperatures.

The primary mechanical force on the rotor is not due to magnetic field interaction (although these are present to some degree), but rather due to rotational forces. The centrifugal force is enormous and unidirectional (radially out). The weight of the

---

[¶] However, owing to a problem called copper dusting (Section 9.3), some manufacturers now apply strand insulation to prevent copper strands rubbing against adjacent copper strands.

copper conductors will tend to compress and/or distort any insulation. Thus, the rotor winding insulation must have very high compression strength and be supported to prevent distortion. An additional mechanical (or more properly, thermomechanical) stress occurs whenever the machine is turned on and off. When the rotor winding is excited, the current through the conductors causes the copper temperature to rise, and the copper will experience axial growth because of the coefficient of thermal expansion. This growth leads to differential movement of the winding components, and the copper or the insulation can be abraded. Therefore, the rotor insulation components should have good abrasion resistance. This is usually obtained using a slippery coating on the slot insulation.

In a synchronous machine rotor, the winding potential is floating with respect to the rotor body. That is, neither the positive nor the negative DC supply is electrically connected to the rotor body (assumed to be at ground potential). Thus, a single ground fault in the rotor winding usually does not cause extensive damage to the rotor. However, if a second ground fault occurs some distance from the first fault, a large closed loop will be formed in the rotor body through which the rotor DC can flow. This can lead to very high currents flowing in the rotor body, causing localized heating at the fault points and possible melting of the rotor itself. A second ground fault must therefore be avoided at all costs. Most synchronous machine rotors come equipped with a ground fault alarm to warn operators of the first ground fault, or even remove the machine from service if the first ground fault occurs. However, as a rotor winding can often (but not always) operate with a single ground fault, machine owners who are willing to take the risk of rotor damage can install a second rotor ground fault relay, which would only remove the machine from service if a second ground fault occurs [42].

Rotor turn insulation faults in synchronous machines are much less important than similar turn faults in the stator winding. As only DC is flowing in the rotor, there is no equivalent to the “transformer effect,” discussed in Section 1.4.2, which will induce a large current to flow around the shorted turn in a stator coil. The main impact of a rotor turn short is to reduce the magnetic field strength from the affected rotor pole. This creates an unsymmetrical magnetic field around the rotor periphery, which tends to increase rotor vibration. Vibration can also occur because of nonuniform heating of the rotor surface, as unfaulted turns in coils will have a higher total current and, consequently, a higher local temperature, than coils containing shorted turns. Thermal expansion of the rotor body will be different around the periphery, bowing the rotor and increasing vibration (Section 16.9). In addition, if too many shorted turns occur, then much more excitation current will be needed to create the magnetic field for the required output. Although shorted rotor turns in themselves may not be hazardous to the machine, if the number of shorts is increasing over time, and then it may be an indicator that there is a greater risk that a rotor ground fault may occur.

Wound induction motor rotors experience much the same thermal and mechanical environments as synchronous machine rotors. However, in motors, instead of a constant DC current, this type of rotor winding sees an initial 50/60 Hz in-rush current during motor starting, followed by a gradual reduction in current and current frequency as the motor comes up to speed. The critical time for the rotor winding then, both in terms of heating and in voltage, is during starting. The open-circuit-induced voltage is normally less than about 1000 V, so the insulation can be very thin. As for synchronous rotors, a single ground fault or multiple turn faults do not necessarily render the motor inoperable.

Wound rotor induction generators are widely used in wind turbines. The rotors in such machines are usually fed by an inverter, whose fundamental frequency is set to add to the changing rotor speed to create a stable stator winding output current of 50 or 60 Hz, for direct connection to the power grid (Figure 1.4). In over-speed conditions that are likely in wind turbine applications, power is also extracted from the rotor winding. These wound rotor generators are called *doubly fed induction generators (DFIGs)*. The inverter supply to the wound rotor is usually of the PWM voltage source type, and hence may result in large voltage impulses being applied to the rotor turn and groundwall insulation systems. As described in Section 8.10, PD caused by these voltage impulses can lead to turn and groundwall insulation failure [43].

The following describes some of the main characteristics of the general physical construction and unique insulation system requirements for each rotor type.

1.6.1 Salient Pole Rotor

Hydrogenerators and four or more pole synchronous motors usually have salient pole rotor windings. Each field pole is constructed separately and the rotor winding made by mounting the completed poles on the rotor rim or directly to an integral solid steel body (Figure 1.20). The poles are then electrically connected to the DC supply in such a way as to create alternating north and south poles around the rim. Each field pole consists of a laminated steel core or solid steel body, which looks rectangular when viewed from the rotor axis. Around the periphery of each pole are the copper windings. Figure 1.20 is a photo of a single field pole from a large motor. There are two basic types of salient pole designs.

The older type of field pole design, and still the design used on motors and generators rated at less than a few megawatts, is called the multilayer wire-wound type. In this design, magnet wire is wrapped around the pole (Figure 1.21). The magnet wire usually has a rectangular or square cross section, and many hundreds of turns

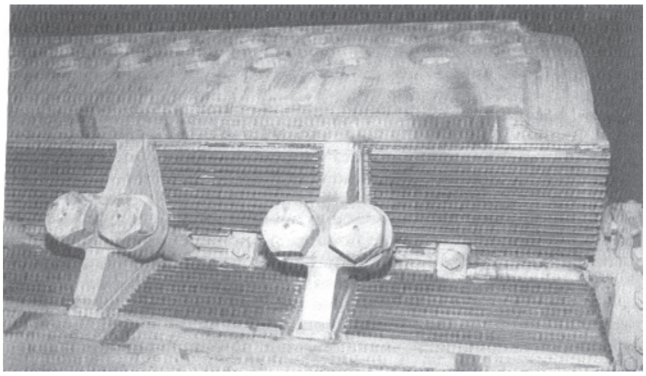


Figure 1.20 Photo of a pole on a salient pole rotor that has a “strip-on-edge” winding. The V block is between two adjacent poles.

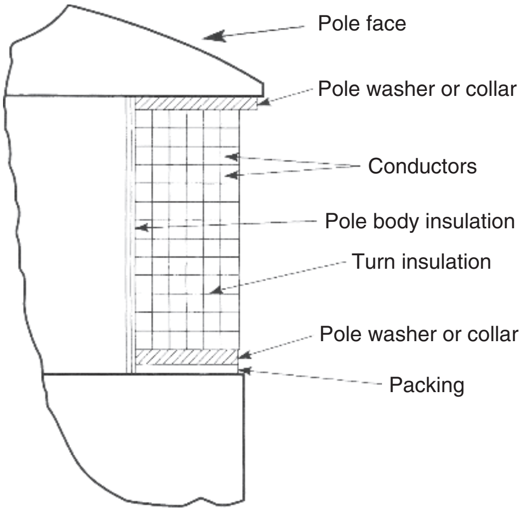


Figure 1.21 Cross section of a multilayer salient pole looking from the top of the pole.

are wound on the pole, several magnet wire layers deep. The turn insulation is the magnet wire insulation. Looking from the axial direction, the laminations are shaped to have a pole tip or pole face (which is the part of the rotor pole closest to the stator) to support the winding against the centrifugal force. Insulating washers and strips are placed between the magnet wire and the laminations to act as the ground insulation.

For larger machines, the “strip-on-edge” design is favored as it can be made to better withstand rotational forces. In this case, a thin copper strip is formed into a “picture frame” shape, so that the “frame” can slide over the pole. Laminated insulating separators act as turn insulation to insulate each copper “frame” from one another. On some copper “frames,” especially those near the pole face, an insulating tape may be applied to the copper to increase the creepage distance. The tape and separators form the turn insulation, and the copper “picture frames” are connected in series to make the coil. An alternative coil construction is to wind a long copper strip helically to form a multi-turn coil. As with the multilayer design, the winding is isolated from the grounded pole body by insulating washers and strips (Figure 1.22). Often, the entire pole may be dipped in an insulating liquid to bond the various components together. For solid pole rotors, the pole tips are usually bolted on (Figure 1.20).

1.6.2 Round Rotors

Round rotors, also called *cylindrical rotors*, are most often found in two- and four-pole turbogenerators as well as in two-pole synchronous motors. The rotor body is usually made from a single steel alloy forging. Axial slots are cut into the forging. The copper turns, made from copper strips up to a few centimeters wide, are placed in these slots. There are usually 5–20 strips (turns) in a slot forming a coil (Figure 1.23). Rather than directly insulating the copper turns with a tape or film insulation, the turns in large rotors are kept separated from each other by insulating strips. Insulating strips or L-shaped channels line the slot, to act as the ground

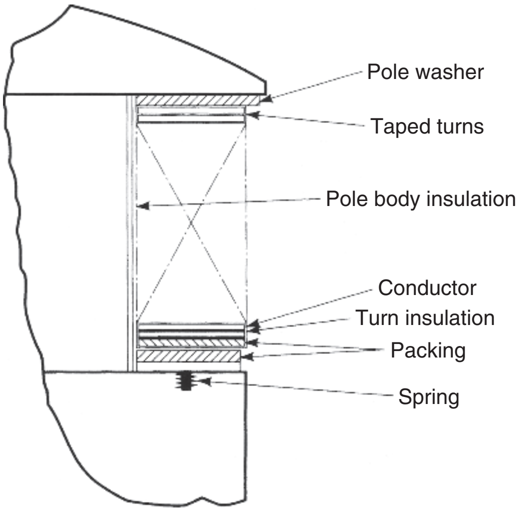


Figure 1.22 Cross section of a "strip-on-edge" salient pole.

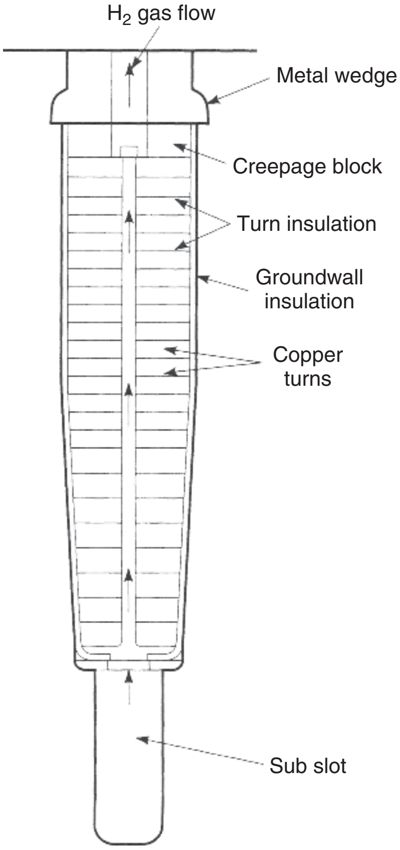


Figure 1.23 Cross section of a round rotor slot. The arrows show the direction of air or hydrogen cooling gas flow.

insulation. As the components are not bonded to one another, the components can slide relative to one another as the current, and thus the temperature, cycles. The copper coils are kept in the slot by means of wedges. As the rotational forces are so enormous (in over-speed conditions, the acceleration can reach in excess of 5000 G), only metal wedges can be used. The wedges are made from copper alloys (in older machines), nonmagnetic steel, magnetic steel, or aluminum alloy. Aluminum is the most common rotor wedge material today. As shown in Figure 1.23, air or hydrogen passages are often cut in the copper turns and wedges, to allow the gas to directly cool the rotor winding. As will be seen in Chapter 9, these passages, together with the use of insulating strips, allow short creepage paths to develop if pollution is present. In addition, these relatively small channels are easily blocked by foreign material or turn insulation migration, causing local hotspots in the rotor.

One of the most challenging design aspects of a round rotor is the end winding. After the copper turns exit from the slot, they go through a 90° bend and are directed around the rotor circumference until they reach the appropriate slot, at which point they go through another 90° bend. This rotor endwinding area must be supported to prevent the centrifugal forces from breaking off the copper conductors. Furthermore, space must be left and slip planes inserted to allow the rotor winding to expand axially as it heats up when current is circulated. In addition, blocking must be installed between coils in the endwinding to prevent distortion from thermal expansion forces. The copper can grow several millimeters along the slot in a large turbogenerator rotor that may be 6 m long.

The end winding is supported against rotational forces by retaining rings at each end of the rotor body (Figure 1.2). In most round rotors for machines larger than about 10 MW, the retaining rings are made from stainless steel. Considerable technology is used to make these rings and shrink them onto the rotor body. An insulating sleeve that allows the components to slip with respect to one another is needed between the copper endwindings and the retaining ring. In open-ventilated air-cooled machines, as well as older machines, the copper turns were often taped in the endwinding region with an insulating tape. However, it is now common to use insulating strips, sheets, and blocks.

1.6.3 Induction Machine Wound Rotors

In motors, these rotors see a 50- or 60-Hz current during motor starting, which gradually reduces to a near DC current once the rotor is up to rated speed. For induction generators especially in wind turbines, the rotor winding is fed by an inverter whose fundamental frequency is determined from the rotor speed, in order to generate 50- or 60-Hz electricity in the stator winding. The rotor consists of a laminated steel core with slots around the periphery. Usually, the slots are partially closed off at the rotor surface by the steel, so that the coils cannot easily be ejected into the air gap. Two basic types of rotor windings have been used.

Random rotor windings are made from magnet wire inserted in the slots (Figure 1.24). The turn insulation is the magnet wire insulation. Once the turns are inserted, an insulating wedge closes off the slot. An insulating slot liner serves as the ground insulation. It is very important to completely fill the slot to ensure

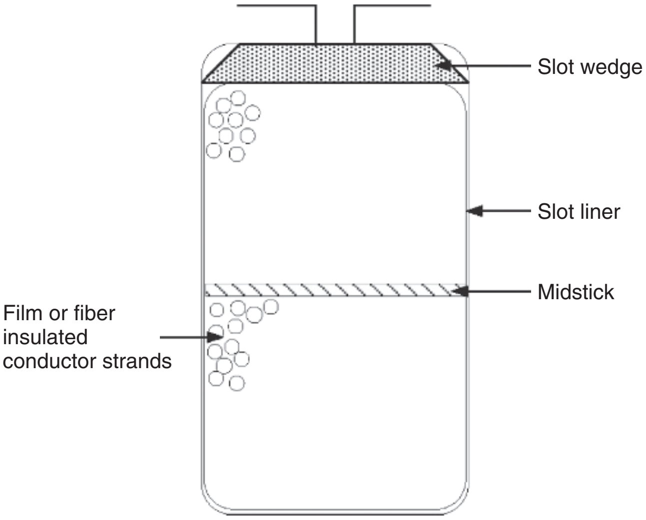


Figure 1.24 Cross section of a small wound-rotor slot.

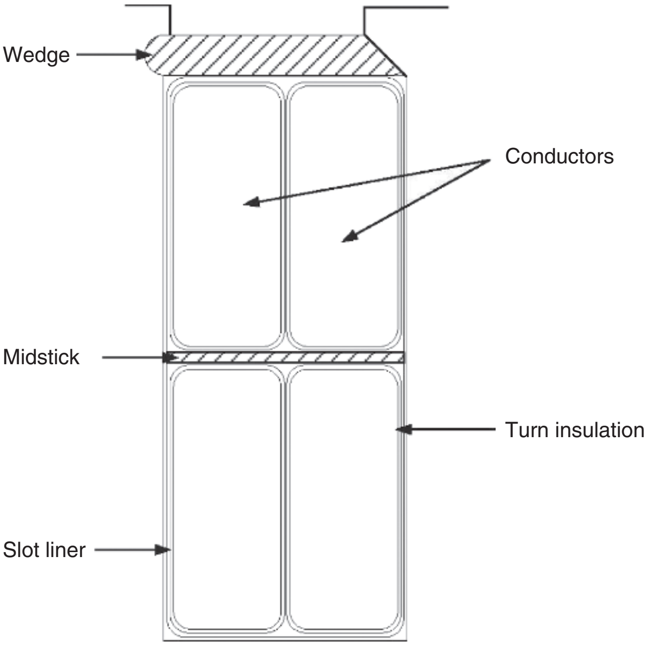


Figure 1.25 Cross section of a large wound rotor slot.

that the turns do not move relative to one another under the rotational forces. All space is filled with insulating strips and the entire rotor is impregnated with a liquid insulation that is cured, using a dipping, trickle impregnation, or GVPI process (Chapter 3). The interturn and ground voltages are low, so the insulation is thin. In the end windings outside of the slot, the end winding region is only several centimeters to 30 cm long, depending on the rotor size and speed, thus end winding movement can be restrained by impregnated cords tying together coils separated by impregnated felt pads. Insulating fiberglass bands are then applied over the end winding area to support it against centrifugal forces.

For larger rotors, copper bars are used for the winding conductors. These bars are rectangular in shape, with the long dimension oriented in the radial direction (Figure 1.25). Usually, either two or four bars are inserted in each slot by dropping through the top, or pushed through the slot from the end of the slot. Before insertion, the bars are preinsulated with a few layers of insulating tape. The ground insulation is a slot liner. As with random-wound rotors, an insulating band restrains the endwindings and the rotor is impregnated to prevent relative movement.

REFERENCES

1. S. J. Chapman, *Electric Machine Fundamentals,* 5th ed., McGraw-Hill, 2012.
2. M. G. Say, *Alternating Current Machines*, 4th ed., Pitman Publishing, 1976.
3. G. Klempner and I. Kerszenbaum, "*Handbook of Large Turbo-Generator Operation and Maintenance*", 2nd ed., Wiley-IEEE Press, 2008.
4. T. Kuwabara et al., "Design and Dynamic Response Characteristics of 400 MW Adjustable Speed Pumped Storage Unit for Ohkawachi Power Station", *IEEE Trans EC*, Vol. 11, 1996, 376–384.
5. M. V. R. Skov Jensen, "Wind Turbines: Electrical System Design, Operating Environment and Maintenance Issues", *Iris Rotating Machine Conference*, New Orleans, May 2009.
6. M. Melfi, S. Evon, and R. Mcelvan, "Induction vs. Permanent Magnet Motors", *IEEE Industrial Applications Magazine*, November 2009, pp 28–35.
7. IEC Standard 60034, "Rotating Electric Machines—Part 5, Classification of Degrees of Protection Provided by Enclosures: Part 6. Methods of Cooling".
8. NEMA Standard MG 1-1998, "Motors and Generators".
9. B. E. B. Gott, "Application of Air-Cooled Generators to Modern Power Plants", *IEEE Electric Machines and Drives Conference,* Seattle, May 1999, pp. 317–319.
10. A. P. Kopp et al., "Comparison of Maximum Rated Air-Cooled Turbogenerators with Modern Hydrogen Cooled Generators", CIGRE Paper 11-202, September 1992.
11. L. Dingzhong, "Selection of Cooling Mode for Giant Hydrogenerator", In *Proceedings of CIGRE Colloquium on New Developments of Rotating Electrical Machines*, Beijing, September 2011, pp 117–124.
12. P. Zhang, Y. Du, T. G. Habetler, and B. Lu, "A Survey of Condition Monitoring and Protection Methods for Medium Voltage Induction Motors", *IEEE T Ind Appl*, Vol. 47, 2011, 34–46.
13. B. J. Moore, R. H. Rehder, and R. E. Draper, "Utilizing Reduced Build Concepts in the Development of Insulation Systems for Large Motors", In *Proceedings of IEEE Electrical Insulation Conference,* Cincinnati, October 1999, pp. 347–352.
14. R. Engelmann and W. H. Middendorf, *Handbook of Electric Motors,* Marcel Dekker, 1995.
15. P. Clark, N. Glew, and R. Regan, "Solutions for MV Motors and Generators in Hazardous Locations", In *Proceedings of IEEE Petroleum and Chemical Industry Conference.* Philadelphia, September 1996, pp. 49–60.
16. B. K. Gupta et al., "Turn Insulation Capability of Large AC Motors, Part 3-Insulation Coordination", *IEEE Trans EC,* 1987, 674–679.

17. C. V. Maughan, “Incapability of Analog Relay Protection to Detect Generator Stator Winding Ground Failures at Neutral End”, *Proceedings IEEE Electrical Insulation Conference*, Ottawa, Canada, June 2013.
18. H. Katayama et al., “Development and Production of the World’s Largest Capacity 2p- 60Hz-670MVA and 4p-60Hz-370MVA Hydrogen-Cooled Turbogenerators for a 60Hz-900MW Cross-Compound Thermal Power Plant”, CIGRE Paper A1-102, Paris, September 2010.
19. F.T. Emery, M. Williams, “Preliminary Evaluation of Flat Glass Backed Mica Paper for HV Coil Groundwall Insulation using VPI”, In *Proceedings of IEEE Electrical Insulation Conference*, Annapolis, MD, June 2009.
20. J. F. Calvert, “Forces in Turbine Generator Stator Windings”, *Trans of AIEE,* 1931, 178–196.
21. IEEE Standard 100-2000: “IEEE Standard Dictionary of Electrical and Electronics Terms”.
22. E. Kuffel, J. Kuffel, and W. S. Zaengl, *High Voltage Engineering,* Butterworth-Heinemann, 1998.
23. R. Bartnikas, “Corona Measurement and Interpretation”, *ASTM, STP* 669, 1980.
24. J. H. Mason, “Breakdown of Solids in Divergent Fields”, *Proc IEE. Part B,* Vol. 102, 1955, 725–727.
25. F. T. Emery, “The Application of Conductive and Stress Grading Tapes to VPI’d High Voltage Stator Coils”, *IEEE Electrical Insulation Magazine,* July 1996, 15–22.
26. J. Thienpont and T. H. Sie, “Suppression of Surface Discharges in the Stator Windings of High Voltage Machines”, *CIGRE,* June 1964.
27. M. Stranges, G. C. Stone, and D. Bogh, “Voltage Endurance Testing of Stator Insulation Systems for Inverter Fed Machines”, *IEEE Industry Applications Magazine*, November 2009, 12–18.
28. E. Sharifi, S. Jayaram, and E. Cherney, “Analysis of Thermal Stresses in Medium Voltage Motor Coils Under Repetitive Fast and High Frequency Pulses”, *IEEE Trans DEI*, 2010, 1378–1384.
29. J. C. G. Wheeler, “Effects of Converter Pulses on the Electrical Insulation in Low and Medium Voltage Motors”. *IEEE Electrical Insulation Magazine*, March 2005, 22–28.
30. F. T. Emery, “Reduction Techniques of PD, Dissipation Factor and External Corona for HV Stator Windings”, *Proceedings of the IEEE Electrical Insulation Conference*, Montreal, June 2009, pp. 315–327.
31. C. Hu, X. Yuan, X. He, and X. Zhang, “Study on the Effect of Different Internal Corona Protection and Electrical Properties of Generator Stator Bars”, *Proceedings of the IEEE International Conference on Properties and Applications of Dielectric Materials*, Harbin, July 2009, pp. 196–199.
32. H. O. Ponce, B. Gott, and G. C. Stone, “Generator Endwinding Vibration Guide”, EPRI Report PID 1021774, 2011.
33. D. S. Hyndman et al., “Twintone Bar/Slot Interface to Maximize the Benefits of Modern High Voltage Stator Ground Insulation”, *Proceedings of IEEE Electrical Insulation Conference,* Chicago, October 1981.
34. K. Nyland and R. Schuler, “Insulation Systems for Synchronous Machines”, *Proceedings of International Conference on Synchronous Machines*, Zurich, August 1991, pp. 182–188.
35. N. Didzun and F. Stobbe, “Indirect Cooled Generator Stator Windings with Micalastic Post Impregnation Technique”, presented at ISOTEC Workshop 93, Section 4, Zurich, November 23–24, 1993.
36. R. Curiac, “Improvements in Energy Efficiency of Induction Motors by the Use of Magnetic Wedges”, *Proceedings of IEEE Petrochemical Industry Conference*, September 2011.
37. M. R. Patel and J. M. Butler, “Endwinding Vibrations in Large Synchronous Generators”, *IEEE Trans PAS,* Vol. 102, 1983, 1371–1377.
38. B. E. Gott, “Electromagnetic Forces in Stator Windings”, EPRI Turbine Generator Users Group Meeting, Albany NY, August 2011.
39. J. M. Butler and H. J. Lehman, “Performance of New Stator Winding Support System for Large Generators”, *Proceedings of American Power Conference,* 1984, p. 461.
40. S. Nagano et al., “Evaluation of Field Insulation of Turbine Generators with Higher Thyristor Excitation”, *IEEE Trans EC,* Vol. 1, 1986, pp. 115–121.
41. R. Ilie and G. C. Stone, “Turbine Generator Rotor and Stator Winding Hipot Testing”, *IEEE Electrical Insulation Magazine*, Vol. 28, 2012, pp. 29–37.
42. J. M. Hodge et al., “Generator Monitoring Systems in the United Kingdom”, CIGRE Paper 11-08, September 1982.
43. K. Alewine and W. Chen, “A Review of Electrical Winding Failures in Wind Turbine Generators”, *IEEE Electrical Insulation Magazine*, July 2012, pp. 8–13.