ELECTRICAL INSULATION FOR ROTATING MACHINES

Design, Evaluation, Aging, Testing, and Repair

GREG C. STONE
EDWARD A. BOULTER
IAN CULBERT
HUSSEIN DHIRANI

IEEE Press Series on Power Engineering
Mohamed E. El-Hawary, *Series Editor*

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PREFACE

This book arose out of the conviction that both designers and users of large motors and generators would appreciate a single reference work about the electrical insulation systems used in rotating machines. We also wanted to document how and why the insulation systems in current use came to be. Since rotating machine insulation is not the most glamorous field of study in the engineering world, it is sometimes treated as an afterthought. The result has been a gradual loss of knowledge as innovators in the field have retired, with few new people specializing in it. We hope that the archiving of the information in this book will slow this gradual loss of knowledge and be a useful starting point for future innovations.

This book is unique in that two of the authors (Alan Boulter and Ian Culbert) have a machine design background, whereas the other two have experience as primarily users of machines. With luck, both users and manufacturers of machines can find their interests represented here.

Collectively, three of us (Greg Stone, Ian Culbert, and Hussein Dhirani) want to thank Ontario Hydro (now Ontario Power Generation) for enabling us to become specialists in this field. It seems that the current business climate enables few engineers to become as specialized as we were allowed to be. We would also like to thank John Lyles, Joe Kapler, and Mo Kurtz, all former employees of Ontario Hydro, who taught us much of what we know. EPRI, and Jan Stein in particular, are acknowledged for allowing the three of us to have a "dry run" at this book when they sponsored the writing of a handbook in the 1980s.

We thank Resi Lloyd, who worked valiantly to put a consistent style on the various chapters, created many of the figures, and brought the book together.

Hussein Dhirani thanks his family for allowing him to sneak away to the office on some weekends to work on the book on the dubious pretext of better productivity. Hussein is grateful for the generosity of the many who shared their knowledge, from tradesmen working on generators, to designers poring over drawings, to staff in sister utilities discussing common problems, to supplier organizations explaining the intricacies of their insulation systems design. The understanding and support of Derek Sawyer and Bill Wallace at Ontario Power Generation is particularly appreciated.

Ian Culbert thanks Ontario Power Generation for allowing him to participate in a number of internal and EPRI projects from which he gained much of the information he contributed to this book. He also appreciates the opportunities his former employers Reliance Electric and Parsons Peebles gave him to learn how to design, test, and troubleshoot motors.

Finally, Greg Stone wants to thank his original partners at Iris Power Engineering—Blake Lloyd, Steve Campbell, and Resi Lloyd—for allowing his attention to wander from day-to-day business matters to something as esoteric as contributing to a book. Of course, Greg's wife, Judy Allan, is thanked because she never did question the premise that most folks use vacations for writing books and papers.

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Toronto, Ontario, Canada
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CHAPTER 1

ROTATING MACHINE INSULATION SYSTEMS

In the hundred years since 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 machines 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: (1) motors, which convert electrical energy into mechanical energy (usually rotating torque) and (2) 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 [1.1, 1.2, 1.3].

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

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AC motor with an electronic “inverter-fed drive” (IFD), DC motors in the 100’s of kW 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.

This book concentrates on AC induction and synchronous motors, as well as synchronous generators. Other types of machines exist, but 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 most types of machines. A discussion of each type of AC motor follows.

Squirrel Cage Induction (SCI) Motor (Figure 1.1). The rotor produces a magnetic field by transformer-like AC induction from the stator (armature) winding. This is by far the most common type of AC motor made, with millions manufactured every year. SCI motors can range in size from a fraction of a horsepower motor (< 1 kW) to tens of thousands of horsepower (greater than 30 MW). The predominance of the squirrel cage induction motor is attributed to the simplicity and ruggedness of the rotor. 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 [1.1, 1.2]. The SCI motor is used for almost every conceivable application, including fluid pumping, fans, conveyor systems, grinding, mixing, 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 due to the extra maintenance required for the slip rings. IFD SCI motors 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 and one south pole) times the AC frequency. There are two main ways of obtaining a DC current in the rotor. The oldest method, still popular, is to feed current onto the rotor by means of two slip rings (one positive, one negative). Alternatively, the “brushless” method uses a DC winding mounted on the stator to induce a current in an auxiliary three-phase 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

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

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 (greater than 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 a SCI motor, and the speed is more constant. Also, the operating energy costs are lower since, by adjusting the rotor DC current, one can improve the power factor of the motor, reducing the need for reactive power and thus the AC supply current. Refer to the section on synchronous generators below for further subdivision of the types of synchronous motor rotors. Two-pole synchronous motors use round rotors, as described in Section 1.1.2.

Permanent Magnet Motors. These motors have rotors made of a special permanently magnetized material. That is, no DC or AC current flows in the rotor, and there is no rotor winding. In the past, such motors were always rated at < 50 HP, since they can be hard to shut down. However, some large permanent magnet motors have been recently used in marine applications, due to their simplicity.

1.1.2 Synchronous Generators

Although induction generators do exist, 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, a 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 (Figure 1.2). Also known as cylindrical rotor machines, round rotors 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 rpm 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. 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 ro-

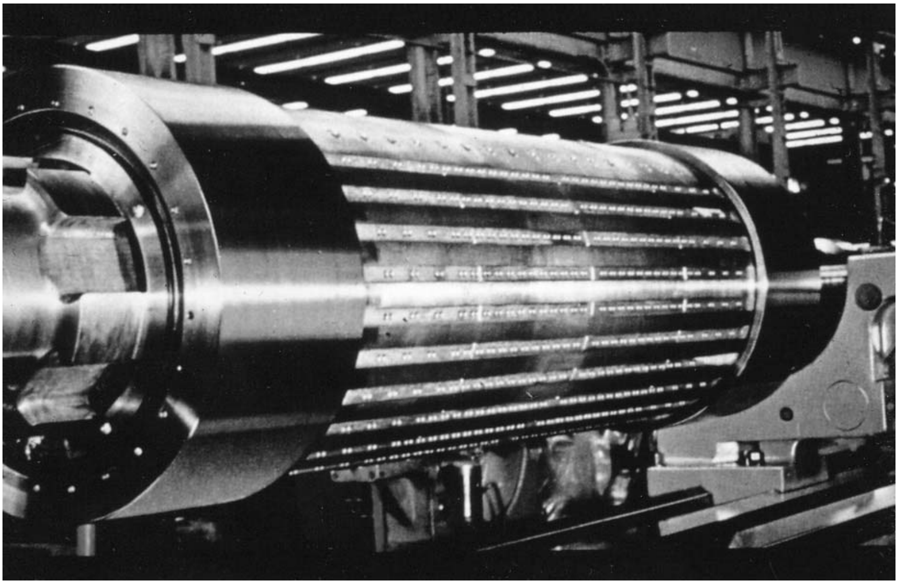

Figure 1.2. Phototgraph of a small round rotor. The retaining rings are at each end of the rotor body.

tors have been made in excess of 1500 MW. (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 generators almost always have a horizontally mounted rotor and are hydrogen-cooled (see Section 1.1.3).

Salient Pole Generators (Figure 1.3). Salient pole rotors usually have individual magnetic field poles that are mounted on a rim, with the rim in turn fastened to the rotor shaft by a "spider"—a set of spokes. Since 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, since the rotational speed is usually significantly less than 1000 rpm, the loss is considered moderate. Salient pole machines typically are used with hydraulic turbines, which have a relatively low rpm (the higher the penstock, i.e., the larger the fall of the water, the faster the speed). 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 requires a large rotor diameter in order to mount all the poles. Hydrogenerators have been made up to about 800 MW. The rotor in a large hydrogenerator is almost always vertically mounted, and may be more than 10 m in diameter.

Pump/Storage 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 ma-

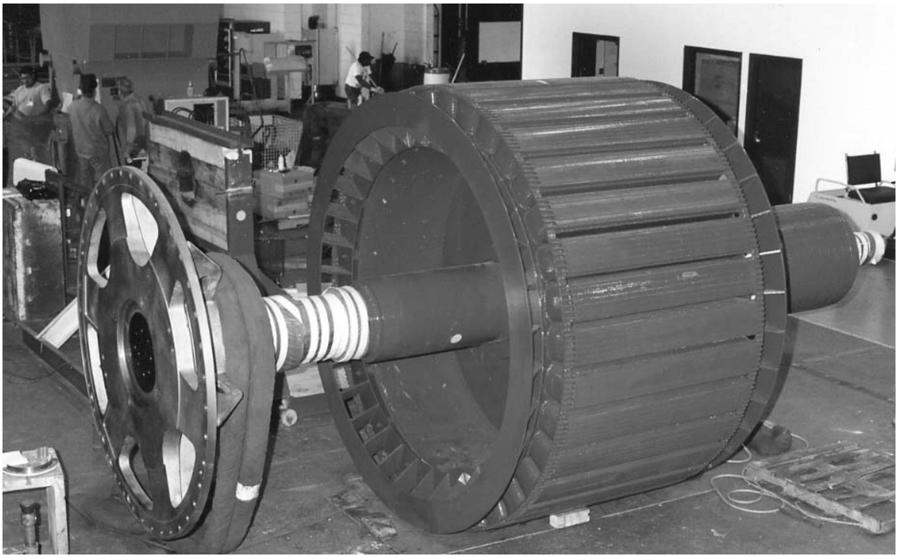

Figure 1.3. Photograph of a salient pole rotor for a large, low-speed motor. (Courtesy TECO-Westinghouse.)

chine 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 by using a SCI-type winding on the rotor (referred to as an amortisseur or damper winding), resulting in a large inrush current, or by using a "pony" motor. If the former is used, the machine is often energized by an inverter-fed drive (IFD) that gradually increases the rotor speed by slowly increasing the AC frequency to the stator. Since the speed is typically less than a few hundred rpm, the rotor is of the salient pole type. Pump storage units have been made up to 500 MW.

1.1.3 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, since 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 and the machine fails due to a short circuit.

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 since the winding conductors are not directly in contact with the cooling air due to 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, 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 or WP.

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 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. IEC and NEMA standards describe the various types of cooling methods in detail [1.4, 1.5].

Although old, small generators may be open-ventilated, the vast majority of hydrogenerators and turbogenerators (rated less than about 50 MVA) have recirculated air flowing through the machine. Virtually all hydrogenerators use recirculated air, 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.

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 better heat transfer than air. It is then cost effective to use hydrogen in spite of the extra expense involved, due to the few percent gain in efficiency. The dividing line for when to use hydrogen cooling is constantly changing. In the 1990s, there was 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 [1.6, 1.7].

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 direct-cooled windings, water or hydrogen is passed internally through the conductors or through ducts immediately adjacent to the conductors. Direct water-cooled stator windings pass very pure water through hollow copper conductors strands, or through stainless steel tubes immediately adjacent to the copper conductors. Since 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 and 8.13.

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 PURPOSE OF WINDINGS

The stator winding and rotor winding consist of several components, each with their own function. Furthermore, different types of machines have different components. Stator and rotor windings are discussed separately below.

1.2.1 Stator Winding

The three main components in a stator are the copper conductors (although aluminum is sometimes 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 1.4 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 since 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 par-

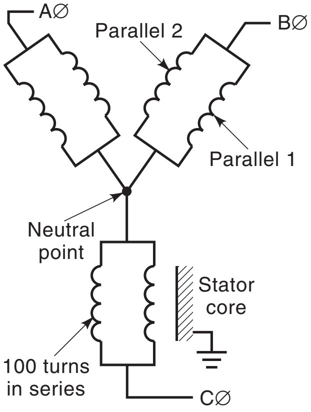

Figure 1.4. Schematic diagram for a three-phase, Y-connected stator or winding, with two parallel circuits per phase.

ticular machine is beyond the scope of this book. The reader is referred to any book on motors and generators, for example references 1.1 to 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 help to produce a magnetic field or guide its path. Generator and motor designers would like nothing better than to eliminate the electrical insulation, since the insulation increases machine size and cost, and reduces efficiency, without helping to create any torque or current [1.8]. 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 1.3 will describe 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 Hz) in induction machines. This lower frequency makes the need for a laminated stator 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 turbogenerator and high-speed salient pole machines are usually made from forged magnetic steel, since 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. (Smaller SCI rotors may have the aluminum conductors 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 only flows in the conductors, electrical insulation is not needed to force the current to flow in the right paths. Reference 1.9 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 [1.10]. Since such applications are rare, for the purposes of this book, we assume that the rotor is not insulated.

Although SCI rotor windings are generally not insulated, for completeness, Section 9.4 does discuss such rotors, and Chapters 12 and 13 present some common tests 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 more than 1000 MW:

1. Random-wound stators
2. Form-wound stators using multiturn coils
3. Form-wound stators using Roebel bars

In general, random-wound stators are typically used for machines less than several hundred kW. Form-wound coil windings are used in most large motors and many generators rated up to 50 to 100 MVA. Roebel bar windings are used for large generators. Although each type of construction is described below, some machine manufacturers have made hybrids that do not fit easily into any of the above 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 1.5). Figure 1.5 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.” Since a turn that is connected to the phase terminal can be adjacent to a turn that is operating at low voltage (i.e., at the neutral point), random-wound stators usually operate at voltages less than 1000 V. This effectively limits random-wound stators to machines less than several hundred kW or HP.

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 prior to insertion in the slots in the stator core (Figure 1.6). The preformed coil consists of a continuous loop of magnet wire shaped into a coil (sometimes referred to as a diamond shape), with additional insulation ap-

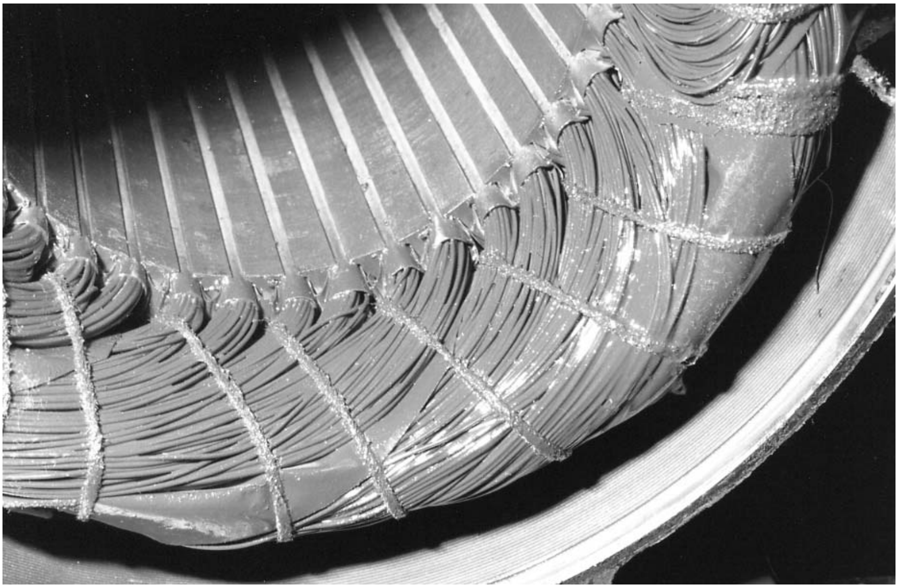

Figure 1.5. Photograph of the end-winding and slots of a random-wound stator. (Courtesy TECO-Westinghouse.)