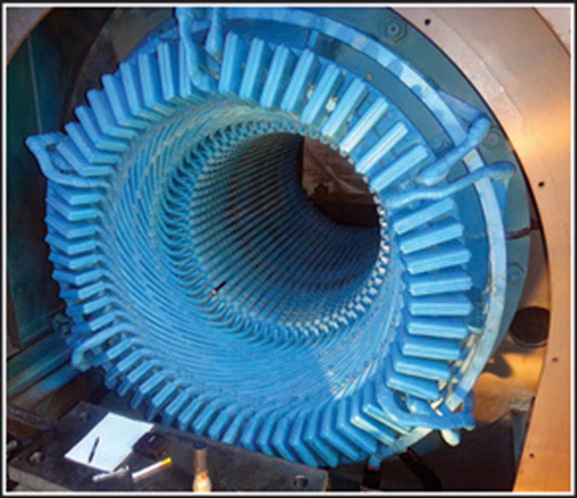
Electrical Insulation for Rotating Machines

Design, Evaluation, Aging, Testing, and Repair

SECOND EDITION



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CONTENTS

CHAPTER 6 *ROTOR AND STATOR LAMINATED CORES* 143

CHAPTER 7 *GENERAL PRINCIPLES OF WINDING FAILURE, REPAIR AND REWINDING* 159

CHAPTER 8 *STATOR FAILURE MECHANISMS AND REPAIR* 171

CHAPTER 20 *MAINTENANCE STRATEGIES* 509

PREFACE

This edition was updated by two of us, Greg Stone and Ian Culbert. Given the developments in rotating machine insulation in the past decade, readers will see expanded information on the effect of drives on insulation, the addition of a number of relatively new failure mechanisms, and new diagnostic tests. Many more photos of deteriorated insulation systems have been added in this edition. Many more references have been added, and recent changes in IEEE and IEC standards have been incorporated. We have also added descriptions of the insulation systems used by Chinese and Indian machine manufacturers. The information on Chinese systems came from Mr. Yamin Bai of North China EPRI. Mr. Bai and his colleagues were also responsible for the Chinese version of the first edition of this book. New appendices were added, which give detailed information on the insulation systems used by many manufacturers, as well as insulation material properties. These tables first appeared in a US Electric Power Research Institute (EPRI) document that is long out of print. However, given the number of machines still using these systems and materials, we thought it will be useful to include the information here.

We again would like to thank our spouses, Judy and Anne, and also our employer, Iris Power L.P. We are also grateful to Ms. Resi Zarb for help in organizing and editing the second edition. Finally, we thank the readers of the first edition who took time to point out errors and omissions in the first edition.

Greg Stone and Ian Culbert

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.

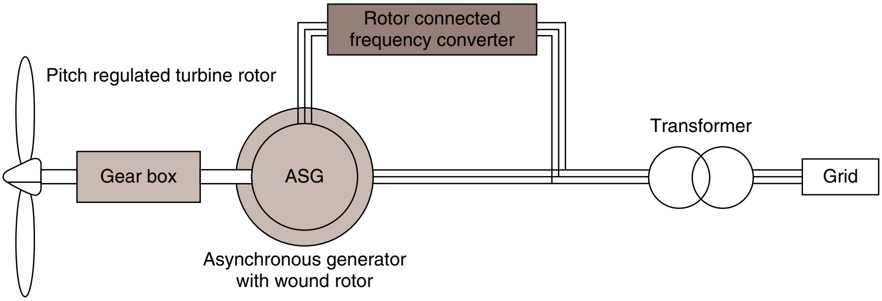

Figure 1.4 Wound rotor induction generator doubly fed configuration [5].

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).