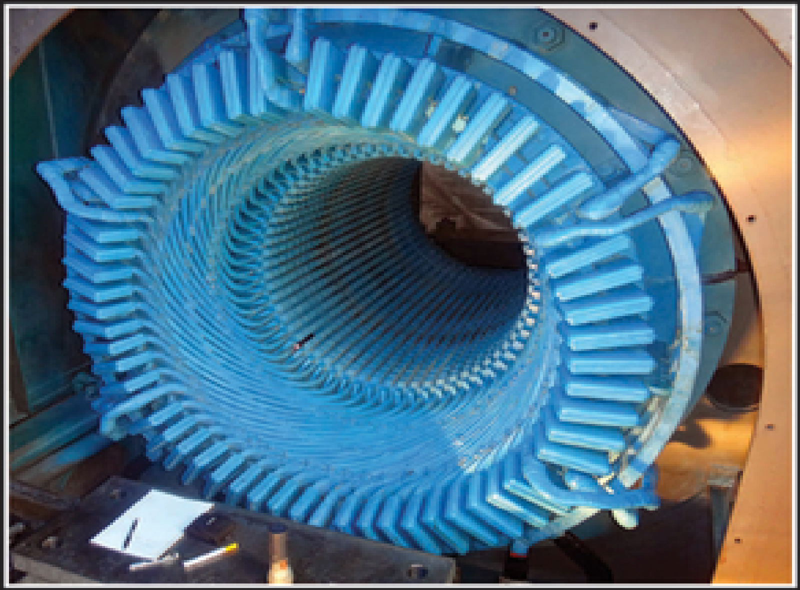
Electrical Insulation for Rotating Machines

Design, Evaluation, Aging, Testing, and Repair

SECOND EDITION



Greg C. Stone, Ian Culbert,
Edward A. Boulter, Hussein Dhirani

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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.

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.

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

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 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).

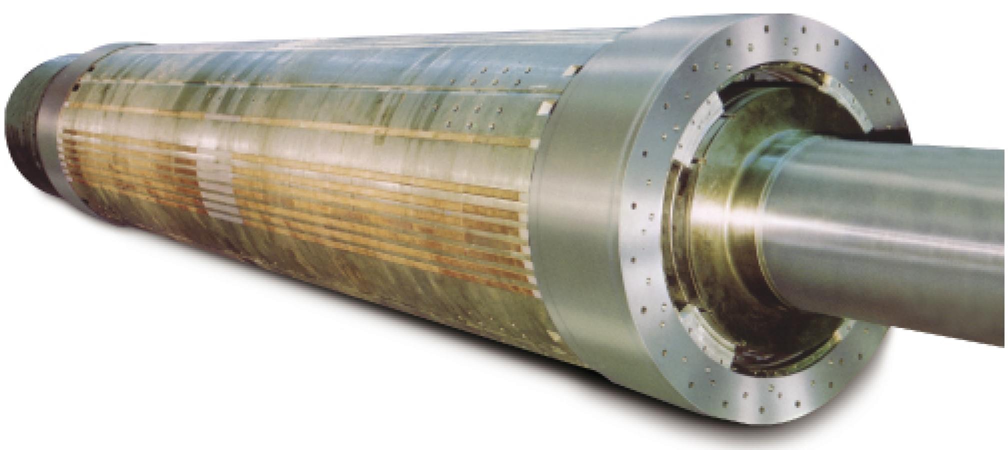

Figure 1.2 Photograph of a round rotor. The retaining rings are at each end of the rotor body.

Salient Pole Generators