ELECTRIC POWER
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# Wind Energy Asynchronous Generator Maintenance Guidelines

2012 TECHNICAL REPORT

# Wind Energy Asynchronous Generator Maintenance Guidelines

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# Product Description

## Background

With the rush to develop today's massive wind energy sites, little attention is being given to the inevitable need to perform routine maintenance and develop practical means of assessing the condition of the components within the nacelles and other outside support equipment for the wind farms. Current operating models have not adequately established accurate assumptions or expectations on the unavailability of the wind turbines and the impact on lost generation. Contracts for purchase of their generation output are being affected by these losses, causing increased concern about overall reliability. The current business model is not adequately focused on equipment health and reliability as is seen in more conventional power generation facilities. However, that is about to change.

There is a developing concern among wind farm owners that generation revenues are being lost at much higher rates than expected because of unavailable machines. Machines that are off-line for long periods due to equipment degradation and failures do not generate revenues to pay back the investments. Even though they might have equipment warranties or maintenance agreements, there are no warranties or liquidated damages for lost generation sales when a wind energy asynchronous generator is off-line due to an unexpected outage.

## Objectives

The objective of this project is to collaborate with wind farm owners, operators, original equipment manufacturers, and vendors to develop tactical guidelines for reliably maintaining 1–2 MWe wind energy asynchronous generators.

## Approach

Researchers contacted wind generator repair vendors for maintenance and troubleshooting recommendations; reviewed existing Electric Power Research Institute (EPRI) technical reports; and searched manufacturer, vendor, and industry databases to provide the most up-to-date information available

## Results

This report describes four wind turbine generator types that are generally encountered and summarizes the most common machines in use. It also reviews the major components used to implement the generator configurations and identifies both electrical and mechanical issues that affect component reliability. The report summarizes operation and maintenance practices, with minimal theoretical content.

## Applications, Value, and Use

These guidelines can be used for in-house development of maintenance crews, to provide training for contract maintenance crews, and to provide a consistent maintenance program for components and parts on typical asynchronous generators typically found in on-shore applications.

## Keywords

Asynchronous
Generator
Maintenance
Wind turbine

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# Section 1: Overview

Four generator configurations are generally encountered on 1–2 MWe wind turbine sets with asynchronous generators: fixed-speed, variable-slip, variable-speed, and full-converter configurations. These four configurations use two basic generator designs: the squirrel-cage induction machine and the wound-rotor induction machine. Figure 1-1 shows the basic outlines of the two designs.

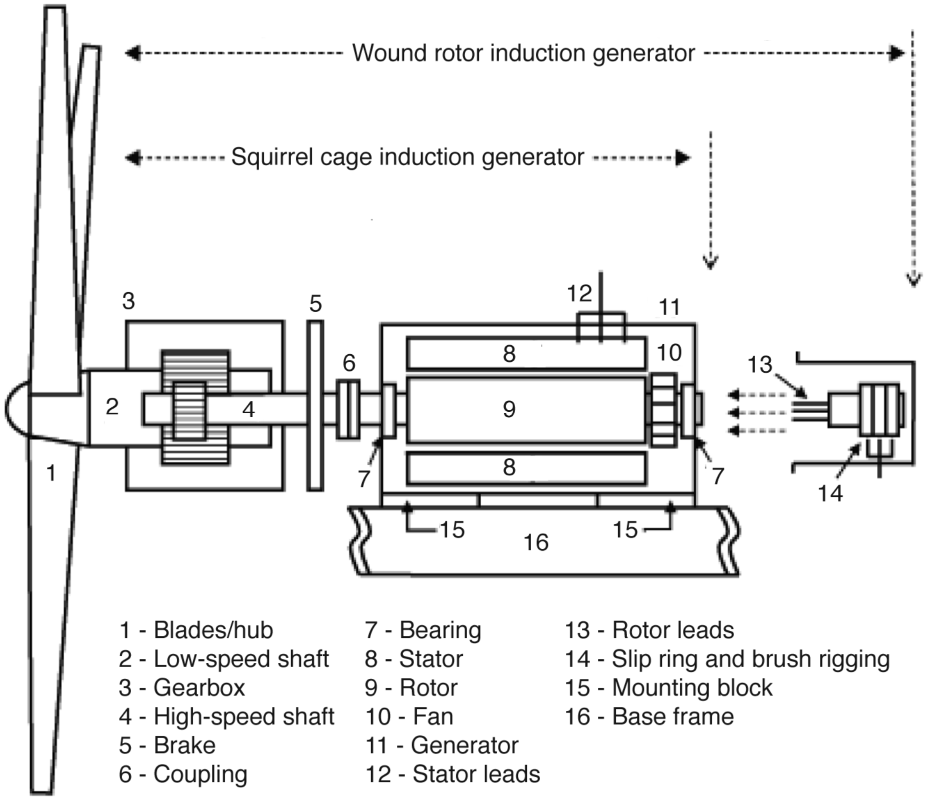

*Figure 1-1*
*Wound-rotor and squirrel-cage induction generators*

The major difference between the two designs is that the wound-rotor design includes windings on both the stator and the rotor and it has a slip ring and brush assembly that permits the rotor to be connected to external electrical equipment. Fixed-speed configurations use a self-excited induction machine design commonly referred to as a *squirrel-cage induction machine*. The generator stator is electrically connected to the main electrical network, and the rotor is mechanically driven beyond the synchronous speed of the network. The machine is designed to operate within a range of about 1% of the synchronous speed of the network.

Variable-slip configurations use a wound-rotor induction machine design. The generator stator is electrically connected to the main electrical network. The generator rotor consists of windings connected through slip rings to an external resistance circuit that is designed to adjust the effective rotor winding resistance. This feature allows the machine to function with a broader slip range than the fixed-speed application.

Variable-speed configurations use a doubly fed induction machine design. These machines use a power converter to provide control for active and reactive power within a specified range of the machine capability. The generator stator is electrically connected to the main electrical network, and the generator rotor is electrically connected to the power converter, and the power converter is connected to the main electrical network. The machine typically has a slip range of ±30% of the synchronous speed of the network.

Full-converter configurations are similar to the variable-speed configuration, in that a power converter is used. In the case of the full-converter design, the power converter is sized to handle the machine's full power rating. The generator stator is electrically connected to the power converter, rather than the main electrical network. The power converter is connected to the main electrical network. This configuration isolates or decouples the generator from the network, while allowing the generator to provide active and reactive power to the network as determined by the wind turbine and power converter controls.

## 1.1 Fixed-Speed Configuration

The fixed-speed configuration is based on a self-excited induction machine. The machine is commonly referred to as a *squirrel-cage induction machine*. For the squirrel-cage induction machine, the rotor resistance is fixed for a given machine and, therefore, results in a single torque-speed curve for the machine. The two primary components of the machine are a stationary frame assembly and a rotating shaft assembly (see Figure 1-2).

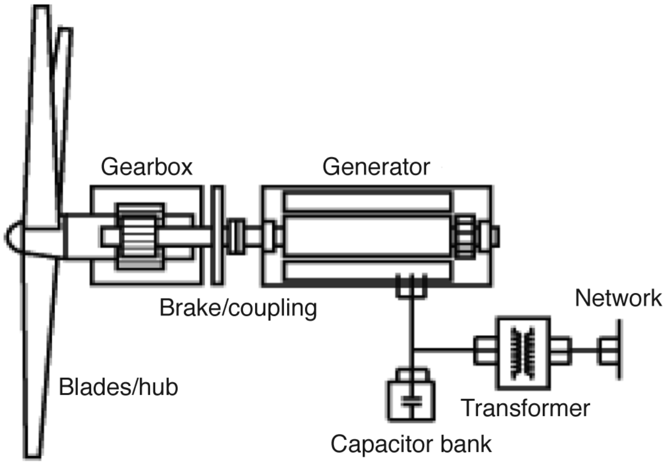

*Figure 1-2*
*Squirrel-cage induction generator*

When the stator is energized by the electrical network, three-phase currents are established in the stator windings. The stator current establishes a magnetic field. For three-phase systems, the phases of the stator windings are physically positioned 120° around the stator core. The sinusoidal phase voltages and currents established in each phase winding of the stator are also electrically displaced 120° from each other. The magnetic flux developed by the stator phase currents effectively result in a flux that moves around the stator at a constant frequency. This resulting frequency is the same as the frequency of the network to which the stator is connected. The synchronous speed of a machine is equal to the frequency of the network, measured in revolutions per minute (rpm), divided by the number of electromagnetic pole pairs of the machine. As seen from a reference point at the physical center of the stator, the stator magnetic field travels around the inside circumference of the stator at the frequency of the network and the synchronous speed of the machine.

As the stator rotating magnetic field moves across the closed circuit formed by the rotor conductors and shorting rings, an electromotive force is induced in the closed circuit, creating a current in the rotor conductors. The presence of a current in a magnetic field produces a force on the conductor. Because the lines of induction are perpendicular to the rotor iron, the force is tangential to the rotor. Given that the conductor forms a coil on the rotor, a force couple is produced that tends to rotate the shaft about the rotor axis and results in a torque that is equal to the force times the radius of the rotor. The torque can then be used to find the electromagnetic power of the machine. In the case of an electric motor, the rotor provides electromagnetic power to the shaft that can be used to supply a mechanical load. In the case of a generator, by way of the wind turbine, the shaft provides mechanical power to the rotor that is then converted to electromagnetic power.

The shaft rotation results in a sinusoidal frequency in the rotor circuit. This rotor frequency is proportional to the difference between the stator synchronous speed and the rotor speed. The difference is normally expressed as a percentage of the synchronous speed. This percentage of synchronous speed difference is referred to as *slip* and is a basic variable of the induction machine. When rotor speed is less than synchronous speed, slip is positive, energy is being taken from the network, and the induction machine is performing as a motor. When rotor speed is greater than synchronous speed, slip is negative, energy is being provided to the network, and the induction machine is performing as a generator.

Two characteristics of an induction machine are noteworthy. First, if slip is zero, the rotor speed equals synchronous speed, and the relative speed between two rotating magnetic fields is zero. Therefore, the rotor cuts no lines of induction, and there is no electromotive force induced in the rotor conductors, no current in the conductors, and no torque applied to the rotor. Second, the rotating magnetic fields of the rotor and the stator are stationary with respect to each other but shifted in space from each other at any rotor speed. This is a necessary condition for the existence of a uniform torque in a polyphase induction machine.

The squirrel-cage induction machine has a narrow range of slip, typically 1%, for which torque-speed curve is fairly linear. The wind turbine and generator controls are designed around this linear range of the machine's torque-speed curve.

Due to the reactive power demand that a self-excited induction machine places on the network, capacitor banks are used to provide the exciting current required during startup. The capacitor bank also provides support for power factor correction and voltage regulation at the point of interconnection with the network.

### 1.2 Variable-Slip Configuration

The variable-slip configuration is designed around a wound-rotor induction machine (see Figure 1-3).

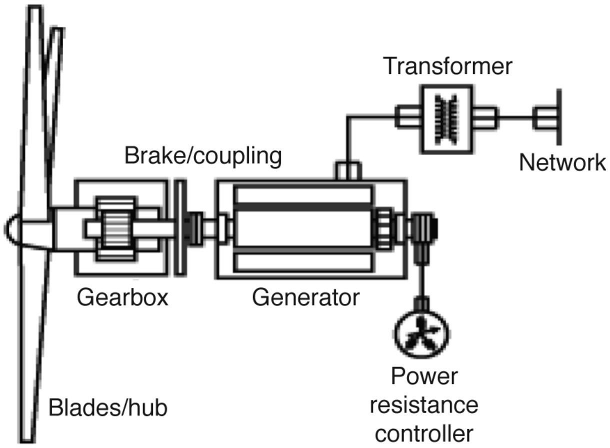

*Figure 1-3*
*Wound-rotor induction generator*

A wound-rotor induction machine is similar to the squirrel-cage induction machine, with the exception that the design provides the ability to adjust the rotor resistance. Because slip for a given torque is proportional to rotor resistance, an adjustment in rotor resistance establishes a different torque-speed curve. The capability to provide a family of torque-speed curves broadens the control characteristics for changing wind speed. These machines typically have a broader slip range than the squirrel-cage induction machine. At low to medium wind speeds, the two machines operate very similarly. That is, power versus slip is fairly linear. At a specified design point, the resistance is adjusted so that the desired power output is achieved for the change in wind speed. A disadvantage of this design is that rotor resistance increases with increasing slip and, therefore, heat loss increases with increasing slip.

## 1.3 Variable-Speed Configuration

The variable-speed configuration is similar to the variable-slip configuration, in that a wound-rotor induction machine is used. The stator is connected to the main electrical network. However, for the variable-speed application, the rotor circuit is connected through a slip ring assembly to a power electronic converter that is also connected to the main electrical network. This arrangement is identified as a *doubly fed induction generator* (see Figure 1-4).

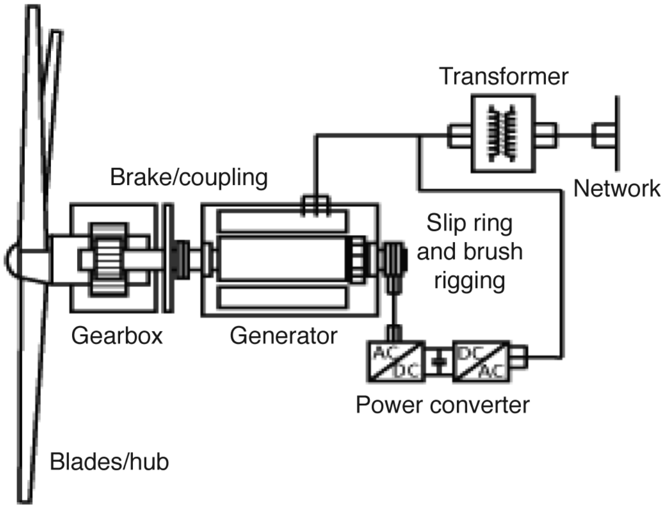

*Figure 1-4*
*Doubly fed induction generator*

The network-side voltage converter rectifies the sinusoid wave form into a dc voltage, and then the rotor-side voltage converter inverts the dc voltage back to a sinusoid wave at the rotor terminals. The voltage and power are regulated by the pulse-width modulation provided in each converter. Typically, the machine is designed to operate with a slip of 30%. This results in a power converter rating of 30% of the generator rating. By regulating the rotor current, the rotor torque-speed curve and the stator active and reactive power can be controlled. This capability allows the control of both the active and reactive power individually at a given operating point. The coupling of the ability to adjust the generator's torque-speed curve, active power, and reactive power with the ability to optimize the wind turbine power coefficient through adjustment of the turbine's blade pitch angle and the blade tip speed ratio creates the opportunity to capture the maximum electrical energy from the available wind energy. Achieving higher energy yields while reducing power fluctuations and improving reactive power supply has made the doubly fed induction generator a popular machine for wind turbine applications.

## 1.4 Full-Converter Configuration

The full-converter configuration is similar to the variable-speed application in that a power converter is used (see Figure 1-5).

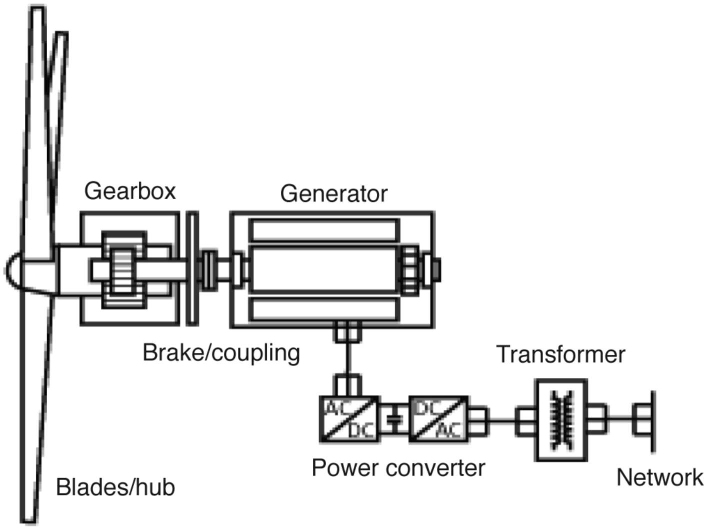

*Figure 1-5*
*Full-converter generator*

In the full-converter design, the power converter is sized to handle the machine's full power rating. The generator stator is electrically connected to the power converter, rather than the main electrical network. The power converter is connected to the main electrical network. Effectively, the generator is isolated or decoupled from the network due to the power converter. The power converter contains back-to-back voltage source converters with a dc link capacitor and pulse-width modulators to regulate the generator frequency, voltage, current, and the active and reactive power delivered to the network. This arrangement also provides the ability to supply reactive power for network voltage control during periods with no turbine rotation or during periods with no active power contribution.

The full-converter design can be used with either asynchronous or synchronous generators and with squirrel-cage induction, wound-rotor induction, or permanent magnetic generators. As wind turbine generator ratings have increased beyond 2 MWe, full-converter designs have become more common.

## 1.5 Wind Turbine Generator Market

An Internet review of the wind turbine generator market as of October 2011 yielded the results shown in Table 1–1.

*Table 1-1*
*Asynchronous wind generator manufacturers*

| Manufacturer | Application or Configuration Type (note 1) | | | |
|---|---|---|---|---|
| | Fixed Speed | Wound Rotor | Doubly Fed | Full Converter |
| ABB | | | Yes | |
| Bonus (note 2) | Yes | | | |
| DeWind | | | Yes | |
| Gamesa | | | Yes | |
| GE | | | Yes | |
| Nordex | | | Yes | |
| REpower (note 3) | | Yes | | |
| Siemens | Yes | | | |
| Suzlon | | Yes | | |
| UGE | Yes | | | |
| Vestas | | Yes | | |
| Winergy | | | Yes | |

Notes:

1. Asynchronous induction machines with nominal ratings ≤2.0 MWe.
2. For Bonus machines, see Siemens.
3. For REpower machines, see Suzlon.

# Section 2: Technical Description

For wind turbines with nominal ratings of around 1.0 MWe and 2.0 MWe, the generators are either of the squirrel-cage design (see Figure 2-1) or the wound-rotor design (see Figure 2-2), with the majority being the wound-rotor, doubly fed configuration. For sites in the United States, these generators are typically three-phase, 690-Vac, 60-Hz, four-pole machines with class F insulation and lap random-wound windings.

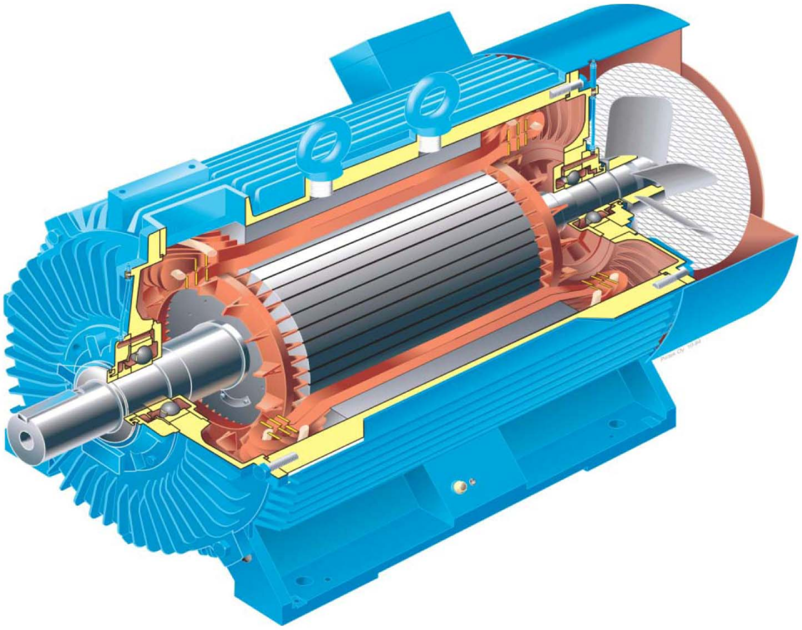

*Figure 2-1*
*Squirrel-cage induction machine*
*Courtesy of ABB*

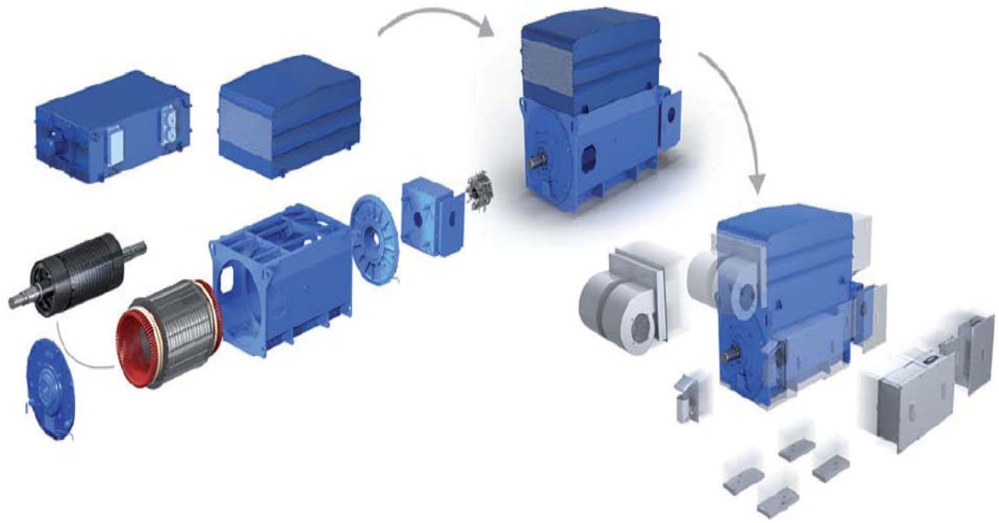

*Figure 2-2*
*Wound-rotor induction machine*
*Courtesy of ABB*

## 2.1 Stator Assembly for Squirrel-Cage and Wound-Rotor Machines

### *2.1.1 Stator Frame*

The stationary frame assembly consists of a housing support structure with end shields for the stator core. Depending on physical size, the frame is made of either reinforced cast iron or fabricated steel plate. The frame is manufactured with axial and radial ribs to provide guides to center the stator core assembly so that the center line of the stator core is coincident to the axial center line of the rotating shaft assembly. The frame bottom is designed to provide a bolting configuration for the torque and inertia requirements of the machine rating.

### *2.1.2 Bearing Housing*

The bearing support housings are positioned on the stator frame so that the bearing center lines place the rotor shaft at the center of the stator core assembly. The design of the housing and end plate structure provide the strength required to support the static and dynamic forces of the rotor. The arrangement also provides the capability for radial and axial alignment of the stator and rotor so that the magnetic centers of the stator and rotor magnetic fields are coincident. The housing is fabricated to accept the bearings, seals, and lubrication system required for the specific machine.

### 2.1.3 Bearings

Two bearings are mounted on the shaft, one on the drive end, closest to the wind turbine/main gear drive, typically referred to as the *drive-end bearing,* and one on the non-drive-end of the shaft, typically referred to as the *non-drive-end bearing*. The bearings are used to provide the support from the stator frame to the rotor while minimizing friction between the rotor and stator frame. Roller bearings and babbitted bearings cover the majority of bearing designs used with rotating machines. Wind turbine sets typically use roller bearings group, including single-row, deep-groove ball bearings; single-row, angular-contact ball bearings; cylindrical roller bearings; tapered roller bearings; spherical roller bearings; and single-direction thrust ball bearings. The bearing is selected based on its ability to handle radial loads, axial loads, combined loads, speed, and angular misalignment.

The bearings commonly used on generators for wind turbine sets are deep-groove ball bearings. The ball assembly includes a cage or retainer ring to position the balls between inner and outer bearing support rings. The internal clearance, radial and axial, between the bearing support rings is a major factor in determining fatigue life, vibration, noise, and operating temperature. The stray currents produced by magnetic fields in the generator and power electronic control equipment decrease bearing life, so either the bearing housing is provided with insulation to break the potential current path or insulated bearings are used to eliminate the potential paths for stray current.

### 2.1.4 Stator Core

The stator core is built of segments of laminated, punched electrical sheet steel coated with insulating film. The sheet steel laminations are punched to provide for clamping bolts and winding slots. The lamination segments are stacked, compressed, and assembled until the core size is achieved. The segments are arranged so that ventilation ducts are provided within the core assembly. Depending on the cooling arrangement, the radial ventilation ducts either lead to a perimeter cavity between the stator core and frame or they align with perimeter ducts running the length of the stator core. The core is placed in the stator frame, aligned, and locked in place with an assembly of nonmagnetic insulated clamping bolts, pressure plate, and nonmagnetic clamping fingers. After the core alignment is achieved, core keys are installed to maintain alignment. Except for one key, the core keys are insulated from the stator frame.

### 2.1.5 Stator Coils

Depending on size and operating voltage, the coils are either random-wound or form-wound coils. Typically, random-wound coils are provided for operating voltages less than 1000 V, and form-wound coils are provided for higher operating voltages. Form-wound coils are distinguished by their rectangular cross section. A varnish film is used to insulate magnetic wire for random-wound conductors, whereas an insulating tape system is used to insulate form-wound magnetic wire conductors.

## 2.2 Stator Insulation Configurations

Stator insulation is designed to meet the mechanical, thermal, and electrical rating and surge level requirements for the machine.

### *2.2.1 Stator Insulation (Random Wound, 690 V Operation)*

The stator insulation system consists of the magnetic wire insulation, slot insulation, coil end winding insulation, impregnating resin, end winding tape, wedges, and finishing varnish. The system is assembled to ensure slot fit, minimal voids in the slot volume and the impregnating resin, and an overall bonding of the insulation materials.

### *2.2.2 Stator Insulation (Form Wound, >1 KV Operation)*

The stator insulation consists of the coil conductor insulation, conductor stack consolidation insulation, ground wall insulation, vacuum pressure impregnation resin, corona protection tape, end winding tape, winding bracing, slot wedges, and finishing varnish. The system is assembled to ensure slot fit, end turn spacing, minimal voids in the overall slot volume and resin, and overall bonding of the insulation materials.

## 2.3 Stator Windings

The stator windings are arranged so that adjacent electromagnetic poles are of opposite polarity. The windings are physically arranged in the stator core so that each phase is mechanically separated by 120°. For 60-Hz, 1800-rpm machines, four electromagnetic poles or two pole pairs are constructed within the stator core.

## 2.4 Instrumentation

The instrumentation typically provided for generator protection consist of thermal sensors for the stator winding, bearing metal, and bearing lubrication; vibration sensors for the rotor; speed sensor for the rotor; ground detection relay; voltage protection relay; current protection relay; synchronizing relay; and motoring detection relay.

## 2.5 Cooling System

### *2.5.1 Internal Fan*

Depending on the air passage design, either axial or radial fans are mounted to the rotor. When the air passage design requires a large airflow at low pressure, axial fan designs are used. When the air passage design requires higher pressures, radial (centrifugal) fan designs are used.

The generator is typically a totally enclosed machine. The internal fan is used to recirculate air through the machine and air ducting. Air ducting routes the heated air to the intake of an externally mounted heat exchanger fan that blows the air through the heat exchanger and returns the cooled air to the machine.

### *2.5.2 External Fan and Heat Exchanger*

The heat exchanger can be either an air-to-air or an air-to-water design. The most common configuration is the air-to-air heat exchangers due to the limited resources available in the nacelle. In the air-to-air heat exchanger, the cooling air is pulled into the intake of fans from the nacelle space. The air is then discharged through exchanger tubes and air ducting so that the heated air is exhausted to the atmosphere.

## 2.6 Anchor Base Plate

Support for rotating equipment is provided through a base mounting structure designed for the necessary mass, strength, and rigidity to handle the static and dynamic loads and forces transmitted by the rotating machine, as well as any loads and forces transmitted to the structure from other sources. The structure is designed so that equipment alignment requires minimal vertical and horizontal adjustment.

The bolting arrangement is an integral component of the base mounting structure and provides the interface to achieve equipment positioning and mounting structure integrity.

## 2.7 Rotor Assembly for Squirrel-Cage Machine

### *2.7.1 Rotor Shaft*

A shaft is provided to accommodate an electromagnetic core, one or more cooling fans, and bearings.

### *2.7.2 Rotor Core*

The rotor core is assembled using laminated, punched electrical sheet steel with an insulating film, as described for the stator core (see Section 2.1.4). For the rotor core assembly, the conductor slots are punched along the outside perimeter of the laminated sheet steel. The laminations are stacked, compressed into segments, and assembled until the design length is achieved. The segments are arranged so that ventilation ducts are provided within the compressed rotor core. The rotor core is fitted and locked to the shaft.

### *2.7.3 Rotor Conductor*

Rigid, uninsulated conductors, either bar or rod, are fitted into the axial slots of the rotor core and are connected to short-circuit rings located at each end of the conductors and rotor core assembly. The conductors are wedged in the rotor slots to maintain peripheral symmetry.

### 2.7.4 Rotor Short Circuiting Rings

A conducting metal ring is attached at each end of the rotor core assembly. The rotor conductors are brazed or welded to the conducting ring.

## 2.8 Rotor Assembly for Wound-Rotor Machine

The major difference between the wound-rotor induction machine and the squirrel-cage induction machine is the rotor assembly. The rotor of the wound-rotor induction machine consists of insulated windings arranged so that three-phase circuits are created by connecting each phase through a slip ring and brush assembly to a three-phase external rotor resistance controller or a power converter controller. The rotor is wound to provide the same number of poles on the rotor as exist in the stator.

### 2.8.1 Rotor Shaft

The shaft is machined to accept an electromagnetic core, rotor winding conductors–to–slip ring assembly, cooling fan, bearings, and slip ring assembly.

### 2.8.2 Rotor Core

The rotor core is constructed much the same as the rotor core for the squirrel-cage machine. However, the slot design for the rotor core is different. The laminated sheet steel is punched to provide a slot to accept rotor windings rather than bar or rod conductors.

### 2.8.3 Rotor Coil

The magnetic wire conductors used for the rotor coils are insulated in a similar process to that for the stator coils (see Section 2.1.5).

### 2.8.4 Rotor Windings

The rotor windings are formed from insulated coils. The coils are stacked in the rotor core slot. Each coil is insulated from its adjacent coil in the stack, and the completed stack of conductors is insulated from the rotor core. The windings are arranged to form the same number of poles as exist in the stator. Each winding is completed so that its adjacent pole is of the opposite polarity. The end turns are braced and supported to maintain spacing and to meet operating electrical and mechanical forces.

### 2.8.5 Rotor Insulation

The rotor slot insulation system consists of the insulation materials applied to the conductors, between the stacked conductors in rotor slots, and around the conductor stacks to insulate them from the rotor core. The insulation is held in place by conductor stack slippage or creepage blocks and slot wedges.

### *2.8.6 Rotor Slip Ring*

The rotor slip ring is an assembly of conductive metal rings insulated from each other and the support hub on which the metal rings are mounted. The hub is bored and machined so that insulated conductors are routed through the bore to each slip ring. The slip ring conductors are terminated on the winding side of the hub in a manner to provide for connections with the rotor winding leads.

## 2.9 Brush Assembly

### *2.9.1 Brush Housing and Rigging*

The brush housing consist of a support structure, brush holder brackets with mechanically adjustable spring assemblies, engineered springs, brush lead termination blocks, and power cable connection assembly brackets.

### *2.9.2 Brushes*

Brushes are selected for the specific application and environment. Brushes are typically grouped by brush grades according to the types of carbons, constituents, and manufacturing processes used. The main brush grades are carbon graphites, electrographics, graphites, and metal graphites. The actual brush selected for an application depends on the brush characteristics, including specific resistance, apparent density, abrasiveness or polishing action, contact voltage drop, current-carrying capability, maximum surface speed, friction coefficients, and transverse strength. Wind turbine generator applications generally use metal graphite brushes to achieve a balance between reliability, electrical performance, and mission life acceptability.

## 2.10 Power Electronic Converter

The power electronic converter consists of back-to-back voltage source converters that are interconnected by a dc link with capacitor. The back-to-back arrangement allows for rectifier and inverter capability. The power converter typically uses isolated-gate, bipolar transistors. Each converter contains pulse-width modulators that can regulate frequency, voltage, current, and power. The converters can be used for partial power conversion or full power conversion. When used with doubly fed induction generators in which the converters are connected between the rotor circuit and the network, the power converter is typically rated at 30% of the nominal generator rating. When used in full conversion applications in which the converters are connected between the stator circuit and the network, the power converter is rated at the nominal generator rating. The power electronic converters dissipate significant heat. Cooling and ventilation systems are critical for their operation.

## 2.11 Instrumentation

The generator instrumentation consists of thermal sensors, vibration sensors, and speed sensors. The thermal sensors include stator winding temperature and bearing temperature, and they can include heat exchanger (air-to-water) temperatures. The vibration sensors include proximity, velocity, and accelerometer devices. Options are available for key phasor reference point and phase angle measurement.

## 2.12 Protective Relays

Protective relay schemes include potential and current transformers. Both analog and digital technologies are used. The schemes installed can include both technologies to achieve a level of redundancy to minimize the risk of a single point of failure. Neutral and ground circuits must be sized and located to provide reference voltage points and conduct fault currents for personnel and equipment protection.

## 2.13 Surge Arresters

Voltage and current transients occur during load-switching events, short-circuit events, and lightning events. An arrester is designed to limit the actual voltage and current at power bus locations during transient events so that equipment and component peak ratings are not exceeded. When the arrester design voltage is reached, the arrester passes current to ground to limit the voltage.

## 2.14 Switchgear and Motor Control Centers

Switchgear and motor control centers are provided for both isolation and interruption capabilities by the installed breakers. The breakers and disconnects are rated to provide isolation, tripping, or both. The equipment is rated to carry the short-duration starting currents and the continuous operating currents of the connected equipment. Isolation breakers are not intended for operation under load. Neither isolation nor tripping breakers are designed to handle short-circuit current. Fuse devices are installed to interrupt short-circuit transients. The switchgear and motor control centers are there for personnel protection and equipment protection. Correct labeling is critical. Lockout mechanisms are provided for personnel safety and equipment security.

## 2.15 Capacitor Bank

Squirrel-cage induction machines require a large exciting current at startup, typically in the magnitude of four to six times the machine's rated current. To limit the demand at the point of interconnection, switched capacitor banks are normally included in the power circuit. The capacitor bank is sized so that the exciting current demand is met while minimizing the voltage drop during startup. The capacitor bank has the added power circuit benefit of providing power factor correction. The use of capacitor banks requires additional precautions during both operation and maintenance. Obvious signage and labeling should be in place to indicate the operating procedures and the grounding methodology required for the capacitor bank.

# Section 3: Troubleshooting

A troubleshooting program is, in effect, the foundation on which preventive and predictive maintenance programs are built. It should detect trends that lead to failure, identify the root cause of failures, and use root cause information to improve operating and maintenance processes. The measure of the effectiveness of the program is how well equipment life spans are extended while achieving reduced operating and maintenance cost.

The resources made available for a troubleshooting program depend on the life-cycle cost–benefit analysis for the equipment included in the program. The basic assumption in this report is that the generator and its auxiliary support equipment are critical to the success of the facility. It is left to the facility owner to determine the scope of the troubleshooting program and whether it is designed to detect, mitigate, and prevent failures or to repair and complete root cause analysis after a failure.

To assess any piece of equipment, one essential step must be completed first. That step is to build a database of benchmark information for each specific piece of equipment and its associated auxiliary components. Without benchmark information, the ability to detect deviations from expected performance and operation is limited.

Regardless of the configuration, generators have several common factors that require attention. These factors influence equipment performance and operation due to structural, mechanical, electrical, and external impacts. The key is to know what is normal—at rest and in operation, at no load and at full load, and during the transition from one status to the other.

To distinguish a deviation in response from a normal operating response, an awareness of the following parameters is helpful: electrical power output, temperature, noise, and vibration. Each of these parameters can be further categorized by voltage, current, power factor, harmonic distortion, differential temperature shifts, sonic shifts, ultrasonic shifts, proximity, velocity, acceleration vibration shifts, resonance shifts, phase angle shifts, and wind speed or rotor speed shifts.

When troubleshooting, key questions are: What is changing? Why is it happening? Until an investigation has gone through at least five iterations of the answers to those questions, the likelihood of gleaning sufficient information to improve a process is doubtful.

## 3.1 Structural Issues

For a structural assessment of potential issues that can affect the generator and its auxiliary equipment, the starting point is that the stator must be attached to a rigid mass that is sufficient to withstand the static and dynamic forces exerted on the stator so that alignment is maintained between the stator and rotor as well as between the rotor and the driver of the rotor.

There should be no signs of relative movement between the stator frame and the mounting frame or between the mounting frame and the supporting structure. When the support structure contains equipment—such as seismic supports, bearing plate supports, spring support systems, noise and vibration isolation components, motion absorption struts, bolts, and shims—each assembly should be intact, free of any obstructions, and within the markings for its operating range.

There should be no signs of relative movement between the stator frame and the bearing housings. For slip ring rotors, there should be no signs of relative movement between the brush assembly and the support ring. There should be no loose or unsecured objects within the open areas of the equipment. There should be no evidence of leakage or condensation on the equipment or in the open areas around the equipment.

The external surfaces of the generator, power converter and auxiliary components should be free of dust layers, contaminants, or other deposits. There should be no signs of corrosion or erosion. Equipment housing and duct joint seals should be intact.

Cooling system assemblies should show no signs of relative movement at subassembly joints or mounting supports. Filter frames should show no signs of bypassing. Air grills or intake and exhaust louvers should be unobstructed for both air movement and mechanical movement.

Air filters should be in place, with acceptable differential pressure for the airflow operating range. Bolts and fasteners should be secure and at design torque value for structural members, mounting assemblies, and electrical cables.

Noise and vibration levels and their associated frequency spectrums as measured on support structures and mounting frames for the generator, ventilating and cooling fans, bearings, auxiliary equipment, gear box, and turbine rotor should be within benchmark levels.

## 3.2 Mechanical Issues

For a mechanical assessment of potential issues that can affect the generator and its auxiliary equipment, it is helpful to know the generator air gap, the number of generator poles, the length of stator and rotor cores, the axial and radial internal clearances of the drive-end and non-drive-end bearings, the bearing metal temperatures for various speed and load points at specified locations, the number of balls in bearings, the number of blades on cooling fan, the generator axial and radial magnetic center reference points, the acoustic levels for various speed and load points at specified locations, the vibration levels for various load points at specified locations, the stator winding temperatures for various speed and load points, and the generator cooling airflow and surface temperatures for various speed and load points at specified locations.

During operation, the status of generator bearings, rotor balance, and rotor alignment can be assessed. Three parameters can be used for the assessment—temperature, noise, and vibration. Instrumentation designed around discrete wavelet transform and fast Fourier transform theory can be used to gather data for the vibration frequency spectrum during startup to determine whether eccentricity frequencies are present and at levels to indicate the presence of broken bars, rotor imbalance, and rotor misalignment.

Ultrasonic sensors can be used to detect the presence of high frequencies during lubrication that indicate proper grease levels and the beginning signs of bearing wear due to pitting, spalling, ball flattening, and scarring of raceways. Sonic sensors can be used to detect the low frequencies that indicate a bearing in advanced stages of deterioration. A trend of bearing temperature, sonic and ultrasonic frequency, vibration amplitude and frequency, and grease consumption can provide an informed indication of bearing health.

In addition, temperatures can be gathered to determine heat exchanger efficiency for the generator and auxiliary equipment. Higher temperatures, for the same operating and environmental conditions, indicate potential for a decrease in efficiency, increases in power losses and airflow deficiencies, or a combination of these.

Power losses can be caused by a potential movement in stator position, potential increase in eccentricity of the rotor; potential looseness of core stacks; potential breakdown of insulation, leading to an increase in leakage current; shorts; and stray currents. Stator or rotor movement can also produce nonuniform magnetic fields in the air gap and at the winding end turns, resulting in increased flux leakage and higher temperatures.

A reduction in airflow, for the same environmental conditions, can result from restrictions in the inlet and discharge air passages, damage to the air passages, change in fan blade clearances, or damage to fan blades. Airflow measurements should be compared with the benchmark reference or the generator fan specification. Increased temperature can also be accompanied by increased noise and vibration.

Vibration spectrum analyzer and acoustic sensor measurements can detect indications of potential stator and rotor movement or looseness, rotor eccentricity, fan blade looseness or damage, and bearing deterioration.

## 3.3 Electrical Issues

For an electrical assessment of potential issues that can affect the generator and its auxiliary equipment, it is helpful to know the type and rating of the generator; the number of poles used; voltage; insulation class of the stator, rotor, and power leads; the method of turbine control; the wind speed–to–power curve; the generator slip range; the generator capability curve; the generator temperature curve; for wound-rotor, the grade of brush or, for brushless design, the type and rating of diode and arrangement; for wound-rotor, the type and specification of the power resistance system and its controls; the type and rating of power electronic converters used; power capacitor bank rating and switching arrangement; protective relay settings; fuse sizes; surge arrester rating and locations; electrical interlocks; permissive start and trip logic; and ground mat electrical characteristics.

During operation, several significant parameters can be assessed. Temperature is a significant factor due to its impact on insulation life and, therefore, generator life. A rule of thumb is that insulation life is halved for every 10°C that the actual temperature rise exceeds the specified temperature rise for the stated insulation class. Because temperature rise is based on an ambient temperature of 40°C, the number of degrees that ambient temperature exceeds 40°C must be subtracted from the temperature rise allowed to prevent exceeding the insulation rating. Thermal aging is a significant factor in the insulation system's ability to withstand dielectric, mechanical, and environmental stresses.

Several electromagnetic issues affect insulation temperature, as follows:

- Voltage imbalance produces unbalanced phase current, negative sequence current, and nonuniform magnetic fields that result in increased power losses and increases in winding temperatures. Voltage imbalance can be present due to power circuit bus, cable, contactor, fuse, switchgear, or connector issues; due to network loading, switching, or lightning events at the point of interconnection; or due to a combination of these.
- Voltage and current harmonic distortion create magnetic flux distortions, resulting in an increase in both power losses and winding temperature. Harmonic distortion can be present due to network loads, network switching, lightning events, or power converter pulse modulation output.
- Voltage spikes impact the dielectric strength of insulation, resulting in increased leakage current, increased power losses, and increased insulation temperature. Voltage spikes can be present due to network switching events, lightning events, or power converter pulse modulation output.

Insulation temperature is affected by surface contamination. When dust, carbon, and lubrication films combine with moisture, conductive paths are created in the presence of the magnetic field that induced currents to circulate on the surface of the insulation. The presence of voids, cracks, and separations in the insulation increase the likelihood of contamination in the insulation. Such contaminants introduce defects into the insulation system that decrease the dielectric strength of the insulation. The dielectric strength decreases with moisture, frequency, and temperature. The surface currents create distortions in the magnetic field flux that tend to increase leakage losses. The combination of increased winding current, leakage current, and surface current produce increased insulation temperature. Increased insulation temperature decreases the insulation resistance and dielectric strength, allowing more leakage current and lower dielectric breakdown voltage.

As winding and insulation components expand and contract, relative movement occurs between conductors and insulation components. Thinning of the insulation occurs due to abrasive wear between conductors and insulation. The relative movement also sets up shear forces that break down the bonding between the conductors and the insulation system. Fatigue cracks and separations in the slot insulation and the winding end turn insulation can result. This weakens the retention and support systems for the slot conductors and winding end turns.

The conductors, windings, and insulation system experience additional abrasive wear due to the repetitive motion caused by the forces resulting from magnetic fields at different frequencies. Small shifts in stator winding relative to the stator core produce increased flux leakage at the winding end turn, creating magnetic field distortion and power losses and resulting in more heating of the winding end turns. The combination of increasing temperature and thinning insulation produced decreased dielectric strength in the insulation, resulting in shorts in the turns and windings and leading to stator slot shorts to ground and winding end turn phase-to-phase and phase-to-ground shorts.

Power converter pulse modulation can superimpose high-frequency, large-magnitude voltage pulses at the winding end turns. The high-frequency pulses cause a nonuniform distribution of voltage impulses across the windings end turns and insulation that produces a high turn-to-turn voltage stress. The voltage stress increases with impulse magnitude and the rate of change in voltage. The combination of increasing temperature, decreasing dielectric strength, and increasing vibration results in winding end turn shorts to ground and phase-to-phase.

As temperature differentials appear due to turn-to-turn shorts in the rotor, the rotor can bow in the direction of the higher temperature. As this bow increases, the magnetic field in the air gap is distorted. The magnetic field exerts nonuniform forces on both the rotor and the stator. The combination of localized higher temperatures and imbalanced magnetic forces generates a cycle of temperature increase and magnetic force imbalance. This continuing process can produce core looseness in both the rotor and the stator. After this process has begun, the looseness increases magnetic field imbalance, magnetic center misalignment, distortion of magnetic flux linkage at end turns, distortion of airflow, and axial and radial movement of the rotor. When any of the possible multiple combinations of this process continue, the forces exerted on the bearings increase, leading to increased bearing clearances, higher bearing temperatures, and, ultimately, bearing failure. When bearing failure begins, rotor-to-stator contact can result, producing significant damage and electrical faults.

Another loss of rotor concentricity can appear due to contamination of the bearing lubrication. When contaminants are introduced, they cause increased friction, bearing metal loss, increased clearance, and increased bearing and lubrication temperature. This cycle to failure can produce a scenario similar to that of the rotor bow.

Bearing failure can also be initiated by current passing through the bearing. Two sources of induced voltage drive the currents through the bearings. One source is the magnetic dissymmetry that can result during the manufacturing and assembly of the stator and rotor. The magnetic dissymmetry causes a shaft voltage to exist between the shaft ends. The shaft voltage drives a current through the rotor to the bearing, through the bearing to the bearing housing, through the bearing housing to the stator frame, through the stator frame to the opposite end bearing housing, through this bearing housing to the opposite end bearing, and through this bearing to the rotor, thus completing the overall circuit. When the magnitude of the shaft voltage approaches 300 mV, the resulting circulating current can initiate pitting, spalling, scoring, and, eventually, bearing failure. Typically, the circulation current can be prevented by introducing insulation at the bearing housing of one bearing or by installing one insulated bearing. The second source of induced voltage results from capacitive coupling of the rotor and stator through the bearing. This occurs when the common modal voltage of a power converter shifts the three-phase neutral voltage point above the ground reference point. The common modal voltage oscillates at high frequency. High frequency produces lower capacitive reactance of the bearing. Thus, current passes through the bearing. The voltage pulses can produce peak voltages between the shaft and ground of 10 V to 40 V. If this condition is present, both bearing housings and bearings are typically insulated. This condition can also produce damage to other shaf- connected equipment. Shaft grounding brushes have been used to protect the bearings.

Brushes used for slip ring rotors can initiate rotor current, insulation, and power impacts. Poor connections and contact surface irregularities can introduce increased resistance, voltage drops, and unbalanced current in the rotor circuit. The unbalanced current can produce a nonuniform magnetic field, increased power losses, and higher winding temperature. Brush–to–slip ring surface contact can produce dusting that introduces contamination on both stator and rotor insulation, leading to a decrease in insulation dielectric strength.

The brush holder assembly can impact overall brush performance. Low spring pressure on the brushes permits brush chatter and sparking that can lead to brush surface deterioration and slip ring surface defects. Both conditions can increase friction and higher brush operating temperature. The elevated brush temperature can cause crystallization of terminal insulators and deteriorate shunt lead connections.

The slip ring can impact overall brush performance due to surface conditions. Slip ring surface contamination can occur due to oxidation, abrasion, and moisture. This contamination can increase friction between contact surfaces. The increased friction can increase brush operating temperature. Slip ring out-of-roundness can produce brush chatter and sparking that can produce higher contact friction and brush operating temperature. The slip ring surface film appearance can also provide indications for machine nonuniform magnetic fields, electrical symmetry, and cyclic mechanical and electrical disturbances.

## 3.4 External Issues

External impacts on generator operation and reliability result from both natural and manmade events. The description here is limited to the point of interconnection and the wind. The type and degree of impact the generator experiences is determined by the capability and response of the overall protection and control systems.

For an assessment of the potential point-of-interconnection issues that can affect the generator and its auxiliary equipment, an awareness of network power system dynamics and stability is helpful. Although power system and stability analysis are beyond the scope of this report, some basic points can be introduced. Network response to changes in load and various disturbances are of primary concern. Network load changes produce network dynamic responses ranging from those encountered with the transfer of energy between the rotating masses in the generators and the loads, to those for the voltage and frequency control changes required to maintain network operating conditions, to those required to adjust generation for cyclic daily load variations. Network disturbances produce dynamic network responses ranging from wave phenomena associated with transmission lines, to those for electromagnetic changes in electrical machines, to those for electromechanical rotor oscillations, to those for turbine and automatic control actions. These dynamic responses can be grouped as wave, electromagnetic, electromechanical, and energy transformation phenomena. The timeframes associated with these phenomena range from microseconds to milliseconds for wave phenomena, from millisecond to seconds for electromagnetic phenomena, from milliseconds to minutes for electromechanical phenomena, and from seconds to hours for energy transformation phenomena.

When evaluating electrical power networks and the associated responses for different phenomena, it is helpful to remember that electrical energy cannot easily and conveniently be stored in large quantities. At any instant in time, the energy demand required by the load must be met by the corresponding generation supply. The reliability of the generation supply is determined by the quality of the installed equipment, the amount of reserve generation, the capability to supply load from alternative connections, and the level of network security. The quality of electrical energy supply is determined by the voltage at regulated and defined levels with low fluctuations, the frequency at regulated and defined levels with low fluctuations, and the minimization of harmonic content.

In reference to generators and the auxiliary equipment, the point of interconnection should have defined limits for voltage sag (undervoltage), voltage swell (overvoltage), harmonic distortion, voltage fluctuation (flicker), phase imbalance (voltage, load), transients, and load interruptions. Voltage swell, harmonic distortion, voltage fluctuations, phase imbalance, and transients cause aging and failure of insulation. Voltage sag, voltage swell, harmonics, and phase imbalance affect electronic equipment operation and cause failures. Network deviations beyond defined limits should be investigated for correction.

For an assessment of wind issues that can affect the generator and its auxiliary equipment, a basic understanding of the energy conversion process for wind energy to mechanical energy and then to electrical energy is helpful. Wind speed fluctuations will produce power fluctuations if not quickly dampened by the turbine controls. The rate of response of the turbine controls to wind fluctuations is critical. Load demand must be instantaneously met by generation supply. When wind speed increases or decreases, a speed, frequency, and voltage deviation exists. How well coordinated the turbine controls are will determine the magnitude of generator power, frequency, and voltage fluctuation. The magnitude of change, the rate of change, and the duration of change in the wind speed can cause the main torque to initiate a slight displacement of mass relative to the mass of the different sections of the overall shaft. Whether this occurs depends on the difference in stiffness of individual sections of the overall shaft. Any movement of mass will create movement in an equivalent mass along the shaft. A relative twist in any section produces a torsion that transmits torque to the adjacent sections of the shaft. The resulting torsional oscillations along the shaft are superimposed on the main torque driving the generator. The total net torque can increase or decrease along the shaft sections, depending on the twist and the phase and frequency of the main torque. Under the right conditions, the torque can become significant enough to reduce shaft fatigue life. These oscillations can also create relative movement in the rotor–to–rotor core fits. Over time, these torsional oscillations can initiate rotor core looseness, resulting in magnetic field distortion, power losses, increased temperature, increased vibration, and increased noise.

## 3.5 Off-Line Actions

Equipment outages provide opportunities to inspect equipment components for visual conditions and actual deviations from standards and specifications. Combining the equipment wear and tear information with the associated operating data of the equipment is instrumental in developing an equipment database. The database can be used to produce reports for predictive indicators and the associated cost to establish and refine preventive and periodic maintenance activities. In addition, the outage maintenance tasks can be identified, prioritized, and planned based on the findings of the troubleshooting and the preventive or periodic maintenance activities documented in the database. Essential to the refinement of the database is that equipment conditions found during an outage (as-found measurements, pictures of equipment condition, and as-left measurements) are entered in the equipment database for further and future evaluation and analysis. With this capability, an informed approach can be used to develop cost-effective preventive, periodic, and condition-based maintenance programs. Table 3-1 provides information for troubleshooting some problems that are commonly found in wind generators.

*Table 3-1*
*Troubleshooting*

| Category | Equipment | Symptom | Possible Cause | Corrective Action |
|---|---|---|---|---|
| Structural | Foundation | Concrete cracking, spalling, loose anchor bolt or nut, corrosion, loose ground cable | Moisture seepage, torsional oscillation, harmonic vibration at natural resonance | Hydraulic seal, bolt torque checks, spectrum frequency analysis, equipment modifications, design modifications |
| | Mounting base | Paint cracks, spalling, corrosion, weld cracks, beam distortion | Condensation, chemical attack, heat, torsional oscillation, fatigue, | Ventilation changes, humidity control, chemical survey and analysis, cleaning, spectrum frequency analysis, equipment modification, design modification |
| | Generator frame | Loose bolts, loose shims, noise, vibration, temperature | Imbalance, misalignment, bearing, magnetic center alignment, magnetic distortion, airflow restrictions | Vibration and frequency analysis, bolt torque checks, ventilation and cooling checks |
| | Ducts | Cracked, broken seals, loose or missing fasteners, elongated bolt holes, air bypassing | Misalignment, vibration, heat, airflow imbalance | Alignment checks, vibration and frequency analysis, airflow checks, fastener checks |
| | Nacelle | Noise, surface film, dust, and deposits, condensation, leaks | Unsecured objects, airflow obstructions, frequency of equipment checks | Housekeeping practices, operation and maintenance practices |
| Mechanical | Generator | Power loss, noise, temperature, vibration | Air gap symmetry, magnetic center alignment, bearing failure, air passage restriction | Vibration and frequency analysis, bearing checks, sonic frequency analysis, generator air gap check, rotor to gear or turbine coupling alignment check, airflow check |
| | Stator | Power loss, winding temperature, noise, vibration | Nonuniform magnetic field, stack core looseness, winding movement, air passage restriction, cleanliness | Load current frequency analysis, vibration frequency analysis, airflow check, winding checks, insulation checks, cleaning |

*Table 3-1 (continued)*
*Troubleshooting*

| Category | Equipment | Symptom | Possible Cause | Corrective Action |
|---|---|---|---|---|
| Mechanical (continued) | Rotor | Power loss, air temperature, noise, vibration | Bearings, broken bars, imbalance, misalignment, nonuniform magnetic fields, winding movement, windage friction, stack core looseness, air fan defect, cleanliness | Vibration frequency analysis, sonic frequency analysis, airflow checks, air fan checks, air gap checks, rotor alignment, winding checks, insulation checks, cleaning |
| | Bearing | Temperature, lubrication consumption, noise, vibration | Lubrication level, lubrication contamination, seal clearance, magnetic center alignment, nonuniform magnetic field, shaft voltage, shaft alignment, rotor imbalance | Ultrasonic and sonic frequency analysis, lubrication analysis, vibration frequency analysis, shaft alignment, rotor balancing, shaft voltage check, bearing insulation check |
| | Shaft fan | Air temperature, airflow, stator winding temperature, power loss, vibration, noise | Air passage restrictions, fan blade defects, fan looseness | Vibration frequency analysis, fan bore to shaft fit, fan inspection, airflow checks, air filter checks, cleaning |
| | Heat exchanger | Efficiency, air temperature, airflow, pressure differential, noise, vibration | Air restrictions, exchanger cleanliness, fan/blower/pump operation, duct leakage, ambient temperature, air quality | Airflow checks, exchanger inspection, fan/blower/pump inspection, cleaning |
| Electrical | Generator | Power loss, stator winding temperature | Voltage imbalance, voltage or current harmonic distortion, voltage spike, insulation | Infrared thermal checks for power circuit component heating issues, survey of network record for switching and lightning events, check power converter operation, check for negative sequence current, check insulation |

*Table 3-1 (continued)*
*Troubleshooting*

| Category | Equipment | Symptom | Possible Cause | Corrective Action |
|---|---|---|---|---|
| Electrical (continued) | Stator | Power losses, winding temperature, air temperature | Moisture, surface contamination, expansion and contraction of coil and insulation, winding end turn movement, insulation deterioration, turn-to-turn shorts, power converter | Dry and clean surfaces, check insulation, check windings, check pulse-width modulator of power converter |
| | Rotor (squirrel-cage induction generator) | Voltage or current harmonics, air temperature, noise, vibration | Broken bars, cracks or breaks at shorting ring, loose bars, nonuniform air gap, eccentricity, stator or rotor rub, magnetic center shift | Vibration frequency analysis, current frequency analysis, check air gap, check magnetic center alignment |
| | Rotor (doubly fed induction generator) | Voltage or current harmonics, air temperature, noise, vibration | Moisture, surface contamination, expansion and contraction of coil and insulation, winding end turn movement, insulation deterioration, nonuniform air gap, eccentricity, stator/rotor rub, magnetic center shift, turn-to-turn shorts, | Vibration frequency analysis, current frequency analysis, check magnetic center, check air gap, dry and clean surfaces, check insulation, check windings, check pulse-width modulator of power converter |
| | Brushes, brush holder, and slip ring | Brush temperature, slip ring surface appearance, Chatter, sparking, dust/particle discharge, insulator crystallization | Spring pressure, brush seating, current density, shunt lead connection, slip ring surface condition, slip ring out of round, power circuit connections | Brush grade check, spring pressure check, current density check, brush seating check, slip ring surface roughness check, slip ring roundness check, slip ring surface cleaning and conditioning, infrared thermal check of power circuit components for heating issues |
| | Power resistor | Resistance range, temperature, response time | Contamination, ventilation, airflow, drive, control tuning | Clean, check air quality, check airflow, check drive, infrared thermal check of power circuit components, tune drive control |
| | Power converter | Power consumption, temperature, response time, noise, cleanliness | Contamination, ventilation, airflow, cabinet seals and filters, power connections | Clean, check air quality, check airflow, check seals and filters, infrared thermal check of power circuit components |

*Table 3-1 (continued)*
*Troubleshooting*

| Category | Equipment | Symptom | Possible Cause | Corrective Action |
|---|---|---|---|---|
| External | Point of interconnection | Generator operation, power equipment thermal aging, insulation deterioration | Voltage swell or overvoltage, harmonic distortion, voltage fluctuations (flicker), phase imbalance in voltage or load, transients | Survey of point-of-interconnection operation deviations from specification, check of high-frequency switching events, check of lightning events |
| | | Power electronic converter operation and performance | Voltage sag or undervoltage, Voltage swell or overvoltage, harmonic distortion, phase unbalance in voltage or load | Survey of point-of-interconnection operation deviations from specifications, check of high-frequency switching events, check of lightning events |
| | Wind | Power loss, temperature, noise, vibration, shaft fatigue | Torsional oscillation, rotor looseness, magnetic field distortion, dynamic brake operation, crow bar operation | Vibration frequency analysis, sonic frequency analysis, analysis of electrical harmonic distortions, turbine control tuning |

## 3.6 Troubleshooting Summary

Timely and efficient troubleshooting depends on the quality of documentation, the availability of operating trends, and the identification of parameters that are beyond acceptable values.

For a generator to function, the stator and rotor windings must handle the voltage, current, electromagnetic forces, and mechanical forces throughout the operating range. Temperature and vibration trends are key indicators for potential conductor, insulation, and bearing damage or failure. As temperature increases across the insulation, the dielectric strength of the insulation decreases. As the number of thermal cycles increase, movement of conductors and insulation impact symmetry between stator and rotor magnetic fields that produce magnetic field distortions, nonuniform current distributions, higher stray losses, and more heat loss. This cycle leads to rotor imbalance and additional loading on bearings.

As machine temperature and bearing friction increase, vibration increases. As vibration increases, movement of conductor and insulation continues. As insulation movement continues, insulation wear, thinning, and eventual breakdown occurs. When insulation thickness is reduced sufficiently, current paths are created between coil turns, phases, windings, and core steel. These currents produce field distortion, nonuniform current distributions, higher stray losses, and more heat loss. Such repetitive cycles continue until unacceptable power loss is experienced or catastrophic failure occurs.

# Section 4: Preventive and Predictive Maintenance

As with any electrical rotating equipment, the generator will experience reliability issues due to design, manufacturing, and installation process impacts during the warranty period and its operating life. Significant impacts typically occur within the first three to five years from installation. During this early period, machine response to network demands can also produce reliability issues. Thereafter, equipment wear and tear and the operating and maintenance practices implemented tend to impact availability and reliability. From an operations and maintenance perspective, the generator components and auxiliary equipment that the operator can monitor, inspect, and analyze are listed in Table 4–1.

## 4.1 Preventive and Predictive Maintenance Basis

Table 4-2 presents preventive and predictive maintenance tasks and the basis for each.

## 4.2 Component Maintenance

The component maintenance tasks are those tasks identified for equipment or unit outage corrective maintenance actions. The tasks are identified based on the troubleshooting and preventive maintenance results before the outage or the planned testing and inspection completed during the outage scope of work. The potential repair and replacement tasks are then segregated into work requiring partial disassembly and work requiring full disassembly. The corrective actions, whether repair or replacement, are identified for each grouping of disassembly and whether the work is potentially done on site or off site. Common maintenance tasks typically performed on wind generators are shown in Table 4–3.

*Table 4-1*
*Component preventive maintenance scope*

| Location | Power | Current | Voltage | Frequency | Harmonics | Heat | Resistance | Vibration | Speed | Noise | Moisture | Contamination |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Network | x | x | x | x | x | | | | | | | |
| Foundation and tower | | | | x | x | | | x | | x | x | x |
| Mounting base | | | | x | x | | | x | | x | | |
| Generator bearings | | x | x | x | x | x | x | x | x | x | x | x |
| Generator stator | | x | x | x | x | x | x | | | | x | x |
| Generator rotor | | x | x | x | x | x | x | x | x | x | x | x |
| Brush assembly | | x | x | x | x | x | | x | | x | x | x |
| Ventilation | | | | | x | x | | x | | x | x | x |
| Lubrication | | | | | | x | | x | x | x | x | x |
| Instrumentation | x | x | x | x | x | x | | x | | | x | x |
| Controls—electrical | x | x | x | x | x | x | | x | | x | x | x |
| Controls—mechanical | | | | x | x | x | | x | x | x | x | x |
| Grounding | | | x | x | x | x | x | x | | | x | x |
| Arresters | | | x | x | x | x | | x | | x | x | x |
| Switchgear | | x | x | x | x | x | | | | x | x | x |
| Motor control center | | x | x | x | x | x | | | | x | x | x |
| Cable and support | | x | x | x | x | x | x | x | | x | x | x |
| Protective relays | | x | x | x | x | x | | | | x | x | x |

*Table 4-2*
*Preventive maintenance tasks and basis*

| Category | Location or Component | Failure Mechanism | Preventive or Predictive Maintenance Task | Basis | Suggested Frequency |
|---|---|---|---|---|---|
| Structural | Foundation | Moisture seepage, torsional oscillation, harmonic vibration at natural resonance | Hydraulic seal checks, spectrum frequency analysis, bolt torque checks | IEC 61400–1, ACI 201.1R-08, AISC ASTM A325/A490 bolts, site design specification | Every 6 months during first year, then every 3-5 years based on findings; every 6 months for bolting |
|  | Mounting base | Condensation, chemical attack, heat, torsional oscillation, fatigue, | Ventilation checks, humidity checks, chemical survey and analysis, cleaning, spectrum frequency analysis | IEC 61400–1, AISC ASTM A325/A490 bolts, site design specification | 3 months |
|  | Generator frame | Imbalance, misalignment, bearing, magnetic center alignment, magnetic distortion, airflow restrictions | Vibration and frequency analysis, bolt torque checks, ventilation—cooling checks | Original equipment manufacturer (OEM) technical manuals, IEC 61400–1 and AISC ASTM A325/A490 bolts, 10% deviation from benchmark | 3 months |
|  | Ducts | Misalignment, vibration, heat, airflow imbalance | Alignment checks, vibration and frequency analysis, airflow checks, fastener checks | Site design specification, site operations and maintenance (O&M) procedure | 3 months |
|  | Nacelle | Unsecured objects, airflow obstructions, frequency of equipment checks | Housekeeping practices, operation and maintenance practices | Site O&M procedure | 3 months |

*Table 4-2 (continued)*
*Preventive maintenance tasks and basis*

| Category | Location or Component | Failure Mechanism | Preventive or Predictive Maintenance Task | Basis | Suggested Frequency |
|---|---|---|---|---|---|
| Mechanical | Generator | Air gap symmetry, magnetic center alignment, bearing failure, air passage restriction | Bearing vibration and frequency analysis, sonic frequency analysis, generator air gap check, rotor to gear/turbine coupling alignment check, airflow check | OEM technical manuals, site O&M procedures | 3 months<br>6 months |
| | Stator | Nonuniform magnetic field, stack core looseness, winding movement, air passage restriction, cleanliness | Load current frequency analysis, vibration frequency analysis, airflow check, winding checks, insulation checks, cleaning | OEM technical manuals | Every 6 months for first year, then 12 months, then every 3–5 years |
| | Rotor | Bearings, broken bars, imbalance, misalignment, nonuniform magnetic fields, winding movement, windage friction, stack core looseness, air fan defect, cleanliness | Vibration frequency analysis, sonic frequency analysis, airflow checks, air fan checks, rotor alignment, winding checks, insulation checks, cleaning | OEM technical manuals, IEEE Std 841 | Every 6 months for first year, then 12 months, then every 3–5 years |
| | Bearing | Lubrication consumption, lubrication contamination, seal clearance, magnetic center alignment, nonuniform magnetic field, shaft voltage, shaft alignment, rotor imbalance | Ultrasonic/sonic frequency analysis, lubrication analysis, vibration frequency analysis, shaft alignment, rotor balancing, shaft voltage check, bearing insulation check | OEM technical manuals, IEEE Std 841 | Every 3 months for first year, then every 6 months for a year based on trend, then every 3¯5 years |

*Table 4-2 (continued)*
*Preventive maintenance tasks and basis*

| Category | Location or Component | Failure Mechanism | Preventive or Predictive Maintenance Task | Basis | Suggested Frequency |
|---|---|---|---|---|---|
| Mechanical (continued) | Shaft fan | Air passage restrictions, fan blade defects, fan looseness | Vibration frequency analysis, fan to rotor connection, fan inspection, airflow checks, air filter checks, cleaning | OEM technical manuals | First year, then every 3–5 years |
| | Heat exchanger | Air restrictions, exchanger cleanliness, fan/blower/pump operation, duct leakage, ambient temperature, air quality | Airflow checks, duct leak check, seal checks, exchanger tube inspection, fan/blower/pump inspection, cleaning | OEM technical manuals | Every 3 months for first year, then every 6 months |
| Electrical | Generator | Voltage imbalance, voltage/current harmonic distortion, voltage spike, insulation | Infrared thermal checks for power circuit component heating issues, survey of network record for switching, lightning events, check power converter operation, check for negative sequence current, check winding and air temperatures | OEM technical manuals,<br>NEMA Std MG-1,<br>IEEE Std 43,<br>IEEE Std 519 | Daily operating records |
| | Stator | Moisture, surface contamination, expansion and contraction of coil and insulation, winding end turn movement, insulation deterioration, turn-to-turn shorts, power converter | Dry and clean external surfaces, check insulation, check windings, | OEM technical manuals,<br>NEMA Std MG-1,<br>IEEE Std 43,<br>IEEE Std 519 | Every 6 months for first year, then every 3–5 years |

*Table 4-2 (continued)*
*Preventive maintenance tasks and basis*

| Category | Location or Component | Failure Mechanism | Preventive or Predictive Maintenance Task | Basis | Suggested Frequency |
|---|---|---|---|---|---|
| Electrical (continued) | Rotor (squirrel-cage induction generator) | Broken bars, cracks or breaks at shorting ring, loose bars, nonuniform air gap, eccentricity, stator/rotor rub, magnetic center shift | Vibration frequency analysis, current frequency analysis, check magnetic center alignment | OEM technical manuals,<br>NEMA Std MG-1,<br>IEEE Std 43,<br>IEEE Std 519 | Every 3 months for first year, then every 6 months for a year based on trend, then every 3–5 years |
| | Rotor (doubly fed induction generator) | Moisture, surface contamination, coil and insulation relative movement, winding end turn movement, insulation deterioration, nonuniform air gap, eccentricity, stator/rotor rub, magnetic center shift, turn-to-turn shorts | Vibration frequency analysis, current frequency analysis, check magnetic center, dry and clean surfaces, check insulation, check windings, | OEM technical manuals,<br>NEMA Std MG-1,<br>IEEE Std 43,<br>IEEE Std 519 | Every 3 months for first year, then every 6 months for a year based on trend, then every 3–5 years |
| | Brushes, brush holder, and slip ring | Spring pressure, brush seating, current density, shunt lead connection, slip ring surface condition, slip ring out of round, power circuit connections | Brush grade check, spring pressure check, current density check, brush seating check, slip ring surface roughness check, slip ring roundness check, slip ring surface cleaning and conditioning, infrared thermal check of power circuit components for heating issues | OEM technical manuals | Every 3 months for first year, then every 6 months based on trend |

*Table 4-2 (continued)*
*Preventive maintenance tasks and basis*

| Category | Location or Component | Failure Mechanism | Preventive or Predictive Maintenance Task | Basis | Suggested Frequency |
|---|---|---|---|---|---|
| Electrical (continued) | Power resistor | Contamination, ventilation, airflow, drive, control tuning | Clean, check air quality, check airflow, check drive, infrared thermal check of power circuit components, tune drive control | OEM technical manuals | Every 3 months for first year, then every 6 months based on trend |
|  | Power converter | Contamination, ventilation, airflow, cabinet seals and filters, power connections | Clean, check air quality, check airflow, check seals and filters, infrared thermal check of power circuit components | OEM technical manuals, IEEE Std 519 | 3 months |
| External | Point of interconnection | Generator operation, power equipment thermal aging, insulation deterioration | Survey of point-of-interconnection operation deviations from specification, check of high-frequency switching events, check of lightning events | Daily operating records, quarterly trends, IEEE Std 519 | To support outage inspection |
|  |  | Power electronic converter operation and performance | Survey of point-of-interconnection operation deviations from specifications, check of high-frequency switching events, check of lightning events | OEM technical manuals, daily operating records, quarterly trends, IEEE Std 519 | To support 3-month inspection |
|  | Wind | Power loss, temperature, noise, vibration, dhaft fatigue | Vibration frequency analysis, sonic frequency analysis, analysis of electrical harmonic distortions, turbine control tuning | OEM technical manuals, daily operating records, quarterly trends | Every 3 months for first year, then every 6 months based on trend |

*Table 4-3*
*Component corrective maintenance tasks*

| Disassembly Status | Task | Evaluation Criteria | Criteria Pass/Work Location | Corrective Action Completed On Site | Corrective Action Completed Off Site |
|---|---|---|---|---|---|
| Partial | Stator phase winding resistance balance test (determines whether off-site work required) | Phase winding resistance; high and low resistance difference within tolerance; typically less than 5% deviation | Yes/on site<br>No/off site | Cleaning | Repair winding and clean or rewind |
| | Stator insulation resistance test (determines whether off-site work is required) | High resistance to ground (using 500 Vdc megohmmeter with readings corrected to 25°C) | Yes/on site<br>No/off site | Cleaning and drying; if questionable readings, complete polarization index, surge test, high-potential test as evaluation progression warrants | Repair and reinsulate |
| | Stator main lead insulation test | Visual condition; high resistance to ground (using 500 Vdc megohmmeter with readings corrected to 25°C) | Yes/on site<br>No/on site | Clean and torque according to OEM standard; repair or replace according to extent of damage and resistance readings | |
| | Bearing inspection | Troubleshooting results; condition and clearance according to OEM specification | No/on site | Replace bearing | |

*Table 4-3 (continued)*
*Component corrective maintenance tasks*

| Disassembly Status | Task | Evaluation Criteria | Criteria Pass/Work Location | Corrective Action Completed On Site | Corrective Action Completed Off Site |
|---|---|---|---|---|---|
| Partial—wound-rotor only | Rotor winding resistance balance test (determines whether off-site work is required) | Phase winding resistance; high and low resistance difference within tolerance; typically less than 5% deviation | Yes/on site<br>No/off site | Cleaning | Repair winding and reinsulate |
| | Rotor insulation resistance test (determines whether off site work is required) | Resistance to ground (using 500 Vdc megohmmeter with readings corrected to 25°C) | Yes/on site<br>No/off site | Cleaning and drying; if insulation is questionable, complete polarization index, surge test, and high-potential test as evaluation progression warrants | Repair or reinsulate |
| | Rotor main lead insulation test | Visual condition; high resistance to ground (using 500 Vdc megohmmeter with readings corrected to 25°C) | Yes/on site<br>No/on site | Clean and torque according to OEM standard; repair or replace according to extent of damage and resistance readings | |
| | Brush inspection | Verify grade and type | No/on site | Replace if incorrect | |
| | | Visual check for mechanical damage | No/on site | Replace brush if chipped, cracked, hot spots | |
| | | Visual check of shunt for fraying, looseness | No/on site | Replace brush if fraying or looseness | |
| | | Brush length according to OEM specification | No/on site | Replace if not according to specification | |

*Table 4-3 (continued)*
*Component corrective maintenance tasks*

| Disassembly Status | Task | Evaluation Criteria | Criteria Pass/Work Location | Corrective Action Completed On Site | Corrective Action Completed Off Site |
|---|---|---|---|---|---|
| Partial—wound-rotor only (continued) | Brush holder inspection | Visual check for metal loss due to arcing | No/on site | Replace holders with metal loss | |
| | | Visual check for brush arm and spring mechanical damage, arcing, or looseness | No/on site | Repair or replace depending on extent of damage | |
| | | Spring tension according to OEM specification | No/on site | Adjust to specification | |
| | | Clearance between holder and slip ring | No/on site | Adjust to specification; typically 0.0625 to 0.125 in. (1.5875 to 3.175 mm) | |
| | Brush rigging | Visual appearance, cleanliness, arcing, crystallization or breakdown of insulators or insulation | No/on site | Clean and repair minor defects; replace crystallized insulators or damaged insulation material | |
| | Slip ring inspection | Visual appearance of slip ring, good film surface, no contamination | No/on site | Remove contamination—carbon dust, silicon, foreign matter | |
| | | No surface defects, eccentricity run-out within specification, typically less than 0.002 in. (0.0508 mm) | No/on site | Resurface according to OEM specification, or replace or exchange program | |

*Table 4-3 (continued)*
*Component corrective maintenance tasks*

| Disassembly Status | Task | Evaluation Criteria | Criteria Pass/Work Location | Corrective Action Completed On Site | Corrective Action Completed Off Site |
|---|---|---|---|---|---|
| Partial—wound-rotor only (continued) | Slip ring inspection (continued) | All slip rings at same outside diameter | No/on site | Resurface according to OEM specification or replace or exchange program | |
| | | Visual appearance of connectors or sleeves show no signs of overheating, deterioration | Yes/on site<br>No/on site | Clean and torque according to OEM specification; replace or exchange slip ring | |
| | | Check conductor bands for cracks, looseness, arc-over according to OEM specification | Yes/on site<br>No/on site | Clean; replace or exchange slip ring | |
| | Brush seating | Brush contact, 100% | No/on site | Seat brush to slip ring until 100% contact with slip ring is achieved (all previous brush and slip ring work should be completed first) | |
| Full | Stator inspection | Troubleshooting results; stator winding or insulation test indeterminate; on-site cleaning possible | Yes/on site<br>No/off site | Disassemble according to OEM manual; clean and dry stator winding and insulation; retest winding and insulation resistance test | If retest fails, rewind |

*Table 4-3 (continued)*
*Component corrective maintenance tasks*

| Disassembly Status | Task | Evaluation Criteria | Criteria Pass/Work Location | Corrective Action Completed On Site | Corrective Action Completed Off Site |
|---|---|---|---|---|---|
| Full—squirrel-cage induction generator | Rotor inspection | Troubleshooting results; mechanical damage: broken bars; loose or broken shorting ring | No/off site | | Repair or replace depending on extent of repairs required |
| Full—wound-rotor induction generator | Rotor inspection | (See Partial disassembly section of this table) | | | |
| | Fan inspection | Troubleshooting results; mechanical damage: blade cracks; hub or ring loose | No/off site | | Repair or replace depending on extent of repairs required; balance |
| | Bearings | (See Partial disassembly section of this table) | | | |
| | Bearing housing | No surface defects; bore dimension and concentricity within bearing OEM technical manual specification | Yes/on site<br>No/on site | Clean and polish; recheck for bore and concentricity tolerances; replace or exchange program | |
| | Shaft journal | No surface defects; outside diameter and eccentricity within bearing OEM technical manual specification | Yes/on site<br>No/off site | Clean and polish; recheck for outside diameter and eccentricity tolerance | Build up and machine or replace (capability, cost, time decision); balance |
| | Brush, brush holder, brush rigging | (See Partial disassembly section of this table) | | | |
| | Slip ring | (See Partial disassembly section of this table) | | | |

# Section 5: Personnel Qualifications and Training

Personnel qualifications and training are identified in Table 5–1.

*Table 5-1*
*Personnel qualifications and training*

| Position | Qualification | Training | Recommendation |
|---|---|---|---|
| Operations | Knowledge of safety procedures, hazardous materials, mechanical and electrical fundamentals | Safety, hazardous materials, use of mechanical and electronic instrumentation, acoustic and vibration measurement, OEM operation manuals, document management technology | Annual review of all areas for updates, new technology impacts, and new equipment; assignments with maintenance personnel; participation in seminar or workshop on equipment and components |
| Maintenance | Knowledge of safety procedures, hazardous materials procedures, electrical fundamentals; use of power tools, measurement tools (mechanical and electrical), electrical instrumentation, lifting and rigging equipment | Safety, hazardous materials, acoustic measurement, vibration measurement, frequency analysis (vibration, sonic/ultrasonic), balance of rotating equipment, equipment alignment, OEM maintenance manuals, document management technology | Annual review of all areas for updates, new technology impacts, and new equipment; assignments with operating personnel; participation in seminar or workshop on equipment and components |

*Table 5-1 (continued)*
*Personnel qualifications and training*

| Position | Qualification | Training | Recommendation |
|---|---|---|---|
| Supervisor | Knowledge of operations and maintenance disciplines; knowledge of work planning software; cost–benefit and prioritization decision making, risk management methods; document management skills; team building skills | Training for operations and maintenance disciplines; frequency analysis techniques (vibration, sonic/ultrasonic), equipment fault analysis techniques, work analysis techniques, equipment benchmarking techniques, personnel analysis and evaluation | Annual review of all areas for updates, new technology impacts, and new equipment; assignments with operating personnel; participation in seminar or workshop on equipment and components; [articipation in technical seminars and workshops on equipment technology, information technology, and personnel skills |

# Section 6: Recommended Reading

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*The Cause and Analysis of Stator and Rotor Failures in AC Induction Machines*. Electrical Apparatus Service Association (EASA), St. Louis, MO: 1999. Tech Note 31-1.

*Wind Power Today: 2010.* U.S. Department of Energy, Energy Efficiency and Renewable Energy: 2010. Available from http://www1.eere.energy.gov/wind/pdfs/47531.pdf.

*Wind Power: Issues and Opportunities for Advancing Technology, Expanding Renewable Generation and Reducing Emissions.* EPRI, Palo Alto, CA: 2011. 1023455.

*Wind Turbine Productivity Improvement Guidelines Development Status and Plan.* EPRI, Palo Alto, CA: 2000. 1001298.

# Appendix A: Summary Highlights

## A.1 Highlights

- Wind turbine generators under review are rated as 690-Vac, 60-Hz, three-phase, 1800 rpm, four-pole machines, nominally rated at 1–2 MWe.
- Two asynchronous generators are commonly used: squirrel-cage induction generator and wound-rotor induction generator.
- Generator applications fall into four basic configurations: fixed-speed, variable-slip, variable-speed, and full-converter configurations.
- The most common generator in the four configurations is the variable-speed, wound-rotor machine using a power electronic converter; referred to as a *doubly fed induction generator*.
- Generator common component failures include bearings, slip ring and brush assemblies, rotor winding, stator windings, cooling systems, and rotor leads.
- Effective and efficient troubleshooting requires development of an equipment database that includes original equipment manufacturer specifications, operations data, equipment benchmark data, equipment failure data, and equipment condition data.
- Useful equipment assessment techniques require visual inspection, vibration analysis (including spectrum analysis), off-line winding evaluations, and on-line power quality evaluations.
- Assessment techniques should more generally be used on rotor axial movement, rotor vibration, bearing temperatures, lubrication quality, electrical hotspots, winding temperatures, cooling air temperature, air filter cleanliness, phase voltage and current imbalance, moisture and weather seal integrity, bolt and fastener torque schedules, grounding integrity, power equipment voltage spikes and harmonics, grid voltage spikes and harmonics, and network transients.

## A.2 General Operating and Maintenance Monitoring and Inspection Actions

- Squirrel-cage induction generator inspection items include the following:
  - Mechanical
    - Machine cleanliness
    - Machine moisture and condensation

        - Machine noise level and frequency
        - Cooling fan performance
        - Lubrication quality
        - Bearing lubrication—levels and consumption changes
        - Bearing temperatures
        - Bearing vibration—level and phase angle
        - Change in vibration resonance points
        - Shaft alignment
        - Assembly bolting torque schedules
        - Electrical connections—torque schedules and thermal deviations
    - Electrical
        - Phase-to-phase current deviations
        - Phase current verses load deviations
        - Winding temperature deviations
        - Turbine speed–to–load deviations
        - Frequency distortion
        - Voltage distortion
        - Current distortion
        - Number of no-load to full-load cycles
        - Starting current variation
        - Number of thermal cycles—ambient to rated
        - No-load to full-load ramp rate
        - Surge events—lightning, network loading, wind
        - Protective relay operation
        - Number of machine trips
        - Grounding integrity
- Wound-rotor induction generator inspection items include those identified for the squirrel-cage induction machine, as well as the following:
    - Mechanical
        - Slip ring surface roundness
        - Slip ring surface roughness
        - Brush holder assembly–to–slip ring alignment
        - Brush holder assembly component part condition

        - Brush alignment to slip ring
        - Brush life
        - Rotor lead connections
    - Electrical
        - Brush arcing
        - Harmonic distortion
- Doubly fed induction generator inspection items include those identified for the squirrel-cage induction machine and wound-rotor induction machine, as well as the following:
    - Mechanical
        - Power electronic converter cleanliness
        - Power electronic converter heater exchanger efficiency
        - Power electronic converter moisture and condensation
        - Power, control, and instrumentation cabling supports
        - Noise
    - Electrical
        - Power electronic converter thermal hot spots
        - Pulse-width modulation deviations
        - Neutral harmonics
- Full-converter induction generator inspection items are similar to those of the doubly fed induction generator.

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