Wind Turbine Generator Reliability Analysis To Reduce Operations and Maintenance (O&M) Costs

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This article was prepared by Raja V. Pulikollu (Electric Power Research Institute, EPRI), William Erdman (Cinch Inc.), Jeff Mclaughlin (Machine Building Specialists), Kevin Alewine (Shermco Industries), Shawn Sheng (National Renewable Energy Laboratory, NREL), and Jim Bezner (Duke Energy).

Abstract

Wind turbine major systems (blades, pitch, main bearing, gearbox, and generator) are integrated into a composite system. Specifications for these systems and components are developed to achieve symmetry of operation, avoiding negative interaction. For instance, the main bearing, gearbox, and generator (drivetrain) components are interdependent, functioning in unison for efficient energy production. Hence, wind resource and grid interactions affecting the drivetrain impact the performance and reliability of the turbine generator. This paper discusses generator reliability covering the technology evolution over the last 20 years. EPRI's Wind Network for Enhanced Reliability (WinNER) web-based tool and Shermco Industries databases are presented, and conclusions are drawn regarding failures specific to generator design, manufacturing, and operating conditions. Additionally, this paper compares the life expectancy of stator-fed configurations and doubly fed generator systems.

Keywords

Wind Turbine, Digitalization, Generator, Reliability, Operations and Maintenance (O&M)

Business Needs – Industrywide Collaboration

The adoption of wind energy as a major utility generation source is obvious with the rapid growth of onshore and offshore installations in the recent years. Currently, cumulative onshore and offshore wind turbine global capacity has reached 836 gigawatt (GW) and 64 GW, respectively, for a total of 900 GW [1]. Global wind capacity is expected to reach 1,800 GW by 2030 [2].

The generator system in wind turbines performs the critical function of converting mechanical power (torque × speed) to electrical power (electrical current × voltage). A typical drivetrain configuration within a turbine nacelle is shown in Figure 1. The large turbine rotor with its blades is shown to the left of the figure; the blades interact with the wind to produce large aerodynamic torques. In the configuration shown, this high torque serves as the input to the turbine gearbox, which increases the speed and reduces the torque to levels compatible with the generator design shown on the right of Figure 1. It should be noted that Figure 1 is an example of a high-speed generator (1,000–1,800 RPM synchronous speeds) and gearbox configuration; this configuration has dominated the modern industry, but modifications to this approach have also had an impact, typically in much smaller adopted quantities. These include direct-drive generators where the gearbox is eliminated entirely, and lower-speed generators (100–300 RPM) where simple single-stage gearboxes are applied. The latter is often referred to as a medium-speed or hybrid drivetrain configuration. While low-speed and direct-drive generators have the advantage of simplifying or eliminating the gearbox, they also require the generator to produce higher torques, which leads to considerably larger volume, weight, and cost of the generator. This is the main reason high-speed generators have continued to have such an impact on turbine design, especially for onshore applications.

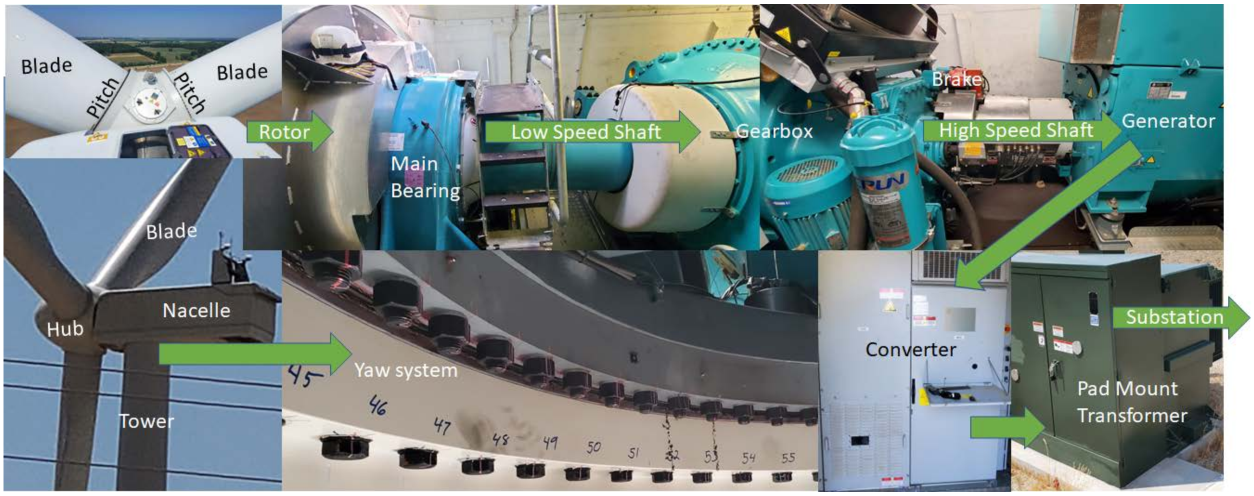

Figure 1: Wind turbine critical systems

Wind turbine generator failures are one of the primary reasons for increased operations and maintenance (O&M) costs and generation asset downtime. Generator issues continue to remain a concern in the wind industry, both for stator-fed synchronous machines as well as for rotor-fed, wound rotor machines. Each of these generator failure events lead to significant loss of production and unplanned repair costs ($100,000–$225,000).

The following are the key issues that operators have been trying to address in their efforts to reduce generator O&M costs.

- What is the impact of design, quality, and operating conditions and maintenance practices on generator life and reliability?
- What are the critical generator parts and their failure mechanisms?
- Are there any early indicators for generator damage that can be used to schedule preventive maintenance?

To address these industry needs, Electric Power Research Institute (EPRI) developed the Wind Network for Enhanced Reliability (WinNER, Figure 2) web-based tool [3] by leveraging industry data for benchmarking at the fleet level, turbine level, and system level and to demonstrate reliability forecasting methods. National Renewable Energy Laboratory (NREL) and Shermco Industries supported this effort by developing reliability data specifications and standards and by sharing generator reliability data and expertise. WinNER helps wind operators effectively compare their fleet reliability with the rest of the industry anonymized data, identify opportunities for O&M improvements, and forecast optimum O&M budget for the next 1–10 years and beyond.

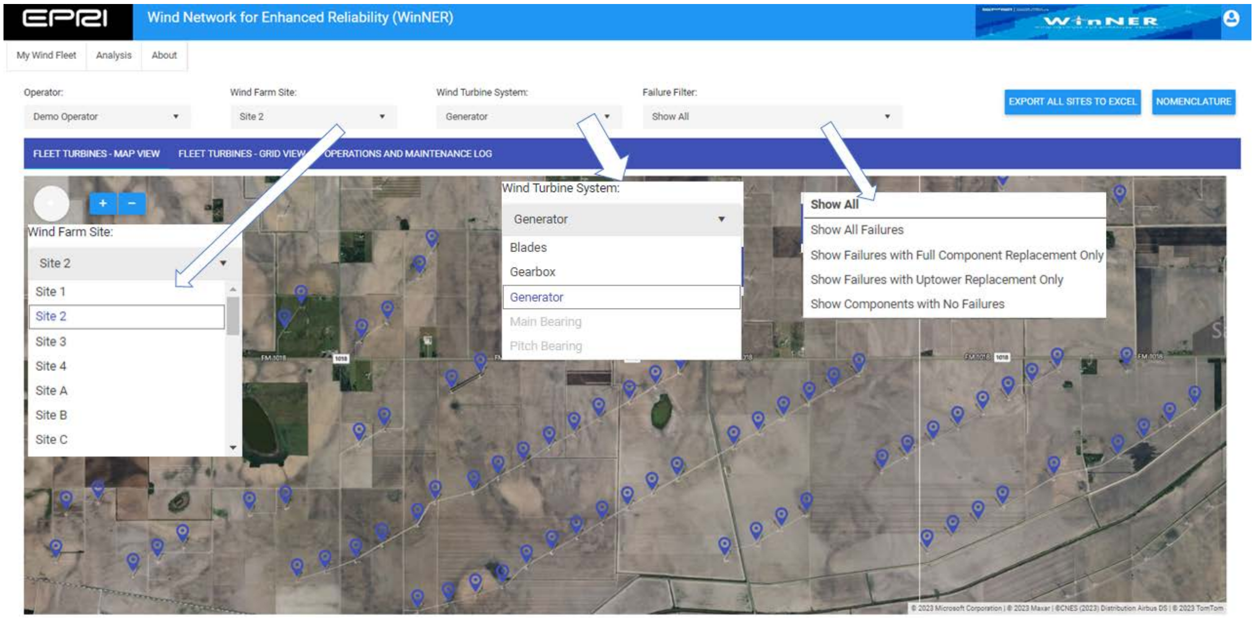

Figure 2: Wind Network for Enhanced Reliability (WinNER) web-based tool for benchmarking, forecasting, and O&M optimization [3]

Generator Reliability and Critical Components

For generator reliability assessment, EPRI has leveraged the WinNER database (35 GW) and the Shermco Industries database (9.2 GW). A combined 44.2 GW is a statistically significant amount of data to conduct generator reliability and failure analysis. WinNER consists of healthy and failed assets data, whereas Shermco data focuses only on failure records.

A detailed generator reliability analysis was conducted to evaluate the impact of turbine technology, design, manufacturing, maintenance strategies, and operational regime on failure rates. EPRI's database includes data collected from 17,000 turbines worldwide, a total capacity of 35 GW. The EPRI database has 1,900 generator failure data points mainly used for the development of reliability and health monitoring models [4]–[6]. More than 200 wind farms covering 12 major turbine original equipment manufacturers (OEMs; GE, Vestas, Siemens, Mitsubishi, Suzlon, Nordex, and Gamesa) with 40 different turbine types/ratings ranging from 1.5 MW to 6.2 MW are included in the database. These turbines contain generators supplied by 17 different manufacturers (including ABB, Hitachi, Winergy, Vestas, GE, Loher, Cantaray, and Suzlon). These generators contain angular contact ball bearings (including insulated, ceramic, and coated) supplied by multiple manufacturers (including Schaeffler and SKF). Hence, digitalization of a generator is a very complicated task for operators/utilities due to the involvement of multiple OEMs, designs, and suppliers. As of today, there are no clear agreements in place between OEMs, suppliers, and utilities/operators for smooth data transfer supporting digitalization. This is a critical gap in the wind industry that utilities/operators have been trying to address with NREL and EPRI's support.

There are several key factors that influence the life expectancy of generators, and the most significant ones are discussed in this paper based on WinNER database findings. This database serves two functions: First, it identifies very specific problems associated with specific turbine designs, which is useful for both current and future owners of the turbines. Second, the results can be used for reliability benchmarking at fleet-level, turbine-level, and system-level, and general maintenance issues can be inferred.

Wind turbine generator performance and life is impacted by the following internal and external factors:

Internal factors:

- Generator technology and quality (design and manufacturing)
- Supplier quality (design and manufacturing)
- Generator assembly, concentricity (air gap between stator and rotor)
- Operational control of temperature (distortion of stator, rotor, and bearings).

External factors:

- Drivetrain issues (deflections, misalignment)
- Site conditions (environment such as ambient temperature)
- Wind loads (such as turbulence intensity, wind shear)
- Operating conditions (grid events, derating or curtailment, controller)
- Maintenance strategies (regrease, periodic cleaning of slipring-brush assemblies).

Because of the popularity of the wound rotor and squirrel cage induction generators in modern wind turbines, these two generators are the focus of this paper. Type III machines utilize a wound rotor, doubly fed induction generator (DFIG). Rotors for these machines are partially connected to the grid, and the stator is isolated from the grid, allowing for additional speed variation. The partial connection of the rotor to the grid helps keep the cost of the controller lower. However, grid issues can affect these machines, and a fully isolated version of this Type III configuration with a full power convertor has been developed. Type IV machines are isolated from the grid with a "full power convertor" and utilize a squirrel cage induction generator (SCIG).

Figure 3 and Figure 4 shows a cross-sectional cut-out view of the DFIG and SCIG, respectively. The biggest difference with the SCIG is the rotor itself. The DFIG machine has copper windings on the rotor, which are brought out through interconnection leads in the rotor shaft to the slip ring assembly, but these are all missing in the squirrel cage machine. Instead, the squirrel cage rotor can be thought of as electrically identical to the DFIG machine but with the three phase windings short-circuited. Because they are short-circuited, there are no rotor "windings." Instead, aluminum (sometimes copper) rotor bars run axially (often with a slight skew) through the rotor, and all the bars are short-circuited at both ends of the rotor lamination stack. This electrical shorting function is accomplished by means of the shorting end ring identified in Figure 4, which is used on both ends of the rotor. Since the rotor is short-circuited, there are no electrical connections made, and the slip ring and brush assembly are eliminated entirely. There is only a stator connection, and all the generator power must flow out of this connection.

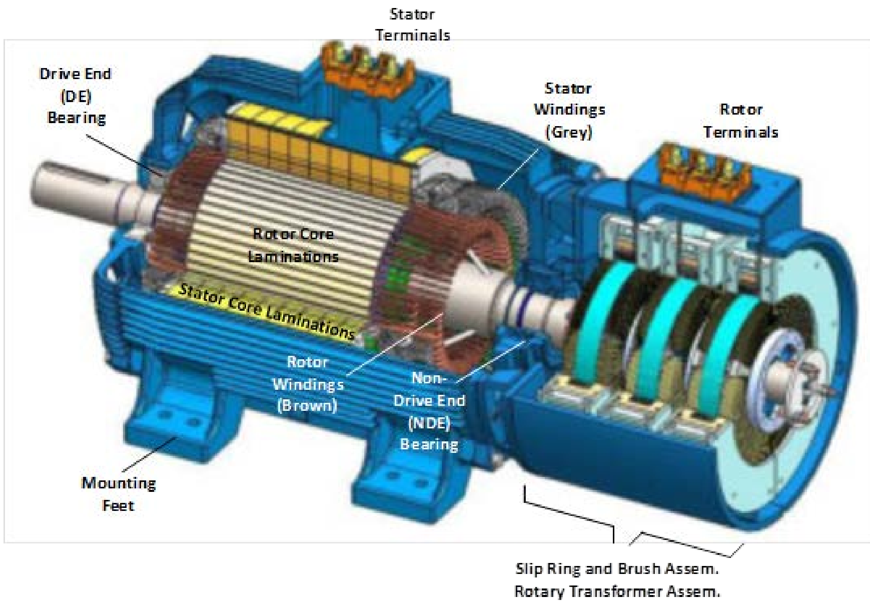

Figure 3: Constituent parts of the doubly fed induction generator

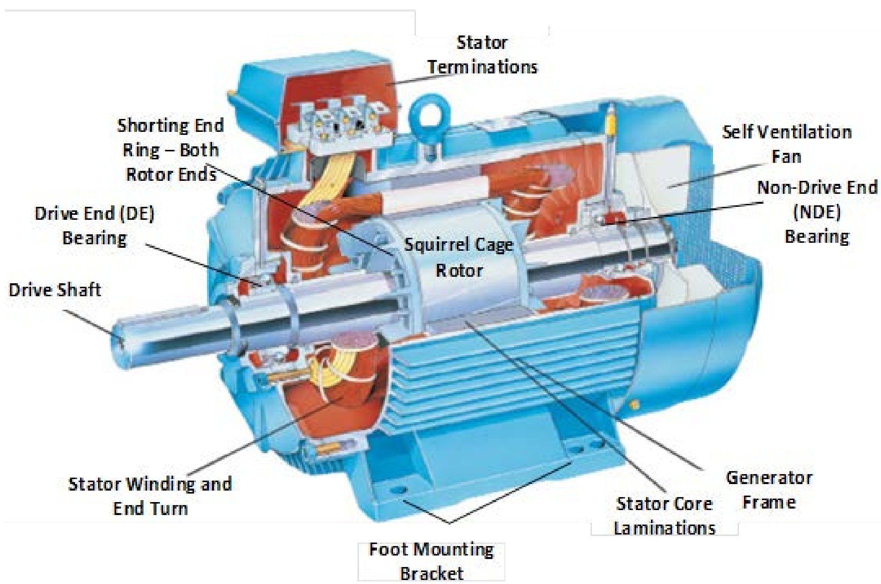

Figure 4: Sectional view of the squirrel cage induction generator

Figure 5 shows generator full replacement and up-tower replacement annual failure rates for various operational years. Most of these data were collected from wind farms installed since 2008. While generator annual failure rate is typically around 1%–4% (including full generator and up-tower replacements), the associated downtime is quite long, and replacement (disassemble/assemble) costs are high. Overall, the generator annual failure rate has increased between 5 and 12 operational years. Early generator failures during the first 5 years of operation are mainly due to design, assembly, and manufacturing/serial defect issues. Generator failures during 6–12 years of operation are mainly due to stator, rotor, bearings, and slip ring issues. A relatively high generator failure rate was noticed in the seventh and eighth years of operation.

Overall, the industry average annual failure rate is 2%, and the cumulative failure rate at the end of the 20th year of operation is 40%.

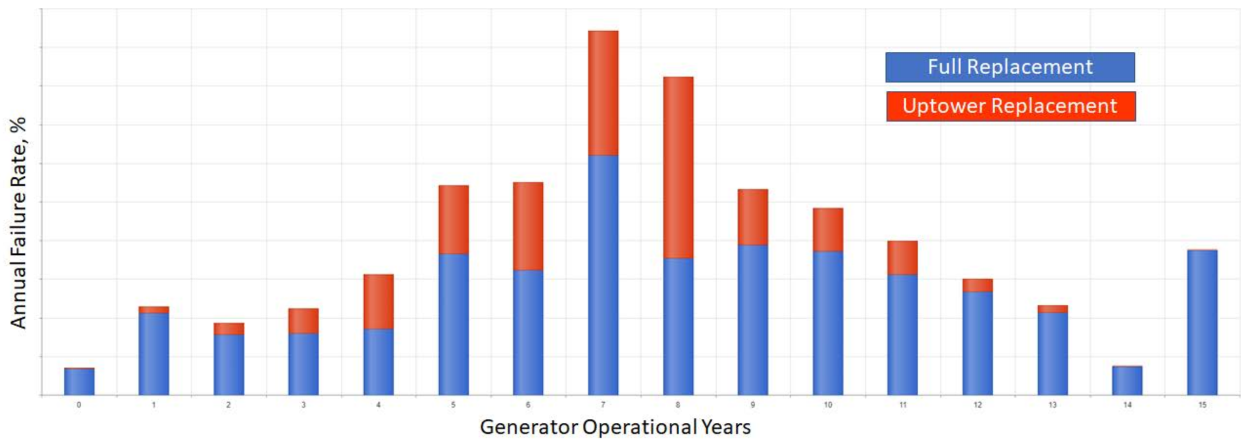

Figure 5: Wind turbine generator annual failure rate vs. operation years (data obtained from WinNER)

The failure modes and contributing causes of generator critical components are systemic. As shown in Figure 6 and Table 1, a combination of the failure modes and contributing causes can usually be identified for each failure. Based on this analysis, the critical components leading to premature generator failures are summarized as follows:

- Stator failure mainly due to loose core, windings, and/or slot wedge issues
- Slip ring (collector ring) failure mainly due to brush wear, fouled, and/or loose slip ring
- Rotor failure mainly due to loose core (Wye ring) issue
- Bearings failure mainly due to electrical discharge, fluting of raceways, slip, skidding, spalling, seizure, and/or fracture.

The critical component ranking order (Figure 6) may vary depending on the turbine model, generator supplier/technology (DFIG, SCIG), manufacturing location, and wind farm O&M.

A rotor winding interconnection to the slipring assembly is a common failure on DFIGs. The Wye ring failure (Figure 7) is an interconnection of slot coils as the diameter of the machine is traversed; again, it is related to rotor windings on doubly fed machines only. There are also numerous slip ring "scoring" incidents. Slip ring scoring can be thought of as a roughening of the slip ring surface where brushes contact the slip ring. This serves as an example of how the DFIG has a complexity level not required in the SCIG.

As stated earlier, there are no slip ring or brush assembly issues associated with SCIG. Additionally, there are no rotor winding interconnection issues like those identified on the DFIG. Despite the simplicity of SCIG, the turbines do suffer from what could be considered a design, material selection, or tolerancing issue. In SCIGs, magnetic slot wedges are notorious for failing

(Figure 7). Catastrophic failure of the stator winding on the non-drive end (NDE) of the generator is a common failure with SCIG.

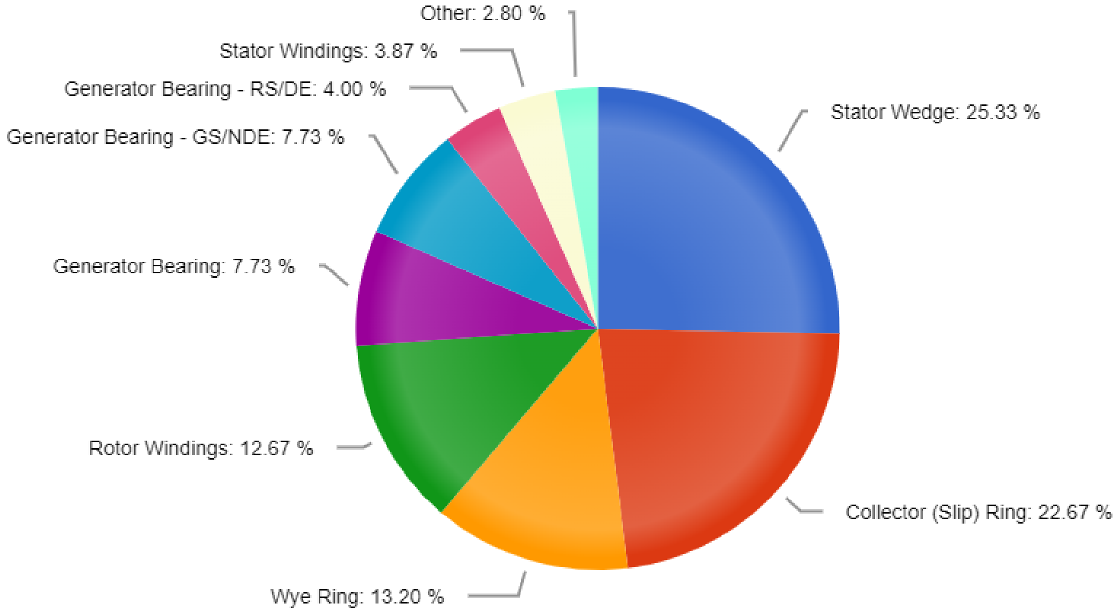

Figure 6: WinNER - Wind turbine generator critical components leading to premature failures

Table 1: Generator critical components, failure modes, and contributing causes

Critical Component	Failure Mode(s)	Frequency of Occurrence	Contributing Causes[a]
Bearing, Drive End (DE), and Non-Drive End (NDE)	Electrical Discharge, Fluting of Raceways due to Stray Currents	Medium/High	A,B,C,D,E,F,G,H,I,J
	Bearing Slip, Skidding, Spalling, Seizure, and Fracture	Medium/High	B,C,D,E,F,G,H,K,L
	Damage Debris in Lubrication	Medium	M
	Brinelling, Flat Spots	Low	N
	End Loading	Low	E,N
Drive (Rotor) Shaft	Pitting, Spalling	Low/Medium	B,C,D,E,F,G
	Fracture, Bent Shaft	Low	C,D,E,N,L
End Bracket, Retainer and Seal Drive End (DE), and Non-Drive End (NDE)	Loss of Concentricity to Generator Housing	Low/Medium	C,D,E
Rotor Core Assembly	Loose Core (Wye Ring)	Medium/High	B,C,D,E,F,L

Critical Component	Failure Mode(s)	Frequency of Occurrence	Contributing Causes[a]
	Winding Failure	Low/Medium	A,B,C,D,E,F,M
	Loose Pole, Coil Connections	Low	B,C,D,E,M
	Insulation, Lamination Failure, Over Temperature	Low	B,C,D,E,M
	Slot Wedge Slip	Low	B,C,D,E,M
Slip Ring/Commutator, Brushes, Holder	Loose Slip Rings	Medium/High	A,B,C,D,E,F,G,K,L,M,N
	Brush Worn, Fouled	Medium/High	B,C,D,E,G,L,M
	Brush Holder Worn, Damaged	Low	B,C,D,E,G,L,M
Shaft Grounding Brush/ Holder	Worn, Fouled Damaged Brush / Holder	Medium	A,B,C,D,E,G,L,M,N
Encoder, Coupling	Loose, Damaged Encoder or Coupling	Medium	B,C,D,E,L,M,N
Stator	Loose Core	Medium/High	B,C,D,E,F,L
	Winding Failure	Medium/High	A,B,C,D,E,F,M
	Loose Coil Connections	Medium	B,C,D,E,M
	Insulation, Lamination Failure, Over Temperature	Medium	B,C,D,E,M
	Slot Wedge Slip	Low/Medium	B,C,D,E,M
Power Cables	Failed Insulation	Medium	M,N
	Loose Connections	Low	M

[a] Legend for contributing causes:

Category	Contributing Cause(s)
A	Loss of ground, worn, fouled, damaged grounding brushes
B	Air gap out of specifications (spec)
C	Concentricity, rotor to stator
D	Imbalance of rotor, magnetic, mechanical
E	Bearing fits, out of specifications, worn, damaged
F	Lubrication failure
G	Misalignment with gearbox coupling
H	Interaction with power electronics
I	Speed fluctuation
J	Power (load) fluctuation
K	Thermal degradation of bearing steel
L	Rotor contact with stator
M	Thermal duress, over temperature
N	Shipping, transportation, storage

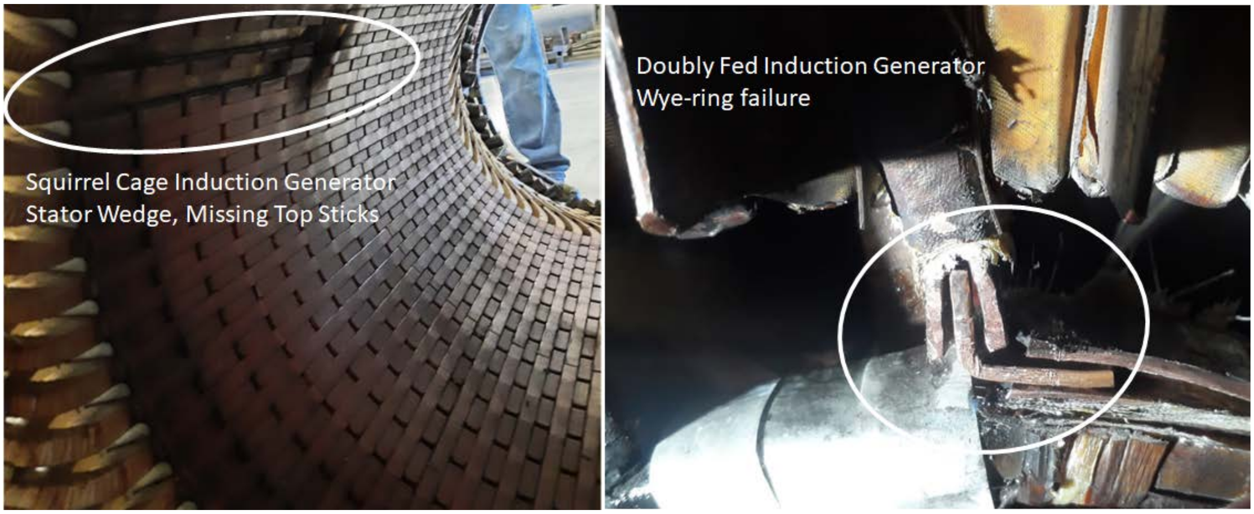

Figure 7: (left) Stator slot wedge failure in SCIG and (right) Wye ring failure in DFIG

Reliability Analysis – Financial Value

Detailed fleet-level, turbine-level, and system/component-level reliability analysis assists owners/operators with critical wind farm and turbine model identification, supplier selection, inventory management, serial defect identification, and rectification.

Historically, operators have mainly focused on tracking failure data only and using it for O&M budget allocation, not always leading to accurate results. It is important to track wind turbine generator healthy and failure data for reliability analysis and optimum O&M budget forecasting (Figure 8).

Reliability data can be used to compare with the original O&M model before site development and for predicting future site-level failures. Comparing actual vs. predicted major component failures and replacement costs can assist in improving O&M models for future site developments. It will also help identify the most critical components for each turbine type for reliability-based maintenance optimization.

Wind industrywide collaboration has enabled better insights into generator component health and reliability, and an understanding of turbine platform failure rates. This effort paired with operators' in-house component predictive capabilities has led to an improved understanding of generator component health/risk and a reduction in failure rates enabled by early detection and mitigation of catastrophic failures (Table 2).

For instance, supplier selections using reliability data can save \$2M–\$4M based on an average cost/replacement of a generator and gearbox at around \$225,000 and \$400,000, respectively, and reduction in failures across a 200-MW wind farm over the remaining 15–20 years. This cost estimate includes component, crane, and labor/travel.

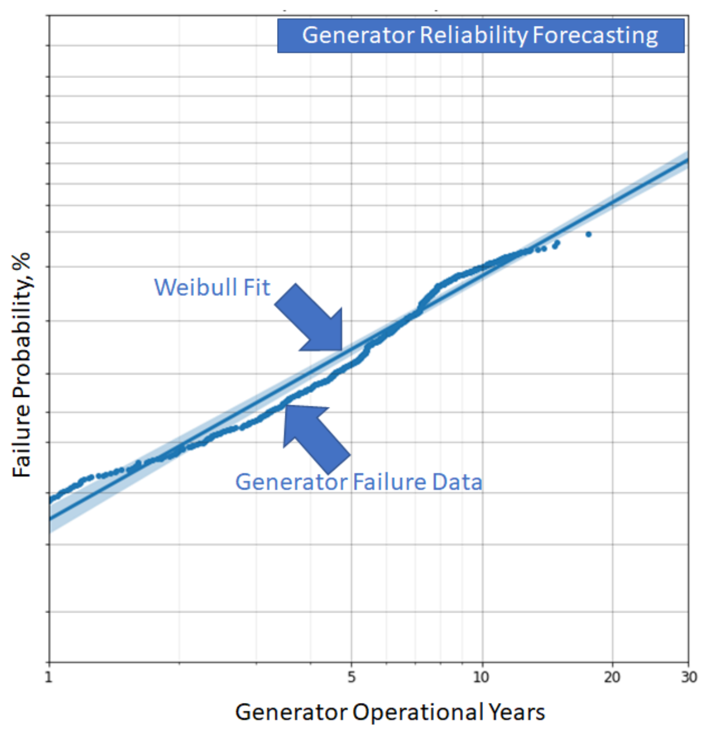

Figure 8: Wind turbine generator reliability benchmarking, and forecasting assists with O&M optimization

Table 2: Generator and gearbox reliability analysis: financial value at a typical 200-MW wind farm during its full life cycle

Wind Farm Issues	Implemented Actions	Financial Benefits
Low-quality parts	Supplier selections based on not just cost and availability but also reliability	\$2M–\$4M O&M cost savings at a typical wind farm by avoiding early failures and replacements
Major component expenses	Cost avoidance using condition-based maintenance tools in conjunction with reliability forecasting	\$1M–\$2M in cost savings/avoidance through predictive initiatives and maintenance and asset strategy optimization
Inadequate O&M budget allocation	Identifying critical wind farms that has higher failure rate assisted in allocating budget, parts and resources in a timely manner. This resulted in reduced downtime	Increase in annual energy production by \$150,000–\$200,000/year

Summary and Next Steps

The generator reliability and critical component analysis included in this paper is based on 44.2 GW of data that were collected from owners/operators and Shermco Industries. These data revealed failure modes associated with specific generator types, and these results are extended to generator life expectancy and financial value.

There are two potential collaborative efforts going forward: The first proposed effort focuses on expanding the WinNER reliability database to support the growing needs of owners/operators in reducing their O&M costs. The second proposed effort is straightforward in that it suggests the writing of a generator specification for wind farm owners. The purpose of this is to make owners aware of detailed issues associated with generator selection and design (temperature rise, bearing designs, etc.) and to use such a document in communicating with turbine suppliers. Such a specification would address the major issues associated with design, operating environment, supplier quality, etc. There are benefits to wind farm owners taking a more aggressive, detailed position early in the turbine specification process and specifying in more detail critical generator issues with the turbine suppliers.

Lastly, it is worth noting that this paper has focused on onshore turbines, as this is the dominant installed base in the world. In the offshore installations, generator maintenance methods and cost are a very important consideration. Offshore generators tend to be quite large and are difficult to remove from the turbines. Entirely different maintenance and repair rules will be required for offshore turbines, which could lead to another collaborative effort going forward to attempt to minimize these future O&M costs. Significant knowledge can be gained from the historical onshore operation and maintenance records, and this needs to be incorporated into new offshore wind turbines.

> *"Duke Energy is using advanced analytics to improve its commercial renewables availability and reliability. EPRI's WinNER and input has enabled optimization of our asset's performance for our company and our customers."*
> *—James Bezner, Director of Commercial Operations, Duke Energy*

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EPRI Resources

Raja V. Pulikollu, Ph.D., Technical Executive, rpulikollu@epri.com

Brandon Fitchett, Program Manager, bfitchett@epri.com