GE Generator Fleet Experience and Reliability

AUTHORS

Janusz Bialik
GE Vernova
Baden, Switzerland

Simon Baldasera
GE Vernova
Newcastle, UK

Ian Hughes
GE Vernova
Schenectady, NY

Joe Worden
GE Vernova
Schenectady, NY

GER 4223

March, 2023

INTRODUCTION

The purpose of this article is to provide an update on generator reliability with focus on the time to rewind based on cooling technology for the GE generator fleet. Since the 19th century GE has manufactured and placed in service over 16,000 medium and large power generators, with approximately 12,000 still in service today. By utilizing progressive designs and developing reliable materials that have been proven in many installations, GE has amassed reliability records for generators that have provided decades of sustained service. Unless otherwise specified when GE generators is mentioned, it includes both legacy GE and legacy Alstom configurations. See Appendix A for a history of legacy consolidations.

The 1980s through early 2000s saw a dramatic growth in the building and upgrading of turbine-driven generators driven by the need to reduce maintenance on aging fleets, while also adding reliable power at minimal cost. As today's operators face the same urgent requirements plus increased number of cycles in load and starts due to renewable energy, the pace of the build and upgrade activity continues.

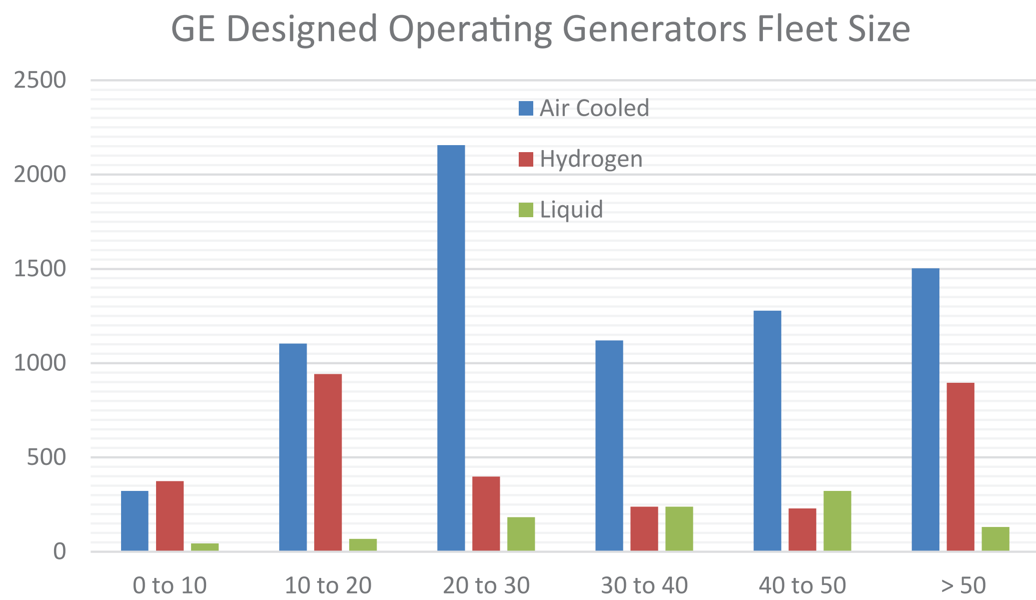

Figure 1 - GE Generator Fleet Demographics

GENERATOR FLEET DEMOGRAPHICS

Many generators currently in service are 25 years old or older. Figure 1 represents all GE generators in service, regardless of design or size, grouped according to age segments.

All generators can be subdivided into three main groups: air-cooled, hydrogen-cooled, and water-cooled generators designed and manufactured by GE. Generators have been manufactured in the range rated from 100 to 1600 MVA. The nucleus of this fleet is the hydrogen-cooled stator winding design generators.

REASONS FOR GENERATOR UPGRADES AND REWINDS

When evaluating generator upgrade alternatives, plant operators must consider many alternatives, including:

- Planned service life
- Baseload or start-stop cyclic duty
- Load requirements (megawatts and megavars)
- Reliability requirements

Using these critical parameters to establish the type and extent of the required upgrade, GE performs a comprehensive review of the total generator design and offers a variety of upgrades that can meet the objective. This review includes the requirements for the generator coolers, excitation system, auxiliaries, and monitoring systems, as well as the stator and rotor windings.

While the intended use of the unit will provide guidelines for the rebuild, the existing condition of the equipment is usually an equally important factor in determining the extent of the rebuild that is necessary. Proper maintenance on a regularly scheduled basis as recommended by the OEM will help retain the excellent reliability of GE turbine-generators. Conversely, lack of regular maintenance, not following the manufacturer's instructions, or operating the generator beyond the prescribed limits can result in accelerated wear and the need for more extensive rebuild later.

This paper also refers the reader to relevant GE publications that address generator reliability concerns in more detail—including GER-4212 (Generator Rotor Design, Operational Issues and Refurbishment Options) and GER-3751 (Understanding, Diagnosing and Repairing Leaks in Water- Cooled Generator Stator Windings). In addition to these reference publications, GE maintains a continually expanding knowledge base of best practices and advanced technology procedures—based on our up-to-date experience with worldwide fleets—that can be applied to generator upgrades and rewinds. This enables GE to provide customers with coherent and comprehensive generator protection systems as part of our full-service offerings.

In recent years there has been a noticeable increase in the number of generator forced outages and planned stator and rotor rewinds. While a variety of reasons contribute to these increases, two key causes have been clearly identified: operational incidents and aging of the generators. Since age is the most common cause of generator failures, this paper primarily focuses on aging generators and optimum solutions to improve their reliability.

GENERATOR RELIABILITY AND AGING

Older units constitute an increasingly higher percentage of installed industry capacity and reserve margins on typical systems—and they represent an important segment of the industry. Examination of industry data reveals several important facts about this segment.

Figure 2 illustrates a typical trend of component failure rates with age for one manufacturer. Though highly reliable, turbine-generator units are not immune to age deterioration. Most technical equipment exhibits a basic pattern of failure rates, which is commonly referred to as a "bathtub" curve. For example, after an initial operating period called the "debugging" stage, the power generator has a normal operating period where unit reliability remains fairly constant. However, after many years of service the failure rate tends to increase in the "wear-out" period. Replacement of the worn components will improve reliability of the generator, resetting the failure rate, as shown on Figure 3.

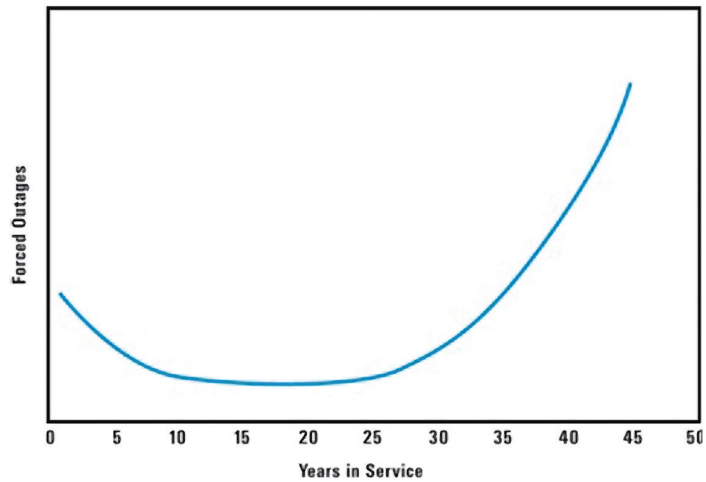

Figure 2

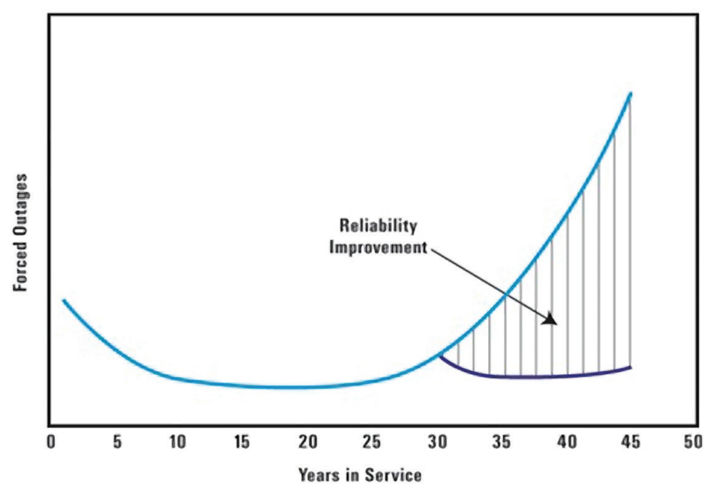

Figure 3

Consistent with the increase in the number of older generators in service, there has been an increase in the number of forced outages for GE generators. This increase in the number of forced outages noticeably coincides with the aging segment of GE's generator fleet as it moves towards the rising edge of the "bathtub" curve. The following represents some examples of types of root causes for rewinds.

Top Reason for Stator Rewinds:

- Grounds
- Shorts
- Mis-operation
- Corona (slot) – Primarily air-cooled generators.
- Bar Armor Damage / Degradation
- Insulation Damage / Degradation
- Stator Bar Insulation Abrasion

Top Reasons for Rotor Rewinds:

- Grounds
- Shorts
- Main Terminal Stud Failures
- High Vibrations
- Thermal Sensitivity
- Insulation Migration / Damage
- Amortisseur Migration / Damage
- Contamination / Foreign Object Damage (FOD)
- Pole to Pole Connector Damage
- Coil to Coil Connector Damage

While there are several reasons that can cause generator outages such as improper maintenance and catastrophic events failures caused by worn generator components can be clearly distinguished. GE has created reliability models based on actual data, which allows for clear risk definitions. See Appendix B for more details on how GE uses these models during reliability studies.

HOW TO IMPROVE RELIABILITY OF AGING GENERATORS

The preceding information leads to the question, "What is needed to prevent a forced outage and to extend the operating life of a generator?" To answer this question and make a meaningful assessment of the condition of an operating unit, a thorough inspection and test must be performed. In addition to these procedures, GE also reviews inspection reports from prior years to look for evidence of mechanical or electrical wear, distress, and aging. By comparing the inspection results of a particular generator with our database of information for similar units, GE can identify components likely to impact the generator's future reliability and make corrective recommendations.

If a unit has not had an inspection for several years, or there has been a recent incident that potentially affected the condition of the generator, it would be prudent to perform an inspection before making any final decisions on rebuild workscope. This could avoid a forced outage and an extended rebuild workscope. If a customer has several GE generators, GE may also perform a fleet study, addressing the upgrade and reliability options applicable to all of them.

REWINDING FOR HIGHER OUTPUT AND EFFICIENCY

While nearly all the generator components may be upgraded during the service life, stator and rotor rewinds are by far the most convenient and powerful means of achieving both a higher efficiency and a higher output.

Rewinds always present an opportunity for the original equipment manufacturer to enhance the performance of the machine and support a turbine uprate. The economics of such design upgrades can often help to justify the cost of the rewind activity. By considering the vintage and type of the original machine design, turbine output, and uprate objectives, GE can develop an optimized solution that is specific to the generator.

REWINDING FOR RELIABILITY

Stator Rewinds

Advances in non-metallic materials, insulation systems and composites allow significant reliability improvements and life extension to be achieved by replacing old materials that are approaching the end of their useful lives. Since the insulation is life-limited, by replacing the stator winding with a new one it is possible to reset the "time clock" on the stator winding. Beyond simple replacement of materials, significant reliability enhancement can be obtained through upgrading the design of the winding insulation and the winding support system. With the new winding GE will design and supply the new stator slot support system as well as the end winding support.

One goal of this paper is to display trends in the stator and rotor rewinds, based on GE experience. The rewind experience data for stators is given in Figure 4, Figure 5 and Figure 6. Major drivers for these rewinds were end of life and reliability improvement. Other reasons included test failures, operational incidents, system faults, output increase and environmental causes.

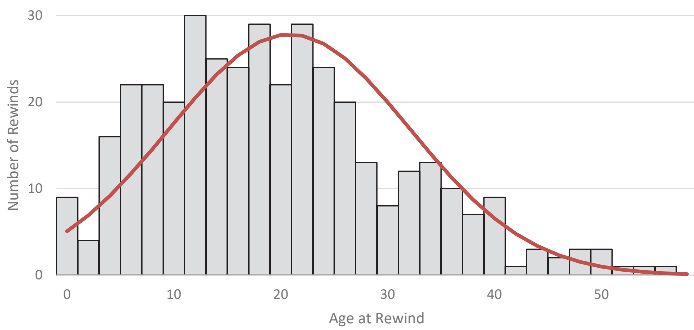

Figure 4 - Air-Cooled Generator Stators

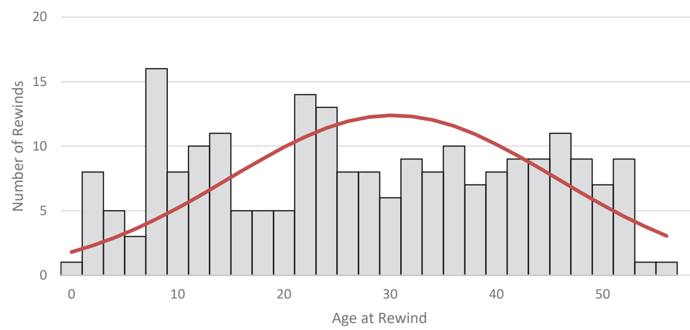

Figure 5 - Hydrogen-Cooled Generator Stators

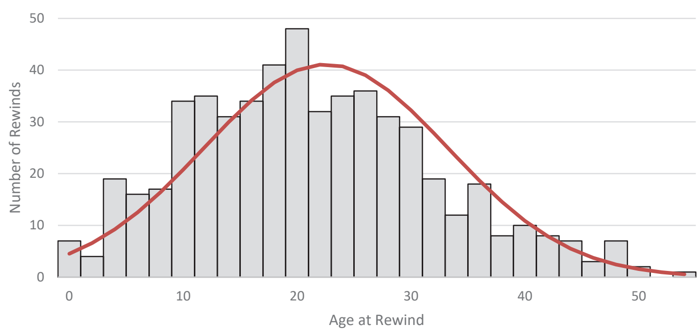

Figure 6 – Liquid-Cooled Generator Stators

Though a variety of reasons have resulted in these stators to be rewound, the histograms in Figure 4, Figure 5 and Figure 6 show a difference in median time to rewind due to different failure modes and operational profiles.

Rotor Rewinds

Experience has shown the generator rotor is a component that requires maintenance. This is not surprising considering that it is operating under very high centrifugal load and thermal cycling. Also, typical operating incidents have the greatest impact on the rotor (motoring, contamination, etc.). Rebuild of the rotor normally focuses on re-insulation of the rotor winding.

However, owners should not lose sight of other considerations. Load level, type of duty, turning gear time, and number of stop-start cycles are the main factors affecting the wear of the generator rotor windings. Other factors include prime mover type (gas or steam turbine), ambient air conditions (for air-cooled generators), cooling and maintenance of a generator.

It is common for older units to be operated at lower power factors to carry more reactive power. Frequent load cycling common for the peaking units also may contribute to accelerated wear and distortion of the rotor winding, and, at times, lead to a rotor current sensitive vibration – thermal sensitivity. (GER-3809 [Generator Rotor Thermal Sensitivity: Theory and Experience] provides a detailed description of this phenomena). A complete replacement of the old rotor winding may be preferred as a retrofit option in such cases.

Reliability of the generator rotor is increased with a rewind. New modern insulating material will replace the original worn out insulation and address the latest service concerns. Conversion from indirect to direct cooling of the rotor may also be affected to permit uprating the generator. GE publication GER-4212 may serve as a good guide for selection of a proper rotor retrofit options.

Due to the multiple causes for the rotor winding degradation, the age in years of a generator rotor serves as a primary time factor to determine when to refurbish. Other factors are known shorts, high rotor vibrations and the other failure modes mentioned previously. Distribution of the time to rewind is presented by age and cooling technology in Figure 7, Figure 8 and Figure 9.

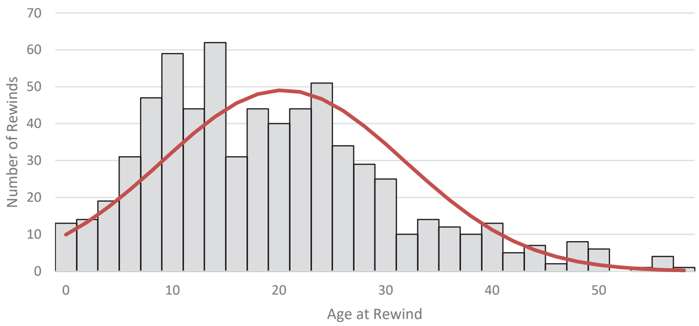

Figure 7 - Air-Cooled Generator Rotors

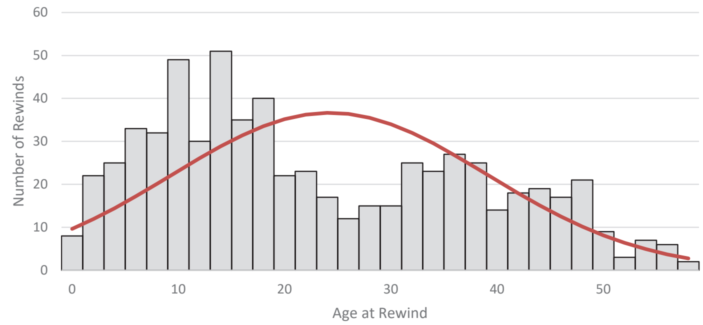

Figure 8 - Hydrogen-Cooled Generator Rotors

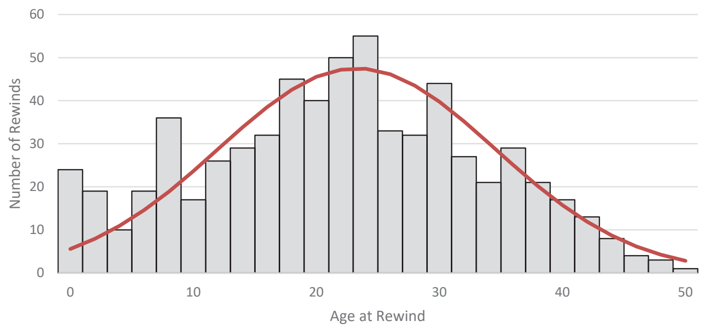

Figure 9 - Liquid-Cooled Generator Rotors

Monitoring the generator condition, testing and inspections performed on regular intervals as recommended in GEK 103566 and other GE publications will determine the actual condition of the rotor winding, wedges, balance weights, journals, retaining rings and other generator components.

If a generator is due for an upgrade—which may not be performed immediately—a good practice would be to stock a rewind kit. This will reduce the downtime in the event of emergency.

If not used for an emergency, the kit may be used later at the time of scheduled outage.

GENERATOR SERVICE ISSUES AND GE RECOMMENDATIONS

Not all generator service concerns require that the stator or rotor be rewound. Careful attention must be paid to the generator auxiliaries, exciter, collector and brushes, hydrogen seals, frame, end shields, water-cooling system, and hydrogen system. Time and wear of the generator components has a combined effect on the generator availability.

Some of the most common stator repairs:

- Connection ring and end winding dusting
- Loose ties and blocking
- Loose stator wedges (rewedges and tightening)
- Corona erosion repairs
- Mechanical damage to insulation repairs
- Hydrogen seal repairs / replacement
- Bearing repairs / replacement
- Stator cooling water system issues

Some of the most common rotor repairs:

- Collector ring issues (flash over, broken brushes, surface finish damage, uneven wear, etc.)
- Slot component migration
- Brushless exciter (ground fault detector, diodes, etc.)
- Journal surface finish issues
- Main terminal and collector stud issues (seals, broken leaves, loose nuts, etc.)
- End winding blocking
- Bore copper
- Pole to pole and coil to coil connectors
- Retaining ring insulation.

GENERATOR HEALTH MONITORING

Today's GE Generator Health Monitoring (GHM) enables the monitoring and trending of some key aging and wear mechanisms allowing the customer to have the time to plan inspection timing and scope while managing risk. Some monitoring options include but are not limited to:

MONITOR	TREND/DEFECT
Partial Discharge Analysis	Stator aging and wear
Temperature	Constantly monitor the generator temperatures in line with the operating conditions, trending deviations from design
Rotor Flux Probe	Number and location of turn-to-turn shorts in the rotor winding
Rotor Shaft Voltage	Continuously monitors the generator rotor shaft for induced voltage, inductive and capacitive disturbances
End Winding Vibration	Continuous monitoring of stator end winding vibrations
Stator Leakage Monitoring System for Liquid Cooled Stators (SLMS)	Detect hydrogen leakage into the Stator Cooling Water System and maintain the oxygen content

Visit https://www.ge.com/gas-power/services/generators/inspection-services/generator-health-monitoring to learn more about the GE Generator Health Monitor.

CONCLUSION

A recent increase in the number of forced outages can be attributed to the aging of GE's generator fleet. With many of these generator units approaching 25 years or older, early diagnosis and correction of a problem is important for reliable operation. The best approach in preventing forced outages is a proactive one.

Based on the expertise and knowledge base accumulated from our worldwide fleet of generators, GE can help customers determine the optimum reliability solution for their specific units with a comprehensive range of offerings that provide everything from maintenance and monitoring through upgrades and rewinds.

Though there is no hard data pointing to a date when a generator must be rewound, GE recommends following relevant publications such as Technical Information Letters and reference manuals that correspond to a particular unit. The GE outage intervals and inspections recommended are listed in GEK 103566.

Some data material presented in this paper may also be used as a trend indicator. The most common and proven generator upgrades and repair solutions offered by GE have been formalized in our Generator Source Book offerings. These articles are available through your area sales representative.

REFERENCES

GER-3751 Understanding, Diagnosing and Repairing Leaks in Water-Cooled Generator Stator Windings

GER-3809 Generator Rotor Thermal Sensitivity: Theory and Experience

GER-4212 Generator Rotor Design, Operational Issues and Refurbishment Options

GEK 103566 Creating a More Effective Generator Maintenance Program

APPENDIX A – LEGACY FLEET INFORMATION

The figure below illustrates the consolidation of legacy fleets that occurred over time under Alstom and then GE.

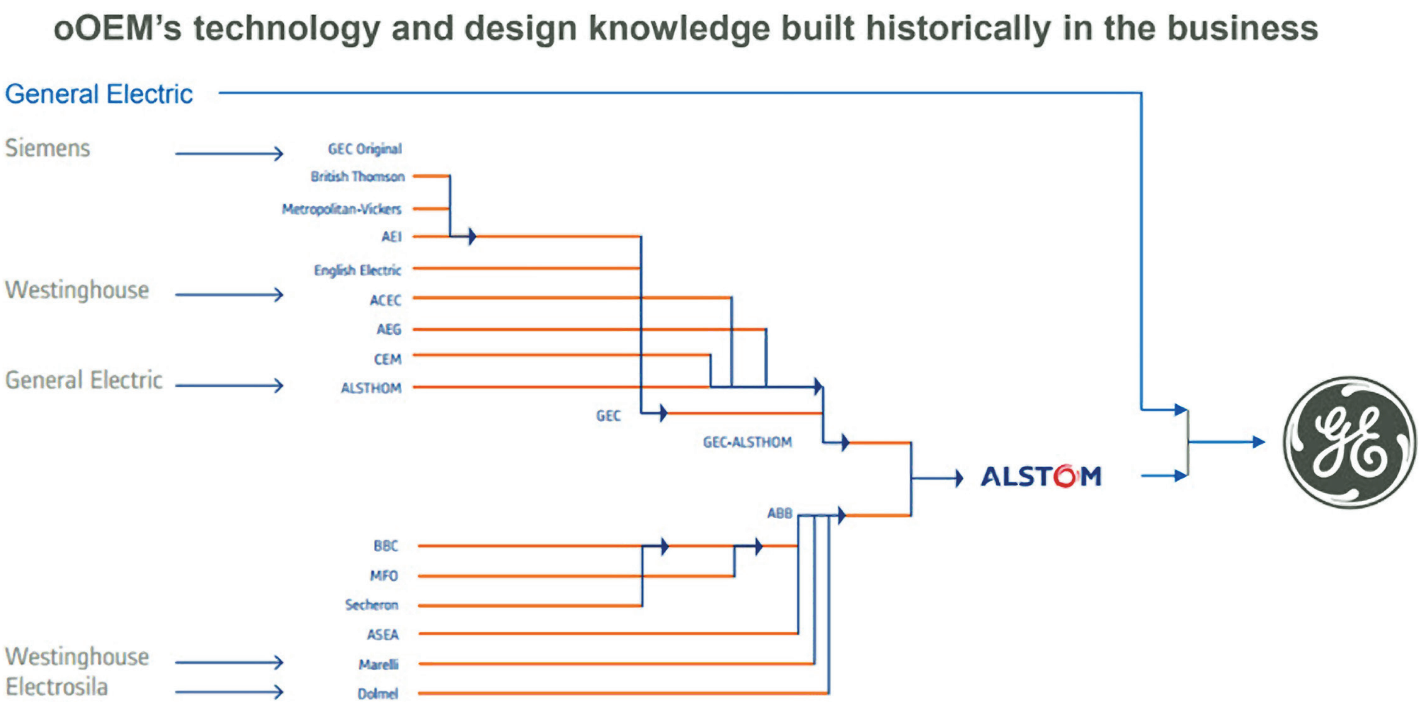

Figure 10 – Legacy Fleet Consolidation

APPENDIX B – GENERATOR RELIABILITY STUDIES

GE has used extensive feedback from worldwide operations to develop reliability models for its generator fleet. These models cover the critical failure modes that are experienced by the generator. They offer customers insight into the reliability of other equipment in the field employing the same designs and operating regimes. Unit specific failure risk can be established from these models by a review of operations and maintenance history specific to the customer unit. Risk projections can be made for future outages, helping customers to plan and budget for future repairs. The process of how a reliability study is performed for a unit is demonstrated in Figure 8.

Generic Reliability Study Process

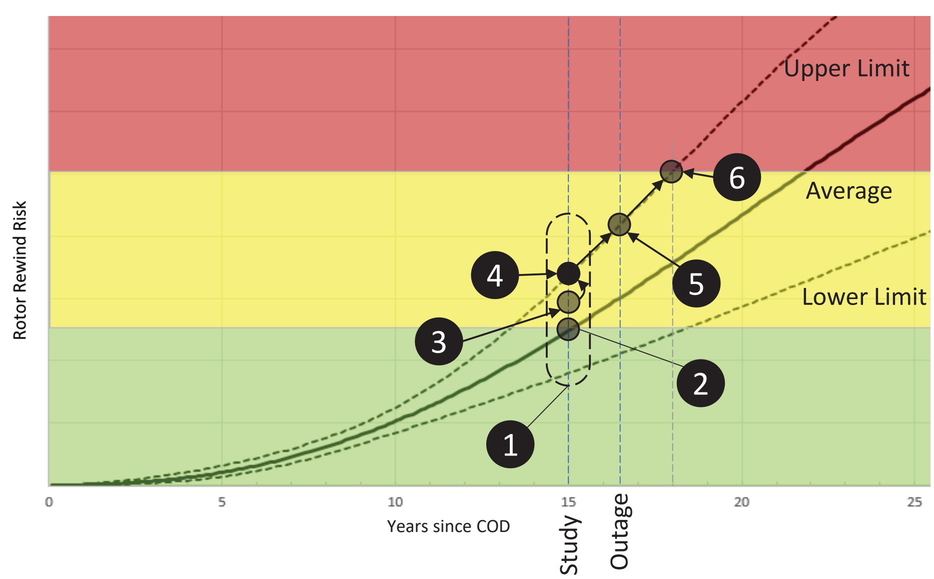

Figure 11 – Reliability Study Process

Steps

1. Based on the age of the insulating system determine area of the starting point on the model specific graph.
2. Start on the fleet average curve.
3. From the hours of operation per year and starts per year adjust from the starting point. In this example based on hours of operation per year and starts per year the unit is moved between the average and upper curve.
4. Review outage reports and test and adjust from point 3. For this example, during an inspection the rotor had insulation migration in the end winding and a few shorted turns were found recently by a flux probe test. Thermal sensitivity analysis did not indicate any issues. Based on this information the rotor would be moved to the upper limit.
5. Project out to next known outage.
6. Determine when the unit will cross into the high risk zone.

A case study below demonstrates GE's modeling capability.

AN ACTUAL CASE STUDY

The reliability model developed represents when a rotor winding has failed in the field, leading to a removal and rewind, partial or full, of the rotor winding. Rewinds are labor intensive activities, as the rotor needs to be removed from the stator and often shipped to the nearest workshop for repairs. In this case study, the material and repair cost impact by doing a generator rotor rewind in planned fashion, as opposed to having an unplanned/reactive event, is reduced by a factor of 3 approximately. In addition, by avoiding an outage reactive event, the duration of the outage is reduced by about 20 days. Both savings on repairs and downtime significantly reduce potential revenue losses.

The rotor winding reliability model for this case study is shown in the figure below. The model consists of 100 units of similar rotor winding design. The operational risk profile is represented by three color bands during the operating lifetime of the rotor winding:

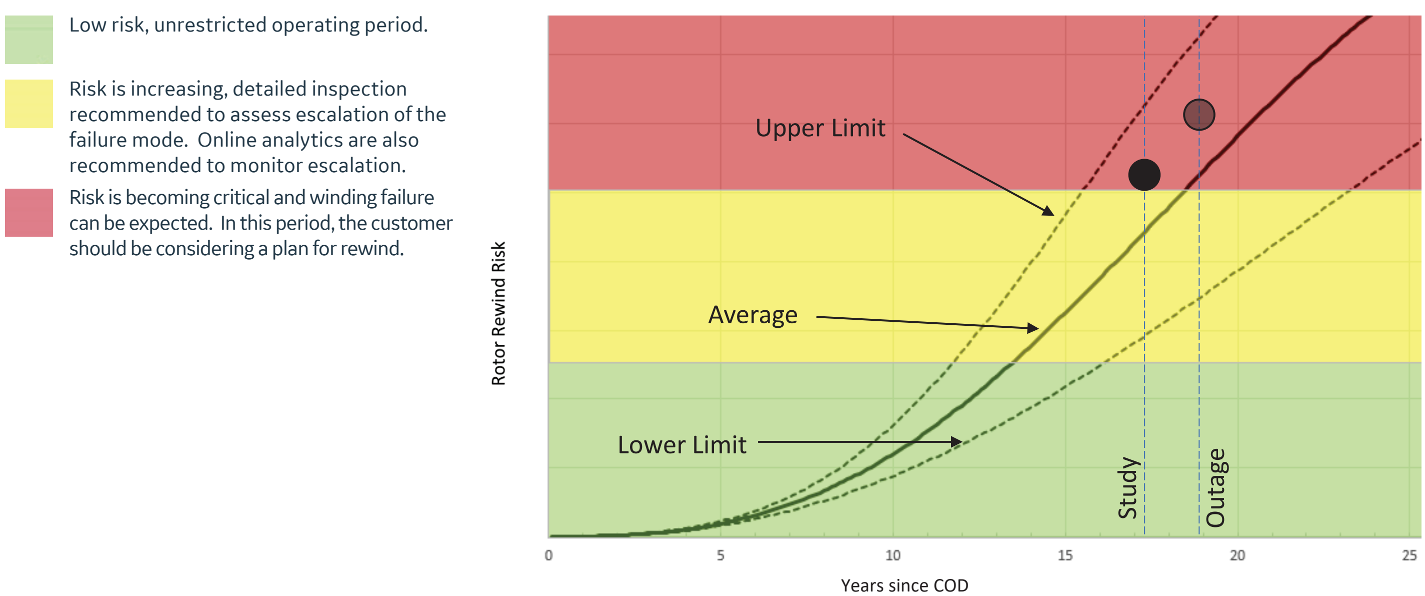

Figure 12

TIMELINE OF EVENTS FOR THE CASE STUDY

- 18m Prior To Outage: Performed initial outage planning and risk analysis.
- 12m Prior: Customer informed that the generator operational risk as defined by the reliability model was moving into the red zone. Prior inspection had also shown indications that the health of the rotor winding was deteriorating in-line with the reliability model. Customer informed of cost comparison scenario (planned rewind vs run to failure).
- 3m Prior: Vibration indicators on the rotor started trending upwards. The vibration indicators in combination with other operational parameters showed that the rotor was experiencing thermal sensitivity, which is consistent with the failure modes associated with the reliability model. The customer could now see the operational performance of their generator deteriorating in line with the predictions from the reliability model. All these factors together gave the customer enough information to support a decision to perform a full rewind on the rotor. A local rewind facility was contacted and plans for rewind were instigated.
- 1m Prior: Final logistics planning on removal and transportation of rotor.
- Outage: Rotor removed and transported to the local facility for rewind during a planned outage on the HRSG. Rotor returned to site, ready for installation and return to service.

In this case study, the customer was given insight into the reliability of other equipment in the field employing the same rotor design and operating regime. They were able to combine this knowledge, along with operational indicators from their own equipment to support a decision to perform a full rewind on the rotor. This enabled them to have sufficient planning time to arrange a rewind during a planned outage on the HRSG, reducing rewind costs and reducing downtime which could have been experienced due to a forced outage.

Stator reliability studies are performed in a similar manner as the rotor study mentioned above. The lead times for obtaining stator rewind material, specifically stator bars, is significantly longer than it is for rotor rewind materials. When a stator approaches into the high risk zone it is prudent to procure a set of stator bar and long self-life materials. Another thing to consider is timing of the next outage and its duration.

GER 4223 (3/2023)