GE Energy

Generator In-Situ Inspections

A Critical Part of Generator Maintenance Cost Reduction

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Introduction

This paper compares in-situ inspection techniques that allow testing with the rotor still installed, to rotor-out inspections. While in-situ inspections provide an alternative to pulling the generator rotor, additional electrical testing is required, at a minimum, to provide a thorough inspection. Other additional tests may be indicated via a Technical Information Letter (TIL) or based on past unit history.

As the increasingly competitive marketplace forces the power generation industry to reduce operating costs, equipment maintenance programs are under increased fiscal scrutiny. Plant maintenance programs, based on periodic disassembly and inspection of critical turbine-generator components, have proven remarkably effective—as evidenced by the industry's consistently favorable plant reliability and availability statistics. However, many plant operators are looking for ways to lower cost while maintaining reliability.

As a leading manufacturer of turbine-generators and a major supplier of power generation services, GE is assisting operators in this objective by:

- Developing improved monitoring and diagnostic instrumentation for online predictive maintenance, allowing for better outage planning and scope control
- Updating equipment maintenance recommendations based on GE's fleet experience
- Developing inspection tools and services that facilitate rapid offline assessment of equipment conditions

Industry insurers also have a vested interest in these objectives and are understandably reluctant to assume greater risks by deviating from proven maintenance practices. Consequently, insurers review proposed plant maintenance protocol modifications with operators and often require supporting recommendations and other evidence from Original Equipment Manufacturers (OEMs) that new protocols are functionally equivalent or superior to the traditional.

This paper offers a comparison of the results, advantages and limitations of GE's modified inspection protocol for generators utilizing in-situ inspection tools compared to a traditional inspection with the rotor removed.

In-Situ Inspection – A Critical Part of Generator Maintenance Cost Reduction

Visual and quantitative inspection techniques play an important role in assessing generator condition. Online monitoring and diagnostic techniques are limited in detecting potential problems such as bar movement and vibration, component damage, copper dusting, coil distortion, and foreign object damage (FOD). Since many of these conditions can lead to a major equipment failure if left unresolved for a period of time, periodic visual inspections are needed to supplement online monitoring and diagnostics. In-situ inspection offers an economical alternative to the traditional rotor pull inspection. Table 1 lists typical generator-related inspections and when they occur in a traditional maintenance plan.

During minor outages, in-situ inspections can be used to assess generator condition and help plan generator maintenance at future outages. The inspection results can indicate if the field will need to be pulled and which components will require maintenance during current or future outages. If the generator condition is acceptable, the field can remain in place and a future in-situ inspection can be planned. GE's in-situ inspection techniques can also be used with traditional inspection and test techniques to provide a complete "major" inspection without field removal.

GE's recommended standard tests for a major outage are described in Technical Information Letter-1154 and GEK-103566. When generator problems are known or suspected to exist, applying

	Continuous Online	Periodic Online	Minor Outage	Major Outage
STATOR				
Stator Wedge Tightness				X
Bar Movement				X
Stator Winding Leaks	**SLMS**		X	X
Core Insulation				X
Stator Winding Insulation Integrity	**ePDA**	**PD**	X	X
Greasing				X
Cracked Connections/Integrity			X	X
Oil Contamination			X	X
HV Connection Bolts			X	X
FIELD				
Blocked Vent Ducts				X
RR NDT				X
Field Coil Distortion			X	X
Field Coil Loose Blocks			X	X
Field Wedge Migration				X
Field Winding Insulation Integrity	**STMS**	X	X	X
Thermal Sensitivity		X		
Rotor Surface Heating				X

Table 1. Generator inspection items

STMS: Shorted Turn Monitoring System – continuously monitors a flux probe and sends an alarm when a shorted turn is detected
ePDA: Enhanced Partial Discharge Analysis – continuously monitors the generator and takes partial discharge data at specified intervals for later analysis
PD: Traditional Partial Discharge Testing where data is taken by a technician
SLMS: Stator Leakage Monitoring System – continuously monitors stator cooling water for the presence of hydrogen indicating a leak

periodic in-situ inspections can postpose the need for field removal until a more convenient time. When abnormal operation such as a negative sequence event warrants a "suitability for service" inspection before the generator can be returned to service, the in-situ inspection is a valuable tool for providing a quick, accurate, documented inspection with minimal generator disassembly. In-situ inspection reduces overall outage duration while gathering high-quality condition assessment data.

Guidelines for Choosing In-Situ Inspection Versus Pulling the Rotor

One question frequently asked is "What if the in-situ inspection finds something and I have to pull my field? I wasted time and money on the in-situ inspection." The answer to this question can be found in previous inspection reports and the operating history of the unit. If there is any indication that the rotor needs significant repair (such as multiple shorted turns, a field ground or thermal sensitivity), then the rotor should be pulled. Similar judgements should be made regarding the stator. However, if the unit has had no known problems and previous inspections have not indicated any issues, then an in-situ inspection is appropriate. GE experience reveals that 1 percent of in-situ inspections uncover an issue which requires that the rotor to be pulled. In many cases, conditions requiring repair are found early enough to allow the repair to be postponed until the next planned outage. Conditions found by in-situ inspections that required the rotor to be pulled for repairs include foreign object damage, damage from negative sequence events, failure of electrical testing indicating the need for rotor rewind, and loose wedges. These conditions are listed in order of highest to least prevalence.

Since GE's goal is to ensure the generator runs trouble-free to the next outage, any significant problem will bring a recommendation to pull the rotor and complete the necessary repairs. For maximum benefit, the in-situ inspection should be planned as early as possible during the outage so that any necessary repairs can be carried out during the planned outage, or at worst, the inspection will cause the minimum delay to restart.

In-Situ Inspection Technologies

GE's in-situ generator inspection capabilities (listed below) were developed to address areas requiring field removal for inspection (Figure 1).

- GE's proprietary Miniature Air Gap Inspection Crawler (MAGIC) system
  - MAGIC Visual Inspection
  - Stator Wedge Tightness Assessment
  - Electromagnetic Core Imperfection Detection (EL CID)
  - Borescope Inspection
- Remote Capacitance Probe
- Retaining Ring Non-Destructive Evaluation (NDE) Scanner
- Other tests and inspections, including electrical testing and hydraulic testing

The in-situ inspection consists of the basic MAGIC visual inspection as well as one or more additional tests or inspections based on the circumstances and customer needs. Table 2 lists critical generator components and the in-situ inspection techniques used for each.

Note: While a borescope inspection is a normal part of a MAGIC inspection, it may also be performed independently. This is typically done when a fast assessment of the generator, especially the end regions, is desired after an event outside of normal operation.

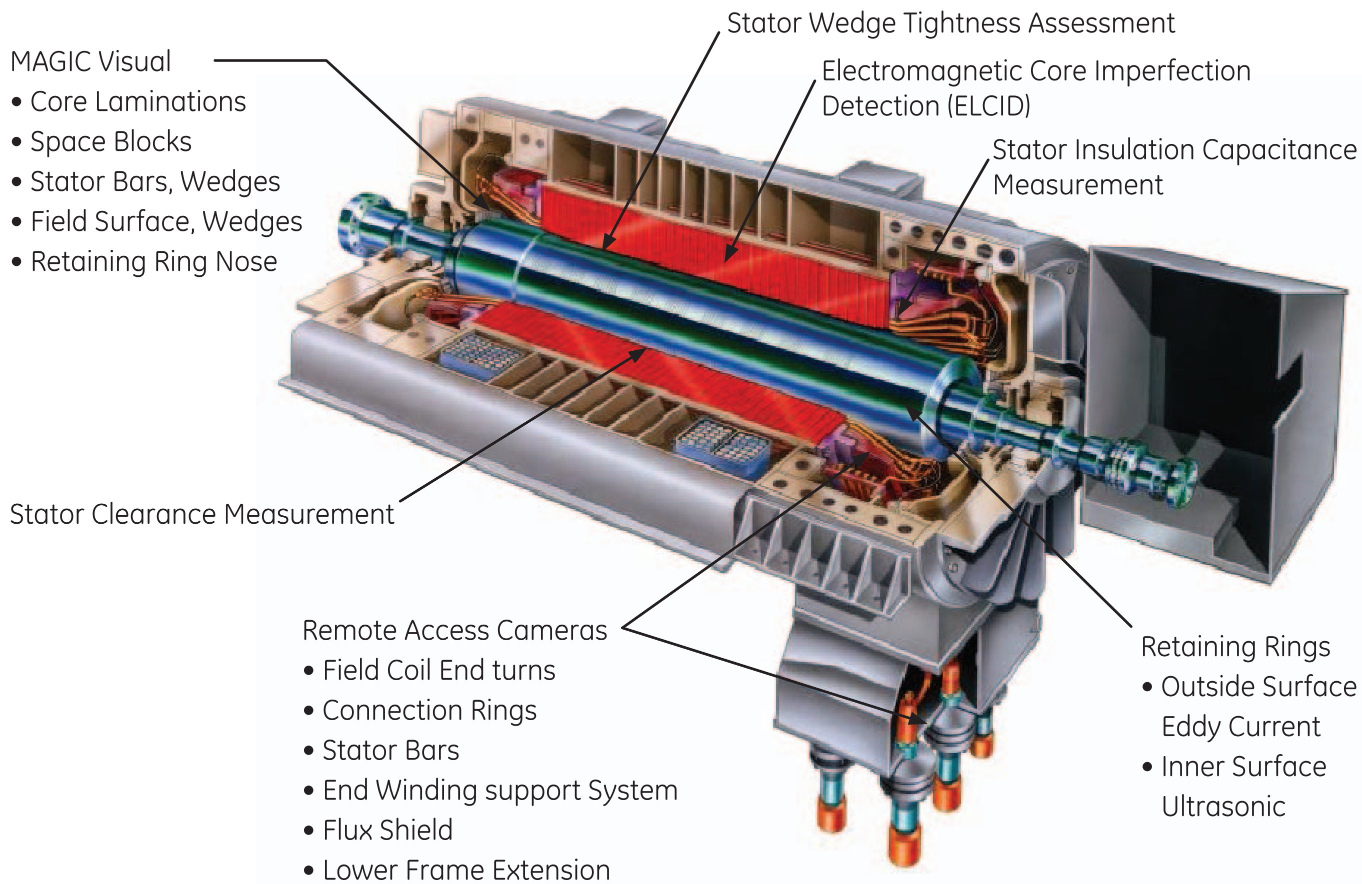

Figure 1. Generator in-situ inspection capabilities

Component	Common Problems	MAGIC Visual	Borescope Visual	Wedge Tapping	ELCID	RR NDE	Capacitance	Clearance Meas.
Stator/Core								
Core Laminations	Foreign object damage, hot spots, evidence of movement	X			X			
Space Blocks	Migration, cooling passage blockage	X	X					
Gas Gap Baffle Studs	Cracked welds, looseness	X	X					
Stator Wedges	Looseness, loss, sparking damage	X		X				
Stator Bars	Foreign object damage, sparking, girth cracks, movement	X	X					X
	Wet groundwall insulation						X	
End Windings and Connection Rings	Bar movement, loose/broken ties, supports, etc., excessive corona activity		X					
Copper Flux Shield	Overheating, looseness, general condition		X					
Instrumentation	RTD, thermocouple wiring ties, flux probe, general condition		X					
Field								
Field Surface	Heating, arcing, foreign object damage	X						
Body Weights	Looseness, staking	X						
Field Wedges	Arcing, migration, cracking	X	X					
Retaining Ring	Wedge contact, arcing, foreign object damage, material cracks, pitting	X	X			X		
Coil End Turns	Blocked ventilation, damaged insulation, coil distortion, contamination		X					
General								
All	Excessive oil or other contamination, foreign object damage, blocked cooling	X	X					
Lower Frame Ext. Bus Leads and Connections	Insulation condition, connection integrity (if exposed), high voltage bushing condition		X					

Table 2. In-Situ Inspection capabilities

Miniature Air Gap Inspection Crawler (MAGIC)

The cornerstone of the MAGIC system is its visual inspection capability. In addition, the system can perform a stator wedge tightness assessment and ELCID testing.

MAGIC Visual Inspection – Trained specialists can use GE's exclusive MAGIC robotic devises to perform a visual inspection of the generator stator and field within the bore region. GE now offers three different MAGIC robots that allow the inspection of generators in a variety of sizes.

Each crawler robot is a precision device that carries two high-resolution video cameras through the gap between the stator core and field. Full inspection coverage of the core inner diameter (ID) and field surface is made possible by the crawler's axial and transverse motion capability. This capability also allows the crawler to navigate around the gas baffles present on many generator designs. High-resolution video provides the specialist with a clear view of the stator core laminations, stator wedges, field wedges and surface on the inboard ends of the retaining rings. Figure 2 shows some core damage captured using the wide angle and close-up cameras on the MAGIC robot.

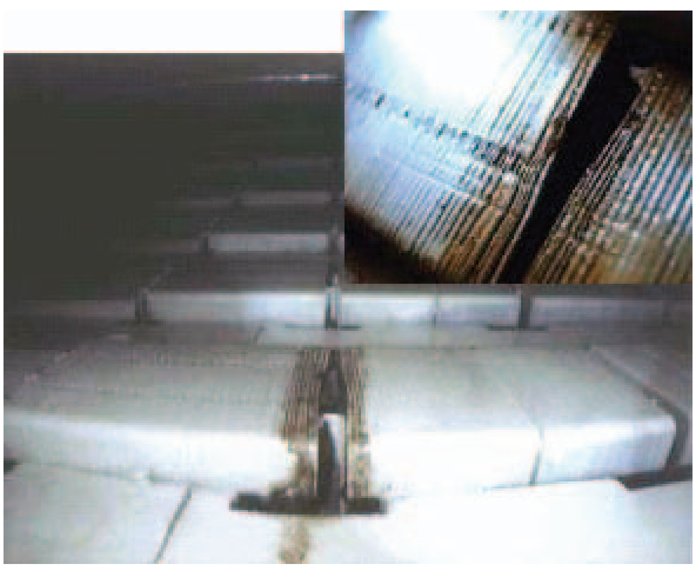

Figure 2. View of core damage taken with MAGIC robot

Stator Wedge Tightness Assessment – This test examines the slot support system for any signs that the stator bars are free to move. A "tight" stator winding can last two or three times as long as a winding that is not firmly held in the stator core. The test performed by the MAGIC system is similar to the test used in the factory for new units.

One component of this assessment is the wedge tightness or wedge tapping test that examines the tightness of the stator slot wedges. The standard method used to determine when a stator rewedge is required is to perform this test on the most critical wedges (the last 36 inches of each end of the generator) and then visually inspect the remaining wedges in the center of the core. When the rotor is removed, the tapping test can be performed manually using a 2-inch hammer or a piece of equipment that can mechanically evaluate wedge tightness. During a MAGIC inspection, a specialized test head is used to perform a wedge tightness map of the critical areas. The remaining wedges can then be visually inspected for any indications of looseness (such as dusting created by the wedge rattling in the dovetail).

The MAGIC system determines wedge tightness by measuring the response of the wedge to a mechanical stimulus (impact). Inspection data is stored in a file and provided with the final report that evaluates the winding condition to determine when repairs are needed. The data is also used to generate a color-coded "wedge tightness map" that clearly shows the wedge tightness within the generator (Figure 3). Some generator designs limit access to all wedges and permit only a partial inspection. The most critical wedges, located closest to the slot ends, are inspected in all cases.

Note: The tapping test does not apply to units with asphalt stator windings or the camelback wedge system. For these units only a visual wedge assessment is performed.

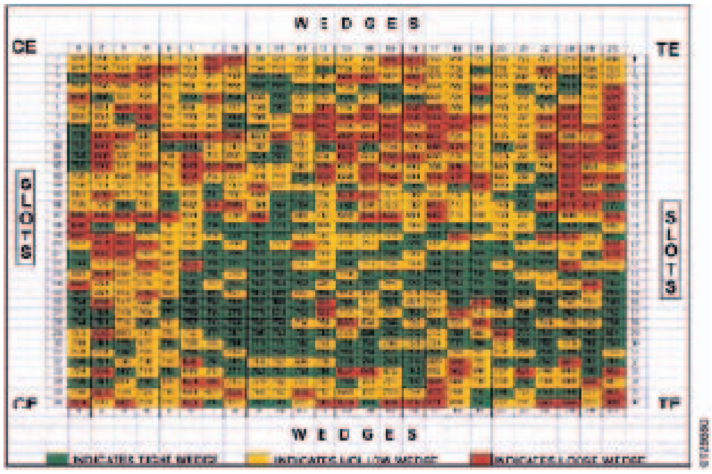

Figure 3. Generator Wedge Tightness

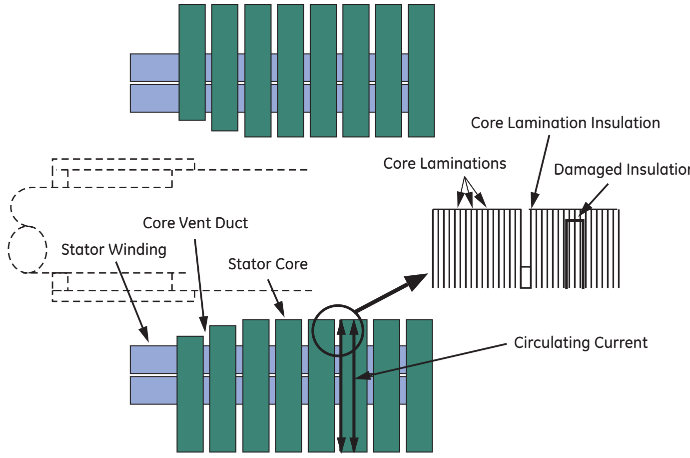

Figure 4. Circulating current due to damaged core insulation

Electromagnetic Core Imperfection Detection (EL CID) Testing* – One of the optional tests that GE performs during generator testing is the ELCID test. This test offers an accurate and economical way to know the condition of the stator core lamination insulation. Damaged insulation can result in circulating currents that can eventually lead to core overheating, stator damage, or even failure (Figure 4). GE typically recommends performing EL CID tests as a quality check to look for any possible stator core iron damage when generator repair work is performed in the stator core, such as a stator rewedge or stator rewind. It can also optionally be performed during a minor or major test and inspection.

While the MAGIC crawlers have the ability to perform an EL CID inspection, there is little to no benefit gained by performing an EL CID test during a routine MAGIC Inspection, because:

- The generator field is not being removed, so there is little possibility of damaging the stator core iron during the inspection.
- The unit was previously running at rated flux (vs. the 4 percent of rated flux at which EL CID is performed) and if there was any preexisting core iron damage of concern, there should be signs of overheating that can easily be spotted during the visual inspection.
- If there are any signs of the core iron overheating or mechanical damage, GE will recommend that the field be removed and the core iron repaired. It should be noted that if visual core damage is found, then a core ring test at close to rated flux will be recommended.

Borescope Inspection – Our in-situ inspections also use the latest borescope technology to provide a high-resolution visual inspection of normally inaccessible areas on the generator, outside of the bore region. While the MAGIC robots travel in the air gap between the rotor and stator, the borescopes inspect the end windings and other areas not associated with the air gap. To provide the most thorough visual inspection possible with the field in place, the normal scope for a MAGIC robotic inspection includes a borescopic examination. A complete inspection includes wedge tapping and any necessary electrical testing.

A borescopic examination of the generator can be made independent of a MAGIC inspection. This is typically done when a fast assessment of the generator, especially the end regions, is desired after an event outside of normal operation.

To facilitate a complete inspection, both end shields must be removed. Figure 5 shows a picture of field coils taken by borescope.

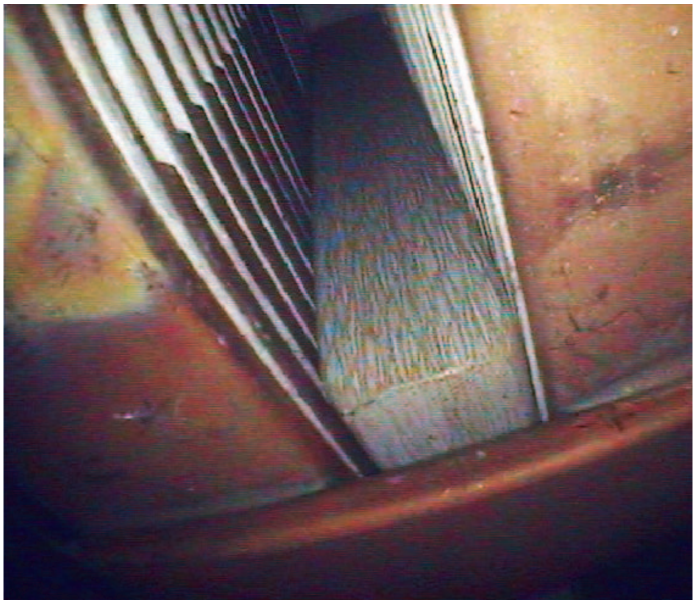

Figure 5. Field coils picture taken by borescope

Remote Capacitance Probe

GE water-cooled generators manufactured before 1986 are susceptible to water leaks and the resulting concerns as described in Technical Information Letter-1098. One of the periodic tests recommended in TIL-1098 is capacitance mapping of the stator bars. This test has proven to be very reliable in identifying stator bars with deteriorated ground-wall insulation resulting from a water leak.

Capacitance mapping requires placing a conductive electrode on the surface of the bar's ground-wall insulation at the location where the bar exits the core slot (Figure 6). A meter is used to measure the capacitance across the insulation between the electrode and the stator bar conductor. Each bar in the winding is measured on both ends of the core and statistical analysis is used to identify those bars with higher than normal expected capacitance. High capacitance is a good indicator of moisture presence in the insulation.

TIL-1098 recommends that a capacitance test be performed at each major outage (approximately every five years). Because performing the capacitance test required field removal, this recommendation presented a roadblock to implementing an in-situ inspection program on water-cooled generators. A tool recently developed by GE engineers now solves that problem, enabling capacitance testing to be performed without removing the field from the stator. As part of the in-situ inspection program, the new tool uses an inflatable electrode, similar to that used with the field removed, and a remote actuator arm for locating the probe.

GE's remote access camera is also used for positioning the probe and identifying its location. This system is being used successfully and provides results similar to those obtained during field-out inspections.

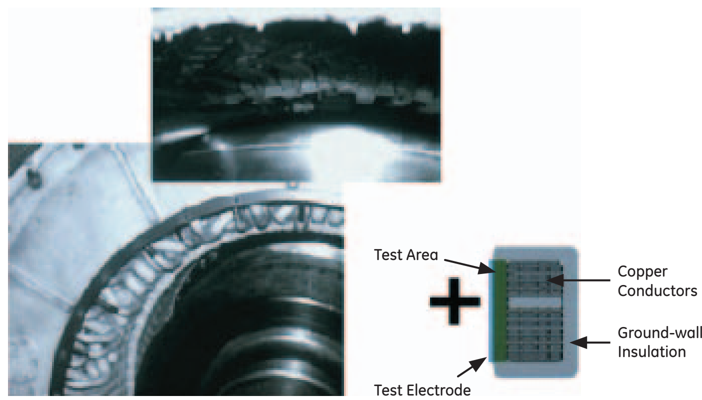

Figure 6. Stator bar capacitance test

Retaining Ring NDE Scanner

Stress Corrosion Cracking (SCC) of 18 Mn-5Cr generator retaining rings is a well-documented industry-wide concern for generator maintenance. SCC develops on the surface of the material in the presence of moisture and stress. As a result of the stress concentration and geometry, which tends to hold moisture, the retaining ring inside diameter (ID) surface tends to be more susceptible to this phenomenon.

GE recommends replacement of 18 Mn-5 Cr rings with the improved 18 Mn-18 Cr alloy, which has not been susceptible to SCC. However, for those customers who choose to periodically inspect and repair the rings, GE offers a complete inspection program. The most thorough NDE inspection can be performed with the rings removed from the field, permitting access to the ID surface where eddy current testing is used to detect very small surface indications. The rings can be tested while installed on the field, however, with less sensitivity to crack detection on the ID surface.

Testing, similar to that performed with the field removed from the stator, can now be completed on many units without removing the field. The NDE test equipment has been modified by miniaturizing the scanner assembly using the same signal processing system as that used with the field removed. The system provides an ultrasonic test (0.050"/1.27 mm crack detection threshold) on the ring ID and an eddy current test (0.050"/1.27 mm crack detection threshold) on the ring OD.

Other Testing

In addition to the above tests and inspections, there are several others that are recommended during minor and major outages. They include electrical testing of the stator and field windings and Resistance Temperature Detectors (RTDs), as well as hydraulic testing of water-cooled stator windings. A complete description of GE-recommended tests is provided in Technical Information Letter-1154 and GEK-103566. In-situ inspection of the generator does not change the need or importance of these tests.

MAGIC Acceptance and Experience

Industry Acceptance

For many years, generator inspection consisted of a minor outage every two-and-a-half years and a major outage with the field removed every five years. This practice proved to be quite successful in maintaining a high level of reliability of the generator fleet. As deregulation led the power generation industry to rethink its philosophy on equipment maintenance, GE developed generator in-situ inspection tools to help our customers reduce cost and cycle. The in-situ inspection strategy has proven successful—providing similar accuracy, sensitivity, and thoroughness as a field-removed inspection. In addition, in-situ inspection does not pose a significant increase in the risk of failure over traditional inspection techniques.

Of the more than 1,000 MAGIC inspections performed by GE, over 190 units have had two or more inspections, including several located at nuclear plants. GE has also performed nearly 100 inspections on generators built by other OEMs. After more than a decade of experience, many insurers now accept MAGIC inspections in lieu of major inspections. Because the rotor is not removed, the risk of consequential damage is reduced to the benefit of the insurer and utility alike.

System Design

MAGIC robotic devices were designed to work without any negative impact to generator components. Each crawler has emergency retrieval capability that is also designed to cause no damage to the generator.

Because GE takes Foreign Material Exclusion (FME) very seriously, GE's technicians conduct a thorough inspection of the crawler before and after the generator inspection to ensure no parts were left behind in the generator. In addition, pictures of the crawler are taken before and after the inspection for reference purposes.

Traditional vs. In-Situ Cost Analysis

Reduced cost to the equipment owner is a significant factor in comparing in-situ inspection programs to traditional inspection programs. Cost reduction is achieved due to three major factors:

- Reduced Outage Duration – In-situ inspection reduces the time required to complete a major generator inspection. The duration of a generator inspection includes the time required for removal from service, disassembly, inspection and reassembly, and preparation for service.
- Reduced Disassembly Requirements – In-situ inspection significantly reduces the time required for disassembly and reassembly of the generator, although it does add some time to the actual inspection process.
- Elimination of Consequential Damage – Since the rotor does not have to be removed, damage that could result from the rotor removal process is eliminated.

Net time savings vary based on the plant and generator design. Table 3 below provides a good estimate of the time savings experienced for a typical large generator at a nuclear plant.

Type of Inspection	Visual	Visual and Wedge Tightness	Visual, Wedge Tightness and ELCID
Traditional	14 Shifts	16 Shifts	18 Shifts
In-Situ	6 Shifts	9 Shifts	12 Shifts
Savings	8 Shifts	7 Shifts	6 Shifts

Table 3. Inspection time savings comparison

Reducing Outage Duration

When a generator is on an outage critical path, the ability to significantly reduce generator inspection time is crucial. Suitability for service inspections are generally recommended for generators following an abnormal operating event that may have caused generator damage, including breaker failures, short circuits, and loss of cooling. Each of these can cause generator damage that can lead to an online major failure if the damage is not repaired. These circumstances provide an ideal application of in-situ inspection technology, where every hour saved directly affects the time spent offline.

In-situ inspection can also be used for advanced outage planning. By performing an in-situ inspection during a minor outage—prior to a planned major outage—you can help determine the necessity and scope of the major outage. The major outage may be postponed altogether if the generator is found to be in good condition. If problems are found, the information gathered during the in-situ inspection can be used to make preparations for repair at the next outage. These preparations include planning the repair, identifying labor and material needs and developing contingency plans. When it comes to generator maintenance, experience has shown that preparation and planning are critical to efficiently executing an outage.

Reducing Disassembly Requirements

In-situ inspection offers significantly reduced cycle time due to the greatly reduced level of generator disassembly required to complete the inspection. However, reducing the level of disassembly has a number of benefits beyond reduced cycle time, including cost savings that result from reduced disassembly and reassembly labor, repair, and planning. In addition, overhead crane availability is not required for the inspection, freeing it up for use on other parts of the outage.

The total cost of field removal and reassembly has been found to be $50,000 to $250,000 for fossil plants and $250,000 to $500,000 for nuclear plants. The cost associated with partial disassembly to allow in-situ inspection varies with the scope of the inspection, but generally runs about one-third the cost of complete disassembly.

Minimize Consequential Damage

Another economic benefit of in-situ inspection is the reduction of generator damage resulting from rotor removal during the outage. Rotor removal requires uncoupling the turbine-generator shafts; careful disassembly of stator end shields on both ends of the generator; removal of bearings, hydrogen seals, oil deflectors and exciter assemblies; and the skillful reassembly and realignment of these same components. Improper end shield reassembly may result in: oil ingestion problems; expensive and time-consuming oil cleanup; undesirable lubrication of the armature slot and endwinding restraining systems; increased armature motion; and accelerated armature insulation wear. (Refer to TIL-1098-3R2 for additional information on the adverse effects of oil ingestion). In addition, rotor removal incurs risk of damage to the precision components of the hydrogen seal oil assemblies and requires the heavy lifting and temporary warm, dry storage of the rotor. Because the problems or damage resulting from disassembly can lead to very costly repairs, the best policy is to minimize disassembly requirements.

[1] The results are a result of the comparison of two different outage schedules for the same unit. Length of the generator, stator diameter, and the number of slots in both the field and stator are significant variables. GEII can work with each customer to develop time savings for each individual unit.

[2] Result of job cost estimations.

GE's Position on In-Situ Inspection

For many applications, GE's MAGIC inspection provides generator component assessment capability comparable to that routinely achieved by rotor removal inspections. Close-up, detailed views of the core and rotor surfaces, stator and rotor wedges, retaining ring tips and vent ducts allow a generator specialist to detect and assess potential problems not generally discernible by electrical testing or other online monitoring—often prior to the occurrence of any significant generator damage.

Periodic in-situ inspections, together with electrical testing and hydraulic checks, can provide an excellent alternative to many traditional OEM maintenance protocols. Skillful interpretation of in-situ inspection observations and related data can provide plant operators with cost-effective opportunities to deduce outages and outage duration while maintaining the outstanding reliability and availability of their generators. Recommended maintenance schedules for traditional and in-situ inspection protocols are compared in Table 4.

	First year Inspection	Inspection Interval (years)	
		2.5	5
Traditional	Major • Visual • Wedge	Minor • Visual	Major • Visual • Wedge
MAGIC In-Situ	In-Situ • Visual • Wedge	In-Situ • Visual	In-Situ • Visual • Wedge

Table 4. Recommended generator inspection schedules

Notes: Electrical and hydraulic testing continue at recommended intervals; NDE testing and TILs may require rotor removal for completion.

Conclusions

The power generation industry is undergoing major changes requiring power producers, OEMs, and insurers to adapt. One way that GE has responded to these changes is through the development of advanced-technology tools that enable in-situ inspection of generators. In many cases, in-situ inspection offers an excellent, reduced cost alternative to traditional field-out generator inspection. GE continues to work to gain acceptance of in-situ inspection techniques throughout the industry.

GE is working on enhancing the capabilities of our in-situ inspection service and expanding the application to smaller generators. In-situ inspection will play an increasing role in reducing power producers' cost of generation.

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