GE’s Modular Generators

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ABSTRACT

GE has been the industry leader in the engineering, manufacture and development of electric generators. Since the early 1900s more than 10,000 GE generators have been shipped, installed and operated for utility and industrial customers worldwide. GE’s latest products build upon this track record and usher in the next generation of hydrogen and water-cooled electric generators. The focus of these new generators has been increased reliability, improved serviceability, high efficiency and optimum plant integration. Major emphasis was placed on using service proven technologies and standardization. This paper presents an overview of the technical approach, construction features and validation testing of these new lines of electric generators.

INTRODUCTION

GE’s modular generators are based upon a long and successful history of engineering and manufacturing turbo-generators. The engineering of these new generators balances the overall size, efficiency, performance capabilities and electrical parameters, while maintaining proven mechanical, thermal and electromagnetic limits. Particular attention was paid to achieving high reliability, availability, and maintainability by having a strong quality focus, utilizing configurations that incorporate in-service lessons-learned, and employing component standardization.

The ratings of these new generators align with GE’s gas turbine offerings, so that the generator will meet or exceed the gas turbine capability over the full operating temperature range, considering expected turbine up-ratings during the lifetime of the generator. Three new generator model families (H6X, H8X, and W8X) cover all foreseeable 50 and 60Hz combined-cycle applications ranging between 200MW to 800MW (Figure 1). The H6X and H8X modular generators are conventional hydrogen-cooled generators that build upon GE’s
successful H73 (390H) and H75 (450H) in-service experience. The W8X model generator is a hydrogen/water-cooled generator that utilizes direct water cooling of the stator bars and connection rings derived from GE’s largest steam turbine generators.

Each generator model family represents a series of generators and employs a modular architecture that utilizes constant cross-section core segments to achieve higher product ratings (Figure 2). Each length version was individually engineered to ensure all electrical and mechanical specifications were met. Extended factory testing of each length version is part of the engineering validation process. Standardization of common end components provides greater spare parts efficiency, interchangeability, and maintenance familiarity. All generator models are configurable as either leads-up or leads-down yielding same delivery times for gas and steam turbine applications while providing flexibility for steam turbines with axial or side exhausts, thus capturing the value of reduced centerline height foundations.

**Figure 1 - Generator Product Portfolio**
CONFIGURATION AND CONSTRUCTION

Product requirements for the modular generators were established based upon customer feedback, lessons learned from in-service experiences, and inputs from all the functions involved in the design, manufacture, marketing and maintenance of the generator. Features such as the Tetraloc™ (trade mark of General Electric Company) end winding support system, once-through hydrogen-cooled rotors and stators, one piece stator frames, Micapal III™ (trade mark of General Electric Company) stator bar insulation, and FOUNDATION Fieldbus™ (trade mark of Fieldbus Foundation) communication were incorporated to increase reliability and improve serviceability. On-line hydrogen sensor calibration, condition-based maintenance, on-line monitoring, and interchangeability of parts were also key product requirements to drive efficient customer operation and improve serviceability.

One of the key tenets of GE’s modular generators was configuration standardization and parts commonality. The number of different configurations was reduced by careful selection of the generator ratings and the application of common components between generator models. For
example, within a generator model the configuration is scalable to accommodate changes in output (Figure 2). The same end bay hardware, such as the end windings support, the end shields and H2 seals are used within a family. The same stator frame, stator core, rotor forging, and packaging are used for 50 Hz and 60 Hz applications. The end shields are identical between the W8X and H8X generators families. Hardware such as fasteners and other small components have been selected to reduce the number of different nut, bolts, and similar items. All of this has resulted in a reduced number of unique configurations, as compared to predecessors, and improvements in quality. From the customer’s viewpoint, configuration standardization and parts commonality yields a simpler machine with fewer unique parts, easier spare parts access and the reliability benefit of a larger fleet of identical machines, with the rapid identification of any performance problems.

**ELECTROMAGNETIC CONFIGURATION**

The electromagnetic configurations of GE’s modular generators were based upon proven technology. Existing electromagnetic limits were respected during the product development process. Where appropriate, technologies used in the largest steam turbine generators were applied to improve the robustness of the machines.

Core end stepping was enhanced using three-dimensional non-linear finite element analyses (FEA), that had been calibrated to extensive search coil data collected on previous configurations during factory and site testing. Furthermore, voltages induced in the frame at the back-of-core were minimized using the same analyses, again calibrated to test data at open circuit, short circuit and leading power factor operation. The result are core end configurations with reduced core end stepping while maintaining nearly uniform flux density levels throughout the packages and thus avoiding high local losses and high back-of-core leakage fields. The reduced stepping provides extended support of the stator bars at the exit of the core, and helps maintain uniformly high core clamping pressure.

Factory testing demonstrated low core end temperatures, and induced voltages that are two-thirds or less of GE’s historical experience limit. As described later, for the H6X and H8X models, use of non-grain oriented (NGO) core steel led to lower nominal yoke flux densities, further reducing electromagnetic loading, and contributing to lower core vibration levels. Finally, in order to ensure robust stator insulation performance, the ground wall insulation thickness was established at nominal stress levels some 3 to 10% less than their qualified capability.
**STATOR CONFIGURATION**

The purpose of the generator stator is five-fold: support the weight of the stator core and rotor, contain hydrogen, withstand all lifting and shipping loads, survive electrical faults, and isolate core vibration to the foundation. The stator frame (Figure 3) is a one-piece welded-steel structure configured to enclose and support the stator core and winding, rotor and coolers. Unlike some existing generator configurations, there are no site-installed pressure vessel components, such as cooler domes, or lower frame extensions.

![Figure 3 - Generator Stator Frame](image)

The frame is also configured to reduce vibration by isolating core vibration via an integral spring bar suspension system. The spring bar suspension system has been employed on large two pole generators since the 1950’s. It provides excellent vibration isolation, dampening the core vibration by a factor of ten or more.

The stator frame defines the generator’s ventilation system and channels hydrogen via a series of ventilation paths to cool the stator and rotor. It also acts as a soundproof enclosure to reduce noise levels. The ventilation scheme is a simple once-through arrangement (Figure 4). Cooling gas travels radially outward through the stator core. This eliminates the need for any
gas baffling at the gas-gap entrance or on the inner diameter of the core. It also facilitates robotic air-gap crawler inspection.

Through the use of two and three dimensional computational fluid dynamics (CFD) the simple once-through ventilation scheme was enhanced to provide uniform stator and rotor cooling. Models calibrated to measurements from dozens of gas pressures and local duct flows in previous units were used to select a pattern of stator core package lengths. Rotor cooling flows and temperatures were also calculated using detailed flow and thermal models calibrated to instrumented rotor tests, in which hundreds of temperatures were measured on the field winding conductors during special factory testing that allowed for application of rated current to the field winding, with the unit in short circuit configuration.

![Figure 4 - Once-through Flow Ventilation System](image)

The stator core supports the armature winding and carries the magnetic flux generated by the field winding. It is comprised of thousands of thin, insulated, low-loss silicon electrical steel laminations and is suspended in the stator frame. The steel laminations are held together at the ends by steel flanges to maintain the core in compression. To ensure consistent core stiffness, the modular generators target core clamping pressures greater than 10% above legacy products. A final heated press and torque process eliminates creep from the core assembly. Dozens of strain gages installed during first unit production confirmed the result. Further, core
end punchings are bonded together, to eliminate any possibility of migration and tooth vibration.

The stator cores for the H6X and H8X modular generators are comprised of grain oriented and non-grain oriented (NGO) laminations. Grain-oriented steel is used in the step iron region of the stator core. Non-grain oriented steel is used in the body iron region of the stator core to increase structural stiffness due to its higher modulus of elasticity.

Grain-orient steel is applied at the ends of the stator core, providing superior performance where end-fringing fields drive up saturation, particularly under leading power factor operation. The superior saturation characteristics of the grain-oriented steel limit the back-of-core leakage fields that contribute to voltages and currents flowing in the frame structure. As noted earlier, the core end configurations have shown induced voltages below operating experience. Furthermore, improvements in the punching and insulating processes have raised the voltage withstand capability of the cores by nearly a factor of two. Greater punching withstand, combined with lower imposed voltages has added margin from potential core failure. Due to higher nominal flux density levels, the W8X generators utilize grain-oriented steel throughout the stator core structure. All cores feature slitting in the teeth at the core end to reduce losses generated by axial fringing fields. Ventilated copper shields reduce losses in the steel clamping flanges.

All of the aforementioned stator cores have been configured to have a four-nodal natural frequency well removed from 100 Hz or 120 Hz. Factory modal and running tests confirmed the predicted natural frequencies.

The stator core is attached to the stator frame via a bolted spring-bar suspension system (Figure 5). The spring-bar suspension system provides vibration isolation to the stator frame by attenuating the dynamic forces transmitted to the stator core. It reduces stator frame vibration, web plate stresses, acoustic noise, and forces transmitted to the foundation. The spring-bar suspension system consists of an assembly of key bars and spring bars which are bolted to welded pads on the stator frame by body-bound high-strength steel bolts. Spring bar stiffness tests were conducted to validate deflection calculations from three dimensional (3D) finite element analysis (FEA) models. Fatigue tests of the weld joints between the spring bar pad and stator frame section plates were carried out to confirm stress levels, manufacturing processes and calibrate life predictions. This suspension system was selected for all of modular generator models based upon its robustness as proven thru experience and high reliability on other GE generators.
The armature winding for the H6X and H8X modular generators uses conventionally-cooled bars. The armature winding for the W8X modular generators is directly water-cooled and constructed in the same manner as GE’s large steam turbine generators. This includes GE’s proprietary phosphorous free brazing technology to avoid stress corrosion cracking. To date, there are over 130 such windings in service, accumulating over 6 million operating hours without failure.

The service-proven industry-leading Micapal™ armature insulation systems are those currently used in GE hydrogen-cooled and water-cooled generators. The materials are all developed and tested to provide reliable performance at Class F temperatures for the life of the generator. It is applied as a resin-rich tape. The volatiles are removed under vacuum, and then the cured under pressure to form a solid, void-free structure. Micapal™ has excellent thermal cycling capability, and is particularly suited for the daily start/stop duty. Both the interior and exterior of the ground wall insulation is taped with a conducting armor in the slot section to ensure voltage stress is applied uniformly to the insulation, and avoid corona activity at the interfaces.
Finally, a semi-conducting grading system is applied to the end arms. In this way the bar is fully protected from the effects of high electrical voltage gradients.

The bars are secured in the core slots (Figure 6) with fillers and top-ripple springs to restrain the bars radially, and with side-ripple springs to increase friction between the bar and the slot wall. The side ripple springs are conductive to ground stator bars to prevent corona effects and vibration sparking. The top ripple springs have been upgraded from legacy units, to provide even greater slot retention force. The slot support system prevents stator bar vibration due to normal running bar forces and averts liberation of the stator bars during a sudden short circuit or mis-synchronization fault. It also permits axial expansion and contraction due to thermal cycling. A top-of-slot, radial force wedge securely holds the stator bars down to the bottom of the slot to prevent potentially destructive bar motion. To accommodate the higher in-slot bar force levels, the direct water-cooled winding of the W8X generators include conforming materials at the bottom and mid-slot filler. The conforming material is molded into the slot. Consistent assembly is ensured by fixturing which locks the slot hardware in place during final bake of the wound stator.

**Figure 6 – W8X Stator Slot Support System**

Armature end windings are cantilevered structures suspended beyond of the stator core. The armature end winding support system for GE’s modular generators is the successful Tetraloc™ system (Figure 7). This system was developed in the early 1970’s and has been
proven extremely reliable in service since its introduction. It provides robust restraint for all anticipated loads, up to and including short circuit and faulty synchronizing current forces. The Tetraloc™ system uses a basket consisting of axial supports, suspended on sliding brackets from the stator flange, and continuous circumferential epoxy fiberglass rings. The axial supports and fiberglass rings provide the mechanical support for the winding. Glass filament ties to secure the armature bars to the fiberglass rings. Conformable bar blocking and tension members are used to maintain bar spacing and provide structural support against normal operation and abnormal bar forces. The armature end winding is flooded with epoxy to form a monolithic structure.

Figure 7 - Tetraloc™ End Winding Support System

Connection rings join the armature winding to the generator high-voltage bushing terminals. Connection rings carry current with minimal losses while maintaining electrical and mechanical integrity under both normal and abnormal operating conditions. The H6X and the H8X generators utilize solid-copper connection rings that are indirectly-cooled in the same fashion as hundreds of conventionally-cooled GE generators. The heat generated in the winding is removed through the ground wall insulation by the hydrogen circulating around the connection ring structure. The W8X generators use direct water-cooled connection rings windings similar to GE large steam turbine generators. The water is circulated through the center of the connection rings such that the heat does not have to flow through the ground wall insulation. The W8X connection rings are circular in cross-section and are clamped to the end winding’s axial support with composite brackets and threaded hardware (Figure 8). This arrangement results in a secured assembly providing determinant support and thermal growth capability. The assembly and its components were extensively tested, both in the lab and in the factory, to
ensure high operational reliability. Static strength capability was determined by loading to failure, and long term capability was demonstrated through cyclic testing.

![Figure 8 - W8X Circular Connection Ring Structure](image)

The joint between the connection rings and high voltage bushing is formed by a series of direct hydrogen-cooled flex leads. These leads are made of laminated sheets of copper that are press-welded together at their ends. Flex leads isolate the vibration and thermal expansion of the winding from the high voltage bushing. The new flex lead assemblies incorporate locking features to ensure assembly clamping load is maintained and underwent extensive component testing, to validate their static and fatigue capabilities.

The complete end winding structure has been characterized by a series of impact and shaker tests. Finally, steady state and dynamic tests during the no-load factory running tests ensured low vibration levels and freedom from resonances under all load conditions and well within GE configuration limits for lifetime duty.

**ROTOR CONFIGURATION**

The generator rotor (Figure 9) for the modular generators is machined from a high-strength steel forging. The direct-cooled field winding is retained by steel wedges in the rotor slots, and non-magnetic stainless steel retaining rings on the end. The field winding is of single layer C-coil construction, based upon GE’s extensive fleet experience. There are over 1100 units in operation, with over 100 million operating hours.
Radial flow cooling is used for all of the modular generators. Cooling of the field winding is accomplished by hydrogen gas passing radially through the conductors and through the creepage blocks and wedges to the air gap, where it is directed radially through the stator core to the hydrogen coolers. The part of the turns located under the retaining rings are cooled by gas introduced into ports near the pole centerline that then flows in axial grooves. These grooves discharge into large radial ducts located just inboard of the retaining ring.

The rotor’s retaining rings, which support the winding end turns against centrifugal force, are shrunk on to the end of the rotor body. The distance from the rotor body to the coil bend in the winding was sized to facilitate installation and prevent cracking of the slot armor. The main terminal lead is located outboard of the retaining ring for easy access and the lead is a flexible gooseneck configuration that incorporates lessons-learned from in-service experience and features of previous flexible main leads (Figure 10). The bore of the generator rotor was configured to simplify assembly and maintenance, and improve long-term running reliability.
COLLECTOR and BRUSH RIGGING

The field DC current supply is delivered to the field winding via carbon brushes mounted in rigging and riding on a pair of collector rings. Figure 11 shows the two standard collector assemblies for the modular generators.

Figure 10 – Field Main Lead

Figure - 11 Collector Assemblies
There are several common features between the single and double-end drive collector assemblies. First, the cooling air path, including inlet and exhaust silencing, is fully above the floor thereby eliminating the need for flow through the foundation and customer ducting. Second is the heater and instrumentation junction boxes are all externally located for easy access. Third is the DC leads to the EX2100E system, via bus bar or cables, are external. Both collector assemblies are IP54W rated and utilize GE’s newest brush holder.

GE’s new proprietary brush holder (Figure 12) incorporates a lightweight aluminum construction with a hard durable anodized surface coating. It includes an integral and insulated changing handle for easy and safe brushes changing while the generator is operating. No tools are required for replacement of the brushes or springs. After the holder is slid radially into the stationary support, the handle and locking pin are rotated 90 degrees to provide indication of a complete installation. The boxes and brushes are tall to provide long brush life without brush hang ups. Extensive validation testing was performed in the lab and on a H33 (7FH2) generator at a customer site to demonstrate reliability and successful operation.

**Figure 12 - New GE Proprietary Brush Holder**

**PACKAGING CONFIGURATION**

The stator frame’s end shields (Figure 13) are welded, fabricated and machined assemblies designed to seal both ends of the generator. They are configured in two halves, a lower and upper, for ease of installation and removal of the rotor, with a pumped-in seal at the split line. The end shields provide static and dynamic sealing of hydrogen and oil; support of the rotor, and increased accessibility for ease of maintenance.
The end shields contain the bearing assembly, oil deflectors and hydrogen seal system. The bearings for the modular generators are all low-loss tilt-pad bearings (Figure 14). Tilt-pad bearings have a number of individual shoes or pads which pivot to develop a pressure field in the oil film to support the load. They provide robust operation, and resistance to oil whirl instability as well as possessing a self-aligning feature which simplifies assembly of the bearing into its support. Tilt-pad bearings also provide static support and dynamic stiffness/damping while reducing power losses for improved efficiency.

The shaft seals and oil deflectors (Figure 15) are located between the stator and rotor as part of the end shield assembly. They form a dynamic sealing system at stator and rotor interface that maintains pressurized hydrogen gas within the hydrogen casing without leaking outside the generator.

Figure 13 - Generator End Shield
The hydrogen seal casing provides structural support and directs oil to the seal rings. The hydrogen seal casing contains the seal rings, springs, and mid-oil deflector. The seal rings direct the oil film and ride on a thin oil film with the rotor. The seal rings on all the modular generators incorporate features that preclude oil-ingress into the generator. The new features have been tested both in the lab and on a complete generator. The mid-oil deflector directs oil to the drains. The inner oil deflector acts as a barrier between pure hydrogen inside the generator and impure hydrogen inside the seal cavity. It also prevents oil from the drain cavity from entering into the generator. The outer oil deflector prevents oil from the bearing cavity from leaking outside the generator. These aforementioned features have been derived from successful GE generators with millions of hours of in-service experience.
TEMPERATURE MONITORING

All of GE’s the modular generators incorporate digital-bus-communication control hardware for all temperature monitoring devices. FOUNDATION Fieldbus™ is an integrated all-digital, serial, two-way LAN communication system that serves as the base-level network in a power plant. It interconnects field equipment to GE’s MarkVI™ (trademark of General Electric Company) controller via high speed Ethernet. FOUNDATION Fieldbus™ provides communication and power via twisted-pair wiring. Multiple devices share the same fieldbus wires, and devices can share the data and determine how to control the process. This arrangement reduces site wiring. Multiple variables from each device can be brought into the control system for archiving, trend analysis, process optimization, reporting, and predictive maintenance.

Figure 15 - Shaft Seals and Oil Deflectors
SPECIAL CONFIGURATIONS

Modern power plant configurations include single shaft combined cycle trains, in which the generator is driven on one end by a combustion gas turbine and on the other end by a steam turbine. Often a clutch is supplied between the steam turbine and generator, to allow the plant to operate in simple cycle as well as combined cycle. While this generator-in-the-middle arrangement provides operational flexibility, it complicates generator design and operation. If the generator field must be removed for maintenance, the entire generator must be temporarily relocated. Inclusion of a facility crane capable of lifting the entire generator comes at a significant cost. In such single-shaft configurations, GE has developed an integrated alternative. The generator is mounted on special steel piers that are purposefully configured to allow lift and translation using typical heavy-lift hydraulic jacks. A series of custom beams have been developed and validated to support the generator during lateral translation. Figure 16 shows the basic concept, as it is being executed during a validation test. The result is a process that cuts the time for relocation by 50% compared to previous GE plants.

Figure 16 – Moving A Generator: In-The-Middle Arrangement
VALIDATION TESTING

From the start, the engineering validation process for modular generators included extensive component, factory, and site characterization testing to mitigate risk and improve reliability. Early component testing of the core suspension system, rotor cooling features, non-grain orientated steel, collector brush wear, rotor fan performance, and stator connection ring support ensured robust high quality designs. The amount of testing for the GE modular generators exceeded that of past new product development programs by over ten times. Some test highlights are outline below.

Connection Ring and Connection Ring Support System Testing for W8X Generators

The W8X generators make use of two new connection ring features: the first is a change in the cross-sectional geometry from square to circular. The second is the use scalloped axial supports and bolted blocking. These features (Figure 8) reduced the connection ring assembly weight by ~ 50% and facilitated a modular and structurally determinant structure, enabling the use of glass bolts (versus glass lashing) to hold the assembly together. The connection rings are also easier to fabricate, insulate and axially position due to the circular cross and the scallops on the axial supports ensuring a more resilient product.

During the product development process, various tests were performed to select the most suitable materials for the assembly given its location in the generator and the duty that it would see during operation. Component tests were performed on:

- The glass nuts and bolts for strength at room and operating temperatures to ensure bolting hardware would not fail during operating
- The rubber interface material to ensure its resiliency, oil resistance, and compression behavior to ensure compliance and dampening. This rubber is the same material that is used on GE’s large steam turbine generator end windings.
- The epoxy adhesive used to bond rubber to axial support to ensure separation between the materials would not occur. The entire assembly is also flooded with resin.

Once the material selection was completed, a preliminary configuration of the bolted on blocking was developed. This preliminary configuration was tested to understand how the system would fare under conditions similar those during operation (Figure 17). The sub assembly was put through cyclic testing at worst case operating temperature (100C) and worst case vibration (20 mil displacement) to understand if the assembly would degrade over time.
Inspections were conducted throughout the testing and pre- and post-cyclic testing load curves were documented to understand if the bonds degraded over time.

Figure 17 - W8X Bolted-on-Blocking Sub-Assembly Testing

The inspection results during the testing did not show any degradation or separation between the blocking and connection rings. In addition, the pre- and post-cyclic testing load curves showed similar results indicating that the bonds did not breakdown over time. Finally a load to failure test was performed on the assembly. This test showed that the joint contained substantial margin for the types of thermal expansion loads and vibratory load that would be experienced during operating.

Following the component testing, full-scale mock-up of connection ring arcs and axial supports were manufactured. Trial assemblies were conducted to evaluate connection ring installation and assembly methods prior to full production. The results of the trials were then incorporated into the subsequent manufacturing production methods.

For the factory test, accelerometers were placed on the connection ring components to evaluate vibratory performance. No vibratory issues were observed during factory testing. The connection ring support structure met internal technical requirements and no dusting was observed following factory test inspections.

FIRST UNIT TEST VALIDATION CAMPAIGN

The factory test philosophy for the modular generators is centered on ensuring all versions meet or exceed technical goals. Full validation and characterization of the first unit of a family (W8X, H6X, and H8X) as well as a comprehensive performance test of each length version is
standard. Additional test scope for each version is based upon factory test lessons learned from the full validation test. Figure 18 depicts a W8X generator being readied for factory test.

Full-scale unit validation testing was divided into two parts: testing during unit assembly and factory running tests.

Testing during unit assembly consisted of in-process tests such as shaker, core ring, wound stator El-Cid, rotor torsional, and overspeed tests. These tests were executed prior to unit factory testing as part of the first piece qualifications. For example, a comprehensive set of shaker tests validated the natural frequencies of the stator frame and armature structures. In both cases, the frame (or stator core) was excited by a large hydraulic shaker, while the vibration response was measured at dozens of locations. To complete the characterization, a modal test was also performed with the generator fully assembled and installed on the generator test stand, just prior to the running test. During these modal tests, mass was added at select locations to verify the sensitivity of the assembly for tuning purposes. Additionally, core clamping loads were confirmed through measurements of the strain in the core clamping flanges and key bars. Dozens of strain gages monitored the load throughout the final press and bake process. These measurements validated that the intended core pressure was achieved, yielding a tight core.

![Generator Installed in Test Stand for No-Load Factory Running Test](image)

**Figure 18 - Generator Installed in Test Stand for No-Load Factory Running Test**
Unit factory running tests were conducted in GE’s Generator Test Facility in Schenectady, New York. The test units were heavily instrumented, with over 1500 sensors monitoring temperatures, vibrations, magnetic fields, currents, etc. This included sensors of newer technologies, such as fiber-optic and traditional temperature measurements on the high voltage winding conductors, and special fiber-optic and capacitive bar vibration probes.

Unit factory running tests consisted of over 100 test runs, including the following:

- Open-circuit electrical characteristic and loss up to 125% of rated voltage
- Short Circuit Electrical characteristic and loss up to 120% of rated current
- Steady-state heat runs with varying cold gas and hydrogen pressure
- Sudden short circuits up to 70% voltage
- Negative and zero sequence reactance
- Ventilation and Acoustic Surveys
- Deceleration tests with:
  - Varied frame tuning using mass and support stiffness
  - Purposeful rotor unbalances
- Thermal cycling/endurance runs

As noted, open circuit and short circuit testing was performed at levels above rated values in order to characterize core end performance by measuring dozens of local flux densities and induced voltages.

The establishment of thermal cycling / endurance running test was new for generator product validation. The intent was to test the unit using highly accelerated life testing (HALT), to identify failure modes typically found only at first year inspection. Examples include connection ring dusting, rotor winding component distortion due to start/stops, etc. Based on monitoring hundreds of generators in service, the new tests were developed to simulate a year of typical operation. Thermal cycling consisted of:

- Short circuit, with significant stator current overload, until the winding reaches full load temperatures
- Rapid switch to open circuit at significant overvoltage, until the core reaches full load temperatures
• Rapid cooling, followed by a mechanical stop/start cycle.

This sequence was repeated dozens of times. Failure modes such as stator end-winding bond breakage, would also be identified by shifts in modal vibrational response.

The thermal cycling tests were made possible by test stand upgrades and modernization. Most critical was the development of a custom open/short circuit switch that allowed rapid conversion from open to short circuit condition, and back, with the generator at rated speed.

Following the thermal cycling tests, extended operation at steady-state overcurrent and overvoltage conditions generated millions of cycles on the unit. These endurance runs lasted over 100 hours each. If the windings were to experience bond breakage during thermal cycling, then endurance runs would have generated “dusting” – an indication of relative motion during the subsequent visual inspection. Additionally, the vibration levels were monitored during the entire unit factory test. Excited deceleration tests before and after the thermal cycling and endurance runs were monitored for any change in vibration characteristics.

In addition to unit factory running tests, site characterization tests are also planned as the final part of the modular generator development process. Full load performance, stator frame and rotor vibration, and acoustic performance will be evaluated prior to unit start-up in the installed condition.

As of August-2015, the full validation campaigns have been completed on the W86 50Hz unit, and an H84 50Hz unit. Both tests showed favorable electrical and observable thermal performance. As noted, open circuit and short circuit testing was performed at levels significantly above rated values in order to characterize core end performance by measuring dozens of local flux densities and induced voltages. Overall losses were lower than expected by 4 to 5%. Electrical characteristics matched pre-test predictions, well within the tolerances defined in international standards. Stator vibration levels were considerably below operational limits. A comprehensive set of visual inspections following thermal cycling/endurance, as well as following 65+% sudden short circuits showed no significant distress as a result of the extensive loading. A final armature shaker test also confirmed the post-test winding modal response.

**FLUID SYSTEM ACCESSORIES**
The new modular generators will utilize GE’s new proprietary hydrogen and seal oil systems (Figures 19 and 20). These systems are an upgrade to earlier systems, automate operation and improve diagnostic monitoring capabilities.

The new seal oil system replaces the traditional float trap for maintaining seal oil level in the seal oil detraining tanks with active level control through the use of guided wave radar level detectors operating level control valves. This arrangement should eliminate the need for tuning of the float trap, and manual bypass during startup. As a result, the new system can provide continuous monitoring of system operation directly to the operator.

For water-cooled units, the deionized water cooling system implements all of the latest technologies for GE’s high oxygen system. The SLMS HP system actively oxygenates the stator cooling water, using instrument air that has been scrubbed of carbon dioxide. Dual strainers and filter bypass allow for on-line maintenance of both components.

![Figure 19 - Schematic of new Seal Oil Control System](image-url)
**MONITORING**

GE’s modular generators are supplied with a proprietary Generator Health Monitor (GHM), which includes standard monitoring devices and algorithms, along with additional modules that, if selected, are fully integrated into the GHM. All units are supplied with an on-line field shorted turn monitor. As noted above, all units with a water-cooled stator include the SLMS system, and a blocked strand detection algorithm.

Additional modules include:

- Stator end winding vibration monitoring
- On-line stator winding partial discharge monitoring
- Collector health monitor

The majorities of these devices connect to the GHM panel, and also interface to the MARK VI turbine control system and GE On-Site Monitor (OSM).

**CONCLUSIONS**

This paper has presented an overview of the technical approach, construction features and validation testing of GE’s new electric generators. The emphasis has been toward industry-leading reliability, availability and maintainability to drive lower cost of operations. The
application of service-proven configurations combined with modern technology will provide efficient, trouble-free service through years of base load or cycling operation. GE is committed to pre-shipment quality and factory validation to ensure high levels of customer satisfaction.