GER-4203

GE Power Systems

GE Generator Technology Update

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Contents

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Abstract

Global deregulation is causing major changes in the market requirements for the power generation industry. Generator designs for today's applications must be cost effective while achieving high reliability and improved efficiency. To meet these challenges, GE Power Systems has introduced three new products during the past 18 months: the 7A7 and the 9A4 air-cooled generators, and the 390H hydrogen-cooled generators. The first 9A4 unit entered service in the second half of 1999. The first 7A7 and 390H generators will achieve commercial operation by the end of 2000. Factory tests for each of these new products were completed with highly positive results.

The focus of this paper is the design activity on a fourth new generator, the 7FH2 model 761/763, to match the 7FB gas turbine planned for introduction in the second half of 2001. This design joins upon the highly proven family of 7FH2 designs, and provides the increased output and improved efficiency needed for the 7FB. Gas turbine ("leads up") applications will use the Model 761, steam turbine ("leads down") applications will use the Model 763. GE Power Systems has established a history of developing new products by applying state-of-the-art design tools and incorporating field tests. Most recently, Design for Six Sigma (DFSS) tools and methodologies have facilitated designing high quality and reliability directly into the new product development process.

The 7FH2 Models 761 and 763 generators will leverage GE's proven track record and advanced DFSS tools to meet rising marketplace expectations. Some areas benefiting from these advanced techniques include insulation improvement, design automation, electromagnetics, structural modeling, and ventilation analysis. The resulting design will satisfy customer Critical to Quality (CTQ) characteristics while providing design flexibility to meet varying customer needs.

Introduction

GE's development of turbine generators for power generation applications began in the late 1800s when GE leadership became interested in Charles G. Curtis' impulse turbine. The initial generator designs coupled to this new product utilized air as the cooling media. Significant effort was invested in optimizing these air-cooled machines before the capability limit of the air-cooled platform was exceeded. Air-cooled platform ratings reached surprisingly high levels of up to 200 MVA at 1800 rpm (the rating achieved by a unit installed in Brooklyn, NY, in 1932). As the need for increased machine rating continued, hydrogen cooling was introduced in the early 1930s. A period of rapid technological/capability growth followed, with GE's first hydrogen-cooled generator entering service in 1937.

Hydrogen-cooled generators were originally introduced because the combination of the low density and high specific heat of hydrogen made it an ideal cooling medium. The operation, installation and maintenance of an air-cooled generator are generally simpler than that of a hydrogen-cooled generator. Technological improvements in generator design have increased the rating breakpoints between air-cooled and hydrogen-cooled machines. However, the lower effectiveness of air as a cooling medium requires a 20% to 30% size increase over a hydrogen-cooled machine of a similar rating. There is also a decrease of approximately 0.3% in generator efficiency for an air-cooled vs. a hydrogen-cooled generator. Hydrogen-cooled machines also can be designed with a higher electrical loading than air-cooled machines due to the better cooling, and tend to have a larger subtransient reactance than an air-cooled machine. These factors make hydrogen-cooled generators preferable for 7FH2 applications. The smaller size reduces civil engineering costs in the plant design, and the higher efficiency provides a lifetime plant output gain. The higher subtransient reactance also limits fault currents, which increases equipment reliability and reduces the interrupt capability needed from the generator breakers.

The 7FH2 generator was introduced in 1990 for use with the newly introduced 7F gas turbine. Throughout its history the reliability, availability and maintainability of the 7FH2 have been excellent. Currently the 7FH2 is being applied to gas and steam turbines at a rating of 230 MVA, with power factor of 0.85 and class “B” insulation temperature rises. As of April 2000, over 80 units have been shipped. Of these, 50 units are in service with combined operating hours of over 500,000 hours. The fleet leader has achieved over 48,000 hours.

As we enter the 2000s, customer requirements are focusing on total installed cost, including installation, operation, and maintenance. Designers and producers of turbine generators have to reduce equipment costs, improve quality, and simplify operations. At the same time they must achieve higher levels of plant efficiency in order to reduce power plant operating costs. The 7FH2 Model 761/763 generator NPI design program was initiated to meet these goals. The new design will accompany the 7FB gas turbine in the same manner that the 7FH2 Model 741/743 is consistently matched with the 7F/7FA line.

Design for Six Sigma Process

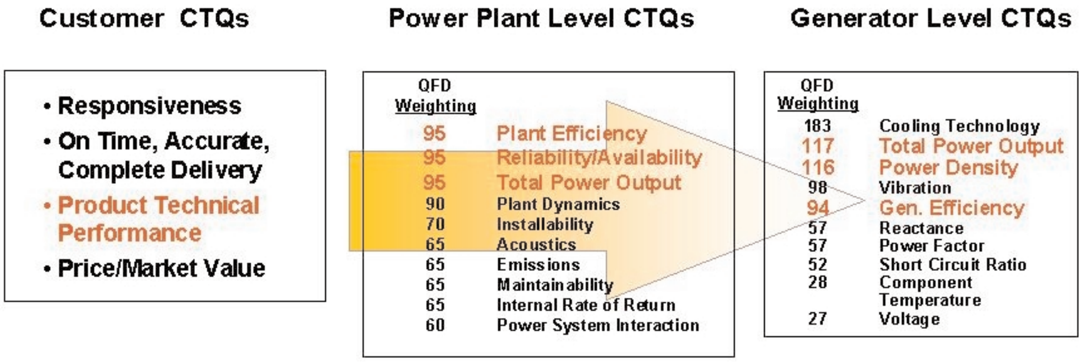
Design for Six Sigma (DFSS) tools are being applied to the design of this newest 7FH2 model. The fundamental concept is to design quality directly into the product by developing transfer functions to predict overall quality and facilitate design trade-offs. Elements of this process are grouped into four phases: Identify, Design, Optimize, and Validate (IDOV). An important aspect of this process is the ability to incorporate experience from more than 6,400 GE generators currently in service around the world. DFSS dovetails with established GE tollgate processes that include formal structures for design reviews from conceptual design through introduction into service.

The four phases of the DFSS process used for major generator development are described below.

Identify

This phase of the design process focuses on defining the overall product requirements. Customer feedback and marketing data are reviewed to quantify and rank benefits to the customer, and then translate them into critical product features. These features are documented in a formal product specification that identifies technical requirements, performance targets, and specification limits. A “House of Quality” is constructed by ranking the importance of features that impact delivery of the performance specifications. This House of Quality method identifies the features that are most important to meeting customer requirements, or those that are Critical to Quality (CTQ).

Top level CTQs for the power plant include: (1) responsiveness; (2) on time, accurate, and complete delivery; (3) product technical performance; and (4) price/market value. The generator has the greatest impact on technical performance, which is most affected by plant efficiency, reliability/availability, and total power output. The CTQs at the power plant level can be further broken down to identify CTQs at the generator level. The resulting rankings from this “flowdown” process clarify the features most important to satisfying customer needs. The generator CTQ flowdown is shown in *Figure 1.*



Customer CTQs

- Responsiveness
- On Time, Accurate, Complete Delivery
- Product Technical Performance
- Price/Market Value

Power Plant Level CTQs

QFD Weighting	
95	Plant Efficiency
95	Reliability/Availability
95	Total Power Output
90	Plant Dynamics
70	Installability
65	Acoustics
65	Emissions
65	Maintainability
65	Internal Rate of Return
60	Power System Interaction

Generator Level CTQs

QFD Weighting	
183	Cooling Technology
117	Total Power Output
116	Power Density
98	Vibration
94	Gen. Efficiency
57	Reactance
57	Power Factor
52	Short Circuit Ratio
28	Component Temperature
27	Voltage

Figure 1. Generator Critical to Quality (CTQ) flowdown process

A formal Risk Management process is incorporated into the design process to significantly reduce potential issues with the design evolution. This process consists of a detailed description of the generator's operational characteristics and features, followed by brainstorming sessions to identify possible risks. Risk items are scored based on their probability of occurrence, and the resulting impact on machine performance. Remediation actions are defined to reduce the risk. An action item list is created to insure that these follow-up actions are fully completed, and that risk is reduced to acceptably low levels.

Design

During this phase, transfer functions are applied to develop the overall layout and product geometry. Transfer functions establish relationships between various parameters, and can approximate overall performance. These variables include power output and MVA rating, generator efficiency, reliability, availability and maintainability (RAM), short circuit ratio, and subtransient reactance. A CTQ flowdown for components and sub-components is performed and the results are entered into baseline Product Quality Scorecards (PQS) as mean outputs and statistical variations. These values are compared with the process specification limits to develop the standard statistical variable, "Z", or, in the short term, "Z_{st}". The baseline PQS are then populated to estimate the quality of the design concept and provide the basis for a statistical, quality-focused approach to the design process.

Entries into the scorecards are generated through use of transfer functions that are developed and refined by:

- Benchmarking historical transfer functions
- Deriving mathematically-based closed form solutions
- Performing analytical simulations, or conducting experiments or tests.

DFSS tools such as Design of Experiments (DOE), Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), and Hypothesis Testing can be applied effectively in this process step.

Optimize

Optimization studies are performed to minimize the sensitivity of generator performance to CTQ design features. These optimization studies identify those processes (e.g., manufacturing or design) most in need of improved capability. Trade-offs are assessed among the electrical, mechanical, and power plant systems to optimize the overall generator quality estimate (Z_{st}). DFSS tools, including Monte Carlo simulations and Robust Design, can be employed during this step. The selection and application of these tools typically is prioritized by the relative Z_{st} scores of each line item and their contribution to defects per unit (DPU). Optimization is an iterative process that can include multiple prototype hardware tests to assess the performance of each optimization attempt.

Process capability data are collected from manufacturing and sub-component vendors for the principle processes used to build the bill of materials (BOM) of the concept generator. Manufacturing process capability is assessed by using the Product Quality Scorecards to list the quality score (Z_{st}) for each BOM item.

The PQS and the process capability assessment results are used to determine tolerances for drawing details. Some tolerances can be statistically expressed for sub-component or assembly features critical to the quality of the generator's performance. Tolerance values for these critical features are best determined by reviewing the PQS and the process capability data available from manufacturing and engineering. As tolerances for each drawing are established and results entered into the PQS, the results are computed to obtain quality ratings (Z_{st}) for each generator performance line item. These line item ratings are used to calculate an overall quality rating for the generator system. The elements and results of this "flow-up" of the quality scores are typically used as a basis for discussion in the detailed design review.

Validate

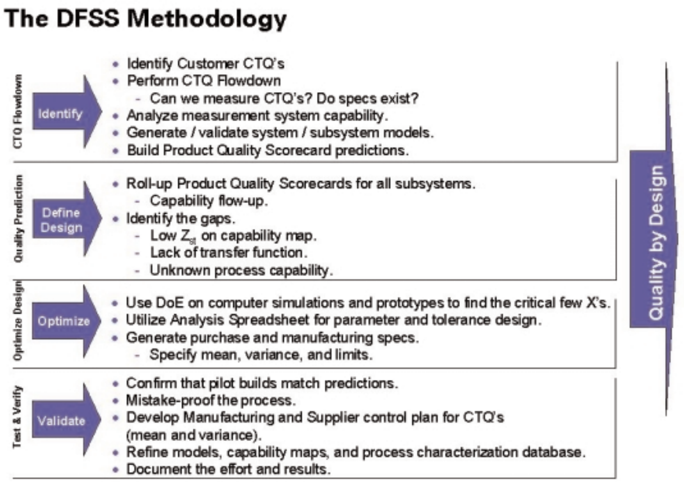
The validation of design tools, transfer functions, and resulting designs is of critical importance. This validation often can be obtained by comparisons to historical results or performance of sub-scale performance tests. Actual component or subsystem operation is, of course, the best measure of design success. This emphasizes the importance of using an evolutionary approach to product design, where existing, proven components are applied to the greatest extent possible.

Finally, factory testing of all NPI generators is performed to validate the overall performance and verify that the performance specifications have been satisfied. DOE techniques are applied to create appropriate test plans and the results are used to generate transfer functions for performance assessment. PQS are used to demonstrate that the required level of quality has been met. Further validation data are collected during startup and subsequent commercial operation of the generator. These data and observations can be used to further confirm that the product meets the required performance specifications.

Figure 2 provides a summary of all four DFSS phases (Identify, Design, Optimize, and Validate).

Evolution to the 7FH2 Model 761 / 763 Generator

The overall approach to design of the Model 761/763 is to apply experience and, when appropriate, existing hardware components from the present 7FH2 models. Common concept allows carryover of production methods that were tailored to the 7FH2. Existing designs of major parts (such as end shields, coolers, and bushings) and small parts (such as fasteners) can be reused. CAD/CAM packages allow for these small parts to be stored as three-dimen-



- Identify Customer CTQ's
- Perform CTQ Flowdown
  - Can we measure CTQ's? Do specs exist?
- Analyze measurement system capability.
- Generate / validate system / subsystem models.
- Build Product Quality Scorecard predictions.

- Roll-up Product Quality Scorecards for all subsystems.
  - Capability flow-up.
- Identify the gaps.
  - Low Z_{st} on capability map.
  - Lack of transfer function.
  - Unknown process capability.

- Use DoE on computer simulations and prototypes to find the critical few X's.
- Utilize Analysis Spreadsheet for parameter and tolerance design.
- Generate purchase and manufacturing specs.
  - Specify mean, variance, and limits.

- Confirm that pilot builds match predictions.
- Mistake-proof the process.
- Develop Manufacturing and Supplier control plan for CTQ's (mean and variance).
- Refine models, capability maps, and process characterization database.
- Document the effort and results.

Figure 2. DFSS IDOV phases

sional models for importing into the new design models. Larger part models can be copied from a previous design and modified for a new design, significantly reducing design and drafting time.

These techniques facilitate design for assembly, further enhancing the quality of the finished product. Modern software can animate 3D graphic models and determine if a path exists for assembly or removal of a component in the presence of other parts. Potential interfaces can be quickly identified and resolved without creating scale models or manipulating hard copies of drawings.

The frame of the 7FH2 Model 761/763 is very similar to existing 7FH2 models, and can accommodate the electrical design geometry with few changes. Efficiency for the new models is increased by approximately 0.1% while maintaining the same basic footprint. The design team will capitalize on proven features and components to best utilize existing drawings. Existing interfaces from the 7FH2 will be carried forward whenever possible to make the transition and introduction of the 761/763 transparent. Overall risk is substantially reduced because both performance and cost structure of the current 7FH2 family are well established. Of particular note, the Model 741/743 end shields will be applied to the Model 761/763. *Table 1* provides a summary of the Model 741/743 and 761/763 performance parameters. *Figure 3* shows the actual Model 761 generator configuration.

To increase overall efficiency of the 7FB, a "once-through" ventilation system has been chosen. This system reduces the required flow and corresponding windage loss, and also simplifies frame construction. The flow configuration employs an axial fan on each end that supplies the overall cooling flow. There are three main parallel flow splits from the fan discharge: the rotor, the stator end turn region, and the air gap.

Rotor (field) coils are cooled through uniformly spaced radial ducts supplied through the axial inlet manifold. Gas enters the rotor under the retaining ring and exits through a series of radial ducts that are machined in the field winding conductors, removing heat from the copper. The gas distribution and heat transfer in the slot region of the rotor are controlled by the

	7FH2 Model 741 / 743	7FH2 Model 761 / 763
Cooling	Hydrogen directly cooled rotor and conventionally cooled stator	same
Configuration	Single-end drive, end shield mounted	same
Rated Speed	3600 rpm/60 Hz	same
Output	195.5 MW/60 Hz	212.5 MW/60 Hz
Power Factor	0.85 lag	Same
MVA Rating	230 MVA/60 Hz	250 MVA/60 Hz
Terminal Voltage	18 kV	Same
Temperature Rises	Allowable Class B per IEC/50 Hz And ANSI/60 Hz Standards	Same
Insulation Class	Rotor - Class F; Stator - Better than Class F	Same
Excitation System	Bus Fed, Static Excitation	Same

Table 1. 7FH2 Model 741/743 and Model 761/763 performance comparison

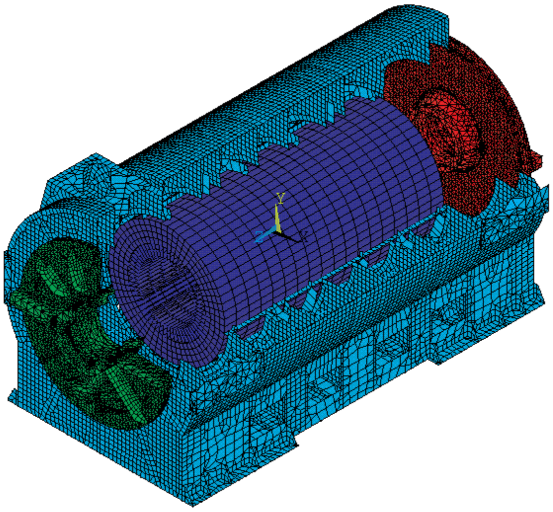


Figure 3. Three-dimensional view of the 7FH2 Model 761/763 generator

design of the subslot and the radial ducts. The size of the subslot controls the quantity of gas entering the radial ducts. Detailed DFSS analysis helps achieve the optimum design of the subslot, given the mechanical and electromagnetic design constraints. Modeling and analysis of the radial ducts allow the selection of a suitable duct profile that can be efficiently manufactured. The rotor end region receives indirect cooling as gas is scooped and circulated within the end-strap cavities.

The stator core also receives cooling via radial ducts. However, non-uniform package sizing is specified to optimize overall cooling efficiency. All outer radial sections are employed as exit regions from the stator core and provide plenums to feed the four coolers.

The air gap is the exit manifold for the rotor, and the inlet manifold for the stator. The flow is comprised of swirling axial flow mixing from the fan and rotating radial jets from the discharge of the radial ducts. The multiple paths of the stator end region receive flow from the fan and discharge directly into the stator outlet radial sections. The rotor end region receives indirect cooling as gas is scooped and circulated within the end-strap cavities. *Figure 4* provides a representation of the Model 761/763 cooling configuration.

Technology Development and Application

Generator design requires skill in a broad range of electrical, mechanical and material technologies, at the heart of which is the development of electromagnetic design tools. Ventilation and heat transfer, structural design, electrical loss evaluation, and rotor dynamics are all critical technologies for hydrogen-cooled generators. For the machine to perform as predicted, the analytical tools used in the design have to be validated.

Insulation systems applied to hydrogen-cooled units have to meet many of the same requirements as those used in air-cooled machines, including low thermal resistance and thermal cycling capability. Larger hydrogen-cooled units tend to be designed for higher terminal voltages and have greater electromagnetic forces than air-cooled designs. They require a somewhat greater level of dielectric capability and mechanical toughness than air-cooled machines, but the differences are not so great that the same insulation systems cannot be used in both applications.

Electromagnetic Analysis

The electromagnetic design of large generators lies at the leading edge of the art. Energy densities are higher than in almost any other electrical apparatus. Flux densities, currents and voltages, and electromagnetic forces are high. Conventionally-cooled designs require a detailed knowledge of the loss distribution in the machine, so the correct amount of cooling can be employed at each loss location.

Electromagnetic analysis of electrical machines is greatly facilitated by the increasing refinement and ease of use of finite element electromagnetic analytical tools. Three dimensional electromagnetic field solutions are derived for

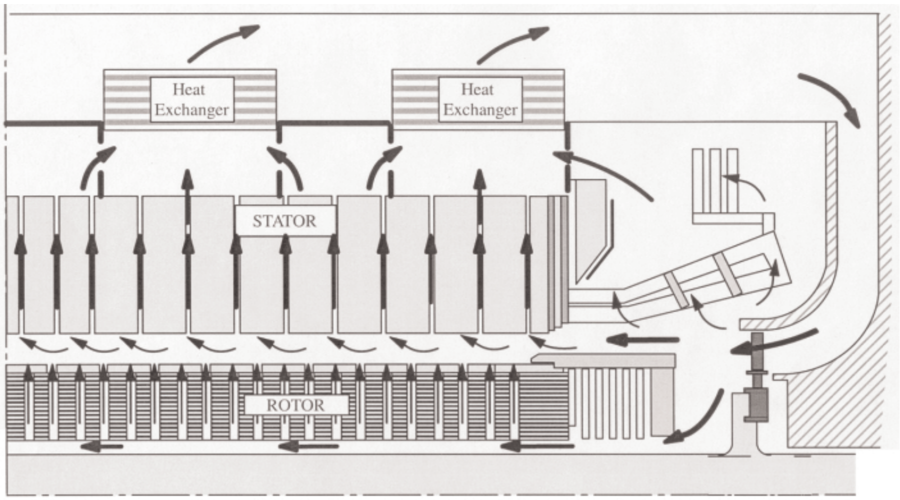


Figure 4. 7FH2 Model 761/763 "once-through" cooling configuration

both the stator and rotor. They allow the designer to accurately predict losses in these components, to adequately cool them, and to minimize design complexity. An example is shown by *Figure 5* example where losses are calculated in the copper flux shield at the end of the core, enabling the designer to confidently choose the correct design for the particular application.

Electromagnetic loss calculations are also used to analyze the excitation requirements of the design to assure adequate excitation system margins. When an application has an unusual operating requirement, such as additional leading power factor capability, these tools are used to design the ends of the stator core, taking into account the leakage fields of the stator and rotor end windings.

Ventilation Design

The ventilation pattern chosen for a given design depends on the length of the machine and the temperature distribution in its various components, particularly the stator and field windings. Gains in product efficiency can be achieved by optimizing the ventilation circuit to minimize pressure drop while maximizing cooling effectiveness. Advances in Computational Fluid Dynamics (CFD) analysis allow detailed evaluation and prediction of the flow in various parts of the ventilation circuit. FLUENT/UNS, a general-purpose computational package for solving a variety of heat transfer and fluid dynamics problems, is used extensively in generator ventilation and cooling analyses. Numerous models are generated, with each one focused upon a given element of the ventilation circuit. Results of an analysis are often applied as boundary conditions for the adjacent model.

One such case is shown by *Figure 6*, where the flow path and pressure drop is modeled at the stator-rotor gap. The ventilating gas is forced to flow into the gap by a ventilating fan mounted on the rotor. A "bottleneck" is formed between the retaining ring nose and the core end taper at the gap entrance. In addition, the retaining ring nose and the rotor core form a backward-facing step. As cooling gas passes the stator-rotor entrance, it generates a large flow circulation at the retaining ring nose. This results in a large pressure drop at the gap entrance. For the Model 761/763, techniques will be evaluated for reducing these losses along the axial cooling

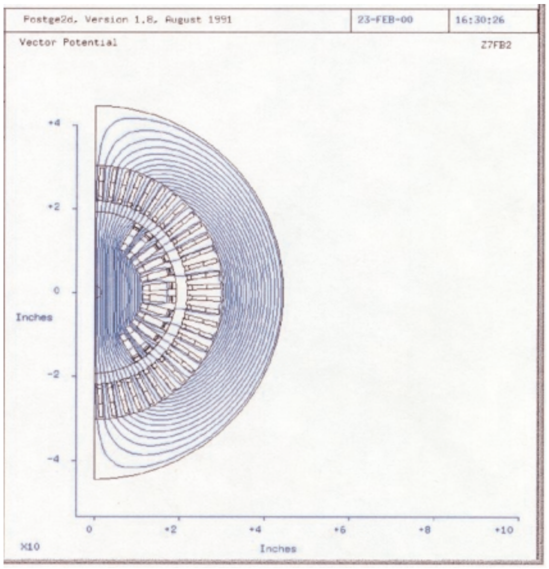


Figure 5. Core end heating analysis

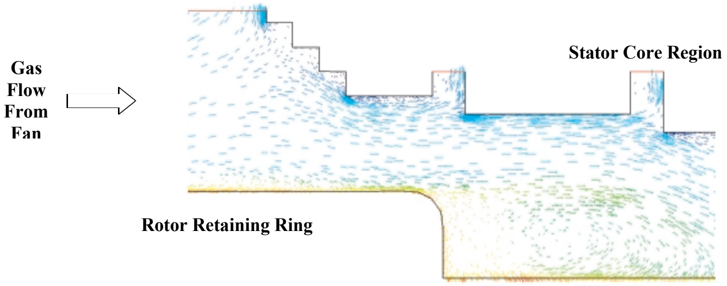


Figure 6. CFD - Cooling gas flow across the retaining ring

flow. Theoretically, it is feasible to reduce the stator-rotor gap entrance pressure drop by approximately 60%.

Cooling of the end winding region and the slot (or body) region are interrelated due to the rising temperature of gas as it exits the end turns, and the axial heat conduction in the copper. The gas flow patterns under the retaining ring are particularly difficult to understand and quantify. Variations in peripheral velocity and gas density, along with the Coriolis effect due to rotation, affect the movement of the cooling gas. CFD analysis is helping to develop a greater understanding of the cooling effects, and leading to enhanced cooling of the end turns.

The design of the fans that circulate the cooling gas through the generator is critical to the overall ventilation performance. The fan needs to be efficient and producible. CFD is used to predict fan performance accurately and determine the impact of changes in fan geometry. *Figure 7* provides a representation of calculated fan performance and overall system resistance. By utilizing CFD, new fan designs can be rapidly developed and optimized in conjunction with the overall ventilation circuit.

Structural Design

Generator structural design requires a thorough understanding of structural interactions

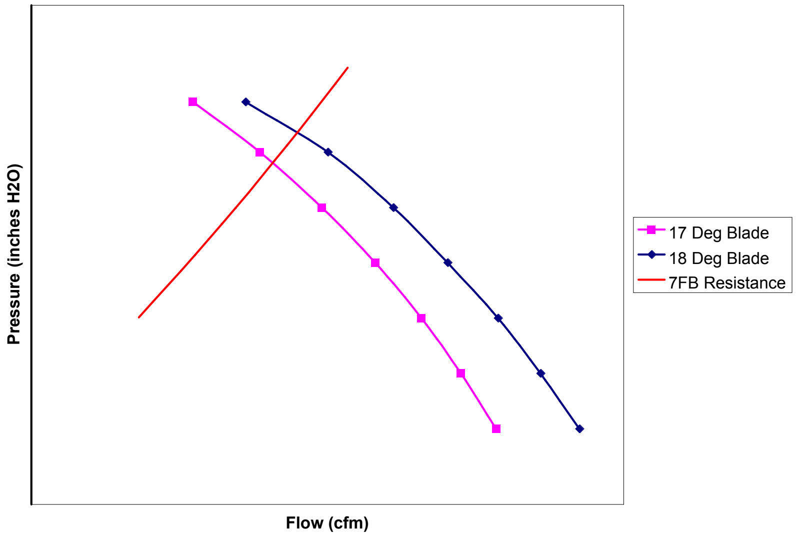


Figure 7. 7FH2 Model 761/763 fan performance

for all internal generator components as well as the interactions between the generator, foundation and drive train. Coupled with the design of component interactions is the requirement to optimize material usage to meet design limits and minimize generator costs. The design of a new generator makes extensive use of Finite Element Analysis. All major components of the generator are modeled and assembled into a complete generator assembly model, as shown in *Figure 8*.

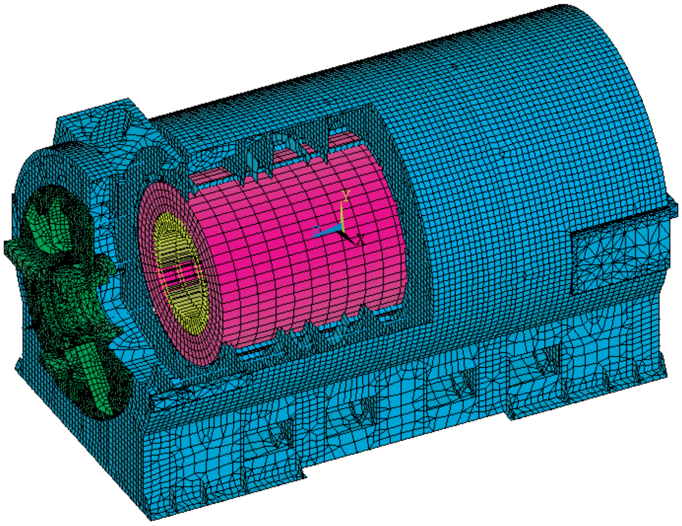


Figure 8. 7FH2 Model 761/763 Finite Element Model

The assembly model is used to analyze the generator vibration due to electromagnetic forces and rotor unbalance. It also evaluates acoustic noise performance and performs stress analysis for all loads to which the generator will be subjected. These loads include normal loads such as generator lifting, shipping and handling, internal operating pressure and rated operating torque. Emergency transient loads are also considered, such as over-pressurization and synchronizing out-of-phase torques.

Robust design tools and techniques can optimize the generator design and ensure adequate performance over a wide range of noise parameters. A parametric geometry-driven program named AMEA (Automated Mesh Analysis Interface) has been developed to allow quick and efficient assembly of Finite Element Models (FEM) for numerous components. AMEA allows concurrent design optimization, modeling and analysis of the various generator components while continuously maintaining the connections to the complete generator assembly model. Tools have been developed to efficiently perform DOE design optimization and performance evaluation over a wide range of uncontrollable noise parameters and external influences.

The Finite Element Model is exercised to interrogate the generator assembly for all loads encountered during assembly and operation. Electromagnetic force is the most likely force to cause structural issues. This force is cyclic and acts in the radial direction at the inside diameter of the stator core with a magnitude of one million pounds. The resulting stator core vibration and the transmission to the generator structure and foundation is a significant design consideration. Forced harmonic response analyses are performed to ensure that the electromagnetic forces cannot excite the machine's natural frequencies.

The structural design of the stationary components also must be considered when calculating the dynamic behavior of the rotor, since the rotor is supported on bearings located in the end shields of the machine. In this load configuration the structural vibratory loads caused by the rotor, and the loading caused by stator vibration that drives rotor behavior, are interrogated. Once again, a forced harmonic analysis is performed to understand and optimize the interactions. Lastly, the structural design has a major impact on the overall producibility and serviceability of the generator. The complexity of the fabrication determines the unit's machining cycles as well as its accessibility for thoroughly cleaning the inner cavities of the machine before shipping.

Rotor Design

As with the structural design, the rotor design is tightly linked to the electromagnetic design. The electromagnetic design determines the size and proportions of the rotor, which, in turn, determines the dynamic behavior of the rotor. The designers will explore a number of possible solutions to the overall machine design, looking for the best combination of rotor critical speeds and overall machine performance. Smooth running generators have been achieved by implementing sophisticated FEM-based rotor dynamics tools and applying rigorous high-speed modal balance procedures. The vibration performance demonstrated in service is excellent and well within ISO Standards requirements (*see Refs. 1, 2, 3, 4, and 5*). The mathematical models that were used accurately represent the dynamic properties of the rotor and its support system, with particular attention to accurate stiffness and damping modeling of the bearing oil film.

Modern design philosophy permits rotor-lateral critical speeds in the vicinity of operation speed, as long as the modes are sufficiently damped. Bearing selection ranges from elliptical pad to tilting pad, which each have application-specific advantages. The rotor dynamics optimization process determines selection of the appropriate bearing type. Torsional vibration design studies ensure that the turbine generator rotor system is robust to transmission network electrical disturbances and malsynchronization accidents. They also address the impact of continuously acting stimuli arising from unbalanced loads (*see Ref. 6 and 7*). The modal damping is extremely low for torsional vibration, so it is vital to demonstrate acceptable frequency separation margins in the design process, particularly in regard to the second harmonic of system electrical frequency.

As gas turbine designs move to higher firing temperatures and higher ratings, the torques required to rotate the turbine during starting increase rapidly. This is particularly true for single-shaft steam turbine and gas turbine (STAG) combined-cycle units. The inertia of both the steam turbine and the gas turbine, along with their aerodynamic losses, have to be supplied by the starting means. This has led to the use of the generator as a starting motor for the gas turbine. Careful design analysis is required to ensure that the effects of the current harmonics from the power supply, and the application of excitation at low speed, are accommodated reliably.

A key design goal for the Model 761/763 generator is increased efficiency. One technique to raise efficiency is to increase the cross-sectional area of the field winding turns, which reduces the resistive losses in the field winding. Rotor wedges are components that hold the field winding turns in the rotor slot while the rotor is spinning. A thinner rotor wedge allows more space for field winding copper and increases generator efficiency. A DFSS project was initiated to optimize the rotor wedge design. The goal was to minimize wedge thickness, while ensuring that the design had sufficient strength to provide high generator reliability. Optimization technology and statistical design methods were applied to achieve this key customer CTQ.

Numerical optimization techniques were applied to create a candidate wedge design. The Design of Experiment approach was then used to create response surfaces that characterized wedge stresses as the dimensions of the candidate design were varied over the tolerance ranges. A response surface example for the Von Mises stress at the top of the wedge dovetail is shown by *Figure 9.*

To ensure adequate stress margin (or high reliability), statistical material strength data from material tests was included with the calculated stresses in a Monte Carlo analysis. This analysis calculated the probability of positive stress margin (the difference between the wedge stress and the design strength limit). Positive stress margin means the wedge has more strength than required. An example of the stress margin probability distribution is shown in *Figure 10.*

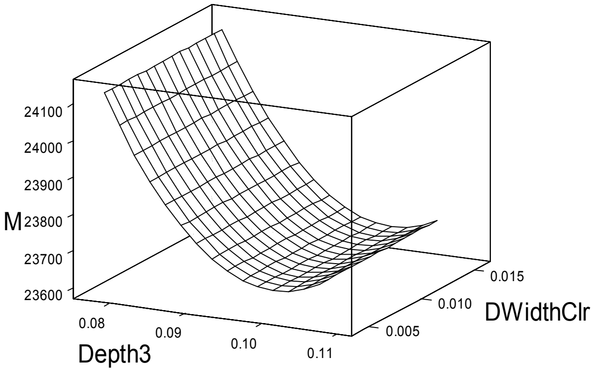


Figure 9. Response surface for rotor wedge optimization

The Monte Carlo analysis shows how application of optimization techniques and statistical design methods can directly improve customer value.

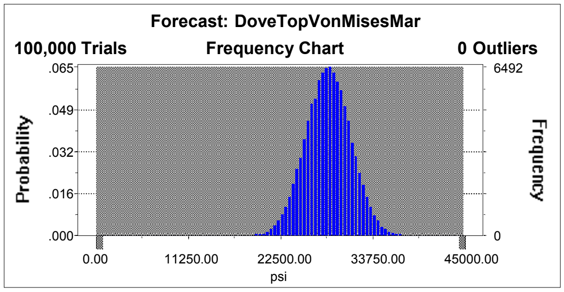


Figure 10. Monte Carlo analysis of rotor wedge stress

Insulation Systems and Dielectric Design

The insulating materials in a high voltage generator occupy valuable space, and must be capable of conducting heat from the winding to the cooling gas. As a result, the insulation system designer is continually challenged to develop insulation systems that occupy minimum space, are capable of handling higher electrical stresses, and have maximum thermal conductivity. *Figure 11* shows how the thickness of the stator groundwall insulation might affect the size of a typical conventionally cooled machine.

The mechanical forces on the insulation system can be very high. Forces on the stator winding are especially high during the time that an electrical fault is applied to the machine. The stator insulation must be a chemically stable, rigid structure that can accommodate modest bend-

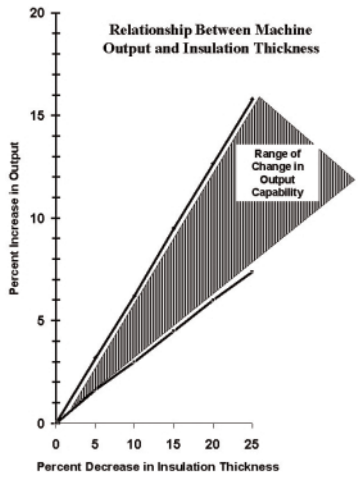


Figure 11. Relationship between machine output and insulation thickness

ing at winding without developing cracks or voids in the ground wall. The rotor insulation systems are exposed to very high “g” loadings due to the centrifugal forces on the copper winding, ranging up to 9000 g on a large 3600-rpm rotor.

Rotor insulation systems are as crucial to the reliability of the machine as the stator winding insulation systems. Due to lower voltages, the rotor insulation is not as thick as the stator insulation. However, the mechanical duty is high during assembly of the windings and during operation. As a result of these operating requirements, the mechanical properties of the insulating materials and the mechanical design of the insulation systems are as crucial as their electrical performance. An additional factor in evaluating the rotor insulation system is the presence of voltage spikes generated by the excitation system. High-response static excitation systems frequently operate with full ceiling voltage applied to their AC or source side. The appropriate level of DC voltage to be applied to the field is determined by controlling the firing angle of the power thyristors in the bridges. The field winding will be exposed to full AC voltage levels and switching spikes that reach the field ceiling voltage several times per cycle.

In addition to the mechanical forces and dielectric duty, thermal expansion of the stator and rotor windings are among one of the major contributors to loss of life of the insulation systems. Restriction of the relative motion of system components produces unacceptable strain, and repeated thermal cycling causes abrasion, both of which can reduce the life expectancy of the insulation. Successful operation over the expected life of the machine requires a thermally stable insulation system in both the stator winding and the field. Thermal cycling and exposure to the hot conductor throughout the life of the generator can break down a poor quality insulation system (materials and/or application of the materials). The properties of the insulation being designed must consider electrical and mechanical performance characteristics at operating temperatures.

The same Six Sigma approach and statistical methods used to design the rest of the machine are used to optimize the combination of materials and processing parameters. DFSS methodology organizes the development process and DOEs are performed to screen material combinations. The Product Quality Scorecards are used to compare performance and select the appropriate insulation system design.

Testing

Validation of the machine design is obtained by combining component, assembly, and machine testing. GE’s philosophy is to test a prototype machine whenever a significant design change is made. It is not possible to factory test the machine under full-load conditions. However, it is possible to perform no-load open and short circuit tests to confirm the electromagnetic and thermal characteristics per ANSI and IEC standards. Sudden short circuit tests are also performed to confirm winding mechanical design and measure reactances. Unbalanced loading tests are performed to confirm negative sequence capability. Special tests to confirm specific design features are performed as required. In addition to the overall machine tests, a number of special tests are performed on prototype machines during assembly to confirm structural frequencies, stator end winding vibration and other important design features.

Conclusions

The newest additions to the 7FH2 family, the Model 761/763 generator design will provide equally high levels of customer satisfaction as do the current models. Their introduction follows closely on the heels of the successful 9A4, 7A7, and 390H product releases. Each of these three designs was thoroughly validated by factory tests and the 9A4 has entered commercial operation.

The 7FH2 Models 761/763 will provide increased efficiency and output beyond the Model 741/743, while incorporating many of the key features and components that have been thoroughly validated through extensive usage. Critical elements such as reliability, availability, and maintainability will be carried forward. Cost effectiveness will be achieved through close coupling of the Model 761/763 program with ongoing product improvement activities for the Model 741/743. The Model 761/763 generator will satisfy all CTQ customer requirements for utilization with the 7FB gas turbine combined-cycle power plant.

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