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GE Power Generation

GE Generators – An Overview

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INTRODUCTION

The history of GE's design, manufacture and development of electric generators has been a long and varied one. Since the early 1900s, more than 10,000 GE generators have been shipped and placed in service at utility companies and industrial plants, and as ship service units. The designs have evolved from slow-speed vertical-shaft units to high-speed horizontal shaft air-cooled units, through indirect hydrogen-cooled units to direct water-cooled units.

During the 1950s through the mid-1970s, much emphasis was placed on developing units to support the rapid growth in unit ratings, which increased from 100 MW to more than 1100 MW. It was during this time frame that such innovative design features as direct water-cooled armature windings, gap-pickup rotor winding cooling, Micapal II™ stator insulation, Class F rotor and stator insulation, advanced Tetraloc™ stator end-winding support systems, and the side ripple-spring armature bar slot support structure were developed.

In the early 1960s, packaged gas-turbine-driven generators were introduced. These applications were characterized by the ambient-temperature-following nature of the gas turbine output and the ability of the gas turbine to provide peaking capability for short periods. Generator designs were developed which were tailored to gas turbine applications. As new gas turbines were introduced, or as older designs were uprated, generator designs were introduced to match the new gas turbine ratings.

Over the course of the past decade, the emphasis in new electric power generation installations has swung away from large units delivering major blocks of power to smaller units operated not only by utilities, but by cogenerators or other smaller independent power production companies. In response to this change, GE is placing a major emphasis on the design and development of generators suited to these applications.

Excluding marine service applications, GE currently has more than 6400 generators in service (Figure 1). These generators can be placed in three major design classifications based on the cooling medium used: air, hydrogen and liquid cooled. This paper will give an overview of each of these basic design classifications.

NUMBER OF UNITS IN SERVICE – BY COOLING TYPE

	Liquid Cooled	Hydrogen Cooled	Air Cooled		Total
			Open Ventilated	TEWAC	
Steam Turbine-Driven	520	3,006	2	1,184	4,712
Gas Turbine-Driven	1	214	1,340	151	1,706
Totals	521	3,220	1,342	1,335	6,418

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Figure 1. GE generator experience

DESIGN CONSIDERATIONS

The design of synchronous generators is an optimization process. A generator design engineer's challenge is to develop a final design that, as best as is practical, optimizes the overall size, efficiency, performance capabilities and electrical parameters, while maintaining mechanical, thermal and magnetic limits. In addition, the designer must be aware of the need to minimize the overall cost impact of the design.

The development of modern analytical calculation methods, including finite-element analysis, supplemented with the use of improved materials, building upon component testing, has aided the generator designer in the pursuit of an optimal design.

AIR-COOLED GENERATORS

Air-cooled generators are produced in two basic configurations: open ventilated (OV) and totally-enclosed water-to-air-cooled (TEWAC). In the OV design, outside air is drawn directly from outside the unit through filters, passes through the generator and is discharged outside the generator. In the TEWAC design, air is circulated within the generator passing through frame-mounted air-to-water heat exchangers.

The recent emphasis in the marketplace on steam and gas turbine-generators in the 20- to 100-MVA size has provided GE with the impetus to restructure its air-cooled machines. A consequence of the historical development of the turbine-generator market was that two lines of generators evolved, one for steam turbine applications and the other for gas turbine applications, with little standardization between the designs. As GE embarked on this design restructuring, it took the opportunity to look at other issues which GE judged were critical to its ability to maintain leadership in the design and manufacture of this size generator. Among these issues were performance parameters, availability of features, cycle time and cost effectiveness.

MARKET NEEDS

The basic design of a generator, while influenced primarily by material and electromagnetic properties, is also impacted by market requirements. Hence, customer discussions as well as recent market trends are used in the development of a final generator design. Some of these include: winding temperature rise, industry standards, generator ratings, etc.

TEMPERATURE RISES

In the early 1970s, GE introduced insulation systems capable of operating at class F temperatures (155 C, 311 F) for the life of the generator. This enabled a significant uprating of generator designs (about 10%) with a minimal increase in cost. To capitalize on this technical capability, GE designed generators with Class F insulation and Class F rises. Many such generators built by GE are in service and operating successfully at Class F temperatures. However, the trend in recent specifications has been toward Class F insulation systems operating at Class B temperatures. In order to be responsive to these requirements, the new designs will operate at Class B temperatures according to ANSI and IEC standards.

GENERATOR RATINGS

In a rapidly developing technology, such as that of the combustion turbine, it is inevitable that the output of a given gas turbine frame size will be increased from time to time. This has required redesign of the generator to keep pace with the rise in turbine output. The ratings of the generators designed to match the gas turbine frame sizes have been set so that the generator will meet or exceed the gas turbine capability over the full operating temperature range, taking into account the expected turbine upratings during the lifetime of the design.

Another important consideration that affects the generator rating which must be taken into account is the use of steam and water injection for NO_X control. The output of the gas turbine can increase by 5% or more above its dry ISO rating, depending on the level of steam or water injection required to meet the emission requirements. An approach that results in the generator having sufficient capacity to match the gas turbine at the required NO_X requirements has been factored into the generator rating.

STANDARDS

All new designs will meet the requirements of the applicable ANSI and IEC standards, as did the older designs.

RELIABILITY

Particular attention has been paid to known problem areas based on in-service generator experience. The new designs strive for a high level of reliability and availability through attention to detail design and to the problems that have caused downtime on older designs. In addition, the reliability of the product will improve through design simplification and standardization, discussed below.

PRODUCT STANDARDIZATION

Standardization of the product line has significant benefits both to the user and to the manufacturer. From the user's viewpoint, the standardization of the product line translates into 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 that this brings. The benefits to the manufacturer are that, with fewer unique parts to track and check, fewer different assemblies to build and fewer drawings to keep up to date, the job of building a high-quality machine becomes simpler.

Standardization is being implemented at three levels. At the highest level, the number of different designs can be reduced by careful selection of generator ratings and the use of common designs for gas and steam turbines. At the time the redesign project was begun, there were 17 unique air-cooled generator designs between 12 MVA and 100 MVA. With careful choice this has been reduced to six basic electromagnetic designs.

The second level of standardization is illustrated in Figure 2. This shows the high level of standardization achieved in covering the basic configurations of the generator for the Frame 6 gas turbine (designated 6A3), 50 Hz or 60 Hz, open

Generator Component	Design Option							
	6A3							
	50 Hz				60 Hz			
	TEWAC		OV		TEWAC		OV	
	B	S	B	S	B	S	B	S
Frame	*	*	*	*	*	*	*	*
Core	*	*	*	*	*	*	*	*
Base	*	*	*	*	*	*	*	*
Stator Bar 50 Hz	*	*	*	*				
Stator Bar 60 Hz					*	*	*	*
Brushless Exc	*		*		*		*	
Static Exc		*		*		*		*
OV Roof			*	*			*	*
TEWAC Roof	*	*			*	*		
Rotor Forging	*	*	*	*	*	*	*	*
Rotor Copper	*	*	*	*	*	*	*	*
Rotor Edg. 50 Hz	*	*	*	*				
Rotor Wdg. 60 Hz					*	*	*	*
Rotor Slot Width	*	*	*	*	*	*	*	*
Rotor Slot Depth 50 Hz	*	*	*	*				
Rotor Slot Depth 60 Hz					*	*	*	*

* Same Component Applied to Design Option

B - Brushless Excitation
S - Static Excitation

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Figure 2. Generator standardization

ventilated (OV) or totally enclosed (TEWAC), and brushless or static excitation. For example, the stator frame, core and base, and the rotor forging and rotor copper cross section are identical for any combination of these features. The only difference between the 50-Hz stator and the 60-Hz stator is the different stator bar. Everything else is the same. This component standardization can be extended to other ratings when the same component is used for two different machines. For example, the generator base is the same for the Frame 5 generator as it is for the Frame 6 generator. In addition, while the gas turbines are the primary application of the new air-cooled generators, they can and have been applied with steam turbine drives as well (Figure 3).

The most detailed level of standardization is with hardware such as fasteners and small components. A carefully constructed list of preferred hardware has been developed and the number of different nuts, bolts and similar items has been drastically reduced.

The impact of standardization is illustrated in Figure 4, which shows the reduction in the number of parts and drawings required to build a sin-

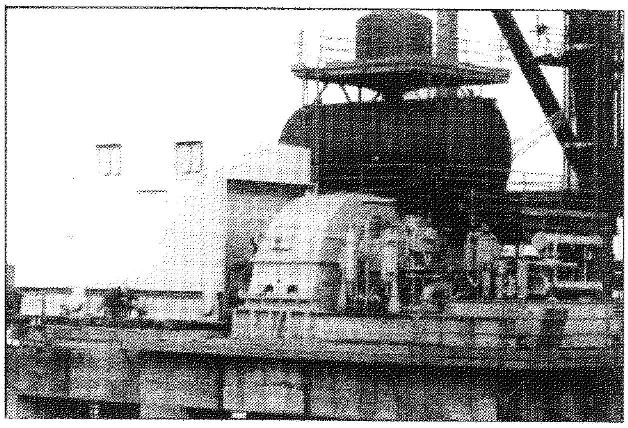

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Figure 3. Air-cooled steam turbine generator

	OLD DESIGN	NEW DESIGN
REL. # OF PARTS	1.0	0.6
REL. # OF DRAWINGS	1.0	0.7

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Figure 4. Impact of standardization

gle new design as compared to its predecessor. When these gains are compounded by the reduced number of unique designs, there is a profound effect on the productivity and quality of the manufacturing operation.

One of the potential adverse effects of standardization can be a loss of flexibility to meet an individual customer's needs. This has been addressed first by building into the design those features that are frequently specified. An example is the use of stainless steel oil feed piping. This feature is not requested by every customer, but it is asked for often enough such that it is easier to build every unit with the stainless steel piping. The second way in which individual needs have been met is through "standard options." These are pre-engineered options commonly requested for which drawings have been prepared ahead of time.

These options can be readily incorporated in the machine, within normal material procurement and manufacturing cycles. An additional group of options is available that have not been pre-engineered due to the low frequency of request. These are available but with longer lead times since the necessary engineering work must be accommodated.

DESIGN AND CONSTRUCTION FEATURES

The design teams involved were organized with representation from all the major business functions, and members of the design teams visited some representative customers to better understand user needs. In this way, the technical requirements of the designs were influenced by the needs of all the functions involved in the design, manufacture, marketing and maintenance of the generator. Features were incorporated into the design specifically to aid producibility. Visits to and discussions with potential vendors influenced the design of components both for improved performance and to suit vendors' capabilities. Careful cost comparisons were made of alternative design approaches to ensure that the final configuration was cost effective.

ELECTROMAGNETIC DESIGN

To achieve the reliability objectives of the project, no new electromagnetic design limits have been used. The designs are based on proven technology used in generators already in service. Where appropriate, the technology used in larger units has been drawn upon to improve the designs of these machines. In reaching the final configuration, a large range of design alternates was considered, and the final choice of design reflects the optimization of the types of consideration described herein.

STATOR DESIGN

The stator frame is divided onto an inner and an outer section, both of which mount on a single base fabrication. The inner frame is a very simple structure designed to support the stator core and winding while providing some guidance to the air flow in the machine. The stator core, made from grain-oriented silicon steel for low loss and high permeability, is mounted rigidly in the inner frame. Isolation of the core vibration from the remainder of the structure is accomplished through the use of flexible pads between the feet on the inner frame and the base structure. The combined core and inner frame are designed to have a four-nodal natural frequency well removed from 100 Hz or 120 Hz, and tests on the assembled inner frame confirmed the predicted natural frequencies.

The outer frame is a simple fabricated enclosure, which supports either the air inlets and silencers if the unit is open ventilated (Figure 5) or the roof and cooler enclosure if the unit is totally enclosed, water-to-air-cooled. The outer frame further acts as an air guide to complete the ventilation paths and as a soundproof enclosure to keep noise levels low. Since the rotor is pedestal mounted, the end shields are very simple structures. As with the inner frame, the outer frame was designed to be free of resonances below 80 Hz, and again, tests of the completed structure confirmed the design analysis.

The entire generator is mounted on a single fabricated base, which supports the pedestals, the inner and outer frames, and the brush rigging or the exciter. The base contains piping for oil supplies, conduit for wiring and a number of components associated with the main leads, such as lightning arresters and surge capacitors. The structural vibration of the base was also confirmed by test to be well away from any frequency of concern.

The stator winding is a conventional lap-wound design. The insulating materials are those used since the early 1970s, thus maintaining the proven reliability record. The materials are all designed and tested to provide reliable performance at Class F temperatures for the life of the machine. The stator bar copper is stranded and insulated with Class F materials and is Roebelled for minimum losses. The ground wall insulation is Micapal HT, a proven Class F system (Reference 1). This is a resin-rich tape system, with the volatiles removed under vacuum, which is then cured under pres-

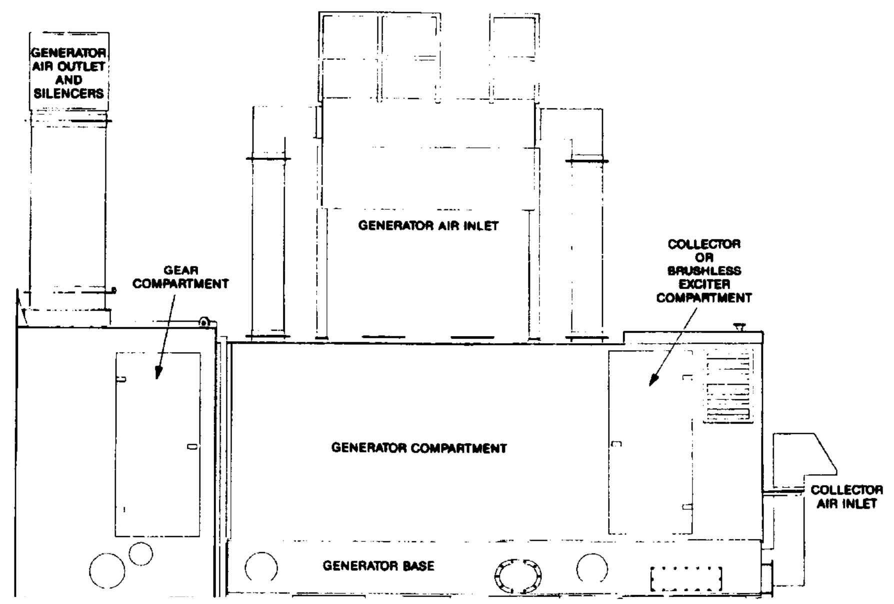

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Figure 5. Generator packaging

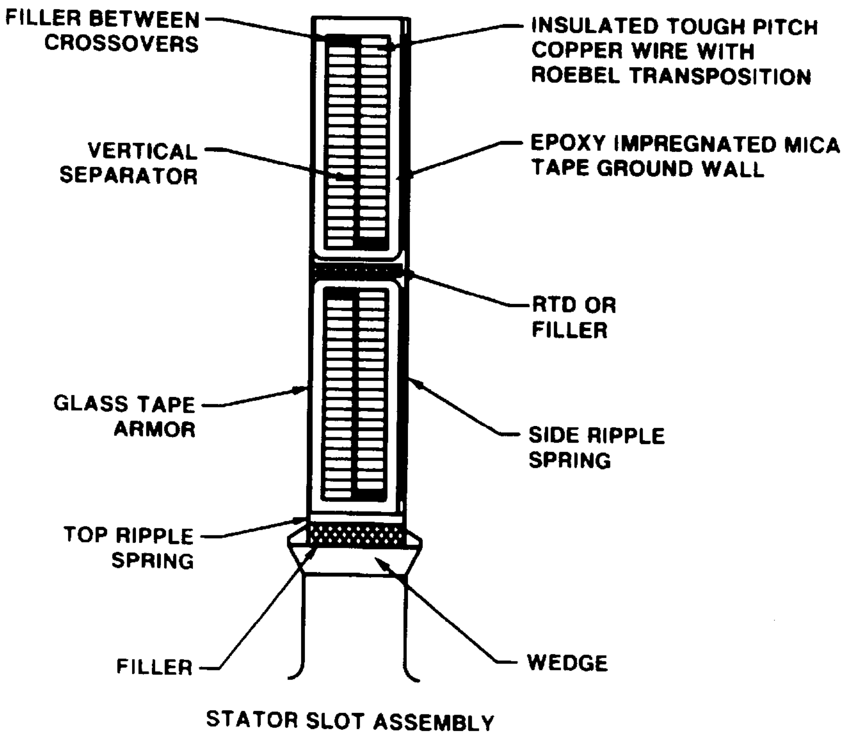

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Figure 6. Stator slot section

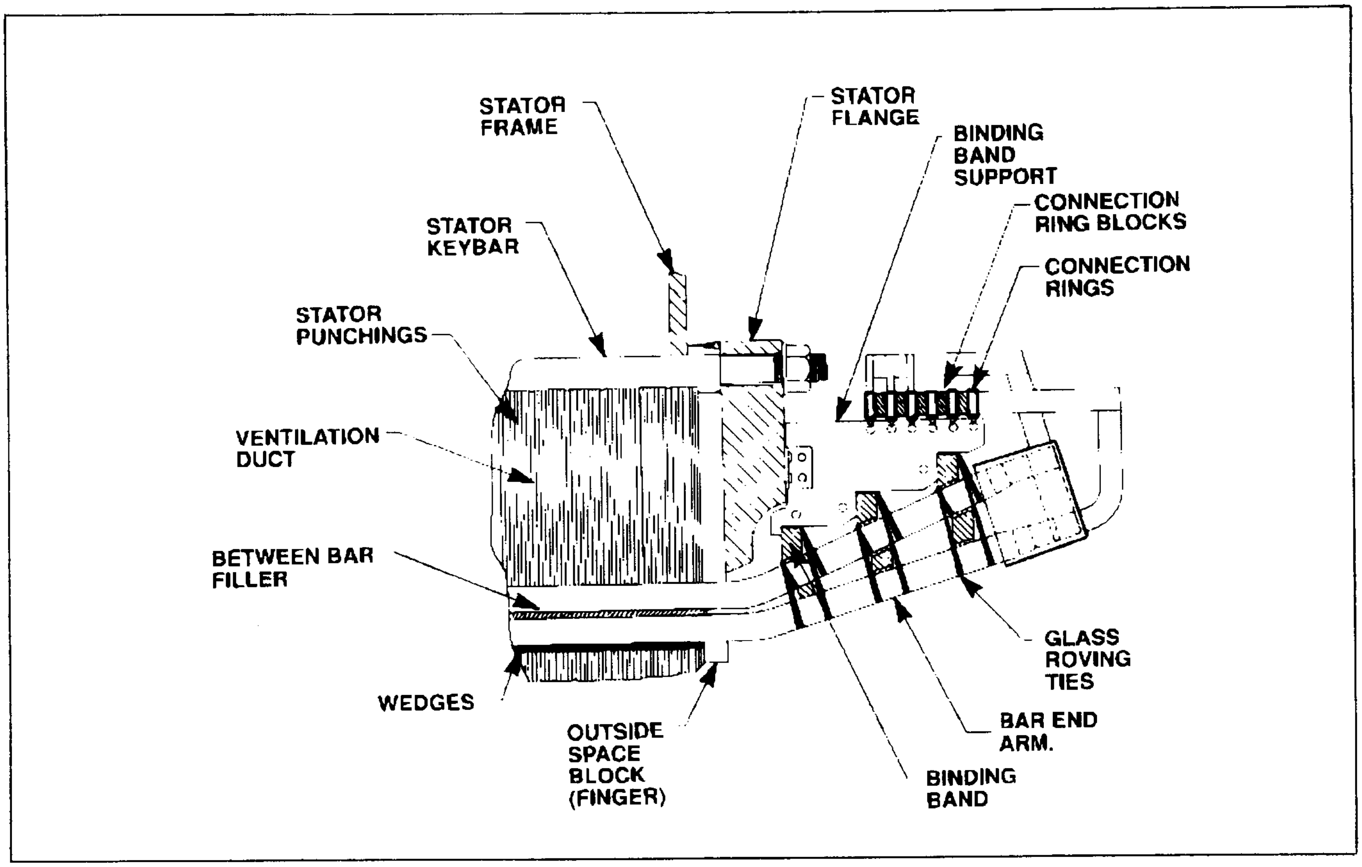

Figure 7. Stator end winding section

sure to a solid, void-free structure. The exterior of the bar is taped with a conducting armor in the slot section, and 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 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 also conducting to ensure proper grounding of the bar surface.

The end winding support system is the proven approach used on conventionally-cooled stators of all sizes built by GE. This system utilizes resin-impregnated glass roving ties (Figure 7).

One design improvement made in response to problems experienced on some designs manufactured in the late 1970s is in the manner in which the series connection between top and bottom bars is made. Until recently, this was accomplished by brazing individual strands together and then solidifying the package with an epoxy. The improved system is to braze all the strands together in a solid block and then to braze top and bottom bars together with solid copper plates. This provides a solid electrical connection and a rugged mechanical joint.

The complete end winding structure has been vibration tested to ensure freedom from critical resonances, and vibration levels measured during running tests were found to be low.

ROTOR DESIGN

The rotor (Figure 8) is a simple single-piece forging, pedestal mounted, with tilting-pad bearings for smooth operation. On smaller units, the rotor is sufficiently short that the second critical speed is above running speed, thus simplifying balance. The retaining ring is nonmagnetic 18 Cr 18 Mn stainless steel for low losses and good stress-corrosion resistance. The rings are shrunk onto the rotor body, thus eliminating any risk of top turn breakage. The retaining ring is secured to the rotor body with a snap ring, a design which minimizes the stresses in the tip of the retaining ring.

Radial-flow fans are mounted on the centering ring at each end of the rotor. The fan is a high-efficiency design, and when tested prior to use in the generator proved to have satisfactory margins compared to the design requirements. The fans provide cooling air for the stator winding and

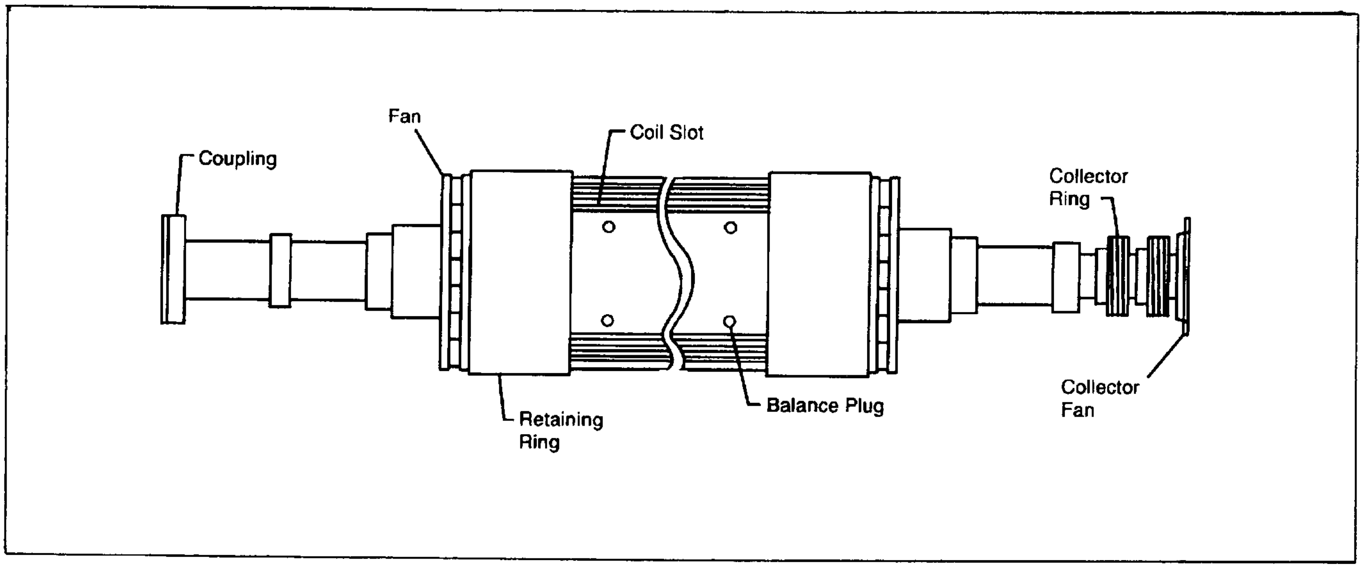

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Figure 8. Generator field

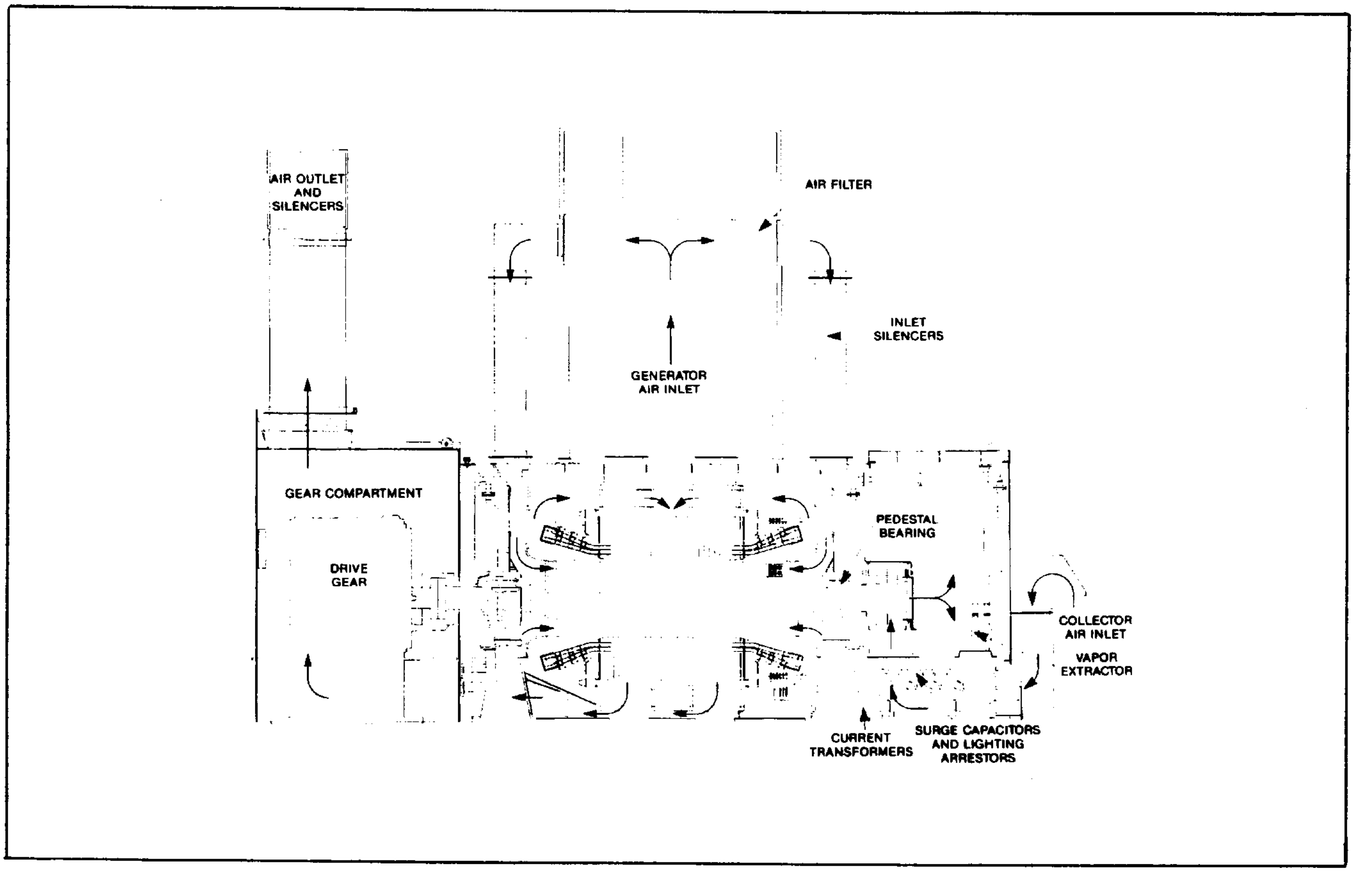

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Figure 9. Generator cross section and ventilation paths

core. The rotor winding, which is a directly-cooled radial flow design, is self-pumping and does not rely on the fan for air flow. The overall ventilation pattern is shown in Figure 9.

The rotor winding fits in a rectangular slot (Figure 10) and is retained by a full-length wedge on the shorter machines. Where cross slots are required on longer rotors, several wedges are used in each slot. The rotor slot insulation, turn insulation and other materials in contact with the winding are full Class F materials and have proven reliability through use on other generator designs.

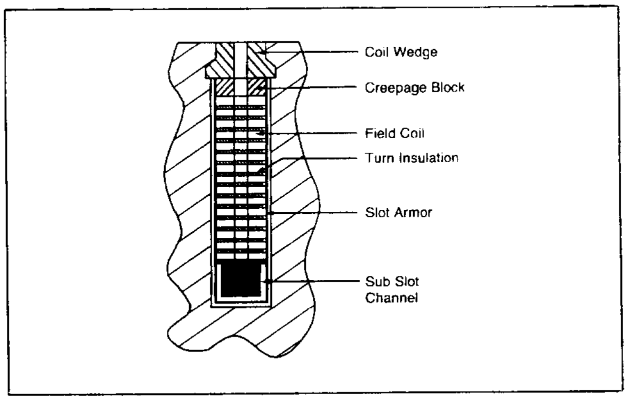

Figure 10. Section through coil slot

PACKAGING DESIGN

The objective in the packaging design has been to reduce the number of sections (Figure 5) to simplify the structure and to improve the piping and wiring design for fewest parts and ease of assembly. The lesser number of package sections leads to a stronger structure, but, more importantly, results in fewer feet of joint through which unfiltered air can leak, thus aiding cleanliness in the generator. Depending on the design, a number of components have been relocated from the auxiliary cubicle into the base, simplifying the design of the auxiliary cubicle. Components in the base are low-maintenance items, and are accessible through covers in the collector compartment.

A great deal of attention has been paid to customer requirements in this area, as the preferences of individual users frequently require packaging changes. Ease of addition or removal of features and hardware is critical to meeting these needs within the normal cycle times.

TESTING

Extensive prototype testing of each of the new designs, both in the factory and under load at a customer's site, has proven that the designs meet all the expected performance requirements throughout the load range. Some of the key test objectives are listed in Figure 11.

Electrical Testing
- Excitation Requirements
- Short Circuit Ratio
- Temperatures

Mechanical Testing
- Rotor Vibration
- Stator Frame Vibration
- Noise
- Stator Winding Vibration
- Ventilation

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Figure 11. Factory and load test objectives

Journal Probe Location and Orientation	Measured Vibration Mils Peak-to-Peak (MM)	
	Broadband	Filtered - 1/Rev
Turbine End Horizontal	0.90 (.023)	0.37 (.009)
Turbine End Vertical	1.00 (.025)	0.46 (.012)
Collector End Horizontal	0.50 (.013)	0.19 (.005)
Collector End Vertical	0.50 (.013)	0.23 (.006)

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Figure 12. 6A3 journal vibration maximum values observed for all speed and operating conditions

Loss measurements confirmed the prediction of generator efficiency at the generator rated output, and heat runs both in the factory and under load confirmed that the generator would meet both NASI and IEC standards for Class B temperature rise.

At the design stage, a great deal of attention was focused on achieving a smooth running rotor. Figure 12 shows the levels measured on a 6A3 at the site. These levels are significantly lower than those required by API, and also are much lower than those in a recently issued draft international standard (7919/3). The API requirements for separation margins of rotor lateral critical speeds from operating speeds were also fully met.

A noise survey was conducted during startup of the first 6A3, using the sound intensity method which compensates for ambient noise effects. The average generator near-field sound pressure was determined from the measurements to be 85.7 dBA, which is very satisfactory, and compares favorably with the design target of 85 dBA.

CURRENT STATUS

Three new machines have been designed to match the GE Frame 5, 6 and 7 gas turbines. More than 130 generators of these new designs have been shipped through the end of 1992, with approximately one-half in service.

The air-cooled generator product line is continuing to evolve. The generator that is being applied with the LM6000 aeroderivative gas turbine (Figure 13) was tested and shipped in 1992. Its basic configuration is open ventilated (with a TEWAC option), brushless exciter, pedestal-mounted bearings, on a "single-lift" base, rated 60

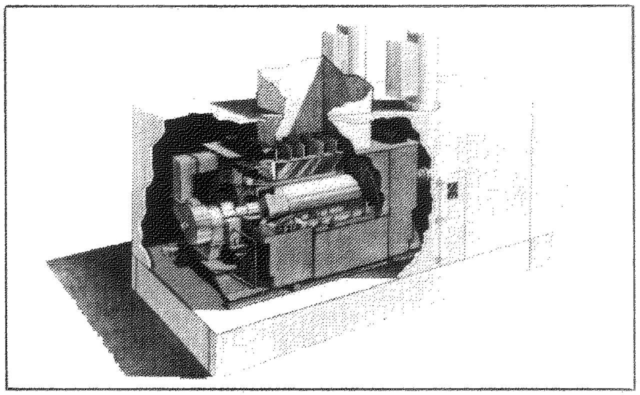
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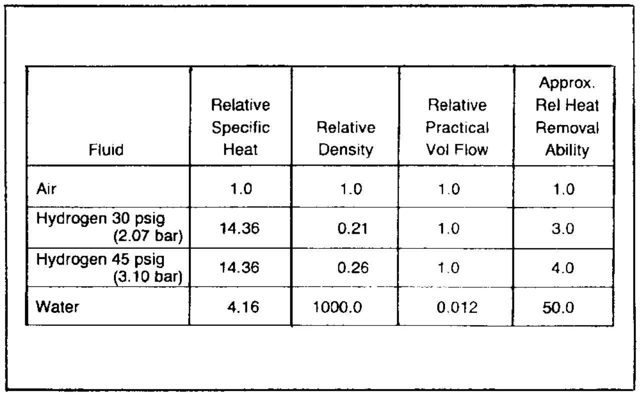
Figure 13. LM6000



Fluid	Relative Specific Heat	Relative Density	Relative Practical Vol Flow	Approx. Rel Heat Removal Ability
Air	1.0	1.0	1.0	1.0
Hydrogen 30 psig (2.07 bar)	14.36	0.21	1.0	3.0
Hydrogen 45 psig (3.10 bar)	14.36	0.26	1.0	4.0
Water	4.16	1000.0	0.012	50.0

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Figure 14. Air, hydrogen, water heat removal comparison

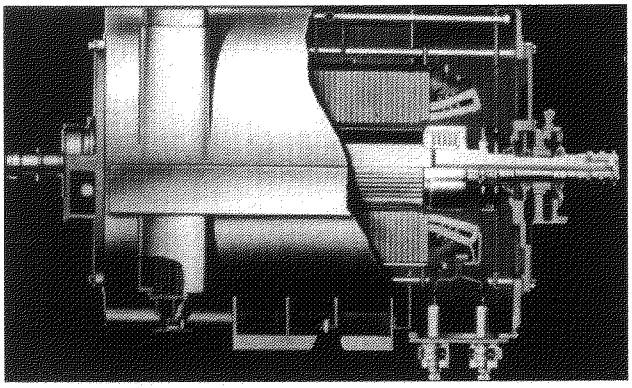
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Figure 15. Hydrogen-cooled generator

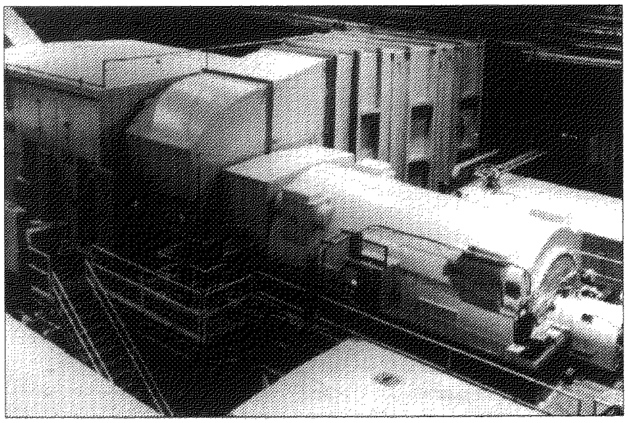
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Figure 16. 7F generator

MVA at 0.8 pf. In 1993, a 160 MVA, 50-Hz air-cooled generator, to be used primarily with the frame 9E gas turbine, will be tested as well.

HYDROGEN-COOLED GENERATORS

As the rating of steam turbines rose in the 1930–1950 time frame, it became clear that in order to keep the size, weight, ability to ship and cost of a generator within reason, a more optimal cooling medium needed to be used. Hence the introduction of hydrogen.

How well the armature winding of a generator is cooled has a significant influence on the overall size of a synchronous generator. The cooling of the armature winding is dependent on a number of factors: cooling medium (air, hydrogen, water); insulation thickness; and overall electrical losses (I^2R + load loss). As Figure 14 shows, relative heat removal capability improves from air to hydrogen, with increased hydrogen pressure, and even more significant with the use of water cooling. Conventional hydrogen cooling can be utilized on generators rated approximately 300 MVA and below, while direct water cooling of armature windings is applied to units above 250 MVA. This division results from design optimization. While it is possible to apply water cooling on machines rated below 250 MVA, the cost/performance benefit suffers. Water cooling adds manufacturing complexity, as well as requires the need for an auxiliary water cooling and deionizing skid, plus associated piping, control and protection features. At higher ratings, the cost of this complexity is offset by the advantage of producing a generator of significantly smaller size than a comparable conventionally-cooled generator.

Hydrogen-cooled generator construction (Figure 15), except for the frame, is very similar to that of air-cooled generators. The stator slot and end winding support designs are essentially like those shown in Figures 6 and 7. Most designs use direct radial flow cooling similar to that shown in Figure 10. The stator frame, on the other hand, because of the need to contain 30 psig (2.07 bar) to 45 psig (3.10 bar) hydrogen, uses thick plate cylindrical construction. End shields are appropriately more rugged, and contain a hydrogen seal system to minimize leakage. Conventional hydrogen cooling, while available

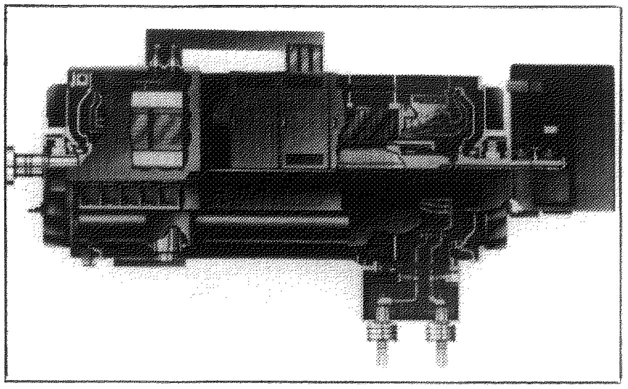

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Figure 17. Water-cooled generator

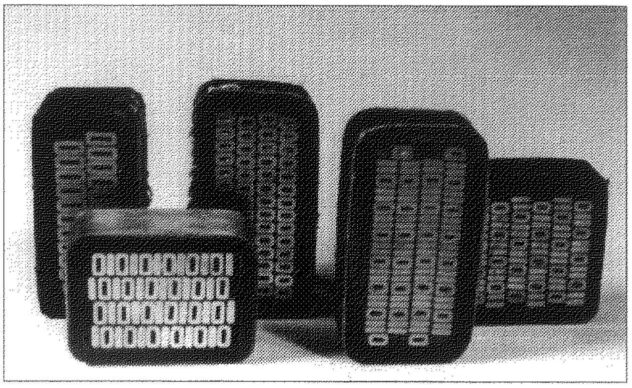

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Figure 18. Hollow copper strand construction

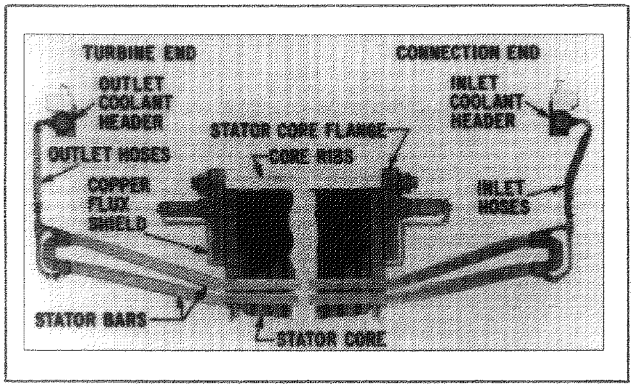

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Figure 19. Water-cooled stator winding arrangement

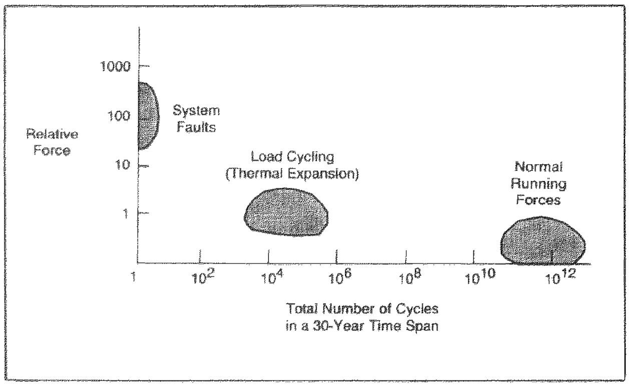

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Figure 20. Cyclic duty on stator winding in 30 years

for generators rated below 100 MVA, is most often applied to steam-turbine-driven units above 100 MVA, as well as with the frame 9 and 7F (Figure 16) and frame 7FA and 9F gas turbines.

HYDROGEN/WATER-COOLED GENERATORS

Even more compact generator designs are achievable through the use of direct water cooling of the generator armature winding (Figure 17). These designs employ hollow copper strands (Figure 18) through which deionized water flows. The cooling water is supplied via a closed-loop auxiliary-base-mounted skid. The cool water enters the winding through a distribution header on the connection end of the generator and the warm water is discharged in a similar manner on the turbine end of the generator (Figure 19).

The armature voltage and current of hydrogen/water-cooled generators are significantly higher than those of air- or hydrogen-cooled units. As a result, the insulation voltage stress and forces on the armature windings can be several orders of magnitude larger than those experienced on lower-rated units. These present unique design requirements must be addressed if high reliability and long life of the equipment is to be maintained.

Insulation

The stator insulation material used in modern GE water-cooled generators consists of an epoxy-mica-based system called Micapal. Micapal I was introduced in 1954, partially as a solution to tape migration and girth cracking problems associated with the then almost universally applied asphalt-insulation-based system.

In 1975, an improved epoxy-mica system was introduced (Micapal II). This all-mica paper insulation has improved mechanical toughness (15%) and voltage endurance (12%). While these properties were developed to meet the requirements of very large ratings, the application of Micapal II on small and midsize units permits further optimization opportunities. Micapal II has excellent thermal cycling capability, and is particularly suited for the daily start/stop duty required of many units today.

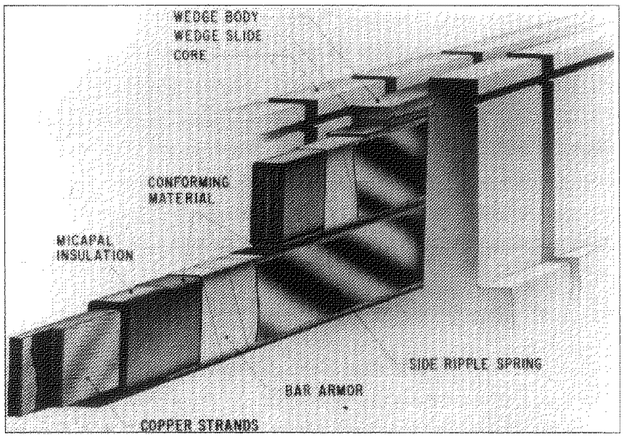

Figure 21. Armature bar restraint in stator slot

Forces on Stator Windings

There are two sources of force on the stator windings: high-level, short-duration transient forces due to system or misoperation faults, as well as those that result from normal load currents and load cycling.

Figure 20 charts frequency of occurrence against relative magnitude for these forces. Each type of force requires careful consideration during the design process. High-level fault currents can cause very high forces, which will cause major winding damage if not suitably restrained. Load cycling, and the thermal expansion which accompanies it, is a daily event that causes expansion and contraction of the entire windings. If components are not suitably designed, or if windings are unduly restrained in the axial direction, low-cycle fatigue damage may occur. Finally, the electromagnetic forces at twice system frequency due to normal load currents may cause fretting or high-cycle fatigue of components, particularly if a component has a mechanical resonance close to double frequency.

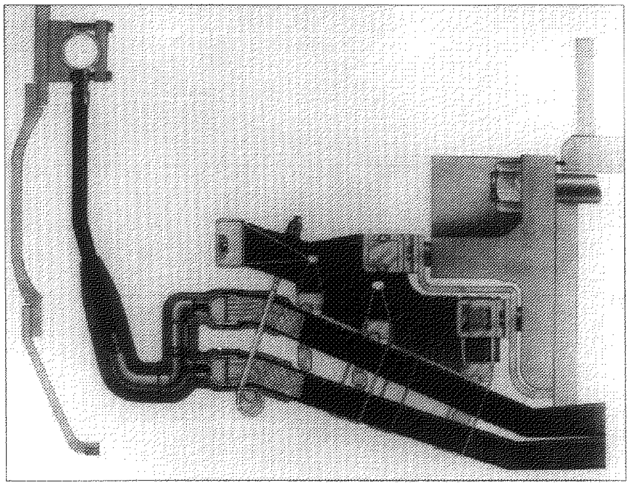

Figure 22. Stator and winding support cross section

These forces require the design engineer to closely examine the detail design of the endwinding and stator slot sections.

Stator Slot Support System

The key elements of the stator-slot support system design (Figure 21) are:

- Careful assembly of the stator core to ensure a uniform slot dimension and avoid "high areas."
- Use of side ripple springs full length along each bar to ground the bar armor to the slot and provide permanent friction damping against tangential and radial motion.
- A top-of-slot, radial force wedge designed to securely hold the armature bars down to the bottom of the slot, preventing potential destructive bar motion.
- Freedom for axial movement to accommodate thermal expansion without component stress.

Endwinding Support Structure

Because the endwindings are suspended beyond the core, short-circuit or faulty synchronizing current forces are much more difficult to restrain than those in the stator slots. In addition, the structure itself has many more "degrees of freedom" complicating the process of avoiding detrimental resonant frequencies. As with the stator slot support system, the endwinding support system for a water-cooled armature design is more complex than that for a conventionally-cooled winding. However, each of the support systems evolved from the same heritage, and both have provided extremely reliable service since their introduction.

The advanced Tetraloc™ endwinding support system (Figure 22) is used on all water-cooled designs and features:

- A support basket consisting of axial supports, supported from the stator flange, and continuous circumferential epoxy fiberglass rings.
- Glass filament ties to secure the armature bars to the fiberglass rings.
- Conformable, resin-impregnated, between-bar blocking to maintain bar spacing and provide mechanical support.

Rotor Electrical Design

The generator rotor contains the field windings that produce the magnetic flux, which, in turn, produces the stator current and voltage. Proper cooling of the field winding is another challenge

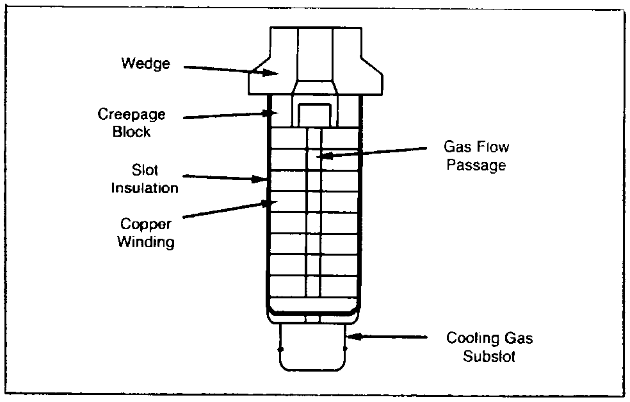

Figure 23. Slot section of generator rotor winding with radial-flow direct cooling

that the generator designer must overcome.

All hydrogen/water-cooled generators use direct conductor cooling of the rotor winding for heat removal. Smaller two-pole and all four-pole generators use the radial-flow design (Figure 23). At the end of the rotor body, hydrogen enters the windings through full-length subslots and is discharged along the length of the rotor body through radial slots, machined or punched, in the copper conductors. The hydrogen passes from the conductors through the creepage blocks and wedges to the "air gap," where it is directed through the stator core to the hydrogen coolers.

As generator ratings, and consequently rotor body length, increase even further, the gap-pickup diagonal-flow cooling method is employed (Figure 24). In this scheme, cold hydrogen is scooped up in the gas gap and driven diagonally through the rotor copper to directly remove the heat. At the bottom of the slot, the gas is turned and passes diagonally outward to the gas gap in a discharge stator core section. The stator core ventilation is coordinated with the rotor-cooling gas flow, thus creating an in-and-out flow of hydrogen through the stator core, through the rotor, and returning to the hydrogen cooler through the core. This cooling method produces a temperature profile, as shown in Figure 25, and results in a design which maintains the same average copper temperature, independent of rotor length.

Rotor Mechanical Design

There are significant challenges to be faced in producing an optimal generator rotor mechanical design. The following describes some of those challenges and features that have been incorporated to meet those challenges.

Retaining Rings

The generator retaining rings, which support the rotor winding end turns against centrifugal force, are the most highly stressed components of the generator. On most designs they are shrunk on to the end of the generator body, as shown in Figure 26. Locking of the retaining ring to the generator body is required to ensure the ring is not pushed off its fit surface due to the axial force generated by thermal expansion of the field winding.

Important design requirements of retaining rings are that they be tolerant to high stress levels, possess adequate low-cycle fatigue capability and have acceptable separating speeds. Therefore, a design is required where careful attention is paid to minimize stress concentrations. Large shrink-fit interferences are required to prevent separation under overspeed conditions, which result in relatively high stress levels at standstill. In most cases,

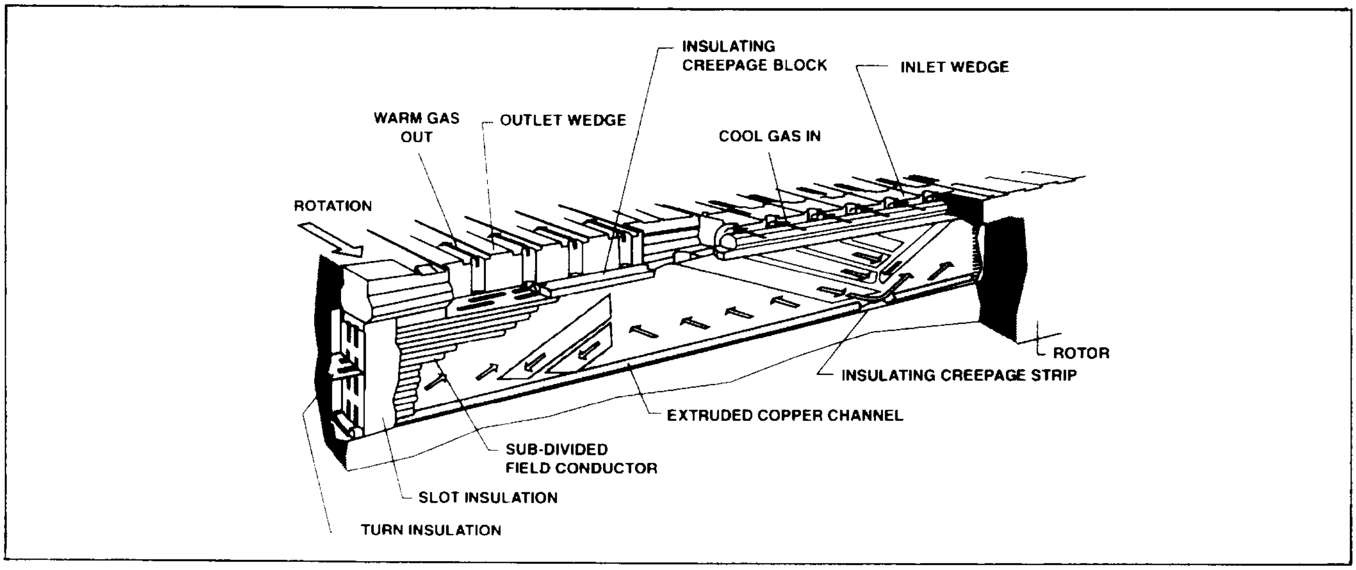

Figure 24. Air gap-pickup diagonal-flow rotor cooling scheme

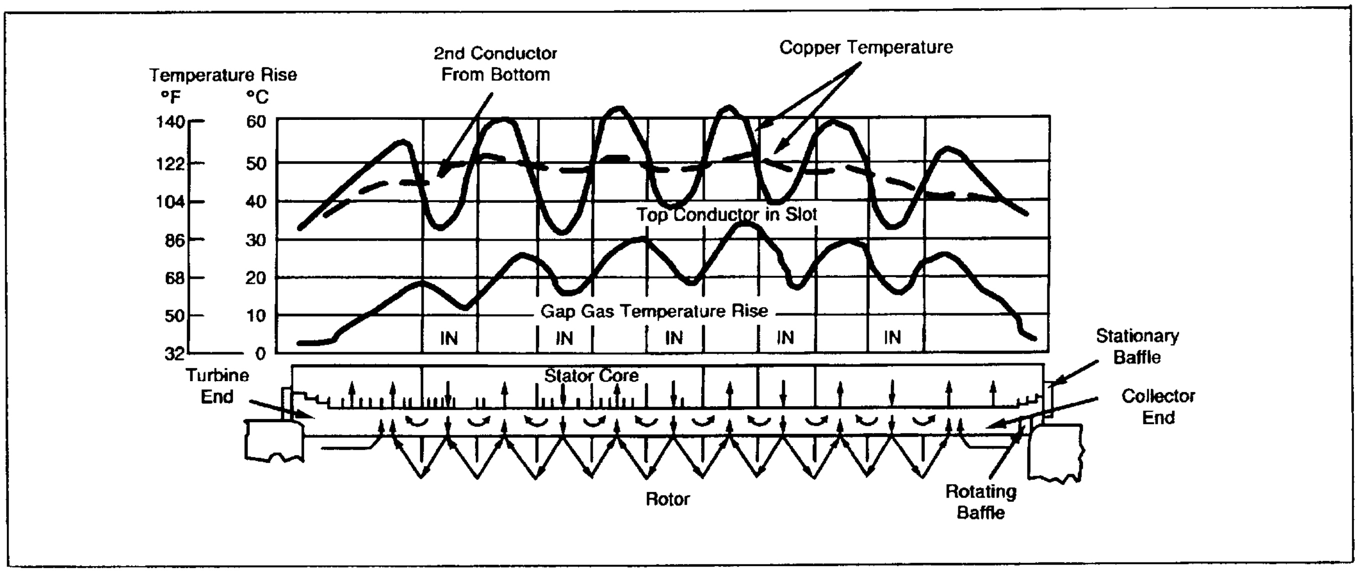

Figure 25. Diagonal-flow cooling field winding temperature profile

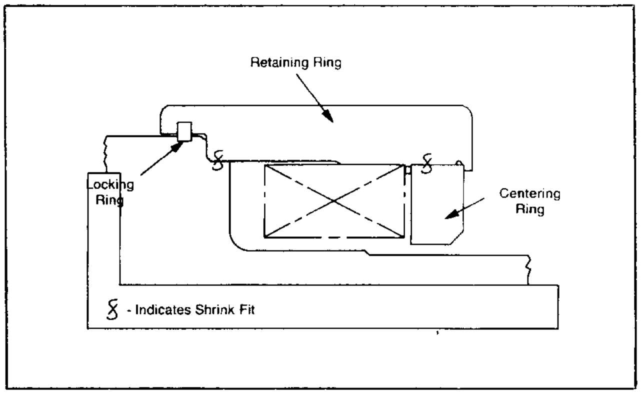

Figure 26. Arrangement of locking key and shrink fit

the ring material must be nonmagnetic to minimize the end leakage flux and reduce heating of the core end structure.

For many years, nonmagnetic retaining rings have been made from an 18Mn-5Cr steel alloy. However, it was not until the mid-1970s that the susceptibility of 18-5 retaining rings to stress-corrosion cracking became known. As a result of cooperative programs with retaining ring suppliers, a different alloy, 18Mn-18Cr (originally proposed by GE), was selected as a better retaining ring material. This material has the required properties, including high resistance to stress-corrosion cracking in the types of environments of which rings may be exposed during the service life of the generator. GE now supplies 18-18 retaining rings on its generators.

Rotor Balance

One of the most critical rotor manufacturing requirements, after all the parts are accurately machined and carefully assembled, is the final balance operation. This ensures that the rotor vibration will be within acceptable limits and that the rotor remains straight within very close tolerances at all running speeds up to and including the maximum specified overspeed.

The design work initially includes the accurate calculation of all shaft stiffness and critical speeds. To correct for the double frequency vibrations which would otherwise occur, cross slots of appropriate depth and number are specified in the pole centers of most two-pole rotors to equalize the bending stiffness between the direct and quadrature axes. Provisions are incorporated for making balance weight corrections. Each GE hydrogen-cooled generator field is supported in its own pair of bearings.

Balancing and overspeed testing are performed in GE's factory balance facility. A high-speed multiplane modal balancing procedure is used. This procedure is done to ensure minimum vibration levels at every speed up to the maximum specified overspeed.

CONCLUSION

While this paper has focused mainly on the "flange-to-flange" generator, the successful operation of a steam or gas turbine generator involves other systems as well. Discussion of excitation, lube oil, hydrogen and stator cooling water systems, as well as generator protection and operation, can be found in other GE publications.

The design of modern generators, whether they are air, hydrogen or hydrogen/water-cooled, requires a blend of time-proven, as well as innovative, design concepts. This successful integration of time-proven concepts with modern technology produces generators that can be expected to provide efficient, trouble-free service through years of baseload or cycling operation.

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