Completion of a 1,120-MVA Turbine Generator for Huadian International Zouxian Power Plant in China

Seijiro Muramatsu
Kado Miyakawa
Mitsuru Onoda
Kazuhiko Takahashi
Kengo Iwashige, Dr. Eng.

OVERVIEW: Hitachi, Ltd. has completed construction of a 1,120-MVA turbine generator (2 poles, 50 Hz) for the Huadian International Zouxian Power Plant of China Huadian Corporation in China, and its performance has been fully verified through factory testing. With a maximum output of 1,230 MVA — some 1.6 times greater capacity than the 778-MVA output of Hitachi's next larger similar generator — the generator is one of the world's largest-class single unit turbine generators ever developed for a thermal power plant. This substantial increase in output could only be achieved through a combination of sophisticated technologies, including an advanced hydrogen gas and distilled water cooling system and 27-kV high-voltage insulation. Every effort was made to enhance the performance and reliability of the generator by fully exploiting advanced analytical procedures and tests including rotor vibration analysis, stator core end electromagnetic analysis, network ventilation analysis, and stress analysis of all key parts of the generator. Full-scale rotational tests including efficiency, temperature increases, shaft vibration, and other performance measures confirm that the 1,120-MVA turbine generator more than satisfies all design specifications.

INTRODUCTION

THERE has been a trend in recent years toward larger capacity turbine generators. Larger output systems draw worldwide interest, and from the standpoint of efficient use of resources, expectations are particularly focused on large-capacity 2-pole generators for coal-fired power plants. Hitachi has been in the forefront of efforts to develop better large-output 2-pole generators to meet these needs, and recently delivered a 1,025-MVA 60-Hz generator to a power plant in the U.S. in 2005(1),(2). This was Hitachi's first 1,000-MVA-class installation of a 2-pole type generator, and extensive factory and onsite testing at the plant has proven the generator's performance and reliability.

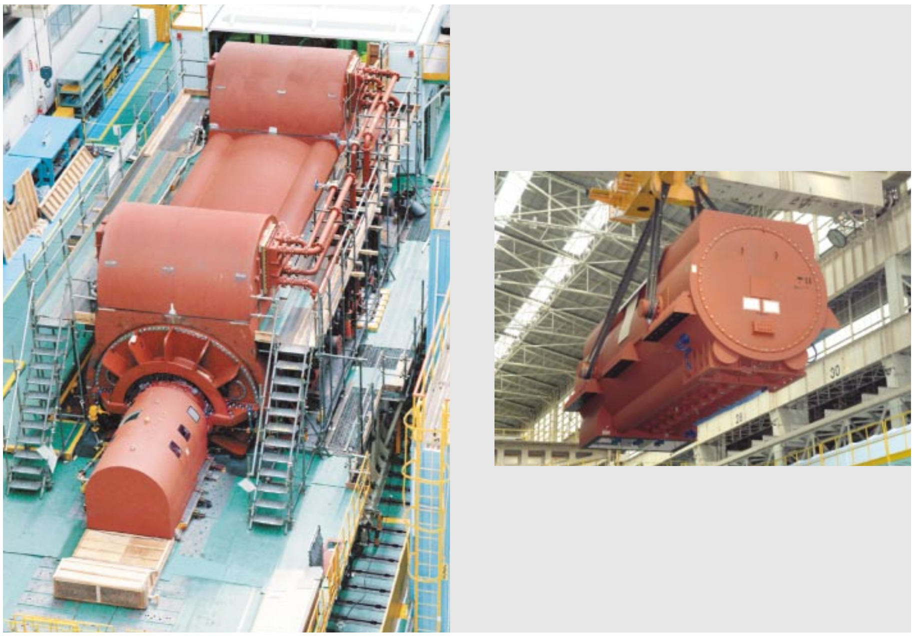

Fig. 1—Completed 1,120-MVA 50-Hz Generator at the Manufacturing Plant (Left), and Stator Frame Being Moved by Crane at the Manufacturing Plant Prior to Delivery (Right).
Reliability and design are closely evaluated at the manufacturing plant through rotational tests and a host of other tests and evaluations.

TABLE 1. Generator Specifications
Specifications for the 1,120-MVA 50-Hz generator are shown.

Rated output	MVA	1,120
Maximum output	MVA	1,230
Rated rotation speed	min^{-1}	3,000
Power factor	—	0.90
Number of poles	—	2
Terminal voltage	kV	27
Armature current (rated)	A	23,949
Armature current (maximum)	A	26,302
Short-circuit ratio	—	≥ 0.50
Hydrogen gas pressure	MPa(G)	0.52
Insulation type	—	F
Temperature rise class	—	B
Cooling method	—	Stator: direct water Rotor: direct hydrogen
Shaft vibration	μm_{P-P}	≤ 60
Bearing vibration	μm_{P-P}	≤ 25
Efficiency	%	≥ 99
Hydrogen consumption	m^3/day	≤ 12

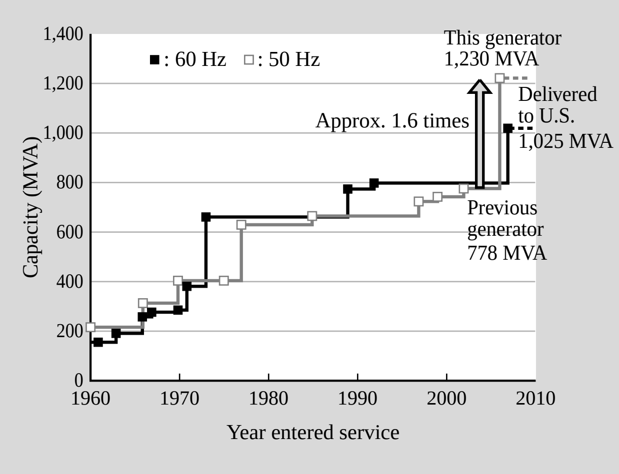

Fig. 2—History of Increasing 2-pole Generator Capacity.
Maximum output of Hitachi's 1,230-MVA 50-Hz generator is some 1.6 times greater than the previous 778-MVA 50-Hz generator.

Turning to 50-Hz generators, the largest output system Hitachi had previously developed was a 778-MVA generator built for Hokkaido Electric Power Co., Inc.'s Tomato-Atsuma Power Station in 2000, and by way of comparison, we will refer to that installation as the previous 778-MVA generator.

Since then, Hitachi has been working on larger scale generators that break the 1,000-MVA capacity barrier, and now those efforts have paid off with the development of the largest output 50-Hz generator with an output capacity of 1,230 MVA that is now installed at the Huadian International Zouxian Power Plant in China (see Fig. 1). Table 1 shows the specifications of the generator. This is one of the world's largest-class single unit turbine generators ever developed for a thermal power plant, with an output capacity some 1.6 times greater than Hitachi's previous generator with an output of 778 MVA (see Fig. 2). This paper will highlight some of the key technologies used in implementing this record-breaking large-capacity generator.

TECHNICAL CHALLENGES TO ACHIEVE INCREASED CAPACITY

The capacity of a generator can be represented by the following formula:

$$P \propto D^2 \times L \times B \times AC \times N$$

where P is output, D is the outer diameter of the rotor, L is the core length, B is magnetic loading, AC is electrical loading, and N is rotational speed.

In order to increase the output capacity of a generator, the physical size of the generator must be increased and the voltage and current capacity of the stator coil must also be increased. Increasing the physical build of a generator involves increasing the dimensions in the diameter and axial directions, both of which present technological challenges. Increasing the diameter, for example, increases stress on the rotor shaft, wedges, retaining ring, and other parts, which requires stronger materials and structural improvements to mitigate the stress. And increasing dimensions in the axial direction increases sensitivity to shaft vibration, which requires more advanced damping techniques to counter hard-to-control vibrations.

Dealing with increased voltage and current of the stator coil required that we develop a high-voltage electrical insulation and a more efficient cooling scheme. Moreover, increased stator coil current increases the leakage flux at the end of the stator core. This causes localized temperature increases that must be dealt with by optimizing the design of the stator core end region and development of a more effective cooling system.

DEVELOPMENT OF THE 1,120-MVA 50-Hz GENERATOR

Many design features and technologies were incorporated in the new 1,120-MVA generator to improve its performance and its reliability. Here we will highlight some of most significant design features (see Table 2).

TABLE 2. Technical Challenges and Solutions
Key technologies are adopted to increase generator output.

Technical challenge		Solution
Increased current, voltage	Stator coil cooling	Different cross-section coils with mixed strands 540˚ transposition Consolidated structure on series connection Independent cooling on phase connection Large diameter insulation hose
	Stator coil end support structure	Tetra-lock structure
	Stator core end structure	Shield core, copper shield
	Rotor coil cooling	Better cooling by optimizing ventilation section pitch
	Cooler structure	Top dome type cooling structure
	Stator coil insulation	High-voltage resistant class 155 (F) insulation
	High voltage bushing	Hydrogen direct cooling bushing
Increased size	Rotor shaft material	High-strength fracture tough shaft material
	Retaining ring material	High strength 18Mn-18Cr steel
	Rotor cross-sectional shape	Stress reduction through optimum design
	Stator frame	Compact frame
	Large diameter bearing	Elliptic bearing with central groove

Internal Hydrogen Pressure

To achieve more efficient cooling of the rotor and stator core, we boosted the internal hydrogen pressure from 0.41 MPa (G) used in the previous 778-MVA generator to 0.52 MPa (G) used in the new generator. Since the heat transfer coefficient is proportional to 0.8 the power of absolute pressure, we anticipate that this should yield approximately a 17% improvement in the heat transfer coefficient. We obtained this performance earlier when applying this internal hydrogen pressure of 0.52 MPa (G) to a generator for a nuclear power plant and to a 1,000-MVA class 60-Hz generator for a thermal power plant.

Rotor Vibration

In order to achieve increased output, we extended the body of the new generator by 20% compared to the previous 778-MVA generator, a modification that made the shaft more sensitive to vibration. To address this potential problem, we optimized the structure and dimensions of the shaft while using vibration analysis to estimate the different vibration modes. More specifically, we implemented the following design changes based on the vibration analysis.

(1) The diameters of the bearings were increased by about 15% compared to the previous 778-MVA generator to suppress or dampen vibrations.

(2) The diameter of damping bearing at the end bearing was increased approximately 30% than the previous 778-MVA generator to prevent the natural frequencies of the rotor shaft around the collector ring from approaching twice per revolution (100 Hz), and an integrated structure to the end of the rotor shaft was adopted to improve the rigidity of rotor end region. We also analyzed the axial-torsional mode, and designed the generator based on the analysis to keep the natural frequencies away from the twice per rotation frequency (100 Hz).

Rotor Stress

The outer diameter of the new generator’s rotor is 10% larger than the previous 778-MVA generator, which increases the centrifugal force by about 20%. To address local stress and fatigue caused by generator starts and stops, we optimized the shaping of the rotor coil slots and rotor wedges to achieve a better stress and fatigue safety factor than the previous 778-MVA generator.

Increased Rotor Temperature

The rotor is directly cooled by hydrogen gas. Since the rated field current of this generator is approximately 5,000 A, the largest class that Hitachi makes, we developed precise estimates of the field winding temperature based on detailed network ventilation analysis, which included not only the rotor, but also the effects of the stator and air gap. The shapes and locations of the ventilation holes on the rotor coil were also based on this analysis. In order to verify the accuracy and suitability of the rotor temperature analysis tool that we used, we measured the local temperature distribution on an analogous generator by

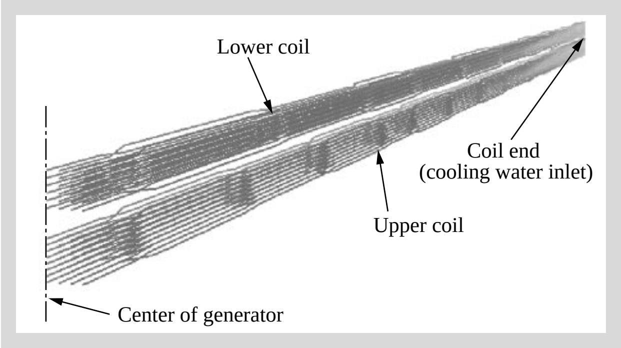

Fig. 3—Stator Coil Cooling Water Temperature Analysis.
Analysis of the results for cooling water flowing through hollow conductor strands are shown.

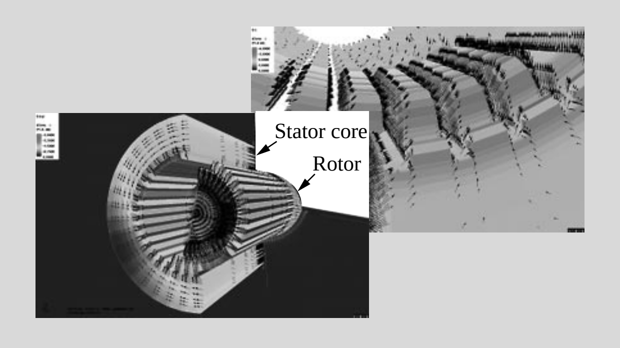

Fig. 4—Three-dimensional Magnetic Field Analysis.
Structure around the stator core is optimized through detailed analysis of magnetic flux around the stator core and generator losses.

embedding thermocouples in the rotor coil.

Water-cooled Stator Coil

The height of the stator coil was restrained by using a combination of hollow and solid conductor strands, and generator losses were reduced by adopting different cross-section coils achieved by varying the dimensions of the conductor strands of the upper and lower coils. A highly accurate loss calculation tool was used to optimize the transposition pitch and wiring layout to reduce generator losses to an absolute minimum(3). Fig. 3 shows the results for the stator coil cooling water temperature analysis. Cooling effects were further enhanced by applying a consolidated structure, in which cooling water flows directly to the upper and lower coil series connection region. And to improve stator coil cooling efficiency even further, we provided cooling of the phase connection that is independent of the system implemented in the slots for cooling the coil. A larger diameter insulation hose was also provided to accommodate the increase in stator cooling water.

27-kV Insulation for Stator Coil

Insulation for the stator coil is provided by a low environmental impact epoxy resin impregnation insulation system called Super HI-RESIN II(4). The epoxy resin impregnation technique was used to accommodate the longer length of the stator coil, and test results confirmed that this approach provides excellent insulation performance satisfying the rated 27-kV insulation requirement. For the coil end suppressor, we adopted a nonlinear resistance material optimized to provide stable electrical potential distribution up to the high-voltage domain.

Stator Core End

Since stator end leakage flux increases as the armature current increases, this can cause excessive heating of the stator core end region. To address the problem, we analyzed the stator core end fields, and used the data to optimize the shapes of the end stepped part, shield core, copper shield, and other components (see Fig. 4).

Stator Coil End Support Structure

The stator coil end support structure was determined by first estimating electromagnetic force caused by short-circuit using an analysis of the electromagnetic fields in the stator coil end region, then using that electromagnetic force for stress analysis. We also performed natural frequency analysis of the stator coil end to determine a structure around the stator coil in which the elliptical mode natural frequencies are kept away from the rated twice per rotation frequency of 100 Hz.

Stator Frame Vibration

The stator core of 2-pole 50-Hz generators vibrates at 100 Hz due to electromagnetic force. To provide vibration isolation between the stator frame and the stator core, springs were adopted to provide insulation in the stator core support structure. By modeling these structures and analyzing the natural frequencies and amplitudes, we designed the optimum stator frame structure that fully reflected the analytical results (see Fig. 5).

PERFORMANCE ASSESSMENT TESTS

We verified that the generator met all design specifications by subjecting it various performance

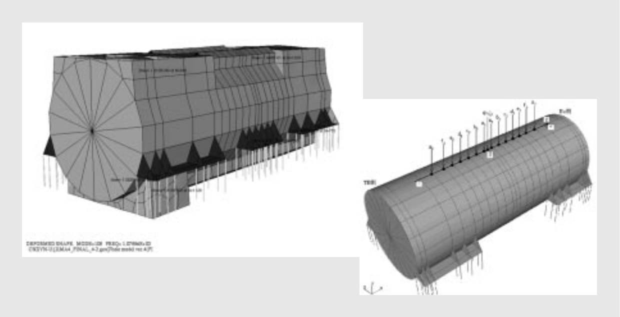

Fig. 5—Stator Frame Vibration Analysis Model.
Natural frequencies and vibration amplitudes are estimated by building models matching actual natural frequency measurements.

assessment tests. First we verified that the stator coil temperature (resistance thermometer), stator cooling water temperature (thermocouple), and rotor coil average temperature (resistance method) were all well within their designed limiting values. Thermocouples were then used to measure the temperatures of stator core ends, shield cores, and copper shields, and it was confirmed that temperature increases were well below their limiting values.

Turning to vibration measurements, we verified that shaft vibration and bearing vibration at the rated rotation speed during the temperature test were within conservative limiting values. We also measured the natural frequencies and vibration amplitudes of stator coil ends and stator frames, and confirmed that the measured results and design estimates were in close agreement and that vibration insulation was perfectly adequate.

CONCLUSIONS

This paper provided a summary overview of the key technologies used to implement a 1,120-MVA 50-Hz turbine generator. Building on our expertise and record of providing advanced generators to thermal power plants, we remain committed to the development of high-performance generators with even larger outputs to meet the needs of large-scale thermal power plants all around the world.

REFERENCES

(1) A. Tateishi et al., “Approach to Overseas EPC Project—Technical Features of MidAmerican Project in the U.S.—,” *HITACHI REVIEW*, Vol. **54**, No. 3, pp. 98-104 (Oct. 2005).

(2) T. Koga et al., “Manufacturing of 1,000 MW Class Thermal Power Turbine Generator,” Research Meeting at Ibaraki Office of the Tokyo Branch, the Institute of Electrical Engineers of Japan (IEEJ), B12 (Nov. 2005) in Japanese.

(3) K. Takahashi et al., “Calculation of Circulating Current in Large Turbine Generator with 4-layer Roebel Transposition Coils,” Papers of the Technical Meeting of Rotating Machinery IEEJ, RM-03-118 (Oct. 2003) in Japanese.

(4) M. Onoda et al., “Development of the Novel Mica-epoxy Insulation Systems for Generator Stator Coils that Cause Less Harm to the Environment,” Papers of the Technical Meeting of the Institute of Electrical Engineers of Japan (IEEJ), DEI-04-53 (Jan. 2004) in Japanese.

ABOUT THE AUTHORS

Seijiro Muramatsu

Joined Hitachi, Ltd. in 2001, and now works at the Power Electric Machine Design Department, Hitachi Works, the Power Systems. He is currently engaged in designing turbine generators.

Kado Miyakawa

Joined Hitachi, Ltd. in 1991, and now works at the Power Electric Machine Design Department, Hitachi Works, the Power Systems. He is currently engaged in designing turbine generators.

Mitsuru Onoda

Joined Hitachi, Ltd. in 1983, and now works at the Power Electric Machine Design Department, Hitachi Works, the Power Systems. He is currently engaged in the development of generator coil insulation. Mr. Onoda is a member of the Institute of Electrical Engineers of Japan (IEEJ)

Kazuhiko Takahashi

Joined Hitachi, Ltd. in 1989, and now works at the Power Electric Machine Design Department, Hitachi Works, the Power Systems. He is currently engaged in the development of turbine generators. Mr. Takahashi is a member of the IEEJ and the Magnetics Society of Japan (MSJ).

Kengo Iwashige, Dr. Eng.

Joined Hitachi, Ltd. in 1983, and now works at the Power & Industrial Systems R&D Laboratory, the Power Systems. He is currently engaged in the development of heat transfer and fluid dynamics for turbo machinery. Dr. Iwashige is a member of the Japan Society of Mechanical Engineers (JSME) and the Visualization Society of Japan (VSJ).