High Efficiency and Low Noise Air-cooled Turbine Generator "GH1550A"

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OVERVIEW: Hitachi, Ltd. has completed development of an air-cooled turbine generator — named GH1550A — that achieves the world's highest efficiency and low noise, and we have already shipped units Nos. 1 to 5 to our customers. The GH1550A achieves the world's highest-level performance among air-cooled generators; namely, efficiency of 98.75% at 60 Hz and PF of 0.85 or 98.77% at 50 Hz and PF of 0.80, and a noise level of 74 dBA for a single generator body during 50-Hz operation or 77 dBA during 60-Hz operation. To attain this performance, network ventilation analysis and stator-core electromagnetic analysis were used, and loss was extensively reduced. Furthermore, a noise-reduction configuration for optimizing sound insulation — based on results from various noise tests — was developed and applied to the GH1550A. In addition, analysis techniques such as rotor-vibrational analysis, temperature analysis, and localized stress analysis were used, and performance and reliability of the generator were improved. The GH1550A was confirmed to satisfy design specifications such as efficiency, noise, temperature rise, and rotor vibration.*

INTRODUCTION

RECENTLY, growth in global demand for electricity has driven increases in the output power of electricity-generating plants and prompted construction of new power plants. From the viewpoint of environmental preservation, achieving high efficiency while lowering noise of power plants has become necessary.

In this surroundings above, many air-cooled generators have been implemented for the power plants with around 100-MW output which are operated only during peak times in order to level the daily load and are used as industrial power facilities because of their low maintenance costs and their simple operation. In general, air-cooled generators tend to be noisier than hydrogen-cooled generators and it is difficult to satisfy the recent noise requirement without enclosure facilities for air-cooled generators in association with their structure and cooling medium. Their efficiency is lower than that of hydrogen-cooled generators and

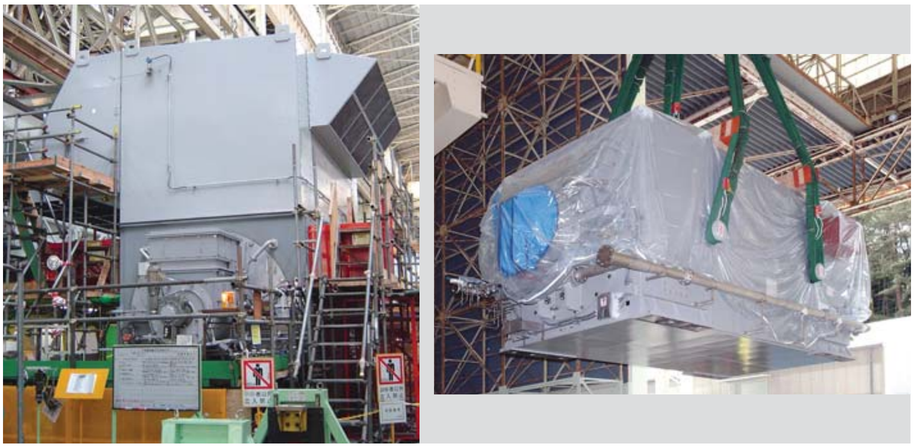

Fig. 1—Shop Test (Left) and Transfer by Indoor Crane for Delivery (Right) of GH1550A.
The GH1550A air-cooled generator underwent various tests including rotational tests in the factory, and in doing so its performance and design were validated.

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* As of September 1st, 2008, surveyed by Hitachi, Ltd.

the efficiency of an air-cooled generator with around 100-MW output is usually around 98.0%.

Hitachi, Ltd. is focusing on improving efficiency and lowering noise of a generator, in the present work, and has completed development of an air-cooled generator named GH1550A, which achieves the world’s highest efficiency and lowest noise (see Fig. 1). The GH1550A achieves the world’s highest-level performance among air-cooled generators, namely, rated efficiency of 98.75% [60 Hz; PF (power factor): 0.85] or 98.77% (50 Hz; PF: 0.8) and noise level of 77 dBA (60 Hz) or 74 dBA (50 Hz) (see Figs. 2 and 3).

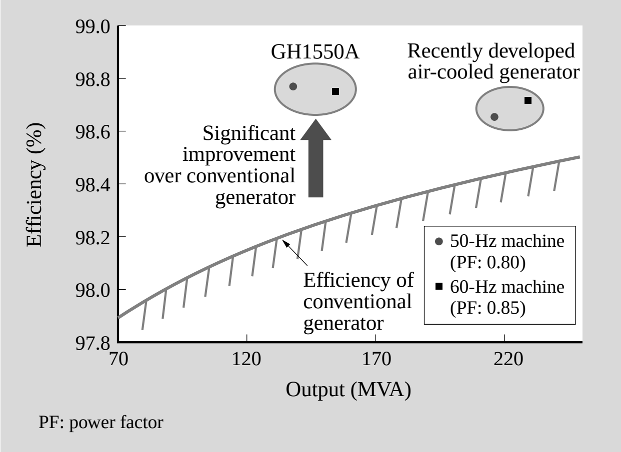

Fig. 2—Comparison of Efficiencies of GH1550A and Conventional Generators.
GH1550A improves efficiency by 0.5 point in comparison with that of the conventional generator. The efficiency of air-cooled generators developed over recent years(5),(6) *is converted into the case of operation under two power factors stated in the figure.*

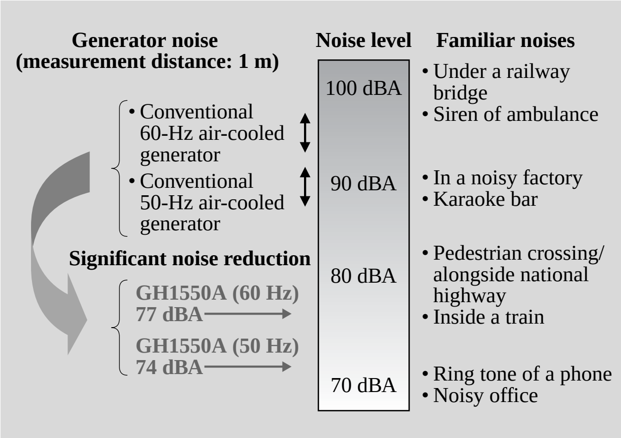

Fig. 3—Comparison of Noise from GH1550A and Conventional Generators.
GH1550A achieves noise reduction of 18 dBA in comparison with that of the conventional generators.

TABLE 1. Specifications of GH1550A
The specifications of low-noise air-cooled turbine generator GH1550A are listed.

Item	Specifications	
Output power	136 MW	110 MW
Voltage	13.8 kV	11.5 kV
Short-circuit ratio	0.5	0.5
Power factor	0.85	0.80
Rotation speed	3,600 rpm	3,000 rpm
Insulation class	class F	class F
Temperature increase	class B	class B
Efficiency	**98.75%**	**98.77%**
Applicable standard	ANSI C50.14	IEC 60034-1
Noise	**77 dBA**	**74 dBA**
Cooling method	Totally enclosed type or open ventilation type	
Weight	Generator body less than 160 t	

These performances correspond to a 38% reduction in loss (770 kW) and an 18-dBA reduction in noise compared to the former 100-MW generators. The specifications of GH1550A are listed in Table 1.

This report describes the technologies applied to the air-cooled turbine generator GH1550A — which is superior to a conventional hydrogen-cooled type with regard to both efficiency and noise.

TECHNICAL CHALLENGES OF GH1550A

The technical challenges concerning the GH1550A are listed in Table 2. The generator, which is shown in Fig. 4, converts rotational energy of the turbine into electrical energy. That is to say, a rotating magnetic field generated by the rotor is transformed into the form of current and voltage to the exterior through a stator coil installed in a stator core. The generator operates in a high magnetic field at high current, and copper loss generated by electrical current flow in conductors, iron loss generated by passage of the magnetic field through the core, and other electrical losses are generated in each component of the generator.

In order to remove the heat arising from these losses, fans are attached to the ends of the rotor shaft, and cooling airflow is circulated around the interior of the generator. The maximum circumferential rotation speed of the rotor is about 200 m/s. Consequently, ventilation loss and friction loss (which depend on circumferential velocities of the fan and

TABLE 2. Technical Challenges Concerning GH1550A
Technical challenges concerning GH1550A are listed.

Design challenges		Usual countermeasures	Challenge points
Creating high efficiency	Reduction of electrical loss	• Optimum conductor size is assumed. • Low-loss magnetic steel sheet is used.	• When conductor size is reduced, copper loss increases. • When conductor size is increased, stray-load loss increases. • Low-loss magnetic steel sheet is not as readily available as standard magnetic steel sheet.
	Reduction of ventilation friction loss and friction loss	• Reduction of ventilation friction loss	• Linked to degradation of cooling performance of generator
Noise reduction	Increase sound insulation	• Increase thickness of steel sheet	• Linked to increase in weight

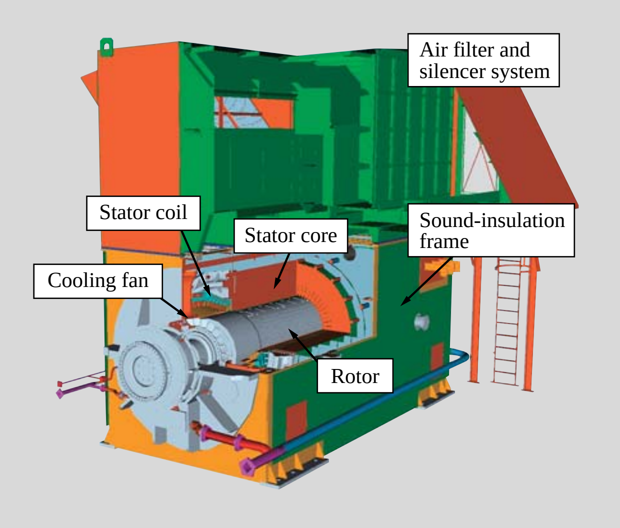

Fig. 4—Open-type Low-noise Air-cooled Turbine Generator GH1550A.
The configuration of the open-type GH1550A is shown.

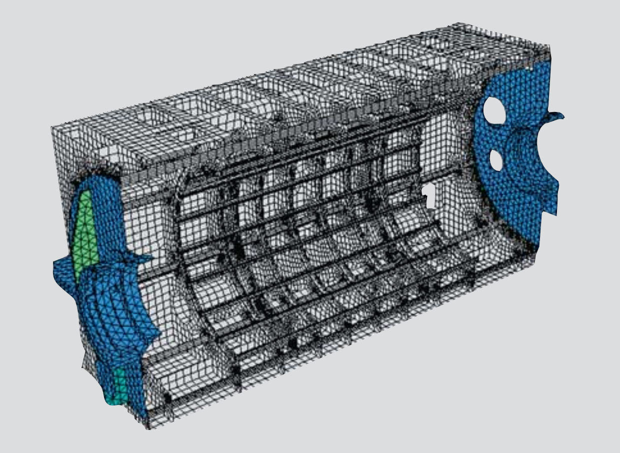

Fig. 5—Analysis Model of Stator Frame.
The whole stator frame is modeled, and vibration analysis and strength analysis are performed.

rotor) are large, and a new loss is generated for performing cooling.

To achieve high efficiency, it is necessary to reduce these losses. Copper loss can be reduced by increasing the size of electrical conductors, and iron loss can be decreased by increasing the size of the stator core and using low-loss magnetic steel sheet. However, as a consequence of the counter measures which are to increase the size of conductors and iron cores, machine size and weight also increase. In addition, procurement of low-loss magnetic steel sheet is difficult, so the use of low-loss magnetic steel sheet has a high probability of impacting a delivery time. Consequently, it is essential to determine how to maintain machine size and to use standard magnetic steel sheet.

Ventilation loss and friction loss can be lowered by reducing the amount of ventilation, which is determined by the amount of heat generated by loss and the internal temperature of the generator. Therefore it is important to adopt an effective configuration for cooling and to reduce ventilation amount with decreasing the heat by lowering the electrical loss including the copper loss and iron loss.

As for noise reduction, it is better to use thicker steel sheets for the stator frame. However, from the viewpoint of shortage of global steel resources and handling weight, a thin-walled frame is desirable. Given those opposing factors, the analyses on vibration and strength by using the analysis model of a stator frame shown in Fig. 5 were performed to optimize the stator frame structure with the minimum mass of the generator main body including the rotor. Accordingly, a sound-insulation configuration that can adequately reduce noise from a thin-walled stator frame is necessary.

LOW-LOSS DESIGN FOR IMPROVING EFFICIENCY

Ventilation Design for Efficient Cooling

Characteristic ventilation for an air-cooled generator is explained in the following. As for a large-scale generator, hydrogen is used as a cooling medium because its mass and flow resistance are low but its cooling capacity is high. Since mass and flow resistance of hydrogen are low, friction loss generated on surfaces is low regardless of the circumferential rotation speed of the rotor. Cooling flow volume and fan motive energy can also be curtailed so that its cooling efficiency is high. On the other hand, the cooling capacity of air is not so high because the density and the flow resistance are high, so the ventilation loss and friction loss can be a major problem for the performance of a generator. Reducing the surface frictional loss requires lowering the rotor diameter and the circumferential rotation speed of the rotor and reducing the ventilation loss requires decreasing fan pressure and air-ventilation volume. However, reducing the surface friction loss and the ventilation loss has negative effects for the generator cooling, so reducing entire loss as well as the efficient cooling is needed in order to reduce the surface friction loss and ventilation loss.

Achieving efficient cooling necessitates an understanding of the ventilation-air distribution in each part of a generator. Conventionally, a database for ventilation design is established by using 3D (three-dimensional) analysis and measurement on cooling air around the fans and air duct of the stator. The database has clarified that ventilation, friction loss, and air-volume distribution in air gaps largely determine the temperature distribution in the stator. As a result of this realization, temperature distribution in air gaps has been measured since 1998, and ventilation measurements on air gaps in actual generators have been performed since 2002. The appearance of such ventilation-distribution measurements on an actual generator is shown in Fig. 6. The figure, which is an inside view of the stator, shows the appearance of ventilation sensors (five-hole pitot tubes) set from the circumference of the stator core to air gaps. These five-hole pitot tubes are used as sensors for measuring air velocity as a 3D vector. The air-velocity vector was obtained for various rotation speeds up to the rated speed, and airflow distribution was measured.

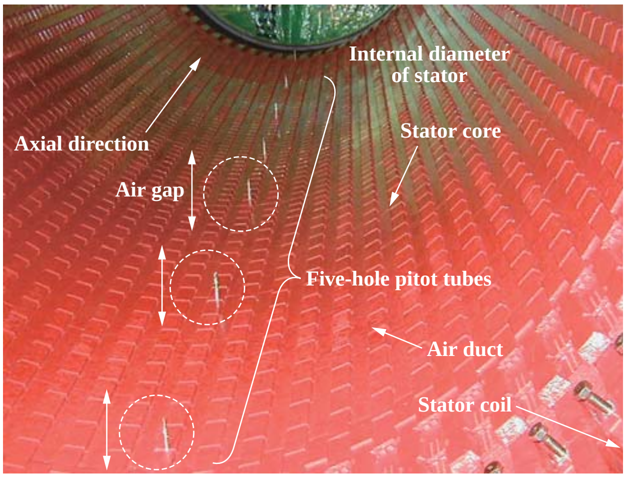

Fig. 6—Condition of Ventilation Sensors in an Actual Machine. Ventilation sensors are placed in the air gaps, and the ventilation distribution is measured.

As a result of these measurements, it became possible to quantitatively evaluate cooling flow in the air gaps and cooling flow to the air ducts of the stator from the air gaps; consequently, techniques for designing airflow ventilation in a generator could be improved largely. Ventilation friction loss is constant regardless of output power of the generator, so it is possible to improve efficiency concerning total output power by lowering such loss.

Reduction of Electrical Loss

Electrical loss is composed of copper loss, i.e. “I^2R (current squared times resistance) loss,” generated in the stator and the rotor, stray-load loss, and iron loss generated in the stator core. Copper loss can be reduced by increasing the cross-sectional area of windings of the stator and rotor, that is, by increasing copper. However, increasing the cross-sectional area of windings leads to increased weight, so it is difficult to significantly reduce copper loss.

To some extent, stray-load loss can be reduced by reducing the size of conductors exposed to magnetic fields, and iron loss can be reduced by utilizing low-loss magnetic steel sheet. It is difficult to evaluate the stray load loss and the iron loss quantitatively, so these are evaluated by using magnetic-field analysis.

The generator model for the loss-calculation is shown in Fig. 7. The entire generator is modeled in three dimensions, and the loss and magnetic field for each part are calculated. The magnetic-field distribution calculated from the entire-generator model is taken as the boundary condition, more detailed parts of the generator are modeled, and particular losses of these parts are calculated. In this way, it can be

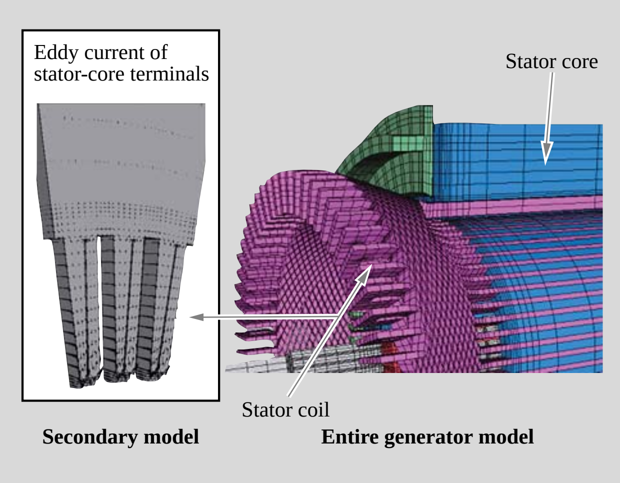

Fig. 7—Loss Calculation Model for Generator.
A three-dimensional model of the whole generator is used, electromagnetic field and loss of each part are calculated, and the fine components are analyzed by local partial models.

determined in which components loss (such as stray-load loss) is being generated, and measures for reducing load can be tailored to each component.

The generation locations and comprising items of stray-load loss are shown by the proportional chart in Fig. 8, and a method for reducing stray-load loss in the generator windings (including these comprising losses) is shown schematically in Fig. 9. It is clear that stray-load loss generated in the generator windings can be divided into circulating-current loss flowing in a cycle between winding strands and eddy-current loss generated locally in strands. The circulating-current loss can be reduced by counterbalancing magnetic fields linking winding strands by means of “wiring transposition” (that is, a method of transposing pairs of strands together), and eddy-current loss can be reduced by segmentalizing winding strands. The number of rows and height of windings are selected in order to minimize the sum of copper loss and stray-load loss.

As regards iron loss, its generation mechanism and generation location were analyzed in a similar manner to the analysis of stray-load loss. The loss-reduction effect due to use of low-loss iron core materials may not necessarily be obtained as expected, and it is understood that losses will be additionally generated by air-duct structures placed in the core for cooling and other structural objects. Accordingly, creating a low-loss environment was undertaken considering these points.

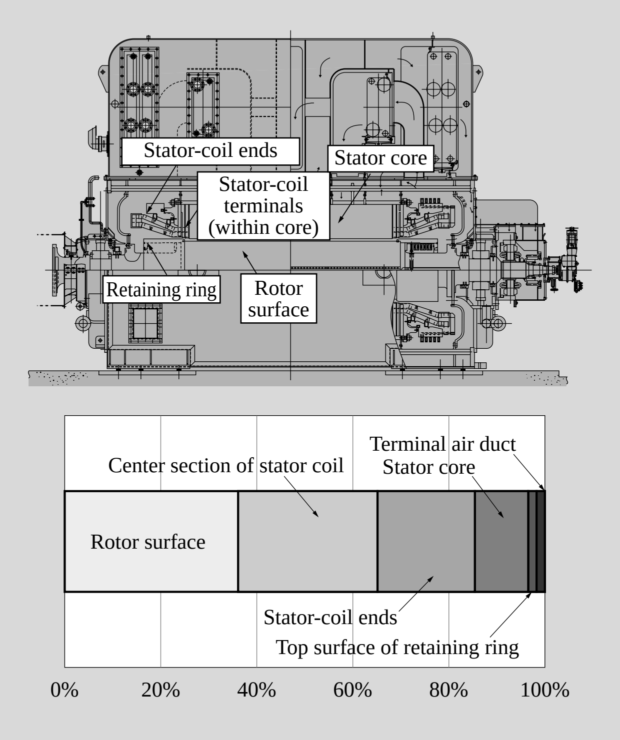

Fig. 8—Comprising Items of Stray-load Loss.
The items that comprise the stray-load loss of the generator are shown schematically.

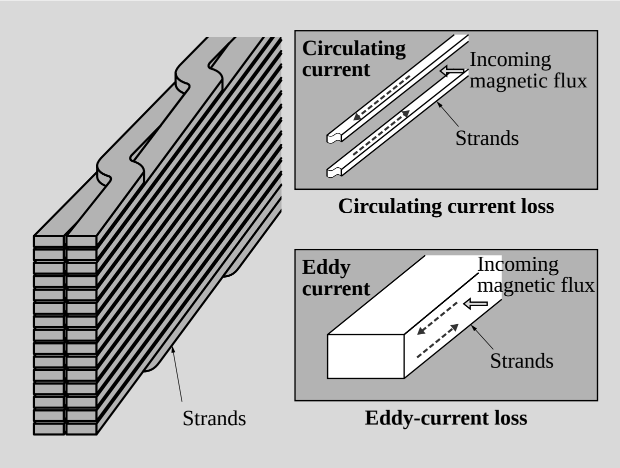

Fig. 9—Loss Reduction in Stator Coil.
Loss is reduced by segmentalizing wires and transposing them.

DESIGN OF LOW-NOISE STATOR FRAME

Noise Source of Generator

Some of main sources of noise from a generator are electromagnetic-vibration sound, aerodynamic sound due to fluid flow, and friction sound from the rotor and the bearings are stated. Electromagnetic-vibration sound is generated when the stator core and stator coils are vibrated by rotating magnetic fields. The noise generated by this electromagnetic vibration is transmitted as solid-borne sound to the stator frame, where it becomes a noise source. In the case of a two-pole turbine generator, a double magnetic vibration is generated per revolution, so this vibrational frequency becomes about twice the rotational frequency.

Aerodynamic sound due to fluid flow is generated by rotation of fans attached to the ends of the rotor and rotation of the rotor itself as well as by cooling airflow circulating inside of the generator. Since a generator produces heat through various kinds of losses, internal fluid is circulated around the fans at the rotor ends. As a result of this circulation, aerodynamic sound is generated by the flow of cooling air inside the generator. And the rotor itself also generates aerodynamic sound through its rotation.

Friction sound from the rotor and the bearings is solid-borne sound caused by friction. That is to say, vibration due to friction propagates and becomes noise, and its vibrational frequency is the same as the rotation frequency of the rotor.

Interior Noise in Generator

When designing noise insulation for the stator frame, sound-source frequency and internal-noise frequency are important parameters to consider. Since they have a great effect on the structure and internal dimensions of a generator, they differ for various kinds of generator. In the present work, in designing the sound insulation of the GH1550A, we went to great length to measure the internal noise of actual generators at sites.

Noise Tests by Mock-up Modeling

Configurations that enable effective sound insulation against vibration were investigated on the basis of internal-noise measurements obtained from actual generators, and noise insulation performance of these configurations was verified by means of mock-up models (see Fig. 10).

As for the sound-insulation configuration, we confirmed that its sound-absorbing performance at each frequency across the whole frequency range changes significantly in accord with material quality and thickness of the outer stator wall, material quality, thickness, and density of the sound-absorbing materials packed between the frame and outer wall, and the method of fixing the outer wall. Some configurations showed little effect of frame outer walls and showed even worse noise insulation than frame itself because of coincidence effect which sound-insulation performance is lowered at certain frequence.

Fig. 10—External Scene of Noise Testing with a Mock-up Model.
Noise performance of a sound-insulating wall with various types was evaluated.

SHOP TEST RESULTS MEASURED EFFICIENCY AND NOISE

Efficiency of Generator

The GH1550A achieves the world’s highest efficiency among air-cooled generators; namely, 98.75% at 60 Hz, 136-MW output, and PF of 0.85 or 98.77% at 50 Hz, 110 MW, and PF of 0.80 both including exciter loss. In particular, under operation at 50 Hz and PF of 1.0, it attains high efficiency in excess of 99.0% (see Fig. 11).

GH1550A is set up for operation at either 50 Hz or 60 Hz, so efficiency stays at the level mentioned above. However, with the optimum design for either 50 Hz or 60 Hz, it is possible to attain even higher efficiency. Although output power decreases a little when the temperature of the cooling gas is high, higher efficiency still can be attained by modifying the fans. The above-described results confirm that GH1550A is an air-cooled generator whose performance, in terms of efficiency, outstrips conventional air-cooled generators.

Noise of Generator

The noise measurements for GH1550A are listed in the table at the top of Fig. 12. The noise value during 50-Hz operation is 74 dBA and that during 60-Hz operation is 77 dBA. These noise-performance values represent a significant reduction in comparison to those of conventional air-cooled generators. In particular,

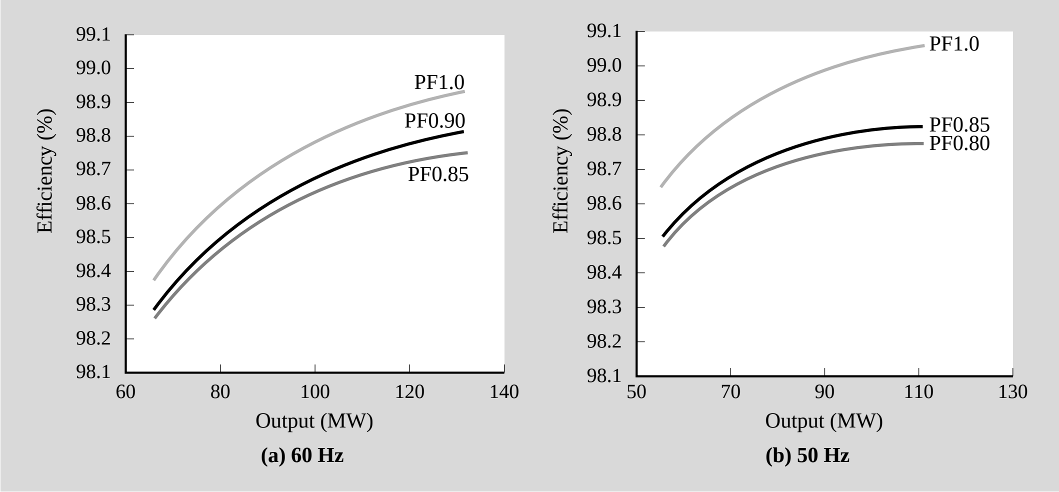

Fig. 11—Efficiency Measurement Results for Air-cooled Generator GH1550A.
As an air-cooled generator, the GH1550A achieves very high efficiency.

Measurement point	A	B	C	D	E	Mean
50-Hz noise level (dBA)	73	74	74	74	73	74
60-Hz noise level (dBA)	75	76	77	77	77	76

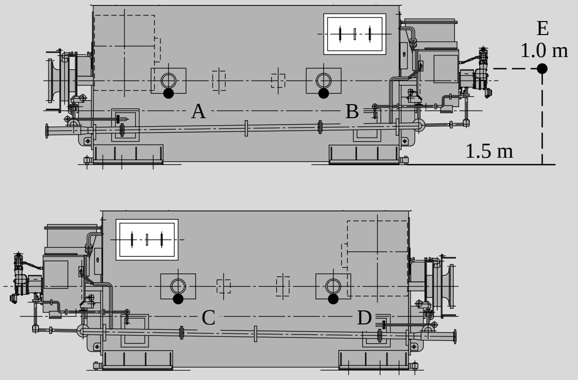

Fig. 12—Noise-measurement Results for GH1550A.
As an air-cooled generator, the GH1550A noise is reduced remarkably.

during 60-Hz operation, noise reduction compared to a conventional generator is 18 dBA, thereby lowering the noise to the level of a conventional hydrogen-cooled generator.

CONCLUSIONS

This report described technologies applied to our air-cooled generator "GH1550A." We confirmed that the efficiency of GH1550A reaches the world's highest level so far achieved by an air-cooled generator and that its noise performance is as good as or better than a conventional hydrogen-cooled generator. From now onwards, by responding to the need of further increasing efficiency while lowering noise of generator equipment by utilizing the capability of the GH1550A, we at Hitachi will continue to make social contributions.

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