Sophisticated Design of Turbine Generator with Inner Cooler Ventilation System

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OVERVIEW: Hitachi, Ltd. has developed a 250-MVA (50/60 Hz) large-capacity, air-cooled generator. This is a high-efficiency air-cooled generator that makes maximum use of an ICVS (inner cooler ventilation system). Its performance has been evaluated by embedding ventilation, temperature, and stress sensors at more than 1,000 points in the machine for taking measurements, and the data so obtained has been applied to the construction of a database for designing future hydrogen-cooled and air-cooled generators. The developed generator was found to satisfy class-B temperature-rise standards of the American National Standards Institute (ANSI) for stator and rotor temperature and to achieve a level of efficiency in excess of 98.8%. In the design of this 250-MVA generator, a number of tools for analyzing large-scale loss, ventilation, temperature, and vibration intensity were prepared, and an appropriate generator structure was determined after conducting a survey of several hundred parameters. The suitability of these tools was also evaluated by actual measurements on this generator.

INTRODUCTION

DESPITE the great demand for low-cost, high-efficiency generators that are easy to operate and maintain, the choice at present generally comes down to either a hydrogen-cooled generator providing high efficiency or an air-cooled generator featuring easy operation and maintenance. In Europe, which uses 50-Hz generators having relatively small ventilation friction loss, the generator of choice is usually the air-cooled type[1], while in the United States, which uses 60-Hz generators having large ventilation friction loss, the hydrogen-cooled generator is favored[2]. Regardless, there is a worldwide need for high-efficiency air-cooled generators or hydrogen-cooled generators that are easy to operate and maintain.

Hitachi has developed an ICVS for air-cooled

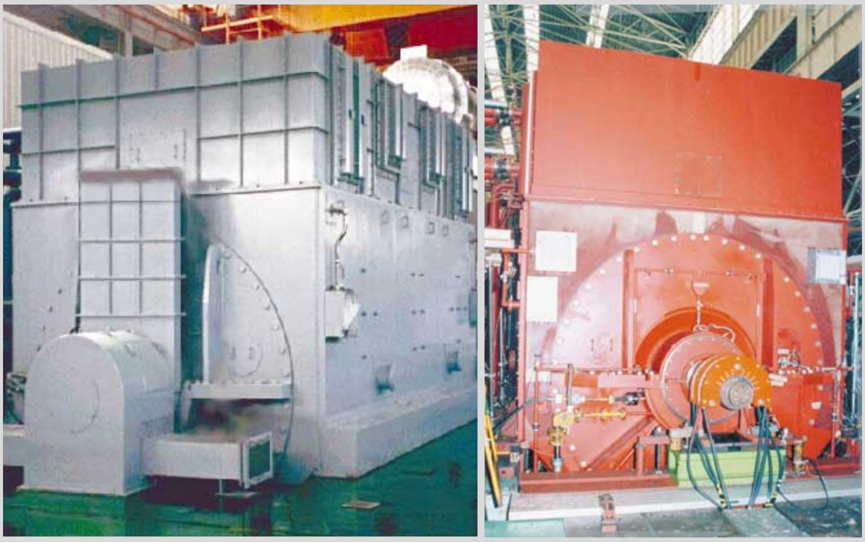

Fig. 1—On-site Turbine Generator with Inner Cooler Ventilation System (left) and 250-MVA (50/60 Hz) Generator in Factory Trials (right).
The turbine generator on the left began commercial operation in October 1999 and has been operating satisfactorily since then. The small cooler near the center of the generator is the inner cooler. The 250-MVA generator on the right has been equipped with more than 1,000 sensors just for examining the relationship between ventilation and temperature, and measurement results have provided a necessary and sufficient database for developing future generators.

generators of 100 MVA or greater with the aim of achieving high-reliability and high-efficiency performance in these generators as needed. The company has also expended much effort in preparing large-scale design-calculation tools so that optimal structures can be designed for either air-cooled or hydrogen-cooled generators.

In this regard, we have targeted a 250-MVA (50/60 Hz) generator as machine No. 1 for applying these tools. With these tools, we conducted a survey covering several hundred parameters and used resulting data to determine the dimensions of each generator section and cooling structure and to achieve high efficiency and low temperature rise in the generator. Furthermore, by taking measurements with more than 1,000 sensors to examine the relationship between ventilation and temperature in the developed generator, we have been able to evaluate the usefulness of these tools and the soundness of the generator as well (see Fig. 1).

In this report, we describe our design of the stator coil, one of the most important components of a turbine generator.

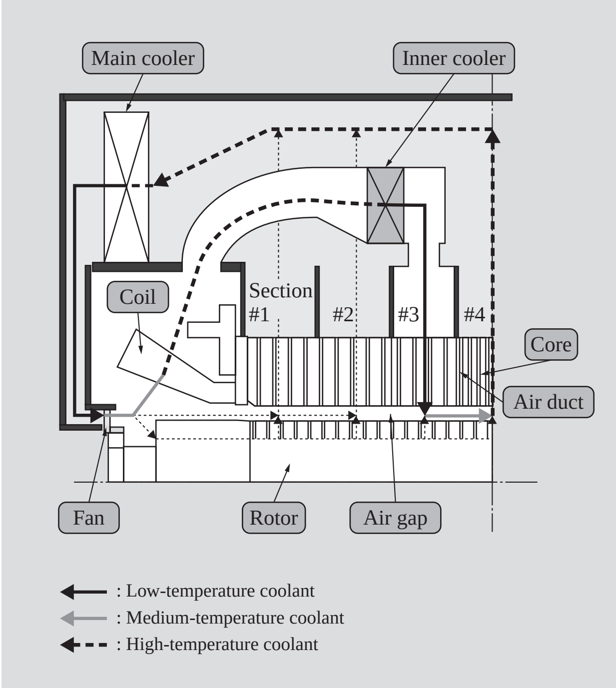

Fig. 2—Inner Cooler Ventilation System.
The ICVS features two coolers in one ventilation loop.

GENERATOR WITH INNER COOLER VENTILATION SYSTEM

A power generator operates with a high magnetic field and high current density and produces heat as a result. The generator must therefore feature a cooling structure to remove this heat.

This is generally accomplished by installing fans at each end of the rotor shaft and circulating cooling air (coolant) throughout each section of the generator. An air cooler, which serves to reduce the temperature of the cooling medium after it cools each generator section, is also installed in the generator. In this scheme, the coolant, which is pressurized by the fan, returns to the cooler after cooling the stator and rotor sections and then recirculates back to the fan. Here, however, as only one cooler is installed for each closed ventilation loop, the temperature of the coolant itself rises as it cools heating elements in the downstream. In particular, the rise in coolant temperature as it initially passes through the fan cannot be ignored in an air-cooled generator.

In response to this problem, Hitachi has been applying the ICVS to air-cooled generators of 100 MVA or greater as needed with the aim of reducing the temperature of generators and improving efficiency[3]. Fig. 2 shows the cooling circuit of the ICVS.

To begin with, the coolant becomes pressurized by the fan, cools the coil and other elements at this end of the rotor shaft, and then proceeds to an inner cooler via the ventilation path shown. In an air-cooled generator, the temperature of the coolant has risen by 10 to 20°C at this point. Next, after passing through the inner cooler and being re-cooled, the coolant flows through an air duct installed in the stator passing from the outside of the core to its inside. It then arrives at the air gap to combine with air emitted from the rotor, and finally returns to the main cooler via another air duct in the stator passing this time from the inside of the core through its outside. In this way, the ICVS features two or more coolers arranged serially in a single ventilation loop and the capability of introducing cooled gas in any core section. In short, we can expect the use of ICVS to suppress thermal vibration of the rotor by lowering the temperature of the air gap and to lower temperature on the stator side.

DESIGN OF THE 250-MVA GENERATOR

Flow of Generator Design

In the design of a generator, generator output and overall structure must first be decided before moving on to electrical design. In electrical design, the dimensions of each generator section are determined so as to satisfy various electrical characteristics required of the generator. Specifically, after computing the loss distribution of each section in detail, ventilation patterns and air-duct arrangement must be decided and ventilation and temperature distributions calculated. Here, electrical design may have to be redone if desired temperature performance is not satisfied. After completing all of the above, vibration and stress design are then performed to determine the detailed structure of each section before commencing actual machine manufacturing.

Design Calculation Method

Electrical, ventilation, and temperature design

The temperature of stator coil insulation, which is subjected to high voltage, can have a major impact on generator reliability and lifetime. The factor that most affects the temperature of this section is loss in the stator cool itself.

Fig. 3 shows the cooling structure of the stator coil and the stray load-loss generation mechanism. A slot encloses upper and lower coils, each of which consists of several tens of strand steps. The loss generated in a strand passes through the core via insulation and flows into the coolant. A strand also consists of circulating current and eddy current for canceling flux linkage in addition to the output current corresponding to generator output. In general, to offset flux linkage within a slot, the strands are subjected to transposition. It is difficult, however, to offset all flux linkage across the entire length of the coils and a small amount of loss from circulating current remains. In addition, electromotive force is generated in the strands themselves for canceling flux linkage and eddy current loss is generated. These forms of stray load loss are deeply related to transposition pitch and strand dimensions, and stray load loss may even increase with increase in the cross-sectional area of strands. Under these circumstances, we developed a loss-calculation program and determined a strand arrangement and strand dimensions that would minimize the sum of stray load loss and ohmic loss[3, 4]. The program can also compute rotor loss and core loss simultaneously.

In the next step of this design process, we networked all of the ventilation paths within the rotor and the stator shown in Fig. 2 and computed axial distributions for generator ventilation and temperature[5]. For the developed generator, we evaluated several hundred combinations of stator-air-duct arrangements, ventilation patterns, and fan structure before the manufacturing stage. In addition, we succeeded in preparing standard design tools for

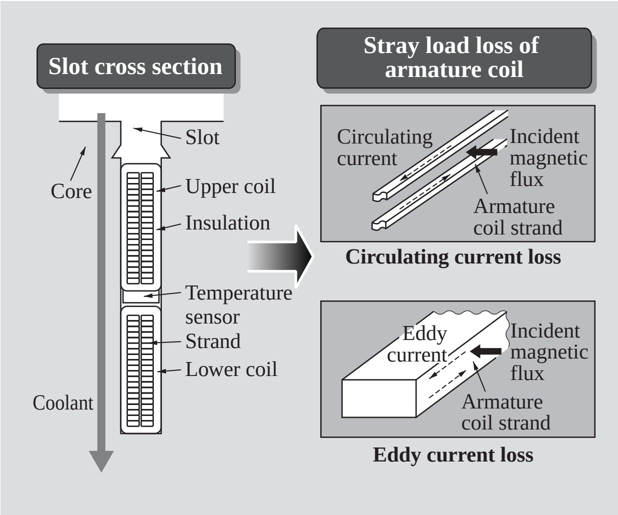

Fig. 3—Cooling of Stator Coil and Loss-generation Mechanism.
Reducing stray load loss is the key to reducing stator loss.

the design flow up to this point.

Vibration/stress design

The coil end section is the most important element in vibration and stress design. It is the section most heavily affected by lightning and similar accidents. To optimize coil structure, large-scale structural analysis must be performed many times. We therefore created an automatic model-creation tool that requires only input of dimensions, and applied the tool to design work[6]. This tool narrows down input data to a range in which analysis accuracy does not suffer, and automatically creates a mesh for structural analysis (see Fig. 4) by simply inputting the spatial dimensions and positional relationships of the structural elements on design drawings.

After model creation, the relationship between circular vibration and operating frequency is examined using the finite element method. In this process, we checked whether vibration modes such as primary circular vibration, which are easily excited by electromagnetic force, exist in the operating frequency domain, and evaluated strength by response and stress analyses. As shown in Fig. 4, vibration modes can easily be examined by presenting a magnified display of displacement.

However, as localized vibration may still occur even if circular vibration does not exist in the operating frequency domain, and because stress conditions are generally complicated, it is essential for design work that the above analysis results be provided graphically to facilitate visualization.

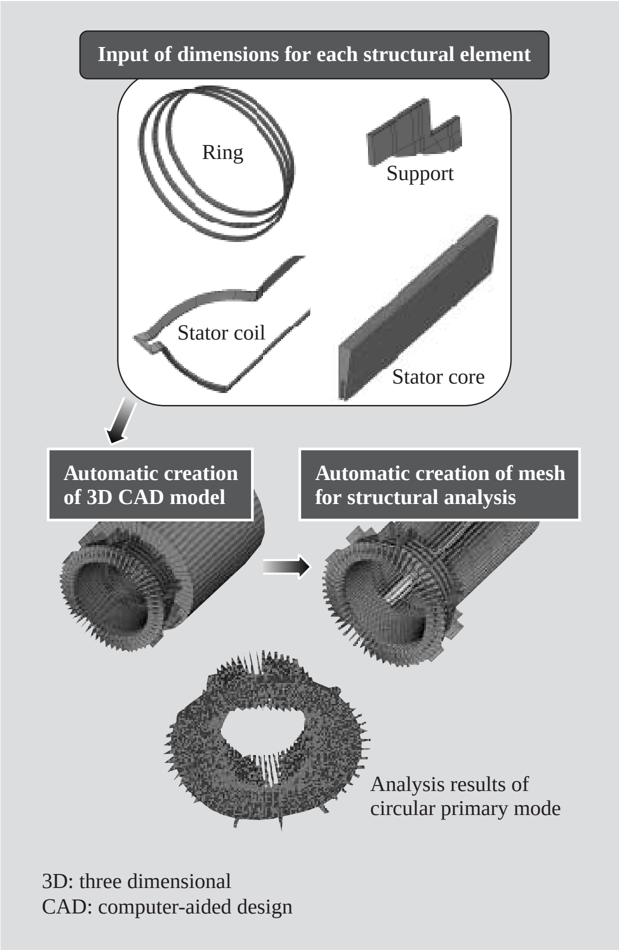

Fig. 4—Vibration/Stress Design of Stator End Section and Analysis Results.
Large-scale vibration calculations are included in design routines. Vibration modes can be visualized through magnified display of displacement.

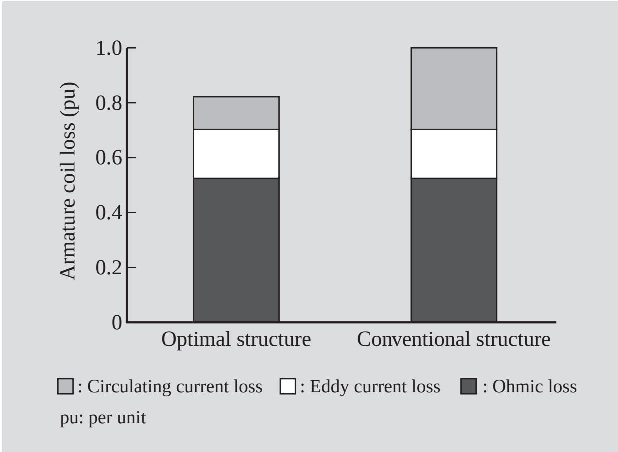

Fig. 5—Loss Reduction by Optimal Design of Stator Coil.
Circulating current loss was reduced by 50% by optimal design of the coil cross section and transposition.

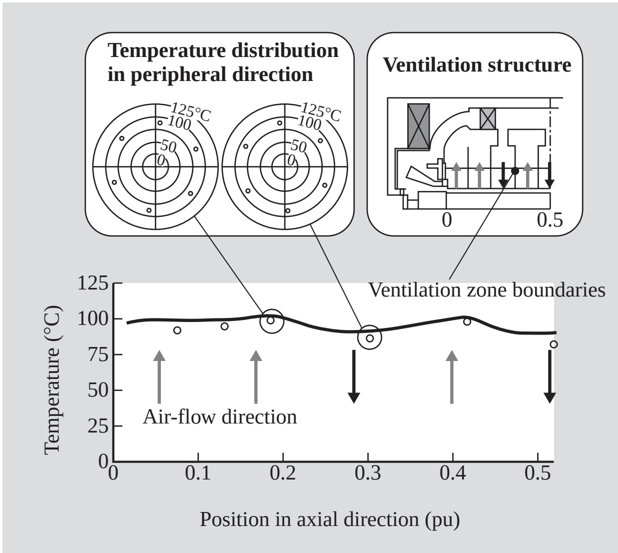

Fig. 6—Comparison of Stator-coil Temperature Design and Measured Values under Rated Operation.
Temperature was lowered and made uniform.

RESULTS OF GENERATOR PERFORMANCE TEST

Design Calculations and Results of Performance Test with Actual Generator

Fig. 5 shows the loss-reduction effect achieved by optimal design of stator coil strands. For circulating current loss, a reduction of over 50% has been achieved with respect to conventional design. When converting to overall stator coil loss, optimal design produces a loss-reduction effect of 20% and succeeds in lowering temperature and raising efficiency.

Fig. 6 shows the results of a temperature rise test targeting the stator coil. As designed, the class-B temperature limit of 110°C has been satisfied. Temperature in the peripheral direction is also uniform.

Vibration and stress for each section were found to be within allowed values, and measured and calculated coil-end stress values at the time of sudden shorts were compared and evaluated. The above measurements demonstrated the suitability of the developed design tools.

Table 1 summarizes the performance of the developed generator. A world-class efficiency of 98.8% has been achieved for an air-cooled generator of this capacity. In addition, this generator has room for improvement with respect to temperature rise-efficiency of even 98.9% which can be achieved by modifying the fan, for example. Our plan is to standardize this generator and enhance our product lineup.

TABLE 1. Performance of Developed Generator
The developed generator achieved efficiency over 98.8%. It has been confirmed that efficiency of 98.9% can be achieved by making modifications to the fan.

Item	50-Hz generator	60-Hz generator
Capacity	250 MVA	250 MVA
Power factor	0.9	0.9
Number of poles	2	2
Insulation type	F class	F class
Temperature rise	B class	B class
Speed	3,000 rpm	3,600 rpm
Efficiency	98.8%	98.6%

CONCLUSIONS

This paper has described a sophisticated generator design method and stator coil design in a 250-MVA turbine generator developed by Hitachi. A large-capacity air-cooled generator with an inner cooler ventilation system was chosen as an example. This design method can also be applied to hydrogen-cooled and water-cooled generators.

REFERENCES

(1) R. Joho et al., "Air-cooled Turbogenerators Superseding Hydrogen-cooling Domain," *IEMD* (Aug. 2001)

(2) J. M. Fogarty., "Connections Between Generator Specifications and Fundamental Design Principles," *IEMD* (Aug. 2001)

(3) K. Hattori et al., "Development of a High-efficiency, Air-cooled Turbine Generator with an Inner Cooler Ventilation System," IEEJ Meeting for Study of Rotating Machinery (Oct. 2001) in Japanese.

(4) K. Takahashi et al., "Strand Current Distributions in an Actual-scale Model of a Turbine Generator Coil," IEEJ Meeting for Study of Rotating Machinery (Oct. 2001) in Japanese.

(5) K. Ide et al., "Design Calculation of Strand Current Distributions in Turbine Generator Armature Windings," IEEJ Meeting for Study of Rotating Machinery (Oct. 2001) in Japanese.

(6) H. Ejima et al., "Electromagnetic Vibration Analysis of Turbine Generator Stator Coil End," IEEJ Meeting for Study of Rotating Machinery (Oct. 2001) in Japanese.

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