Present Developmental Status of Fuji Electric's Turbine Generator

Hiromichi Hiwasa
Toru Hase
Kohji Haga

1. Introduction

The capacities of air-cooled, two-pole turbine generators have increased dramatically. About 10 years ago, hydrogen-cooled generator was used in 150 MVA-class turbine generators, but nowadays, air-cooled generator is even being used in 200 MVA-class and above turbine generators.

Meanwhile, at combined cycle power plants, 400 MVA-class generators are being coupled to single-shaft or multi-shaft type steam turbines, and the directly hydrogen-cooled stator winding type or the directly water-cooled stator winding type are applied for the generators. Based on customer needs for economy, maintainability and operability, the generator having the indirectly hydrogen-cooled stator winding (hereafter referred to as indirectly hydrogen-cooled generators) is most suitable. Fuji Electric has developed a series of 300 MVA air-cooled generators and up-to-450 MVA indirectly hydrogen-cooled generators that use a global vacuum pressure impregnated insulation system (F resin/GII), (hereafter referred to as the Global VPI insulation system).

An overview of the technical development in involved in the creation of this product series, important developments of the Global VPI insulation system for high voltage large-capacity generators, and automatic manufacturing technology are described below.

Fig.1 280 MVA air-cooled turbine generator

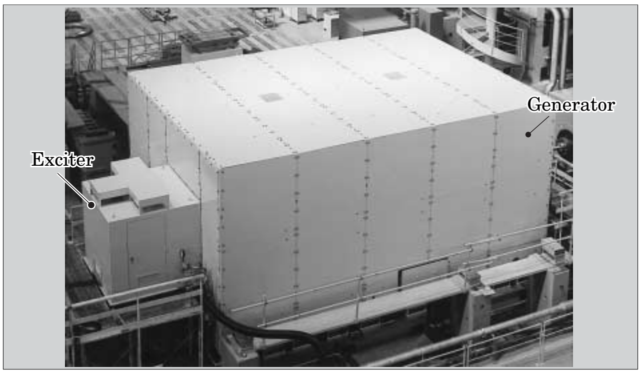
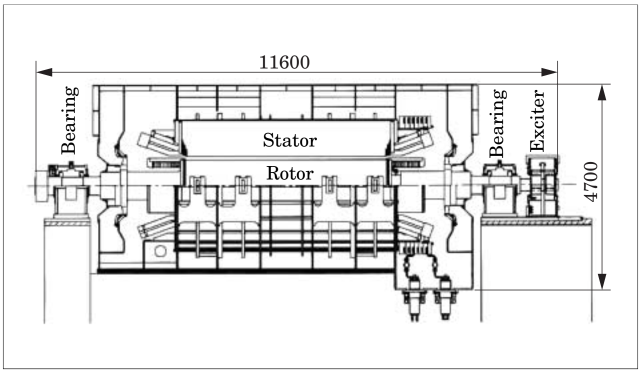


Fig.2 Cross-sectional view of 280 MVA air-cooled turbine generator



2. Practical Application of Large-capacity Air-cooled Generators

Air-cooled generators have a simpler structure than hydrogen-cooled generators and because they require no auxiliary systems such as a hydrogen gas supply system or a sealing oil supply system, the installation, operation and maintenance of air-cooled generators is quick and easy. Furthermore, air-cooled generators are advantageous because their production lead-time is short and initial investment cost is low. Based on the results of verification testing of a 126 MVA prototype generator built in 1999, Fuji Electric has worked to develop larger capacity air-cooled generators and has shiped 50 Hz, 280 MVA air-cooled generator into practical use. Figures 1 and 2 show a photograph of the external appearance and a drawing of the cross-section of this generator.

2.1 Technical features

As regards the cooling methods, the indirect cooling is applied for the stator winding and the direct cooling (radial flow) is applied for the rotor winding. And air coolers are installed in the side of the stator frame. The rotor is supported by two bearing pedestals positioned on a bed plate, and the exciter or the collector rings are mounted on the anti-turbine side shaft.

For the stator winding, Global VPI insulation system is applied. The stator winding is impregnated

Table 1 Factory test results of 280 MVA air-cooled turbine generator

Specification	Output	280 MVA
	Voltage	14.7 kV
	Current	10,997 A
	Power factor	0.9
	Rotating speed	3,000 r/min
	Frequency	50 Hz
	Thermal class	155 (F class)
	Coolant temperature	40°C
	Excitation system	Thyristor excitation
	Standard	IEC60034-3
Factory test results	Stator winding temperature rise	≦ 81 K
	Rotor winding temperature rise	≦ 80 K
	Short circuit ratio	0.52
	Transient reactance	26.7 % unsaturated value
	Sub-transient reactance	20.1 % unsaturated value
	Efficiency	98.82 % conventional efficiency

with epoxy resin throughout the entire stator after stator winding insertion into the stator core.

The following analysis and evaluation techniques were used to advance the increase in capacity of air-cooled generators.

(1) Evaluation of stator and rotor winding temperature using three-dimensional flow and temperature analytical techniques utilizing the finite element method (FEM)
(2) Analysis of stray load loss using electromagnetic field analytical techniques utilizing FEM
(3) Evaluation of fatigue strength of the rotor using strength analytical techniques utilizing FEM

2.2 Shop test results of the 280 MVA air-cooled turbine generator

In the abovementioned 50 Hz, 280 MVA air-cooled turbine generator, the type rating was tested with no-load characteristic test, short circuit characteristic test, temperature rise test, and by measurement of the loss. Type rating specifications and the shop test results for this generator are listed in Table 1. All the results are satisfactory and demonstrate that the required performance has been achieved. Additionally, as part of the shop test, the rotor winding temperature distribution, the stator winding temperature distribution and the stator vibration were measured. These measured results were then compared to the design values and to data measurements from previously manufactured generators, and then evaluated. Based on the comparisons and evaluation, the excellent characteristics and high reliability of this generator have been verified.

Fig.3 Cross-sectional view of 450 MVA indirectly hydrogen-cooled turbine generator

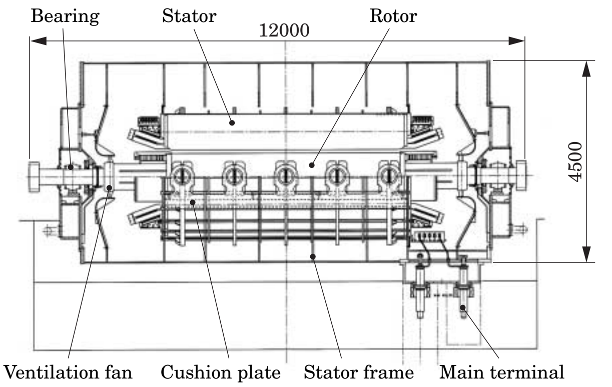


Table 2 Specifications of the 450 MVA indirectly hydrogen-cooled turbine generator

Output	450 MVA
Voltage	21 kV
Current	12,372 A
Power factor	0.85
Rotating speed	3,600 r/min
Frequency	60 Hz
Thermal class	155 (F class)
Coolant temperature	40°C
Coolant pressure	400 kPa (g)
Excitation system	Thyristor excitation
Standard	IEC60034-3

3. Technology for Enlargement in the Capacity of Indirectly Hydrogen-cooled Turbine Generators

A 400 MVA-class indirectly hydrogen-cooled turbine generator in which Global VPI insulation system is applied to the stator winding has been developed. As a representative example, Fig. 3 shows a cross-sectional view and Table 2 lists the ratings and specifications of a 450 MVA generator.

In consideration of the economic reasons and Fuji Electric's proprietary technology and manufacturing facilities, the following guidelines were adopted to during development.

(1) The maximum output of the generator to be developed shall be limited by the capability of Global VPI facility.
(2) The rotor and stator of the generator to be developed shall adopt the same structure or the same production method as an indirect air-cooled turbine generator.
(3) Newly installed manufacturing facilities such as automatic brazing equipment for the rotor wind-

ing (to be described later) shall be used to the maximum extent possible.

3.1 Construction

The 400 MVA-class indirectly hydrogen-cooled turbine generator differs from an air-cooled generator in that the stator frame functions as a pressure vessel and bracket type bearings are used, since hydrogen is used as the coolant. The stator and rotor both basically adopt the same construction and manufacturing method as the air-cooled generator, however.

Moreover, similar to the air-cooled generator, the stator winding also utilizes a Global VPI insulation system, which is one of Fuji Electric's principal technologies. In order to realize this configuration, it was necessary to make the Global VPI insulation system compatible with high voltages. The relevant technical development is described in detail in chapter 4.

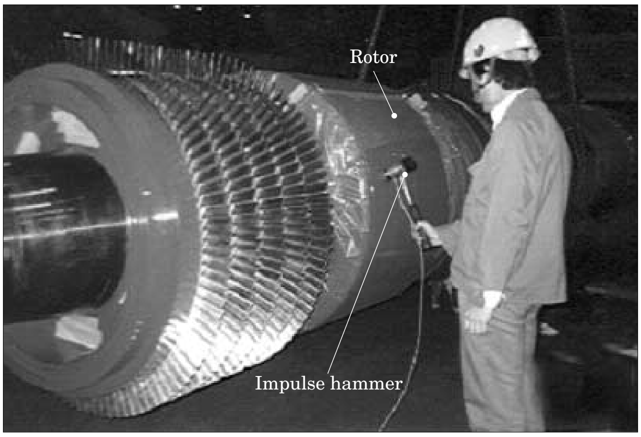
After Global VPI processing, the completed stator is inserted into the cylindrical stator frame, which is a pressure vessel, and secured via a spring plate to the stator frame. The spring plate, stator and stator frame are welded in the same manner as a large air-cooled generator.

The rotor winding utilizes the same radial flow direct cooling as the air-cooled generator, but has a thicker conductor due to the larger field current. In the case of the air-cooled generator, the ventilation hole for the conductor is formed with a punch-process in order to enhance the economic efficiency of the processing. In the case of the indirectly hydrogen-cooled turbine generator, that same punch processing cannot be used due to the deformation of the punch-out part of the conductor, capacity of manufacturing facilities, and other such factors. However, after careful investigation of many factors, including the clearance of the punching die and the sectional profile of the conductor, a punch process was realized for this fabrication step.

3.2 Ventilation and cooling

In a large capacity air-cooled turbine generator, ventilation is implemented using a "double flow" design. In this design, in order to achieve a uniform distribution of the stator winding temperature, the middle portion of the stator core is provided with a structure that flows a coolant gas from the outer diameter to the inner diameter of the stator core. On the other hand, since hydrogen gas has a lower density and larger thermal capacity, when the coolant gas passes through the ventilation fan and generator gap, the gas temperature rise is less than in the case of air. Accordingly, ventilation of the 450 MVA indirect hydrogen-cooled turbine generator is implemented with a "single flow" design in which a coolant gas flows only from the inner diameter to the outer diameter of the stator core. In order to optimize the gas flow volume distribution in the axial direction, the optimum thickness and arrangement of the stator core block and the axial arrangement of the rotor winding ventilation hole were determined using analytical techniques that had been verified with the abovementioned 126 MVA prototype generator.

Fig.4 Impulse-force hammer test



3.3 Suppressing the vibration of a long rotor

As generator capacities increase, rotors are designed to be longer in the axial direction. Consequently however, mass unbalance and asymmetry in the stiffness of the rotor readily cause the shaft to vibrate. Thus, the issue of vibration must be given due consideration.

In order to verify double frequency vibration caused by asymmetry in the stiffness of the rotor, a factor which cannot be reduced by balancing the rotor, an impulse-force hammer test was performed as shown in Fig. 4 to compute the natural frequency in the principal axis direction of moment of inertia of area, and the asymmetry was compared with the calculation results. The results of this analysis and comparison were reflected in the design of the compensation slit for the rotor pole, which compensates asymmetry in the stiffness of the shaft.

4. Insulation Technology for the Stator Winding

Using its Global VPI insulation technology, which has been acquired over many years, and its world-leading Global VPI manufacturing equipment, Fuji Electric has been appling Global VPI insulation technology to turbine generators since 1993, and has subsequently delivered approximately 100 units. As the capacities of the abovementioned indirectly hydrogen-cooled turbine generators increase, the capability to withstand high voltages and provide stable insulation quality are required of Global VPI insulation technology. Accordingly, Fuji Electric has developed a Global VPI insulation system for 22 kV-class rated turbine generators.

4.1 Features of Global VPI insulation for turbine generators

Global VPI insulation system is advantageous because the stator windings and the stator core are impregnated and hardened together, thereby improving the cooling performance of the stator windings and reliability against loosening of the windings, and realizing less maintenance work. Figure 5 shows the appearance of a Global VPI insulated stator and Fig. 6 shows the cross-section of the stator winding. This Global VPI insulation for turbine generators utilizes the following insulation technologies in order to ensure the reliability of the insulation.

(1) Highly heat-resistant epoxy resin
(2) Highly pregnable mica paper tape
(3) Internal electric field relaxation layer providing high voltage endurance and a long service life
(4) Thermal stress relaxation layer providing high heat cycle resistance

Fig.5 Appearance of stator after Global VPI (280 MVA air-cooled generator)

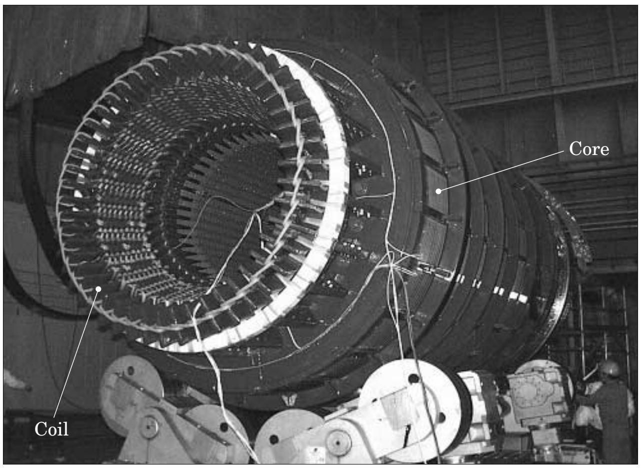
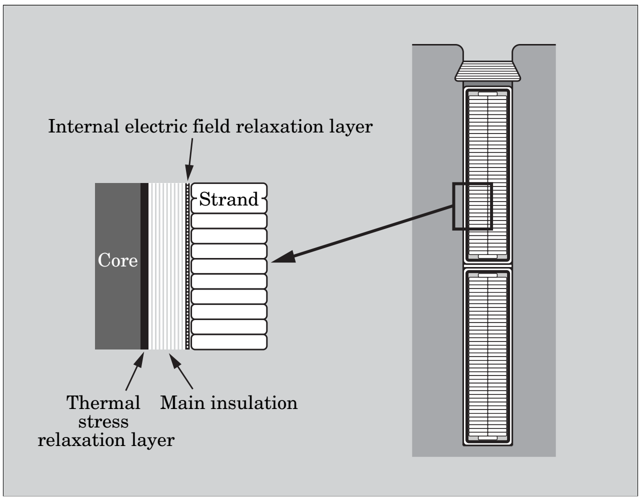


Fig.6 Cross-sectional view of stator winding



4.2 Development of 22 kV-class Global VPI insulation for turbine generators

The 22 kV-class Global VPI insulation for application to 400 MVA-class hydrogen-cooled generators, the coils are longer, the insulation is thicker and the withstand voltage is higher than in previous stator coil. Thus, Fuji Electric developed this technology by focusing on the taping characteristics and impregnation characteristics of the main insulation layer and the reliability of the end corona shield, and by evaluating the reliability of the Global VPI insulation.

4.2.1 Analysis of the main insulation taping

The stator coil is insulated by winding a main insulation tape of mica paper several times around the coil. The insulation characteristics of this stator coil are influenced by the taping method and the thickness and width of the tape. For an example, overlapping state of the main insulation tape affects the break down voltage (BDV) value, so that it is required to study the taping method in order to achieve the maximum BVD value with the same layer numbers. In order to obtain the optimum condition for taping, an analytical software program had been developed and applied. In the operating voltage and withstand voltage, the electric field was observed to concentrate at the corners of the cross-section of the stator coil insulation. While taping, the number of overlapping layers must not decrease at these locations. Figure 7 shows the analysis results of taping with 22 kV-class insulation. The number of overlapped tape layers increases at the coil corners, and it was verified that the taping is regular. This result is reflected in the taping process of the 22 kV coil.

4.2.2 Temperature distribution of end corona shields

End corona shield zones are provided at the end of the stator to relieve the potential gradient from the end of the coil. The temperature distribution of the end corona shield zones was quantified with this 22 kV-class insulation. Figure 8 shows the temperature distribution of the end corona shield zone while the nominal operating voltage is applied. The maximum temperature occurs near the edge of the slot corona shield, and this is in agreement with the results of surface potential measurements. The maximum temperature rise of 1.6 K was a small value, however. Even in withstand voltage tests, ($2E+1$, where E is the rated voltage [kV]), no abnormalities such as flashover or surface discharge were observed. Thus, it has been verified that the end corona shield zones with 22 kV-class insulation provide sufficient functionality.

4.2.3 Evaluation of insulation reliability

A straight bar model and full-scale model were manufactured for the evaluation of insulation reliability. A heat cycle test and V-t test were performed with the straight bar model, verifying that that insulation provided stable performance in response to heat stress and a sufficient voltage endurance lifetime. Moreover,

Fig.7 Isolayer distribution over coil surface in 22 kV model with taping in both directions

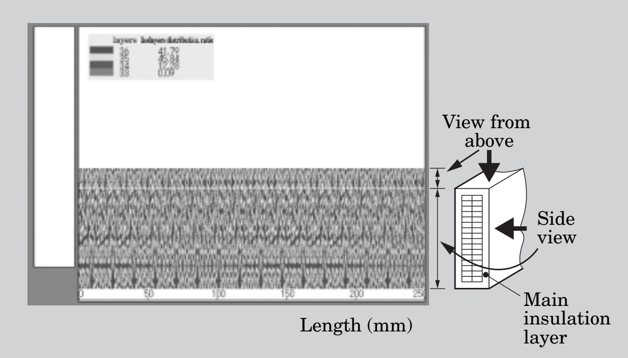


Fig.8 Surface temperature distribution on end corona shield in 22 kV model

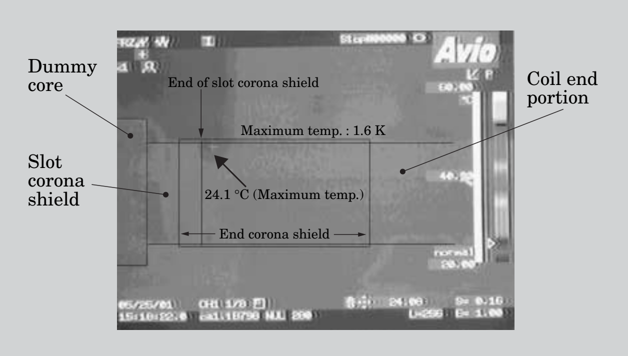


Fig.9 Appearance of 22 kV full-scale model

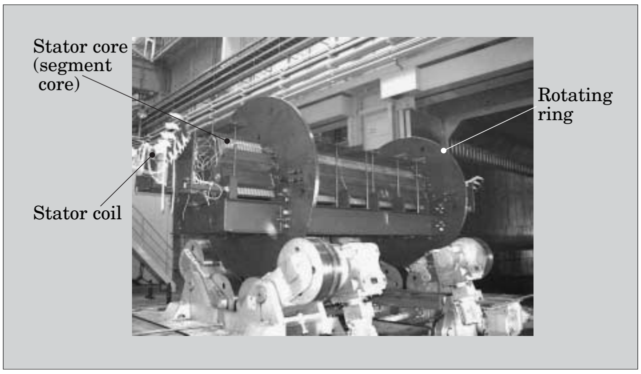
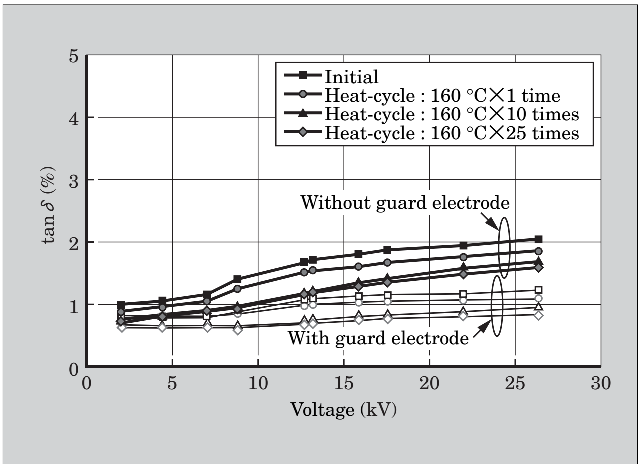


Fig.10 Tanδ - V characteristics of full-scale model during thermal cycle testing



the full-scale model shown in Fig. 9 was also manufactured in order to verify reliability of the insulation, including its method of manufacture. The full-scale model assumes a 450 MVA indirectly hydrogen-cooled turbine generator. The model core is 4.5 m in length and has 5 slots. The full-scale model is built with the same configuration as an actual generator, i.e. with an inserted stator coil, a fastened coil end and Global VPI processing, and therefore a coil end support and support ring are attached to the stator core of the full-scale model so that after the vacuum pressure impregnation procedure, the stator coils and core can be cured while rotating.

After the initial withstand voltage ($2E+1$) test, 25 iterations of a heat cycle test are then carried out with the full-scale model. The tan δ vs. voltage characteristics during the heat cycle testing are shown in Fig. 10. Since the tan δ characteristics do not exhibit much change from their initial value to their value at the 25th iteration of the thermal cycle test, the stability of the insulation performance was verified. Moreover, after the 25th heat cycle, an insulation breakdown voltage test of the full-scale model was performed in an atmosphere of air, and the breakdown voltage was verified to be at least three times greater than the rated voltage (in air).

5. Manufacturing Automation Technology

The market place demands turbine generators to have short delivery times, low price and stable quality. In order to meet with these demands, Fuji Electric has developed and applied technology for the automation and mechanization of manufacturing processes. A portion of this technology is introduced below. Previously, generator manufacturing technology depended largely upon the skill of the manufacturing workers, but the introduction of automated and mechanized manufacturing processes has made if possible to achieve stable quality.

5.1 Automatic brazing equipment for the rotor coil

Until now, the process of manufacturing a rotor coil involved the manual brazing of a copper bar. Automatic brazing equipment has been newly developed, however, and is shown in Fig. 11. This automatic brazing equipment continuously brazes copper bars with a high-frequency brazing machine, and then finishes the copper bars to form spiral-shaped rotor coils. In changing over the brazing work from a manual to an automated operation, the temperature during high-frequency heating and the timing for

Fig.11 Automatic brazing equipment

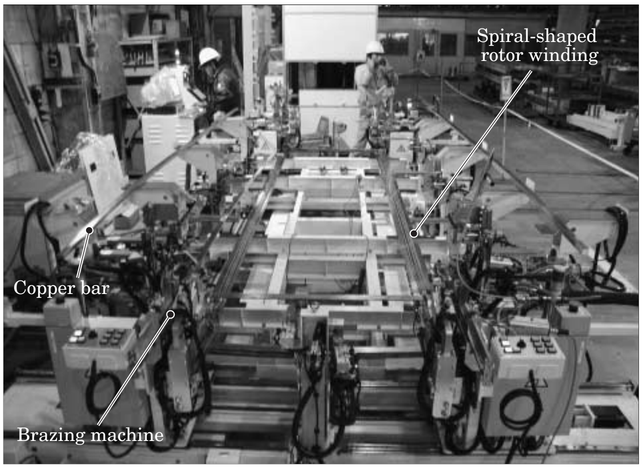
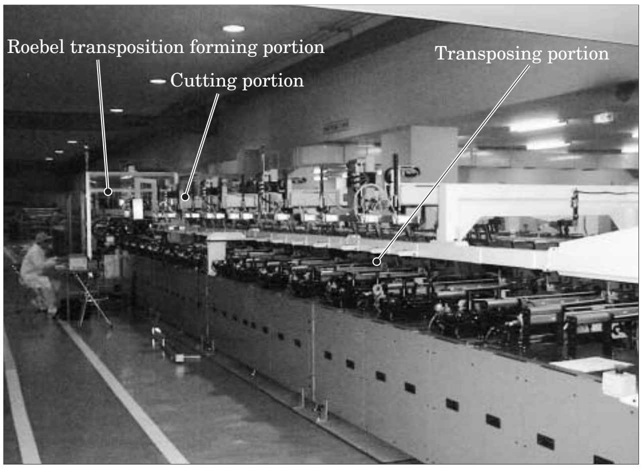


Fig.12 Automatic transposing equipment

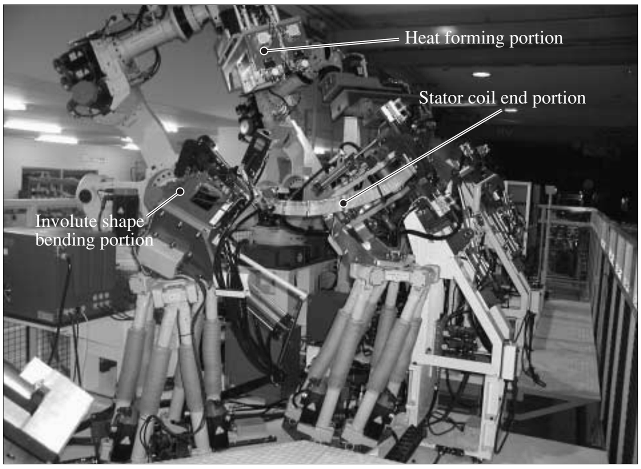


inserting the brazing filler metal were computed, and conditional settings for the automated machinery were determined based on such relationships as the material strength and cross-sectional analysis of the brazed portion. Moreover, in the case of a rotor coil copper bar of different dimensions, prior to manufacturing an actual generator, a brazed sample is fabricated and a strength test performed to verify whether the conditional settings are appropriate and to ensure good quality.

5.2 Auto-transposing machine

In order to reduce loss in the stator coil, Roebel transposition, in other words, strand transposition, is utilized. Previously, the tasks of strand cutting, forming, and transposing were performed manually for each work process. An auto-transposing machine has been newly developed, however, and is shown in Fig. 12. This auto-transposing machine automates the series of work processes from strand cutting, stripping of insulation from the strand ends, strand forming, transposing, and inserting of insulation material, to strand bundling. When strand wire and insulating

Fig.13 Automatic bending machine



material are input into the auto-transposing machine, the machine transposes the strands and outputs a coil. The auto-transposing machine is designed with a proprietary transposing mechanism to realize homogeneity of the transposing.

5.3 Automatic bending machine

Previously, the end portion of the stator coil has been formed by manually bending the coil, placing it in a shape, and then hardening it. An automatic bending machine has been newly developed, however, and is shown in Fig. 13. The automatic bending machine uses robotic technology to automate all processes from bending the coil end portion into an involute shape and heat forming, to cutting the conductor at the coil end. Use of this automatic bending machine achieves uniformity of the involute shape of the coil end and shorter lead-times.

5.4 Automatic process control for the Global VPI system

Moreover, in the Global VPI process, which is the most important manufacturing technique, the impregnating resin used is controlled strictly and the impregnation and rotational hardening processes are regulated automatically. Also, during the impregnation process, an impregnation monitoring system is utilized to ensure that the resin has impregnated the insulation layer of the coil. Thus, the Global VPI process is implemented under strict manufacturing process control, aiming to realize automation and good stability of the quality.

6. Conclusion

The present status of Fuji Electric's development of turbine generators has been described.

Fuji Electric intends to continue to develop technology to produce high quality and highly reliable turbine generators in response to market needs.