Progress of Geothermal Turbine-Generator Technology

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1. Introduction

An essential problem of the geothermal turbine-generator is protection against corrosion by hydrogen sulfide gas. Geothermal steam contains corrosive matter such as hydrogen sulfide, and there is a possibility of hydrogen sulfide intruding into the generator.

It is common knowledge that hydrogen sulfide causes heavy corrosion to metals, particularly copper and copper alloys. But the use of copper and copper alloys in electrical machines cannot be avoided. In order to avert electrical problems due to corrosion, protection against hydrogen sulfide corrosion is necessary.

In 1974, Fuji Electric began general research on corrosive gases such as hydrogen sulfide in geothermal turbine-generators. We have accumulated exposure tests performed in a corrosive atmosphere in the field and studies of basic technologies such as material characteristics in the laboratory. The measures taken against hydrogen sulfide for the past 20 years have been effective enough. Recently, Fuji Electric developed a new series of 2-pole, air-cooled turbine-generators with reinforced geothermal protection. This paper introduces the features and geothermal corrosion protection method of the new series of generators.

2. Output Ranges and Specifications of the Air-Cooled Generators

Figure 1 shows the output ranges classified according to the cooling system of Fuji Electric's 2-pole turbine-generators. The maximum practicable output of an air-cooled generator is 300MVA. We have manufactured 91MVA machine of the largest capacity in the geothermal air-cooled machine.

The main specifications of Fuji Electric's air-cooled generators are as follows:

(1) Output: 10 to 300MVA for 50Hz
10 to 240MVA for 60Hz
(2) Voltage: 11kV or 13.8kV for 190MVA or less
16kV for 200MVA or more
(3) Power factor: 0.85 (lag)
(4) Speed: 3,000r/min or 3,600r/min
(5) Insulation: Class F

Fig.1 Cooling systems and outputs of 2-pole turbine generators

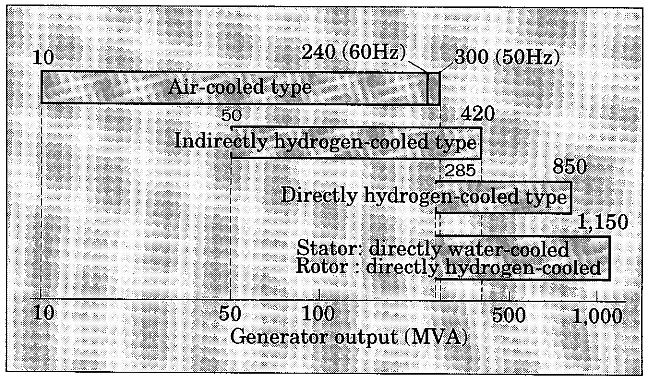
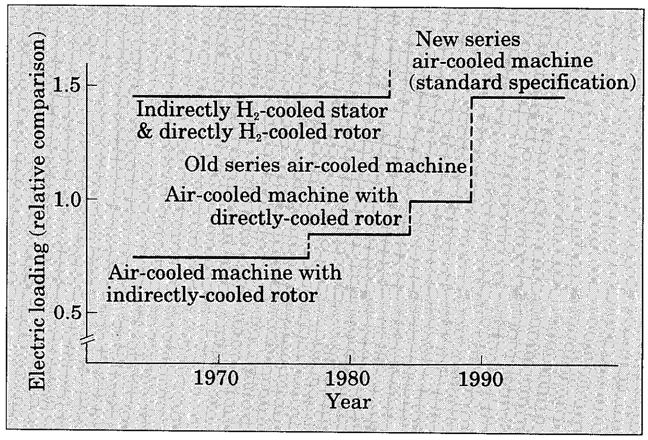


Fig.2 Transition of ampere loadings (AC/cm) of Fuji Electric's air-cooled generators



(6) Cooling system: indirect cooling for the stators radial-flow direct cooling for the rotors
(7) Exciting system: brushless exciting system

3. Cooling

3.1 Electric loading

In an air-cooled generator, as shown in Fig. 2, electric loading has been raised to the level of Fuji Electric's past hydrogen-cooled generator. This was attained by introducing a new cooling system and by optimizing the elements of electrical (ampere and magnetic) loading, ventilation, and temperature using the computer-aided ventilation-temperature network analysis technique. To verify the calculated values of the process, we have continued feedback of comparisons with the measured values in the calculation and tried to improve calculation accuracy.

In addition, because of an increase in ampere loading, the generator subtransient reactance $\chi_{d''}$, which is proportional to ampere loading can be increased to about 16%. This results in a reduction in the short-circuit current.

3.2 Temperature rise and distribution

The rise in temperature in the slot portion of the indirectly-cooled stator winding is higher in the core block center and lower in the duct section. Thus, it is important to reduce temperature rise of the coil in the block portion.

Temperature rise in this portion is primarily dependent on the sum of the core's thermal resistance in the axial direction (direction of lamination) and the core surface's thermal resistance in the duct portion. To reduce temperature rise, maintaining the same active core length ratio (ratio of active core length to total core length) and the same duct airflow, it is advantageous to increase the number of ducts and to decrease the thickness of the core block.

Therefore, as much as the constructional restriction allows, the minimum thickness of the core block is selected. Increasing airflow volume in the duct portion to reduce thermal resistance is not advantageous because the drop in pressure increases.

Geothermal power plants are often built far from the consuming city, and there is a possibility of it becoming the leading operation. Because the ampere loading is the same as that of hydrogen cooling, temperature rise at the core end must be carefully monitored. The block thickness at the core end is subdivided and airflow is increased at the finger and press-ring to intensify cooling. On the other hand, the measures taken for the rotor are as follows: in the turbine-generator, the stator dimensions and overall dimensions are determined according to the rotor dimensions. Therefore, improving the rotor's cooling effect and making the temperature rise uniform lead to a reduction in the rotor diameter and overall dimensions.

Figure 3 shows the rotor's airflow passages. The ventilation of this rotor is characterized by the directly cooled rotor winding.

To make uniform the rise in temperature in the rotor winding slot and the coil end portions, the cooling air passage is divided into the slot and coil end portions to separate airflow in the axial and circumferential directions.

As shown in Fig. 4, uniform temperature distribution in the rotor winding has been attained as a result of optimizing the cooling air passages and airflow distribution.

3.3 Distribution of ventilation

The main pressure drop in the turbine-generator is caused by the stator and an air gap. Therefore, single-flow ventilation has been generally used for small machines with a short core length and a low pressure drop in the air gap. Double-flow ventilation introduces cooled air in the middle of the core for medium and large machines. However, from the calculation of ventilation networks and the result of various experiments with actual machines, it has been shown that single-flow ventilation can be applied to medium and large machines as well. This is due to (1) the enlargement of the airgap based on the assessment of an improvement

Fig.3 Ventilation passages of the rotor winding

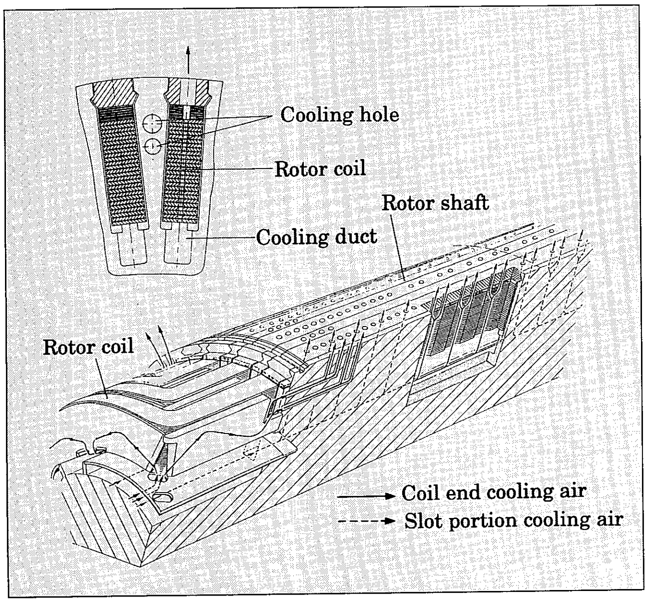


Fig.4 Temperature distribution in the rotor winding

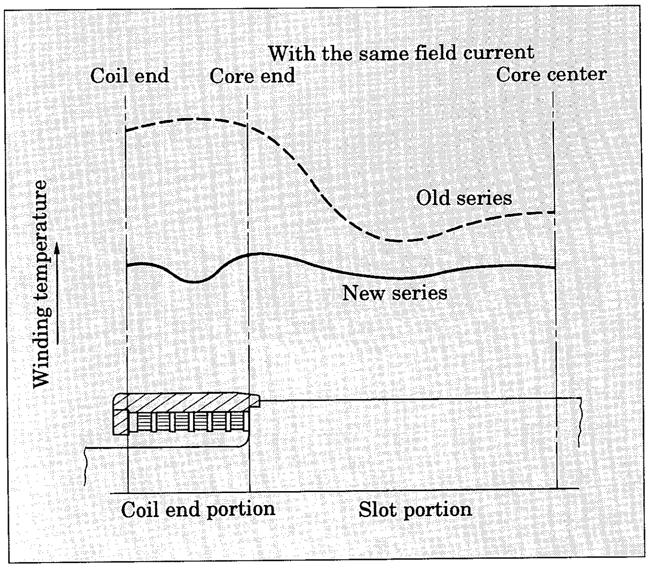
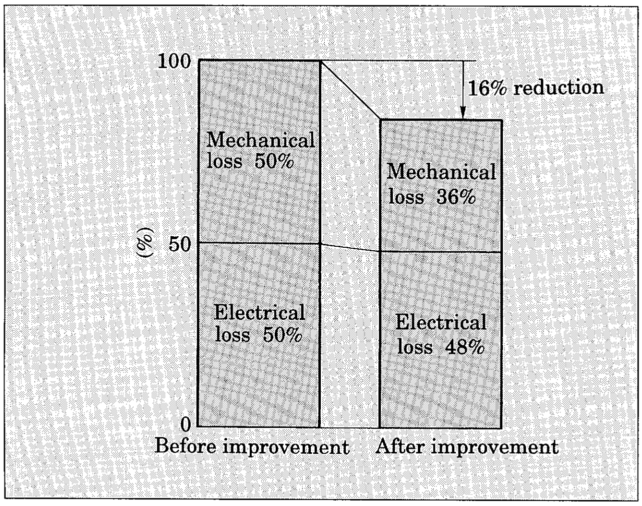


Fig.5 Example of reduction in generator loss by improvement in cooling



in the rotor cooling; (2) optimization of the distribution of stator ventilation ducts; and (3) a reduction in the required cooling airflow due to windage loss reduction by reducing stator ventilation resistance, etc.

As a result, the 160MVA class air-cooled machine performs satisfactorily with single-flow ventilation.

4. Improvement in Efficiency

A comparison between the loss before and after the improvement in the cooling capacity of the 160MVA class of air-cooled generators is shown in Fig. 5.

Before the improvement in the cooling capacity, generator loss can be roughly broken down into 50% mechanical loss and 50% electrical loss. The 50% mechanical loss, accounts 40% for windage loss and 10% bearing loss.

When ampere loading increases as the cooling effect improves, an increase in electrical loss (Joule losses and stray load losses) cannot be avoided. But to improve efficiency, reduction in the mechanical loss, in particular the windage loss, is achieved. The windage losses consists of fan and windage loss around the rotor body. The ratio of these constituents is about 2:1. Fan losses are proportional to the product of airflow and pressure, and windage losses are generally proportional to the third power of the rotor diameter. Required airflow has been minimized by optimizing the air passage and reducing the size of the rotor, both of which are closely related to an improvement in efficiency. In addition, bearing loss has been reduced by about 30%.

5. Construction of the Generator

Figure 6 shows construction of the generator. This figure illustrates a skid type construction. With this type of construction, the rotor and stator can be transported in a united body.

Fig.6 Construction of the generator

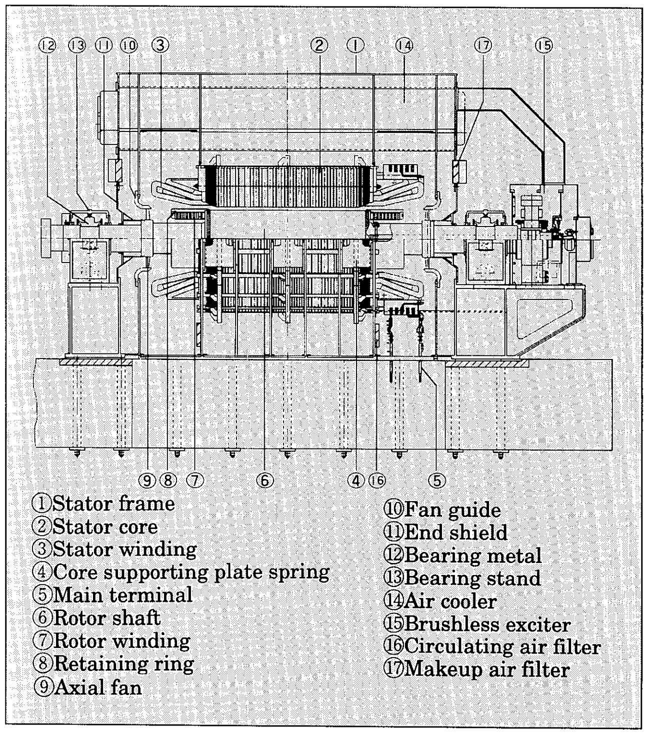
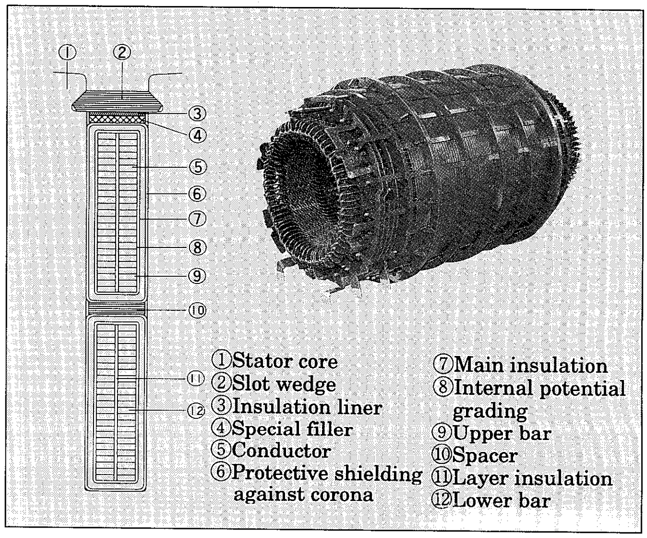


Fig.7 Slot section and external view of the stator winding



For corrosive gases such as hydrogen sulfide, the following measures are adopted for the stator frame:

(1) To prevent external corrosive gases into the generator, a totally enclosed and internally cooled type is used. The effectiveness of the airtight seal to the external atmosphere is increased by introducing air from the high-pressure portion of the machine into the shaft penetrating portion.

(2) To keep the concentration of hydrogen sulfide in the cooling air of the generator low enough to render it harmless, a circulation filter (oxidation catalyst filter) is provided internally. To clean the

unavoidable “make-up air” from outside, a makeup air filter (oxidation catalyst filter) is provided.

5.1 The stator

To inhibit corrosion due to corrosive gases, the new series of machines uses a totally-impregnated insulation system to the stator. In this system, all stator core and stator coils are impregnated in a vacuum with a permeative epoxy resin. As a result, the main stator parts are coated with epoxy resin; thus, reliability against corrosion is enhanced. In addition, protection against the loosening of wedges with the use of a special filler placed under the insulation liner eliminates wedge inspection, which is advantageous to geothermal plants undergoing continuous operation.

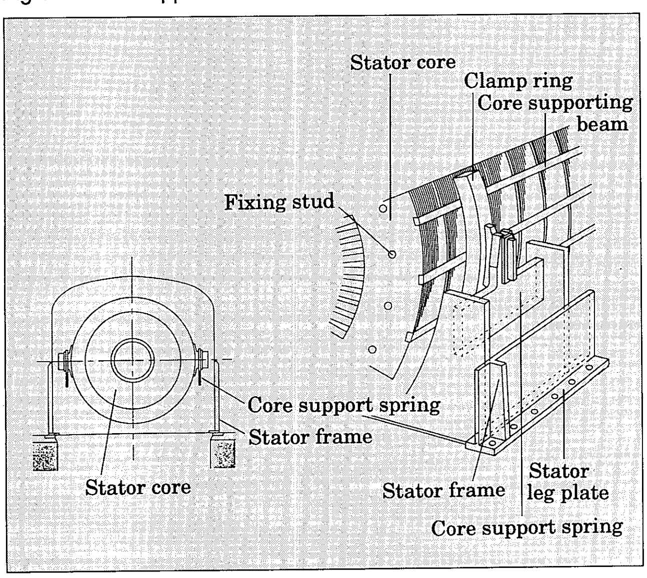
The stator is characterized by (1) the stator winding with totally-impregnated insulation and (2) elastic support of the core. These features are introduced below.

(1) The stator winding

The stator winding has F class insulation. The coil uses strands insulated with glass fiber, and the main insulation uses highly reliable mica tape. The coils wound with the main insulating tape are inserted into the stator core slots. They are then coated with epoxy resin and impregnated in a vacuum, united with the core. Figure 7 shows the slot section and appearance of the stator winding.

Various contrivances are applied to the main insulation and low resistances to improve their insulating strength. To prevent the generation of corona, semiconductive tape is put on the coil in the slot portion, and the coil at the core end portion is provided with electric field grading. The stator coil strands using the Roebel transposition reduce any losses due to the skin effect. Also, the connection at the top of the coil ends is designed to reduce stray load loss.

Fig.8 Elastic support construction of the stator core



The coil ends have a spacer inserted between the coils. They are bound to each other, and fixed to the support provided on the press-ring. This results in a durable construction that does not cause coil deformation or damage even in the event of a line fault or any other problem.

(2) Elastic support of the core on the stator frame

The stator frame is horizontally divided into two. The totally-impregnated core is mounted on the lower stator frame with plate springs between the core and the frame. This elastic support can reduce the transmission of core magnetic vibration onto the foundation to a fraction of its original value. It also reduces noise, which is about 5 dB without solid support. Figure 8 shows the elastic support construction for the stator core.

When there are limitations on the transportation of the generator unit to a geothermal power plant, this construction facilitates transportation. Transporting the core and coil, the upper frame, and the lower frame

Fig.9 Slot section of the rotor

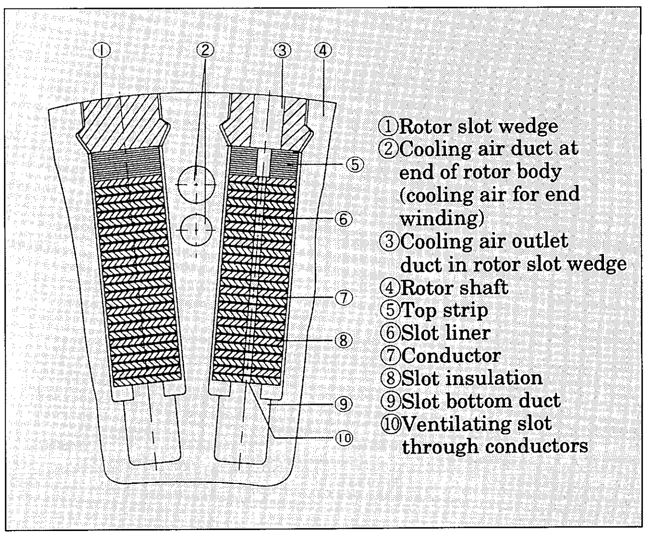


Fig.10 Coil end section of the rotor

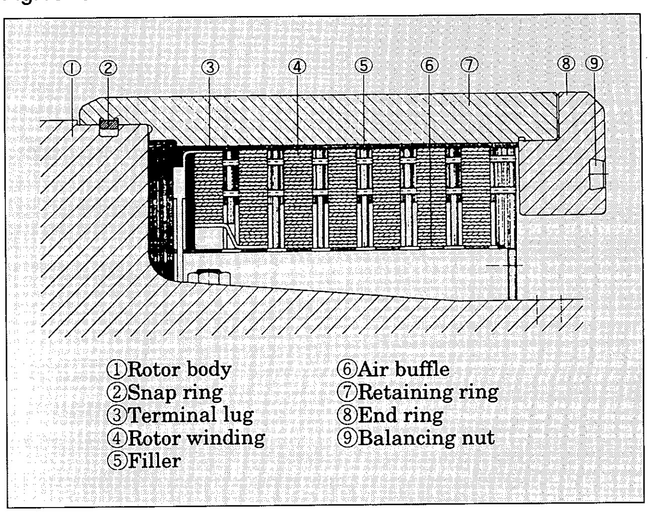


Fig.11 Brushless exciter

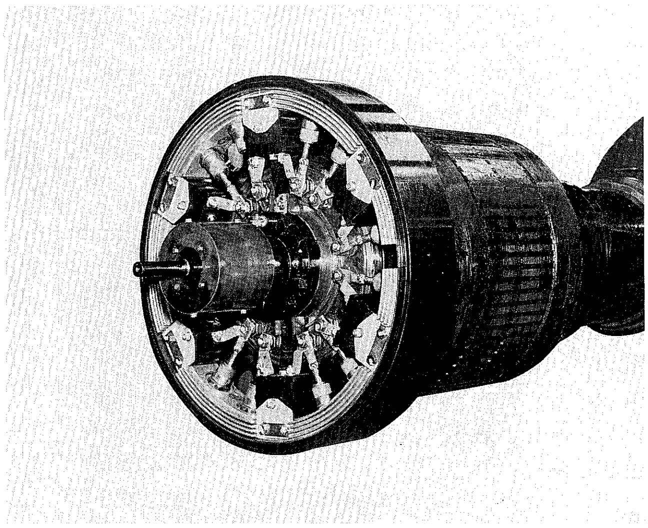
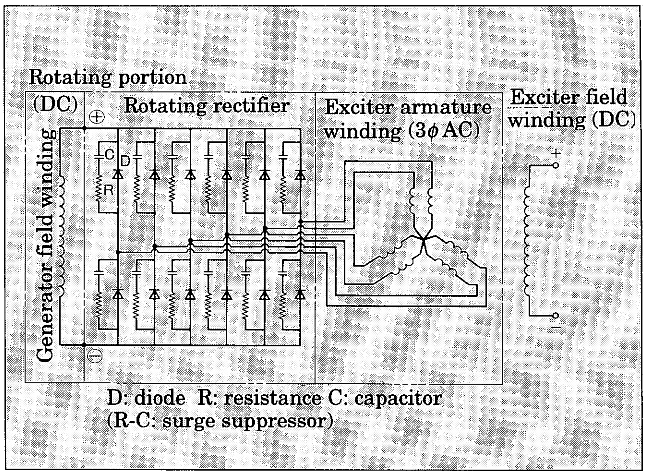


Fig.12 Schematic diagram of the brushless exciter



separately and then assembling them on-site can reduce transport weight and size.

5.2 The rotor

The rotor has been reduced in size and weight by an improvement in cooling. The geothermal measures below have been adopted.

(1) The rotor winding

The rotor coil, directly in contact with the cooling air, is completely tin-plated, which provides corrosion resistance to hydrogen sulfide gas. In addition, the coil end is coated with epoxy varnish. The insulation of the rotor winding is F class. For the layer insulation, epoxy glass sheets are used. These are stuck on the surfaces of each rotor coil under the sufficiently heated and compressed condition. The conductor with several cooling holes is directly cooled in the radial direction. Also, the coil end is effectively cooled with a flow of cool air divided into axial and circumferential directions. Figure 9 shows the rotor slot section.

(2) The retaining ring

The centrifugal force of the rotor coil end is retained by the retaining ring shrunk on one side of the rotor body.

The retaining ring is positioned in the magnetic leakage flux passage, so the use of a nonmagnetic retaining ring can reduce stray load losses caused by leakage flux at the rotor end. It further serves to suppress losses at the stator end in leading operations and prevents localized heating. The retaining ring uses 18Mn18Cr material which has a very low susceptibility to stress corrosion cracking and has a construction that makes it difficult for stress concentration to occur. Figure 10 shows the rotor coil end section.

5.3 The bearing

The bearing adopts a forced lubrication system and a counterflow bearing, reducing lubricant volume and friction loss .

The bearing has a spherical supporting surface for the bearing stand and bearing metal. This allows the bearing a self-aligning action to avoid any contact with the metal, even if the axes are unexpectedly out of alignment.

To improve stability against vibration, the inside surface of the bearing metal has a special curve in the shape of a lemon. The bearing stand with a welded steel construction is very rigid.

5.4 The air cooler

The air cooler is built into the generator stator frame. It consists of an inlet-outlet water chamber, a turnabout water chamber, and finned tubes with both sides fixed in the header plate holes with an expander. Because cooling water for geothermal generators contains such corrosive elements as hydrogen sulfide, the cooling tubes of the air cooler, the header plates, and the water chambers use stainless steel which has a high resistance to corrosion.

5.5 The brushless exciter

The brushless exciter is a overhang-type mounted on the generator's end. This overhanging-construction has the advantages of reducing installation and transportation size as well as reducing maintenance due to the omission of bearings. Figure 11 shows the appearance of the brushless exciter and Figure 12 shows the schematic diagram. Although Fuji Electric's brushless exciter has had no problems with the diodes in the 30 years since it was first supplied, a diode failure detector is provided in the exciter system in case of a failure.

The permanent magnet generator as the subexciter uses high-performance magnets which reduce its size. This is important in reducing the axial length and weight of the overhanging portion and preventing-vibration.

The geothermal measures taken are as follows:

(1) The armature winding and field winding of the AC

exciter

After the coils are assembled on the core, the consolidated core and coils are impregnated with epoxy resin in the vacuum .

(2) The rotating rectifier

The bare conductors are completely tin-plated. The flexible leads are coated with a special masking material.

(3) The armature winding of the permanent magnet generator

After the coils are assembled on the core, the consolidated core and coils are impregnated with epoxy resin in the vacuum .

5.6 Other geothermal measures

(1) Instrumentation wiring

For the wiring cables, tinned wires are used, and the bare copper surfaces of the cable terminals are coated with a special masking material.

(2) The switch contacts of meters

Enclosed meters or sealed contacts are used. When the use of an open-type contact is unavoidable, gold-plated contacts are used.

6. Conclusion

The new series of geothermal turbine-generators was developed with the aim of improving reliability and reducing the amount of maintenance on the basis of existing geothermal technology. We believe the concept of the new series of generators introduced in this paper is superior due to its high reliability against corrosive gases and reduction of labor in maintenance. We will further strive to improve the technology of geothermal generation, which is now seen in a new light as clean energy.