UDC 621. 313. 322-81

# FUJI TURBINE GENERATOR

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## I. FOREWORD

There has been a remarkable increase in the individual output of turbine generators in recent years. The tendency toward increase of the steam pressure and temperature for improving the efficiency of the thermal power generating facilities demands an acute increase in the individual generator output. In the past, manufacturing technique was the main factor limiting the capacity record of this country. At present, however, the problem does not lie in deciding whether generators of more than 500 Mva can be manufactured or not because of technical difficulties, but rather in deciding the optimum unit capacity to be set by the power supplier in consideration of economical and systematic operation.

Fuji Electric engages in technical cooperation with Siemens of West Germany, a representative company of European techniques in this field, and has been making utmost efforts in the field of the commercial-use large-scale turbine generator. On the other hand, in the industrial field, construction of small and medium capacity thermal power plants has been actively carried out in consideration of overall factory efficiency, such as use of steam, waste gas and waste heat. In this field as well, Fuji Electric has a number of achievements to its credit.

Given in this paper are the outlines of the air-cooled and, large-capacity hydrogen-cooled type turbine generator.

## II. SELECTION OF TYPE AND RATING

### 1. Cooling Methods

The cooling method of the turbine generater is a vital factor, as it clearly indicates the extent of the progress of the turbine generator. Cooling methods can be roughly divided into two types, one using air as a cooling medium the other using hydrogen.

Hydrogen cooling methods can be further classified into direct and indirect cooling system. In fact, there are many types of cooling methods differing according to the construction of the passage of the cooling medium, type and circulation method.

It is necessary to properly combine these various types upon setting up a generator construction project of a certain capacity for utmost economical and functional advantages, incorporating the optimum cooling method for the generator into the plan. Our cooling methods can be roughly classified into the six types shown in *Table 1* below, together with their respective advantages:

*Table 1* **Classification of Cooling Methods**

| System | Cooling of Stator Coil | Cooling of Rotor Coil | Application Range |
|---|---|---|---|
| I | Air cooling | Air cooling | Up to 50 Mva |
| II | $H_2$ gas indirect cooling | $H_2$ gas indirect cooling | 40 to 160 Mva |
| III | $H_2$ gas indirect cooling | $H_2$ gas radial direct cooling | 50 to 125 Mva |
| IV | $H_2$ gas indirect cooling | $H_2$ gas axial direct cooling | 125 to 250 Mva |
| V | $H_2$ gas direct cooling | $H_2$ gas axial direct cooling | 200 to 500 Mva |
| VI | Liquid direct cooling | $H_2$ gas axial cooling | $>$ 500 Mva |

Methods I and II are of the same construction, differing only in the cooling medium used. That is, holes are made in the axial direction in the teeth of the rotor as shown in *Fig. 1*, through which the cooling medium flows from the both shaft ends to the shaft center, the flow changing to the radial direction at the center before being exhausted into the air gap.

The heat produced in the rotor coil passes through the slot insulation, and the metal portion of the teeth and is dissipated by the cooling medium flowing through the above-mentioned holes. Being of hydrogen cooling type, method II can be applied to generators from 40 to 160 Mva. However, there are many portions in the large-capacity range which overlap methods III and IV, so that method II is used mainly in the small-capacity range. It features simple construction but the cooling efficiency is inferior to the other methods, so that it cannot be economically used for a large-capacity generator. In method III

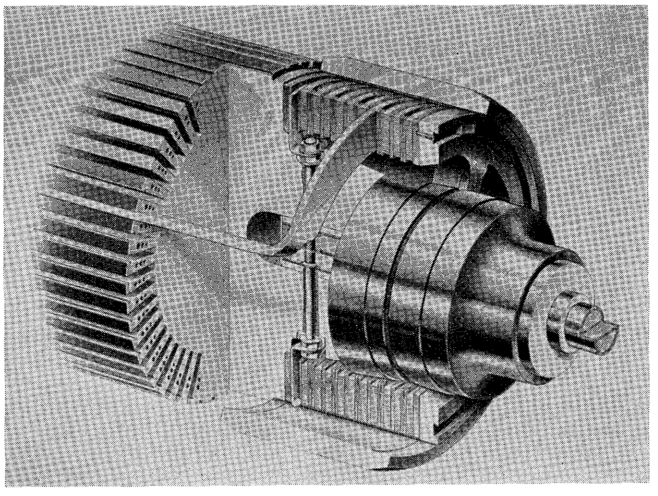


*Fig. 1* Rotor coil used in cooling methods I, II

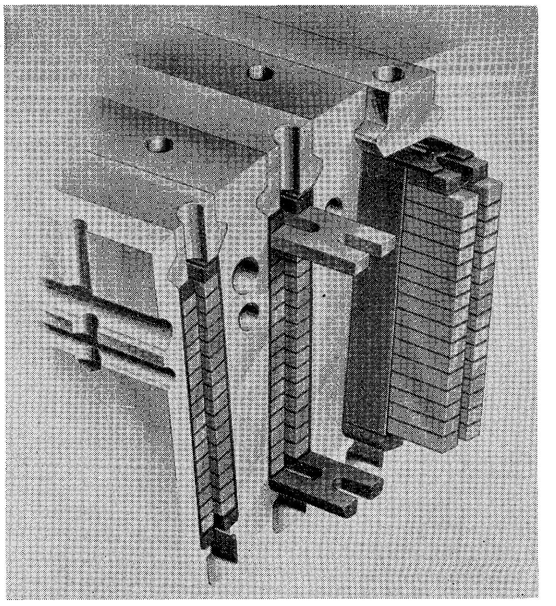


*Fig. 2* Rotor coil used in cooling method III

the stator is of the $H_2$ gas indirect cooling type, with the partially direct-cooled rotor coil; the cooling method adopted for rotor coil is called radial cooling and its cooling efficiency is far superior to that of method II. *Fig. 2* shows a cross-sectional view of arotor employing cooling method III.

The axial gas duct provided at the bottom of each slot forms a passage through which fresh gas is fed from both shaft ends toward the center of the shaft. Holes are made in the conductor at reasonable intervals in the radial direction. These holes are connected to the gas duct at the slot bottom and the air gap through the wedge and the solt insulation. The $H_2$ gas flows into the gas duct from the end portion of the shaft and then flows radially through the holes of the conductor into the air gap. When flowing through the conductor, holes the $H_2$ gas makes direct contact with the conductor, so that the direct cooling is well effected. In this system, proper arrangement of the size, number and distribution of the radial cooling holes permits uniform temperature distribution of the coil in the axial direction. By the time of arrival at the radial cooling holes, the $H_2$ gas temperature isnot rising yet, so that effective cooling with cold gas can be achieved. In addition to a sufficient direct-cooling effect, the rotor coil's simple construction and unlimited thickness permit a sufficient number of turns, thus avoiding increase of the exciting current. Fuji Electric considers this cooling method to be suitable for generator from 50 Mva to 125 Mva.

Method IV is for internal direct cooling of only the rotor. Needless to say, the rotor coil cooling effect is excellent. Generally, in the rotary electrical machinery, the fewer the number of poles, the smaller the space for accommodation of the rotor coil, so that the rotor determines the overall size of the machine. The same may be said in the case of turbine generator; even when the short-circuit ratio is made smaller to alleviate the amper turn loading on the rotor, the rotor is still overloaded compared to the stator. Accordingly, to achieve balance of the entire machinery, the stator is left as it is, the indirect cooling type, only the rotor being directly cooled. This consideration naturally arises. Method IV is to be employed in this range. We consider the generator from 125 to 250 Mva to be in the applicable range of this method.

*Fig. 3.* is a cross-sectional view of a rotor employing method IV, in which the conductor is formed of one turn with two laminated conductors of U-shaped cross-section, thus forming an $H_2$ gas duct of rectangular cross-section inside the conductor. The $H_2$ gas is fed into the gas duct inside the conductor from the gas feeding opening provided

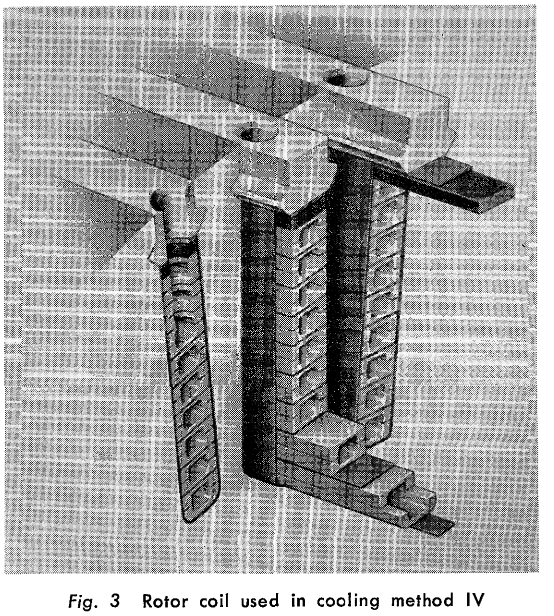


*Fig. 3* Rotor coil used in cooling method IV

at the coil end of the rotor coil, effecting direct cooling in the axial direction as far as the center of the rotor. At the center of the rotor, there are radial holes which open for exhaust purposes, being pressed out into the air gap by its own fan effect. Unlike the direct cooling of the stator winding, that of the rotor winding does not require special installation of a high pressure compressor for gas circulation, its own fan effect being used. This prevents the construction from being complicated. Because of the use of hollow conductors, the number of conductors that can be accommodated is very small, and the number of turns that can be wound is insufficient so that the exciting current is great and the exciting capacity increases.

When the output further increases, the problem arises of increasing the ampereloading of the startor. When the ampere loading of the starter is increased, a special arrangement for cooling the stator, with direct cooling of the rotor, becomes necessary. In this respect, Fuji Electric employs a direct cooling method for the stator coil by means of $H_2$ gas as in method V. The rotor is cooled in exactly the same manner as method IV. For direct cooling of the starter coil, a cooling duct is provided inside the slot insulation of the coil, a permitting $H_2$ gas to flow through in the axial direction, as shown in *Fig. 4*.

Arranged on both sides of the figure are the conductors with Roebel transposition. Intervened between these conductors is a metal-made cooling duct through which $H_2$ gas flows in the axial direction. The heat produced in the conductor flows directly to the $H_2$ gas instead of flowing through the slot insulation, so that the cooling efficiency is remarkably improved. This method is most suitable for a generator from 200 Mva to 500 Mva.

The applications of IV and those of V are overlapped in a range of 200 to 250 Mva. As seen in *Fig. 4*, as the slot insulation becomes thicker, the effect of the direct cooling, its heat resistance and the temperature difference between outside and inside

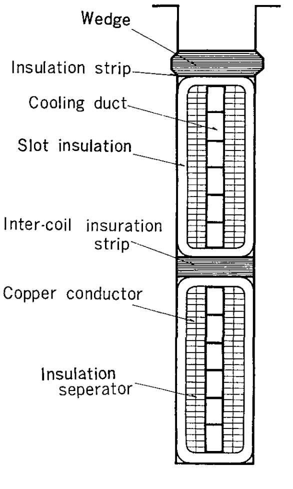



*Fig. 4* Stator coil used in cooling method IV

of the insulator, all increase. In the range where the above mentioned complexity occurs, when the voltage is high and the insulation thickness is great (for instance more than 15 kv), method V is preferable, while in the case of low voltage, method IV is preferable.

Method VI is to be used for machinery of more than 500 Mva, in which water is used to cool the stator coil, since water has maximum cooling effect.

### 2. Rated Voltage

The theoretically optimum voltage is primarily dependent upon the major dimensions which are determined by the output and cooling method. However, the theoretically optimum voltage is not necessarily employed in all cases. Concerning stator coil insulation techniques, Fuji Electric has actual production records of insulation of machinery of less than 25 kv, being thus capable of selecting resonable voltage of less than 25 kv. As already stated, there may be a case where selection between the indirect and direct cooling methods depends upon the voltage value. The selection of the rated voltage has a considerable influence on economy. The most economical voltage should be selected in overall consideration of the breaker connection, bus line as well as the generator main unit itself.

### 3. Gas Pressure

In the case of hydrogen cooling type machinery, there always arises the problem of selecting the pressure of $H_2$ gas. Usually, however, the gas pressure corresponding to the rated output belong in the following ranges. Namely, a gauge pressure of 1 to 2 $kg/cm^2$ is employed in method II, 2 to 3 $kg/cm^2$ in methods III and IV and 3 to 4 $kg/cm^2$ in methods V and VI. In the case of the indirect cooling, increase of the gas pressure above 3 $kg/cm^2$ serves only to increase the temperature inclination, with less gain, so that 3 $kg/cm^2$ is set as a limit. For both the stator and rotor, in the case of the direct cooling method, increase of the gas pressure is directly related to increase of the cooling effect, so that the gas pressure is increased up to 4 $kg/cm^2$.

## III. OPERATION CHARACTERISTICS

The turbine generator has a low operating limit of under exciting range because of its construction. With the rotor coil space limited, the over-excitation margin is small. Therefore, upon operation of the generator, it is necessary that constant care be directed to keep the operation within the operation limit curve. As shown in *Fig. 5*, *a–b* is a limit set so that the field current does not exceed the rated current of the rated load condition. Therefore, when the rated power factor changes from $\cos\varphi_0$ to $\cos\varphi_0'$, thus approaching 1, the operating range changes from *a–b* to *a′–b′*, becoming narrower. *B–c* is a curve of

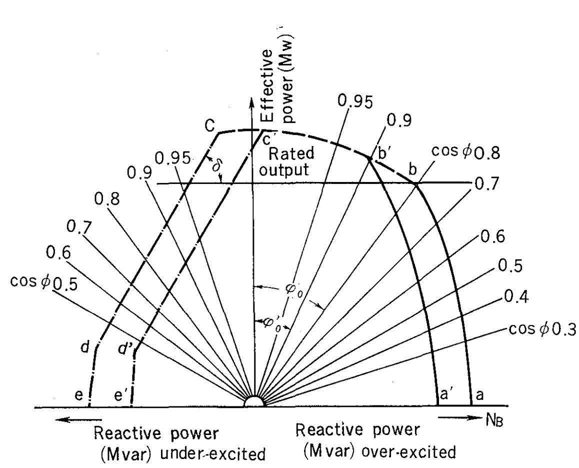



*Fig. 5* Capability curves for turbine generator

constant stator current, and is a limit due to stator temperature. The angle $\delta$ between *c–d* and the horizontal axis is an internal phase angle. The $\delta$ at the time of stabilizing limit is of course 90°. It has been confirmed that for the generator with the regulator of quick response there is safe operation range above 110°. Fuji Electric provides a margin for it by setting the operation limit at 70. *D–e* is a regulating margin in case of the field current near zero. *C–d* is influenced by the short-circuit ratio. As the short-circuit ratio is smaller, it shifts to *c′–d′*, thus considerably narrowing the operating range. Recent operation power factor at power stations is close to 1. In particular the power factor at night is improved. However the leading power factor range becomes narrow near the rated output, largely affecting the operation. One of the factors which determine the minimum value of the short-circuit ratio is this operation limit. Fuji Electric provides an under excitation protective device which is designed to operate when the operating point of the generator exceed the set *c–d* curve, thus permitting operation with high reliability within the limit curve. This protective device is capable of distinguishing hunting due to system vibration, as well as serving as a hunting protective device. Fuji Electric has set the short-circuit ratio of generator of conventional type at 0.5 to 0.6 as recommended by IEC. The ordinary air cooled generator of Fuji Electric is not provided with a damper winding. However, it is capable of absorbing a negative sequence current of less than 12.5%. In this regard, all the hydrogen-cooled generators of this company are provided with copper damper-bars inserted into the rotor surface of the magnetic pole portion. Use of this damper serves to reduce to half the stray load loss otherwise present due to the negative sequence field. The negative sequence current considered permissible by IEC is more than 8% in the case of more than 100 Mva, or 12.5% in the case of less than 100 Mva; both can be absorbed by this kind of damper. For those exceeding the permissible range set by IEC, a end ring is provided under the retaining ring for pole-to-pole connection; when requirement for the negative sequence current has further increased, damper bar is additionally installed to each slot of the rotor and magnetic pole. Also installed is a end ring which connects them thus absorbing the negative sequence current.

Regarding the reactance of the turbine generator, the upper limit is not standardized, only a lower limit being given. The reactance of the turbine generator tends to be excessively small due to its 2-pole system. Upon designing the generator, consideration should be made to make its X”d more than 10% in order to lessen both the maximum current value at the time of three-phase short circuiting and breaker capacity.

## IV. INSULATION

Among Fuji Electric’s small-capacity air-cooled turbine generators, the stator coil of machines with rated voltage of 3 kv and 6 kv are provided with shellac mica insulation which has demonstrated satisfactory performance through long actual use. On the other hand, air-cooled generator and all hydrogen-cooled generator with a rated voltage of more than 10 kv are provided with F resin coil, which uses epoxy resin unique to Fuji Electric. The F resin coil does not cause peeling of the insulation layer at the outlet portion of the iron core due to repeated expansion and contraction of the coil, always a problem with a large-capacity turbine generator having a long coil. It well meets the expansion and contraction of the conductor, providing satisfactory breakdown voltage, insulation resistance, and tan$\delta$ as well as strength against mechanical shock due to short-circuit. The F resin coil is manufactured through continuous taping of mica tape processed with epoxy resin on the slot portion and coil end portion, with the low-viscosity liquid type epoxy resin vacuum-impregnated. Since the viscosity is low during impregnation, sufficient resin penetrates into the small clearance of the coil insulation. The coil with resin vacuum-impregnated is heated for hardening. Since the F resin has a well-selected composition of epoxy resin, components of herdener and mixing ratio, the contraction, when it occurs, is minimized to a mere fraction of that of the polyester. Perfect penetration at the time of vacuum impregnation, minimum contraction at the time of heating and no peeling are combined to obtain a void-free insulation layer. The thermal expansion coeffiicient of the F resin insulation layer is nearly $16.5 \times 10^{-6}$ that of copper, and the expansion difference between the two is small. There is almost no insulation damage during mutual motion between the conductor and insulation layer at the time of repeated thermal cycling. The breakdown voltage of the F resin is 35 kv/mm, and does not lower in a temperature range from the normal value to 130°C.

The heat and corona resistivity are, as well as the characteristics of the epoxy resin, excellent. Concerning use of the F resin coil, sufficient study has been made in various phases, with a long-term thermal cycling test conducted on actual coils, for testing the mechanical deterioration of the coil due to expansion and contraction.

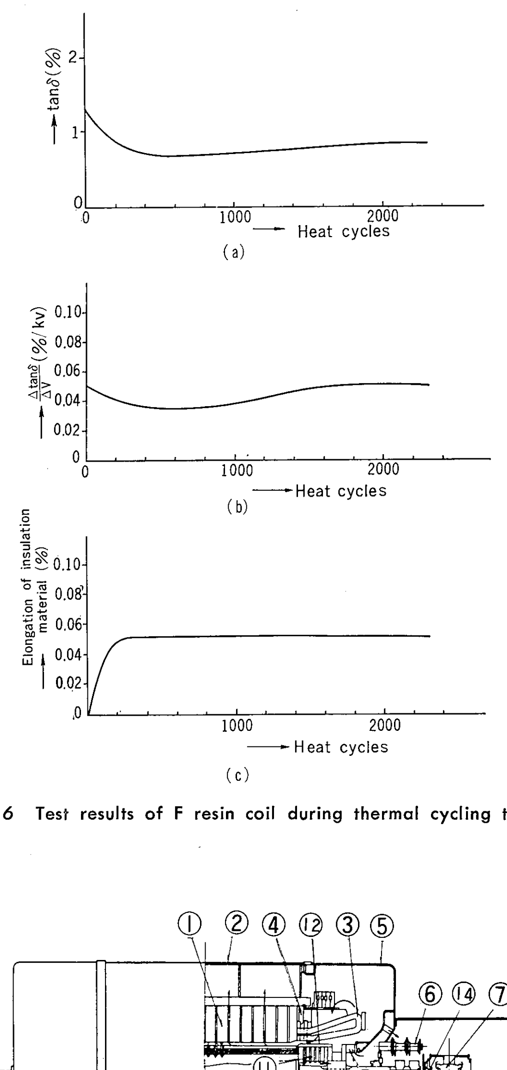
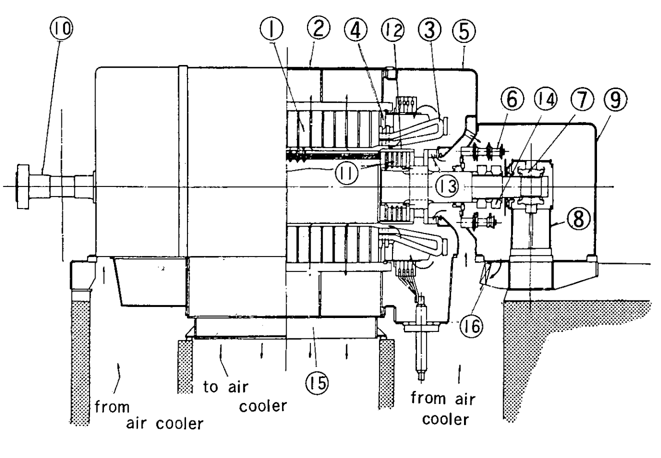



*Fig. 6* Test results of F resin coil during thermal cycling test




① Stator core
② Stator frame
③ Stator winding
④ Press ring
⑤ Fan shield
⑥ Brush holder
⑦ Bearing bushing
⑧ Bearing stand
⑨ Slip ring cover
⑩ Rotor shaft
⑪ Rotor winding
⑫ Retaining ring
⑬ Fan
⑭ Slip ring
⑮ Exhaust duct
⑯ Filter

*Fig. 7* Cross-sectional drawing of generator (single flow type)

Shown in *Fig. 6* are the results of the recent thermal cycling test of 2000 times of the recent F resin coil. The test was conducted, heating for a 90-minute period in the regular iron core from the room temperature to the room temperature+60°C, and returning it to the room temperature in 60 minutes. The voltage applied in this test was constantly maintained at $\sqrt{3}$ times that of normal operating conditions. The F resin coil showed in this severe test almost no change with respect to tanδ and the tanδ-voltage characteristics, and hardly any internal voids developed. The permanent strain of the insulation balanced at around 200 cycles, an extremely low value, so that there is no danger of peeling in the vicinity of the outlet of the iron core. The F resin also has sufficient strength to resist mechanical shock caused by short-circuit of the generator. Some insulation weakens when cold although it is strong when hot. As for the F resin, short circuit was effected at a low temperature below zero and no change was noted in the insulation characteristics.

## V. OUTLINE OF CONSTRUCTION

### 1. Cooling Gas Circuit

The cooling method commonly used for air-cooled generators is closed circulation, self-ventilating, the air cooler often being installed on the generator pit. There are two cooling methods for the stator, single flow and double flow. The latter is used for generator having a long iron core. *Fig. 7* is a construction drawing of the single flow type.

The cooling gas circuit of the hydrogen-cooled generator can be divided roughly into two types, one with indirect cooling of the stator, with two or four gas coolers provided in the axial direction inside the stator frame. A fan for self-ventilation is provided at each side of the rotor. The peripheral ribs of the stator frame axially divide the space between the back of the core assembly and the frame jacket into cold and hot gas chambers.

The gas whose pressure has been increased by means of the fan flows through three passages shown in *Fig. 8*, thus cooling the entire machine. The first passage leads into the air gap from both sides of the machine, passes through the ventilating ducts corresponding to the hot chamber of the stator, emerges at the back of the stator core, reaching the gas cooler. The second passage leads into the cool chamber of the stator through the sta tor coil end portions, passes through the iron core ducts, emerging at the air gap section. It then changes direction and flows through the ducts corresponding to the following hot chamber, arriving at the gas cooler at the back of the stator core. The third passage leads through the cooling duct of the rotor under the retaining ring of the rotor, emerging at the air

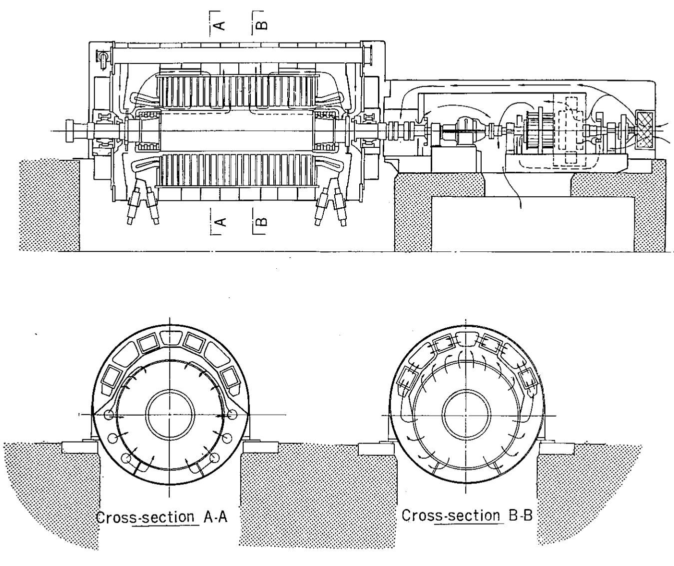



*Fig. 8* Gas circuit of stator indirectly-cooled generator

gap at the center portion. It further leads through the stator hot chamber and arrives at the gas cooler at the back of the stator core.

A hollow conductor is used for direct cooling, while an oval duct in the radial direction at the conductor is used for radial cooling. The gas which has passed through the gas cooler and has been cooled is collected and returned to the fan suction side, where it is fur- ther pressurized by means of the fan.

This system employs a double flow method for the stator with the gas cooler arranged in the axial direction, so that gas circulates uniformly in the axial direction, thus enabling prevention particularly of the local temperature rise of the coil, which tends to occur with a machines having a long iron core. This therefore prevents deterioration of the insulation and other troubles due to heat expansion.

Since the duct cross-sectional area is small, gas circulation for the rotor requires considerable pressure. However, this can be fully achieved by the fan effect of the rotor itself. The exciter and the slip ring are located outside the bearing of the main unit, and are cooled with air. As seen from the figure, the air which flows through the filter located at the end section of the exciter cover is circulated by means of the air circulating fan provided at the exciter and the slip ring, thus being exhausted to the outside of the cover.

The second type is used for direct cooling of the stator, the fan for self-circulation is a multi-stage type at the turbine side, while the two gas coolrs are arranged vertically at the turbine side. Gas whose pressure has been increased by the blower flows through the gas cooler and is cooled, before flowing through the three passages shown in *Fig. 9*, thus cooling the machine.

The first passage leads underneath the rotor coil retaining ring at the turbine side, through the rotor cooling duct, emerges at the air gap at the center portion and returns to the blower suction side. The second passage leads into the stator coil end chamber at the exciter side by means of the air guide pipe installed at the stator frame, where it is divided into three branches, one leading through the stator coil cooling duct, arriving at the stator coil end chamber at the turbine side and reaching the blower suction side, another leading through the rotor cooling duct from under the rotor coil retaining ring at the exciter machine side, emerging at the air gap at the center portion and another leading through the duct in the stator end-connection and the bushing, emerging at the stator coil end chamber at the turbine side by means of air guide pipe installed on the stator frame, before reaching the blower suction side. The third passage leads through the stator iron core duct from the air guide pipe around the stator frame, emerging at the air gap and reaching the blower suction section.

As for the cooling of the stator coil, there is inevitably some difference in the temperature rise along the coil, because cooling gas flows through the coil from one side to another. This may be compensated by leading a relatively cool gas, which has flowed through the cooling duct of the bushing, to the stator coil end at the turbine side.

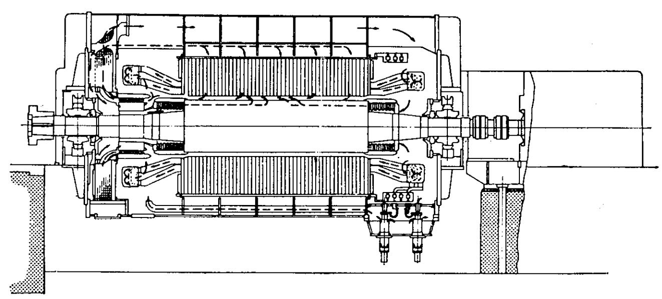


*Fig. 9* Gas circuit of stator directly-cooled generator

## 2. Stator

The stator frame of the air-cooled generator is of welded sheet steel construction, with the skin stress construction adopted at various sections, thereby curtailing overall weight and increasing rigidity. Shown in *Fig. 10* is the stator of the air-cooled generator.

The stator frame of the hydrogen-cooled generator is of explosion-proof and welded sheet steel construction. The welding of the portions where hydrogen-tightness is required has been closely inspected for elimination of any defects.

Furthermore, a hydraulic test at pressure of 10 kg/cm$^2$ gauge is conducted to prevent occurrence of gas explosions. A number of the peripheral ribs joined together by axial struts are arranged with consideration of resistance to vibration, these also serving as partition plates for air circulation through the stator. Arranged axially on top of the stator frame are two or four gas coolers for cooling the hydrogen gas which circulates inside the machine.

The iron core is supported by means of the dovetail keys installed at the inner circum ference of the stator frame. When the core plates are laminated, they are heated and of compressed repeatedly to form a uniform rigid stator core.

As for the stator coil, the number of turns is determined according to the capacity and rated voltage of the generator. In most cases, however, one turn coil is used. In this case, bar coils are used whose conductors are Roebel transposed, with a special coil end connection method employed for preventing unbalance of the induced voltage between conductors due to magnetic flux leakage of the coil end. The coil end is firmly fixed with consideration made for it to be sufficiently resistive to high electromagnetic force, such as upon short-circuit. *Fig. 11* shows the stator of the hydrogen-cooled generator. Shown in *Fig. 12* is a 175 Mw turbine generator cross-sectional view.

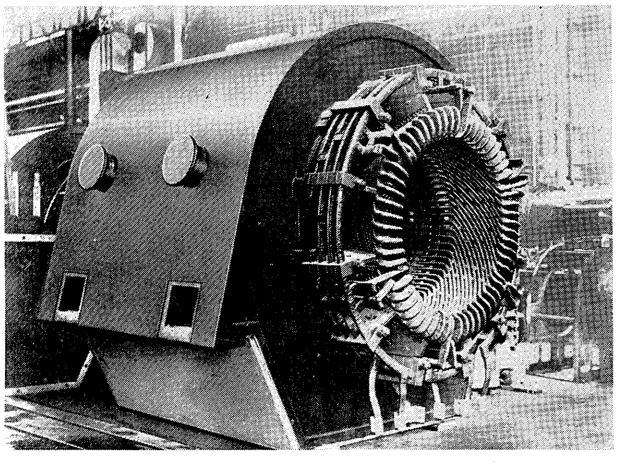


*Fig. 10* Stator

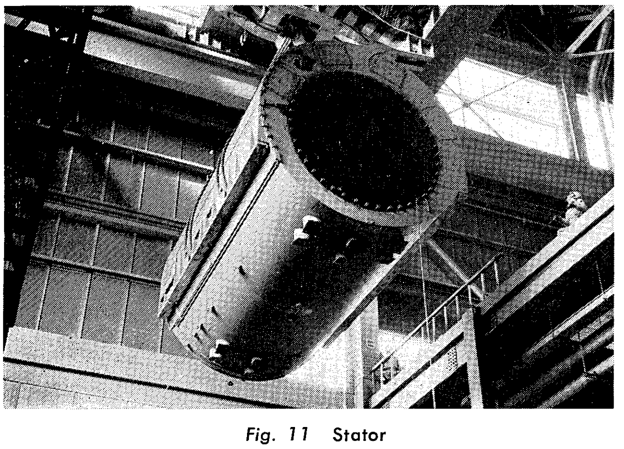


*Fig. 11* Stator

## 3. Rotor

The rotor shaft is of single-piece and is made of special forged steel. Gas is removed from the material by means of the vacuum casting method. With proper forging and heat treatment, the shifting temperature is made lower to minimize the residual stress, so that the safety of the machine has been even further improved.

For the conductor, except for that for a small-type machine having a low peripheral speed, silver-containing copper of high creep strength is used. Otherwise, the conductor creeps because of the heat stress, thus often causing the coil deformation and layer short circuiting. The end portion being securely fixed by means of spacers, the coil is held in the slot by a wedge which is made of special material. The retaining ring at the coil end should have high mechanical strength as in the case of the rotor shaft, and it is also necessary that it be non-magnetic for curtailment of stray load loss, so that high-strength alloy, non-magnetic steel is used.

Generally, the turbine generator rotor shaft is designed as a flexible shaft and has a critical speed that is lower than the operating speed. The critical speed is precisely calculated after experimentally confirming the spring constant of the bracket. On the other hand, in the stage of the manufacture, since the flexible shaft, multi-surface balance is obtained

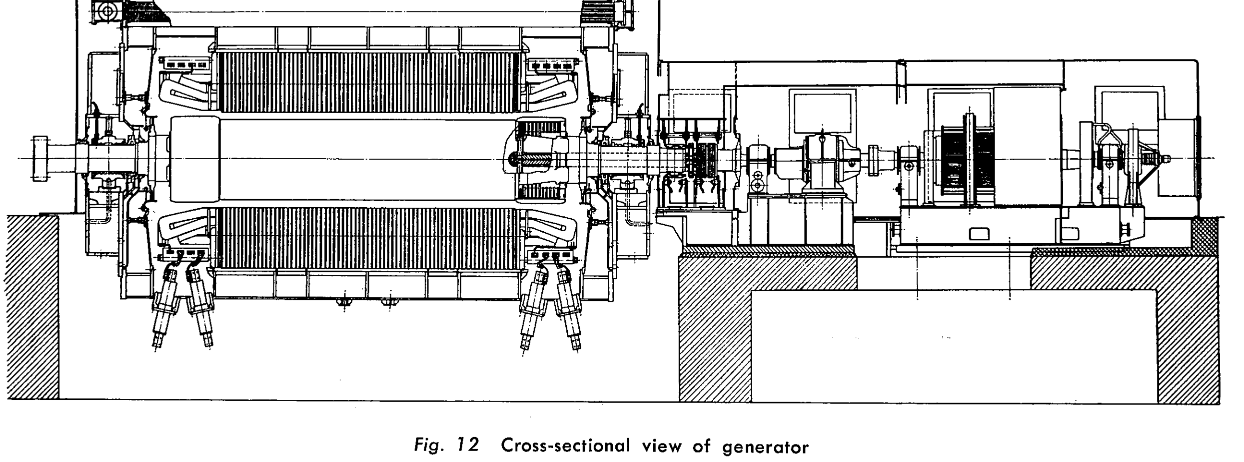


*Fig. 12* Cross-sectional view of generator

(a) Single-unit primary critical speed
Generator: 1443 rpm
Low-pressure turbine: 4052 rpm
Medium-pressure turbine: 2047 rpm
High-pressure turbine: 4098rpm

(b) Critical speed of direct-coupled turbine set and amplitude characteristic

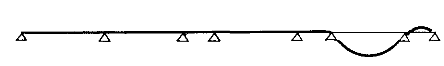
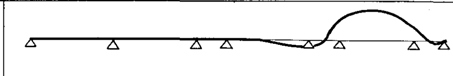
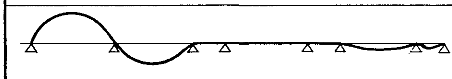
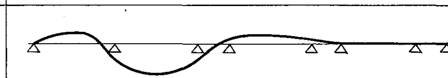
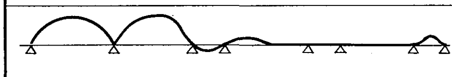
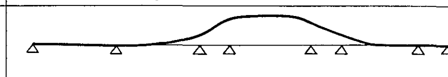
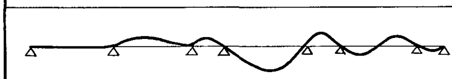
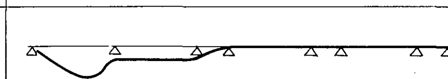
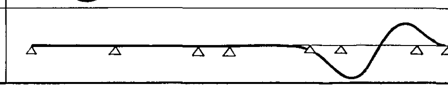
| Case when oil film influence is not considered | | Case when only the elasticity of oil film is considered | | Case when oil film elasticity and attenuation are considered |
|---|---|---|---|---|
| Amplitude characteristic | Critical speed rpm | Amplitude characteristic | Critical speed rpm | Critical speed rpm |
|  | 1895 |  | 1387 | 1550 |
|  | 4051 |  | 1879 | 2150 |
|  | 4275 |  | 2056 | 2300 |
|  | 4497 |  | 2428 | 2600 |
| | |  | 3498 | 3650 |

*Fig. 13* An example of analysis of rotor vibrational characteristics

through heating the coil, repeated overspeed rotation is performed for stabilizing the insulation of the rotor winding.

*Fig. 13* shows an example of calculation of the critical speed of the generator and amplitude characteristics analysis results of the generator directly connected to the turbine. Generally, the critical speed increases with direct coupling of the shafts. The elasticity of the oil film tends to lower critical speed, but damping effect of the oil film tends to increase it. These effects become greater for critical speed of higher order. With these effects remarkable change in the amplitude characteristics is observed. *Fig. 14* shows the completed rotor.

## 4. Bearing

The bearing bushing has a white alloy cast into the base metal. It is lubricated and cooled by a forced oil circulation system. The retaining surface between the bracket and the bearing bushing is made spherical and self-aligning.

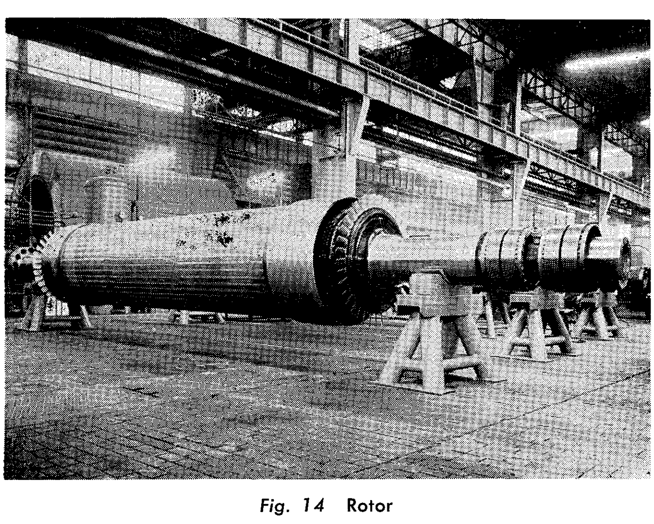


*Fig. 14* Rotor

What matters in the case of a large capacity turbine generator is the phenomenon referred to as oil whirl, that is, self-excited vibration of the rotor by the oil film and the effect caused by the previously-mentioned elasticity and attenuation coefficient of the oil film upon the critical speed. The inside diameter shape of the bearing can be divided into two types, one having true roundness with diameter slightly larger than the journal diameter, the other the diameter much greater than the former one having the shape shown in *Fig. 15* (b). The former is called a circular bearing, the latter a 2-arc bearing.

Each has its own advantages and disadvantages. The round bearing is sensitive to the oil whirl, there being great danger of oil whirl if the primary critical speed is less than half the rated speed. The 2-arc bearing is designed to prevent this oil whirl, with the clearance ratio made large and with the oil film formed on the upper and lower side of bearing, thus best preventing vibration of the shaft. However, the elasticity of the oil film is slightly lower than the one with the round bearing. The effect of the oil film if exactly calculated, may be taken into consideration in the design, so that we use the 2-arc bearing or the similar "Tragespiegel" bearing, in order to avoid a danger of oil whirl. *Fig. 15* is an explanatory diagram of the bearing shape of this type.

Further provided with the bearing is a high pressure oil starting device for alleviating the friction force upon starting, by which feed oil at a pressure of approximately 100 $kg/cm^2$ is fed in order to form an oil film between the bearing surface and the journal.

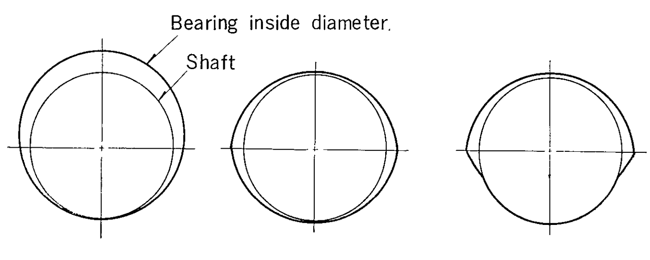



*Fig. 15* **Bearing shape**

## 5. Gas Control Device, Shaft Seal Device and Sealing Oil Supply Device

Attached to the hydrogen-cooled generator are the hydrogen gas controller, shaft seal device and sealing oil supply device. Given below are the outlines of these units.

(1) Hydrogen gas control device

This device charges hydrogen gas in the generator, detects and makes up for gas purity deterioration and leakage and protects the equipment from the danger of explosion during charging and discharging the hydrogen. Prior to charging the hydrogen inside, the generator is charged with carbon dioxide gas from the diffusion pipe at thebottom of the generator through the carburetor from the carbon dioxide bottles. A resistance-wire type gas purity meter used to measure the purity of the exhaust gas. When the purity of the carbon dioxide gas has exceeded a certain value, the hydrogen gas is charged from the diffusion pipe at the top of the generator through the pressure reducing valve from the bottles. After completing mersurement of the purity of the exhaust gas by means of the purity meter and confirmation of the completion of the hydrogen substitution, the pressure inside the generator is increased to the required value by setting the pressure reducing valve. Next, the leakage of the hydrogen is automatically compensated for by an additional supply, thus preventing lowering of the pressure.

A gas dryer which uses desiccant is provided for the control of moisture inside the equipment. This desiccant is easily restored by the heater furnised with the equipment. Alarm deviecs are provided to warn of impurity or pressure reduction of the gas, as will as increase of gas temperature, with all the meters and valves assembled into one control panel.

(2) Shaft seal device and shaft seal oil supply device.

Provided with each bracket is a shaft seal device for prevention of hydrogen gas inside the generator from leaking out of the machine along the shaft. *Fig. 16* is a diagram of its construction.

In the shaft seal device, there is a ring, having a narrow clearance, placed between sealing ring holder and the shaft; into this narrow clearance oil is fed under a higher pressure than the inside,

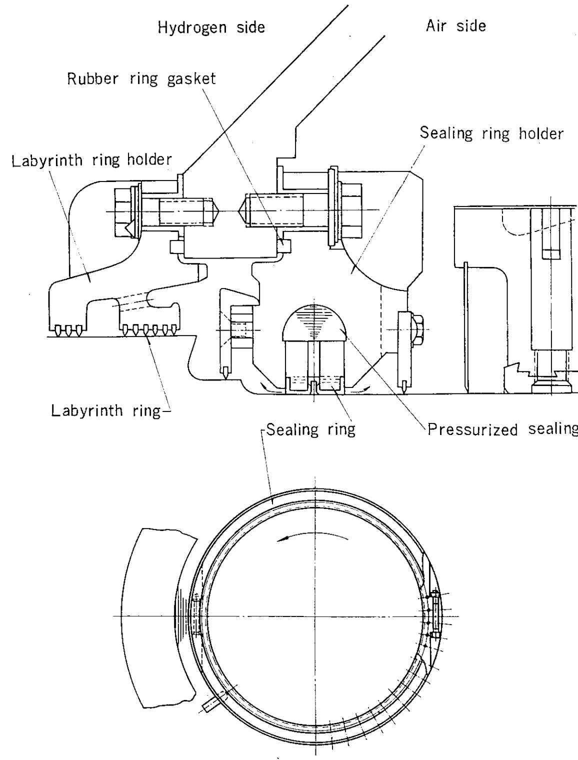



*Fig. 16* **Shaft sealing**

thus breaking the $H_2$ leakage path between the air side and the hydrogen side. If the ring is pressed to the air side by the hydrogen pressure inside, and the free movement of the ring is restricted, the ring and shaft may be locally heated, resulting in thermal damage of the ring. In order to prevent this, pressurized oil is supplied to the air side, thus compensating for the pressure difference between the inside and the outside of the machine.

For the shaft seal device to have a enough sealing effect, it is necessary to minimize clearance from the shaft. Therefore, it is necessary that the ring be constructed so that even deformation be effected by the heat, thus not resulting the thermal damage. It is important that the construction be made to prevent thermal damage. To this end, a steel-made ring with white metal cast inside is emplyed.

The shaft seal oil is supplied from the shaft seal oil supply device installed outside the generator, while the oil pressure is adjusted to be always at a pressure 1 $kg/cm^2$ higher than the pressure inside by means of the diaphram type differential pressure valve. In order to prevent even momentary interruption of the supply of shaft seal oil, a spare shaft seal oil pump unit is provided. Also the shaft seal oil system is connected to the turbine control oil system by a differential pressure valve other than the one for nomal use. Should both the normal and stand-by shaft seal oil pump fail to function properly, the required oil is automatically supplied from the

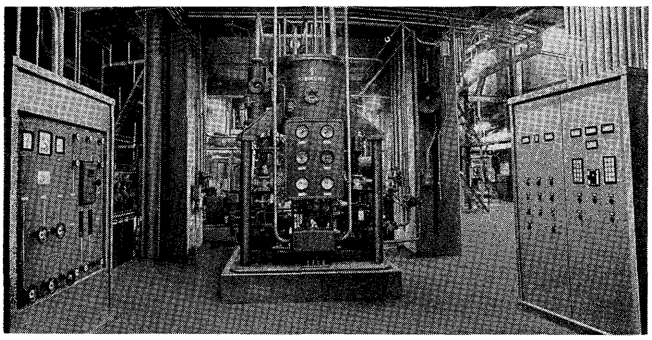


*Fig. 17* Gas controller (left), shaft seal oil supply device (center) and alarm device (right)

turbine control oil system to the shaft seal section. Furthermore, if there is a malfunction of the differential pressure valve, oil can be supplied by manual means. In order to prevent trouble, alarm devices are provided regarding the oil level of various tanks located in the shaft seal oil supply system, oil temperature, oil pressure and vacuum. These alarm devices and all the valves of the various tanks are concentrated underthe floor of the generator together with the previously mentioned hydrogen gas controller for easy control. *Fig. 17* shows the arrangement of these units.

## VI. EXCITER SYSTEM

What is most important in the exciting power supply is reliability. When, for instance, power is supplied directly from the system and short circuiting around the terminal occurs, the case arises where the exciting power supply will be lost and both the recovery voltage and stability lowered. This case requires the installation of an independent spare power supply, separate from the system. The following is a classification of the excitation according to the supply method of the exciter power:

The exciter which is directly connected to the generator is supported by the energy of inertia of the generator and the turbine at the system disturbance, so that the reliability is sufficient. The speed response characteristics are inferior to those of the type with compound characteristics, but it has the advantages of easier adjustment and high economy.

Method (1) is sufficient for small-capacity equipment. However, if the output of the exciter is more than 500 kw, the direct connection type is naturally limited because of the manufacturing limit of the dc machine, and therefore method (2) combining the speed reduction device should be used. The reduction is carried out usually from high speed of 3000 rpm or 3600 rpm to low speed of 1000 or 750 rpm. When the exciting power has increased further, the dc machine having a commutator cannot be employed for reasons of economy, and direct connection of the ac exciter is required.

Even for a small-capacity machine, this type can be used in a chemical plant when there is active gas because the commutator may be omited. This method is often used because of this advantage. Not only the commutator but also the slip ring may be omitted in the brushless exciting system of (4). The slip rings and the brushes used at a high speed with heavy current always bring forth problems of maintenance, and the number of the brushes used in this condition is great. The brushless system has many advantages in both operation and maintenance. Regarding this system, Fuji Electric has been performing much research and has an actual record of manufacturing a brushless 22.5 kva turbine generator. The separately installed exciter MG must have a spare power source besides the main system. In the case of the system trouble, the MG has to be transfered to the spare system and keep the required power supply. However, in the case of method (9), there is a compound winding effect and the exciting

- Exciter directly connected to generator
  - Dc exciter
    - Direct coupling (1)
    - Reduction gear coupling (2)
  - Ac exciter plus rectifier
    - Provided with slip ring (3)
    - Rotary rectifier (4) (without brushes)
- Exciter indirectly connected to generator
  - By means of separately installed MG
    - Without booster (5)
    - With booster (6)
  - To be supplied from the system
    - Through the transformer without compound winding effect
      - By means of mercury rectifier (7)
      - Others (8)
    - Through transformer and current transformer (with compound winding effect) (9)

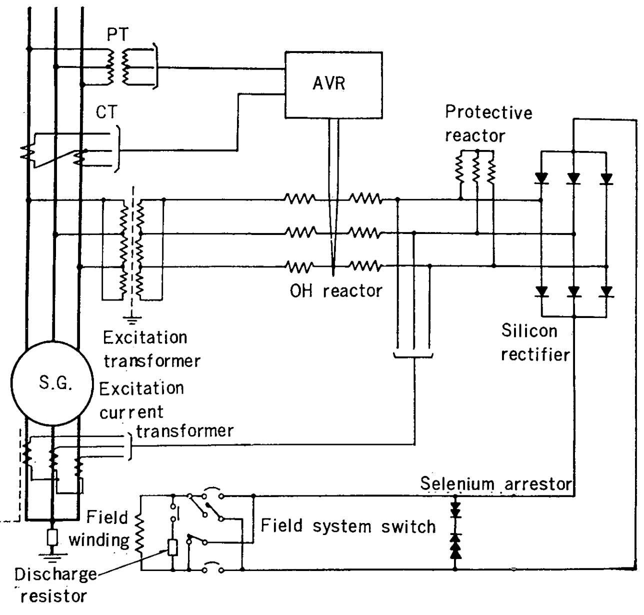



*Fig. 18* Connection diagram of OH type exciting system

power is maintained through the current transformer effect, so that even single unit operation is fully reliable. The purpose of indirect connection is to drive the intermediate-speed dc exciter without a reduction gear to minimize the shaft size because of the existing limit, and also particularly to carry out the exciting control of the high speed response. Since, however, the reduction gear can be operated with sufficient reliability, and the ac exciter has been popularized, there is scarcely any chance involved in using methods (5) and (6), and either method (7) or (9) is far superior for meeting the requirements of size restriction and high speed response in exciting control.

Regarding particularly the self excited compound winding excitation (9), Fuji Electric has a unique OH type exciting system, using it with the small and medium capacity generator for excellent results. *Fig. 18* shows the connection diagram of the system.

Each system of (1) through (9) above has been fully studied and is ready to meet the requirements of customers. Depending upon the character and output of the power station, the resultant control conditions naturally vary, and the most suitable exciting system should be selected to best suit the requirements.

## VII. STANDARD AIR-COOLED TURBINE GENERATOR

Fuji Electric has a standard series of air-cooled turbine generators. The standard turbine generators come in two series, one for 50 cps use and another for 60 cps use. The output ranges from 2.5 to 31.25 Mva for both 50 and 60 cps, with 12 standard outputs provided in this range. For machinery with an output of more than 12.5 Mva, the relevant standard output is set forth in the IEC standards concerned with the 50 cps turbine generator. The standard output of this new system conforms to the IEC standard.

The standard voltage of the generator is 6.6 kv for 12.5 Mva or less. When this value is exceeded, the standard voltage is 11 kv. When a rated voltage of 11 kv with an output of less than 12.5 Mva is required, there is no difficulty in manufacturing to meet the requirements, though there may arise some alterations in application of the frame number. The rated power factor of the generator has a standard 0.8 lagging in accordance with the IEC standard. If a value other than 0.8 is required for the generator power factor, the frame number is changed in application.

The short-circuit ratio of the generator is set at more than 0.47 and less than 0.63 in the IEC standard, then 0.6 is adopted in this standard system.

Given in the following are the standard specifications of this new system turbine generator:

(1) Type: Horizontal shaft, cylindrical rotor type and totally enclosed type provided with air cooler

(2) Air circulation system: Self-ventilating type

(3) Ratings
- Rating: Continuous
- Output: 2.5 Mva to 31.25 Mva
- Terminal voltage: 6.6 kv at less than 12.5 Mva, 11 kv at over 12.5 Mva
- Number of phases: 3
- Frequency: 50 or 60 cps
- Speed: 3000 or 3600 rpm
- Power factor: 0.8 lagging

(4) Insulation: Class B

(5) Temperature rise limit: 80°C for stator coil (embedded thermometer method)
90°C for rotor coil (resistance method)

(6) Stator connection: Star connection (neutral side terminal drawn out)

(7) Cooling method: Totally enclosed, internal cooling type by means of air cooler

(8) Exciting system: Separately installed static type exciter device, using silicon rectifier (OH type)

(9) Cooling water temperature: 32°C

Given below are the major specifications of the standard air-cooled turbine generators:

(1) Short-circuit ratio: Approx. 0.6

(2) Voltage regulation: Approx. 40%, when power factor is 0.8
Approx. 30%, when power factor is 1.0

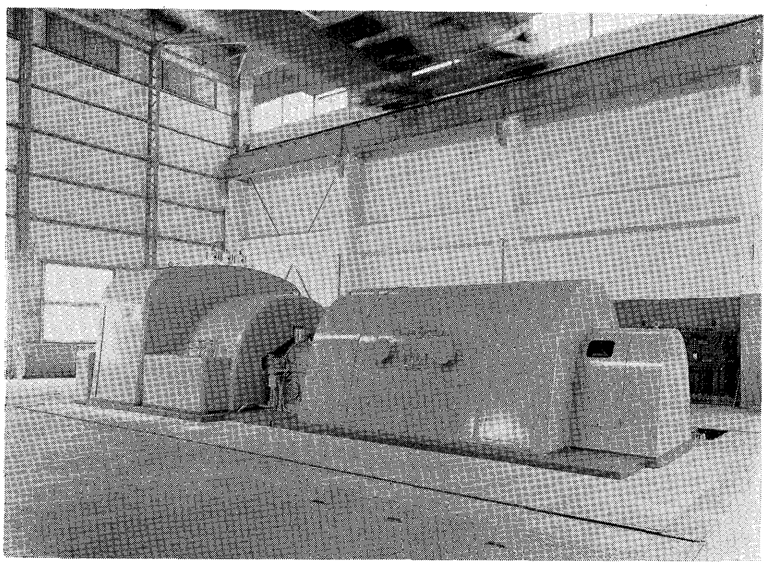


*Fig. 19* Outside view of standard air-cooled turbine generator

(3) Impedance: Xd approx. 167%
Xd′ approx. 16%
Xd″ approx. 11%

(4) Deviation factor of the voltage wave: Less than 5%

(5) Permissible unbalanced load Negative sequence current: Less than 12.5%

Shown in *Fig. 19* is the outside view of the standard air cooled turbine generator.

## VIII. CONCLUSION

This paper contains a general explanation of the Fuji Electric turbine generator. Fuji Electric will continue its efforts to contribute to future progress and development in rationalization of the private steam power supply as well as to enlarging the capacity of the commercial steam power supply as the demand for energy increases.