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# ADVANCED TECHNOLOGY OF TURBINE GENERATOR


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## 1 FOREWORD

With the extension settling of power demand in Japan in recent years, not only the pursuit of larger capacity generation facilities, but also securing their economy and reliability are becoming increasingly important topics.

The capacity of the turbine generator has been increased and the machine has been made smaller by technological advances based mainly on improvement of the cooling system. However, since this increases the machine internal loss density, it causes a lowering in reliability.

High speed reclosing, DDS operation, response excitation starting, leading zone operation, harmonic unbalance operation, etc. are steadily increasing the machine stress and together with the increase of the loss density previously mentioned, reliability cannot be secured only by extending existing technology.

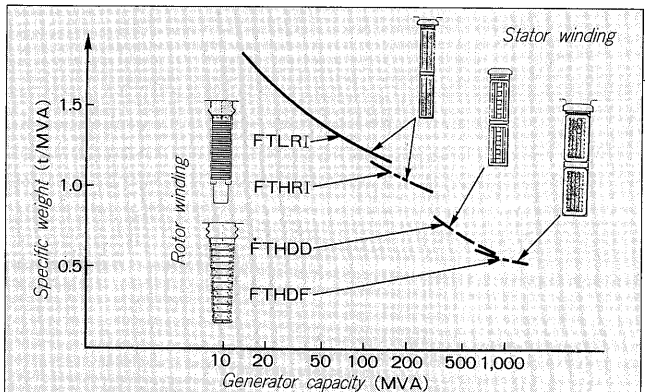
To overcome these causes of a lowering of reliability and to perform reliable and safe operation, studies are added from the standpoints of both theory and experimentation and reliability improvement measures are taken from the standpoint of manufacture and research and development which monitors and diagnoses the health of the machinery is performed.

Recent turbine generator technological advances of the hydrogen direct cooled turbine generator suitable for the 300 MVA to 700 MVA class thermal power generators which will become the mainstream of the power facilities of the future, are described here.

## 2 GENERATOR SERIES

Generator capacity is determined not only by the machine dimensions, but also by the kind of the cooling system. The tremendous increase of generator capacity recently was reached by technological advances based mainly on improvement of the cooling system. The cooling medium used has changed from air to hydrogen gas to water and technology has advanced from the indirect cooling method, which cools the winding through the insulation, to the direct coolig method by which the cooling medium contacts the winding directly. These have increased the usage rate of the machine and lowered the specific weight (t/MVA) of the two-pole turbine generator shown in *Fig. 1* considerably. Two-pole turbine generators are grouped by cooling system into the following three series.

*Fig. 1* Specific weight of two-pole turbine generator




| Series \ Cooling system | Cooling medium | Rotor winding | Stator winding |
|---|---|---|---|
| FTLRI | Air (L) | Radial direction direct cooling (R) | Indirect cooling (I) |
| FTHRI | Hydrogen (H) | Radial direction direct cooling (R) | Indirect cooling (I) |
| FTHDD | Hydrogen (H) | Direct cooling (D) | Direct cooling (D) |
| FTHDF | Hydrogen (H) | Direct cooling (D) | —— |
| | Water (F) | —— | Direct cooling (F) |

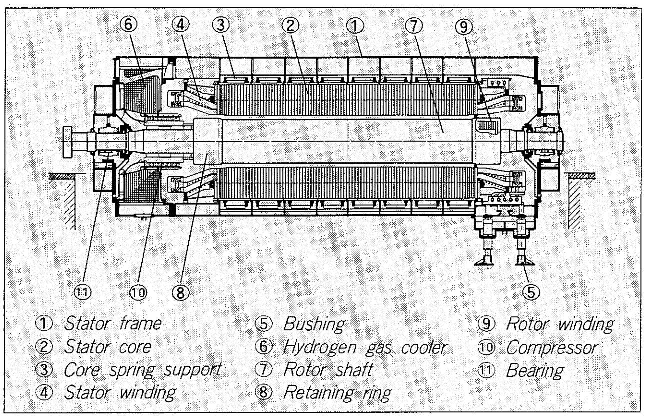
### 2.1 Air cooled series (FTLRI)

This series is mainly manufactured for industrial use and can be manufactured with a capacity of up to 170MVA. Fuji Electric's manufacturing record is currently 105.8MVA.

### 2.2 Hydrogen cooled series (FTHRI, FTHDD)

These series are subdivided into two series by generator capacity. Machines having a capacity of 300MVA or less are made the stator winding indirect cooled series (FTHRI) and machines having a capacity exceeding this are made the stator winding direct cooled series (FTHDD). The basic construction of the FTHRI series is the same as that of the air cooled series, except for the construction related to

*Fig. 2* Sectional view of turbine generator (FTHDD)




the hydrogen gas.

Machines with a capacity of up to 850MVA can be manufactured in the FTHDD series. A 670MVA unit is now being designed. A sectional view of the FTHDD series is shown in *Fig. 2*. To reduce vibration transmission and noise, the stator core is fastened to the stator frame through plate springs. The hydrogen gas is circulated inside the stator and rotor by a compressor at the turbine side. A brushless type exciting system is standard.

### 2.3 Water cooled series (FTDF)

Most of the applicable capacities overlap the FTHDD series. Machines having a capacity of 850MVA or less are used when there are shipping restrictions, customer specifications, etc.

## 3 RELIABILITY IMPROVEMENT TECHNOLOGY

### 3.1 Daily start and stop operation.

Frequent start and stop subjects each part of a generator to repeated stress by centrifugal force or temperature changes and their life is expended. The West German Electric Industry Association (VDEW) evaluates the equivalent operating time, which is the generator routine inspection interval criteria, with the following equation:

Equivalent operating time $T_a = T_B + 20 \cdot N$ (h)

$T_B$: Real operating time (h), $N$: Number of startings. That is, when a generator is started once a day for at least one year, the effect of starting and stopping on the machine is evaluated as the same as if it was operated continuously for one year. How much affect the start and stop operations have on the machine can be found by this. VDEW recommends that inspection accompanying removal of the rotor should be performed for the first time at $T_a$ = 10,000 to 20,000h after the start of operation and every $T_a$ = 40,000 to 60,000h thereafter. IEC34-3 (turbine generator) specifies that a generator be designed to withstand starting at least 3,000 times.

Fuji Electric considers the life of parts which can crack and designs them to withstand starting at least 10,000 times. The reliability improvement measures for main rotating parts are described below.

#### 3.1.1 Rotor shaft

At the shaft body, wedges are inserted into groove in the shaft teeth to maintain the centrifugal force of the rotor winding, etc. Retaining ring which support the centrifugal force of the winding end are also shrink fit to the ends of the shaft. Therefore, since the compression force created by shrinkage of the ring acts on the retaining ring shrink fitting part of shaft at standstill and the centrifugal force of the winding and wedges is added during operation, the stress amplitude of the shaft end portion where stresses are concentrated is approximately 1.7 times then that at the shaft center portion so the conditions are the most severe.

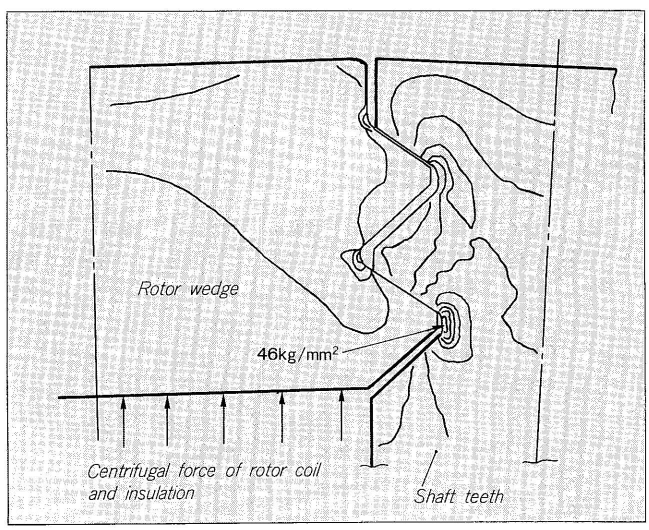
There is also the possiblibity of minute defects which cannot be detected by ultrasonic inspection existing in the shaft material, which is a large forging. As shown by fracture mechanics, when a load is applied repeatedly, defects grow and when they reach the critical size, a brittle fracture occurs at the shaft. Since a shaft center bore for rotor lead is provided at the end of the shaft body, the stress amplitude near the shaft center bore becomes larger and the number of allowable cycles of start and stop is reduced to approximately 1/10 that of the center of the shaft where there is no center bore. The main reliability improvement measures are:

(1) Improvement of calculation accuracy using the finite element method, etc.—Wedge groove and wedge stress distribution is shown in *Fig. 3* as an example.
(2) Verification of calculation accuracy by measurement of the deformation of an actual size model.
(3) Improvement of wedge groove machining accuracy by using a forming tool.
(4) Use of NiCrMoV steel with high fracture toughness.

#### 3.1.2 Rotor wedge

At unbalance load and line faults, AC current flows in the wedge that supports the centrifugal force of the rotor winding and causes the wedge temperature to rise. Therefore, a wedge material that is strong and has a high conduc-

*Fig. 3* Stress distribution of rotor shaft teeth



tivity and a small drop of strength at high temperatures is selected. A two-stage teeth wedge (*Fig. 3*) is used with the FTHDD series. The stress amplitude at the bottom tooth root is 20% larger than the top. The radius (*R*) of the tooth root is 2 mm as standard, but since the stress amplitude is increased about 20% when this is 1 mm, management of the *R* dimension is important. The main reliability improvement measure are:

(1) Confirmation of static and fatigue strength by actual size model.
    If was confirmed that cracks were not produced at 10,000 cycles even when supported by only the bottom teeth of the two-stage teeth of the wedge.
(2) Improvement of wedge machining accuracy by using a forming tool.
(3) Use of high strength and high conductivity beryllium copper.

### 3.1.3 Rotor winding end (coil end) pole connection coil

A pole is formed at the coil end by inter-connecting the coils with silver solder. Pole connection coils are also provided to connect two poles. Since the retaining ring is enlarged about 1 mm by the centrifugal force of the coil end during operation, the coil end also moves in the radial direction. When constraint by centrifugal force is large, the pole connection coils are deformed equivalent to the movement of the retaining ring. Repeated start and stop may cause the deformation of the connection coils to increase and not only damage the coils, but also develop into a short circuit. The main reliability improvement measures are:

(1) Use of a bottom pole connection coil

Centrifugal force is reduced by connecting the pole connection material at the innermost diameter side.

(2) Monotype coil and unannealing forming.

The pole connection coil is the same material (shape and material) as the rotor coil and made, with no splices.

Strength is secured by forming the coil without annealing.

(3) Temperature reduction by direct gas cooling.

The temperature of connection coil is reduced by flowing hydrogen gas inside the pole connection coil same as the rotor coil.

(4) Use of teflon coated insulation plate.

The friction coefficient is lowered by using insulation coated with teflon at contact side of the coil end.

## 3.2 Unbalance load operation.

When generator has a balanced load, only positive phase current flows. The armature reaction generated by this current produces a DC magnetic flux on the rotor. However, when the generator current includes harmonic components or is unbalanced due to a short circuitor system trouble, the generator includes a negative phase sequence current and a direct current, besides the positive phase current. Since the magnetic fields created by these currents become an alternative magnetic field to the rotor, an AC current is induced in the rotor surface. Since the rotor is designed for a DC magnetic field, naturally there is an allowable limit for the current generated by the alternative magnetic field. The magnitude of the rotor current generated by the negative phase sequence current is limited by overheating of the retaining ring, wedges, damper bar, and rotor core surface.

The negative phase sequence currents are consited of unbalanced load and harmonic current. The two phase short circuit at the generator terminal is the most severe case of a short term negative phase load. The main reliability improvement measures are:

(1) Use of full length damper bar

A short length damper bar is used with the FTHRI series and a full length damper bar is used with the FTHDD series. The negative phase sequence loss of the rotor of the full length damper bar construction is approximately 40% less than that of the short length damper bar construction.

(2) Securing of electrical contact between retaining ring and damper bars.

Since conduction between the retaining ring and rotor wedges and damper bar is performed through the contact surfaces, the surface pressure at these contact surfaces is made 200 kg/cm$^2$ or more. A special additional pressure piece is provided at the damper bar slot for this purpose. The contact resistance is also reduced by silver coating and silver plating the contact surfaces.

(3) Use of material having a high heatproof strength

The heatproof strength of the main materials of the rotor is shown in *Table 1*.

## 3.3 Leading zone operation

The air gap flux of a generator is composed of the flux generated by the field current and the flux generated by the armature current and is almost proportional to the terminal voltage. However, since the magnetomotive force and magnetic path at the core end are different from the air gap, the core end leakage flux differs with load, even if the terminal voltage is constant, and becomes the largest value at leading zone operation.

At leading zone operation, the stator winding end flux has the same phase relative to the leakage component of the air gap main flux. Moreover, since the core end flux enters at a right angle to the silicon steel plate, a large eddy current loss is generated at the core end. For the reason above, core end overheating is a problem at leading zone operation.

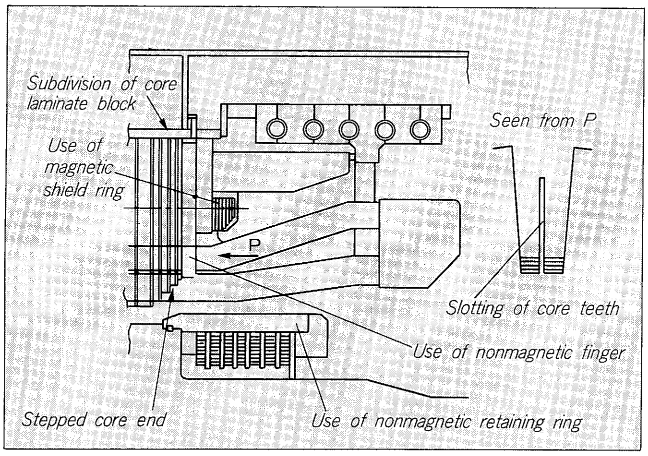
The main reliability improvement measures are show below. (See *Fig. 4*.)

(1) Axial direction flux reduction measures

*Table 1* Heatproof strength of main materials of rotor

| Part \ Item | Material | Allowable temperature (°C) | |
|---|---|---|---|
| | | Short time | Continous |
| Rotor shaft | NiCrMoV steel | 425 | 425 |
| Rotor wedge | Beryllium copper | 300 | 150 |
| Retaining ring | Non-magnetic steel | 380 | – |
| Damper bar | Hardened copper | 380 | 200 |

*Fig. 4* Prevention of overheating of core end at leading zone operation.




(a) Stepped core end
(b) Magnetic shield ring
(c) Nonmagnetic rotor retaining ring

(2) Loss reduction measures
(a) Core teeth slitting
(b) Nonmagnetic finger

(3) Cooling improvement measures
(a) Subdivision of core laminate block length at core end

### 3.4 Rotor thermal unbalance

As generator capacity is increased, the volume of the rotor must be increased. However, the rotor diameter is limited by the strength of the material, it must be compensated by making the core longer. The trend is toward increasing the length/diameter ratio $L/D$, which represents the ratio of the rotor core length $L$ and diameter $D$.

Since increasing the $L/D$ increases the sensitivity to bending of the shaft and the small nonuniformity of the temperature, friction, and other constraining forces at the circumference of the rotor increases the possibility of shaft vibration, $L/D$ is limited to about 7. Therefore, as the $L/D$ is made larger, balance adjustment must be performed more carefully and at the same time, the non-uniform temperature at the circumference of the rotor accompanying a change of the operating state and non-uniform constraint accompanying thermal expansion must be avoided.

The causes of thermal unbalance and its generation mechanism and reliability improvement measures are summarized in *Table 2*.

### 3.5 Stator winding slot fixing method

A double cycle magnetic force proportional to the square of the current is used at the stator winding in the slots of a generator. When the capacity of the machine is made large, since the magnetic force also becomes large, to prevent damaging of the winding insulation, vibration of the winding in the slot must be suppressed.

Therefore, the stator winding vibration is damped by inserting a top ripple spring liner between the wedges and top coil at the indirect cooling stator winding of comparatively small magnetic force for 60 MVA and greater air cooled units (FTLRI) and hydrogen cooled units (FTHRI). With direct cooled units (FTHDD, FTHDF), the vibration-damping affect is improved and coil and core contact is made positive by inserting a semi-conductor side spring liner between the side and teeth of the stator core, besides the top spring liner described above.

To prevent loosening of the stator winding, initial aging promotion work is performed at the factory. After the winding is inserted into the slot, a pressure hose is fastened with a temporary wedge as shown in *Fig. 5*. In the winding heated state, pressure is applied to this hose and it is left in that state for the specified time. This promotes aging of the winding and reduces permanent deformation there-

*Table 2* Reliability improvement measures for thermal unbalance

| Cause | Thermal vibration generation function | Reliability improvement measure |
|---|---|---|
| Shaft material nonuniformity | When the ambient temperature is changed by a circumference thermal expansion difference by material nonuniformity, bending is produced at the shaft. | • Steelmaking and heat treatment method specification.<br>• Specification of allowable residual stress and confirmation by measurement. |
| Winding temperature rise nonuniformity | • Generated loss and cooling nonuniformity by material machining error.<br>• Shaft temperature distribution becomes circumference nonuniformity and bending is produced at the shaft because of nonuniform cooling due to faulty assembly with insulation. | • Control by conductor dimensions gauge and lot mixing prevention.<br>• Use of jig at gas outlet machining.<br>• Shifting prevention of coil end insulator spacer, layer insulation, and wedge bottom insulation. |
| Winding layer short | Unequal temperature rise due to nonuniform magnetic force due to winding layer short. | • Layer check when operation and standstill at each step. |
| Nonuniform winding thermal expansion constraint | When circumference thermal expansion constraint is nonuniform, bending is produced at the shaft by the constraining force difference. | • Securing of comparatively high friction between conductor and wedge insulation.<br>• Use of teflon coating as retaining ring inner circumference insulation. |
| Nonuniformity of wedge and damper winding constraint | When the wedge and damper winding circumference constraint is not uniform, bending is produced at the shaft by the constraining force management. | • Maintenance of suitable gap with slot and insertion force management. |

*Fig. 5* Stator core winding aging promotion processing

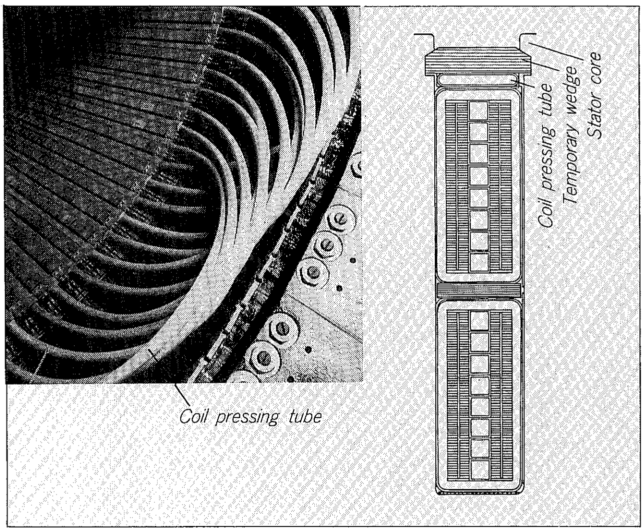
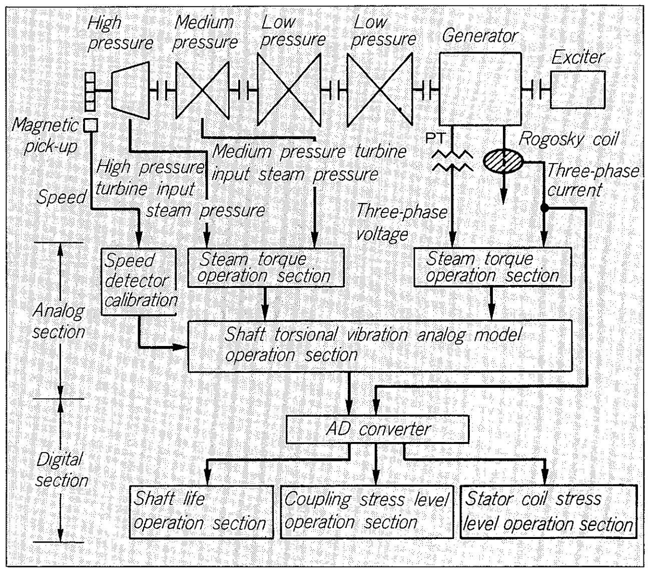



*Fig. 6* Functions and composition of Torsional Stress Analyzer




after.

## 4 PREVENTIVE MAINTENANCE TECHNOLOGY

To increase generator reliability, not only countermeasures from the manufacturing standpoint, but monitoring and diagnosis of the health of the generator is also important. The newest preventive maintenance technology is described below.

### 4.1 Shaft vibration analyzer

To measure and analyze the vibration of the turbine-generator at a power plant, a container type field shaft vibration analyzer with minicomputer was developed and offered for practical use.

Shaft vibration evaluation can be performed immediately from a wide field of view at each test stage by using this field shaft vibration analyzer.

### 4.2 Torsional stress analyzer (TSA)

Continuous monitoring of the shaft torsional vibration during operation and forecasting the shaft life expenditure for general system disturbances are important from the standpoint of safe operation of the machine.

A torsional stress analyzer (TSA) that performs accumulated shaft life expenditure calculation and analysis, etc. on-line was developed for this purpose.

The functions and composition of this analyzer are shown in *Fig. 6*.

The electric torque is computed from the generator voltage and current signals at the analog section electric torque computation section. However, current measurement uses a Rogosky coil to accurately find the DC current. At the steam torque computation section, the steam torque is found from the main steam pressure and control valve opening angle or the high pressure turbine inlet steam pressure and medium pressure turbine inlet steam pressure.

Analog model calculation of the shaft system torsional vibration of high pressure, medium pressure, and low pressure turbines and generator-exciters is based on the above inputs.

At this time, to correct the calculated and actual shaft vibration error, an angular speed meter (magnetic pick-up) installed to the shaft end of the high pressure turbine is used as the calibration signal.

Shaft life, etc. are calculated after shaft torsional stress calculation.

### 4.3 Rotor winding layer monitor

When a layer short occurs at the rotor winding, a difference is produced in the rotor surface temperature. This difference may cause a so-called thermal unbalance which causes vibration. However, since thermal unbalance is also caused by unequal cooling, etc., clarifying whether thermal unbalance was caused by a layer short is important.

The layer monitor performs judgement with the flux distribution of the rotor. There are the following two methods of using the search coil to measure the flux distribution of the rotor winding as shown in *Fig. 7*.

(1) Installation to the stator teeth
(2) Insertion into the air gap from the outside edge of the stator

*Fig. 7* Layer monitor search coil

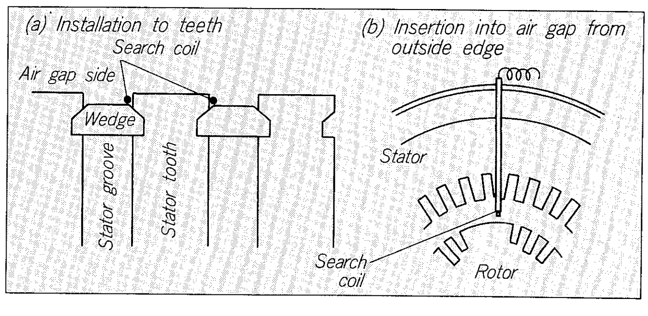
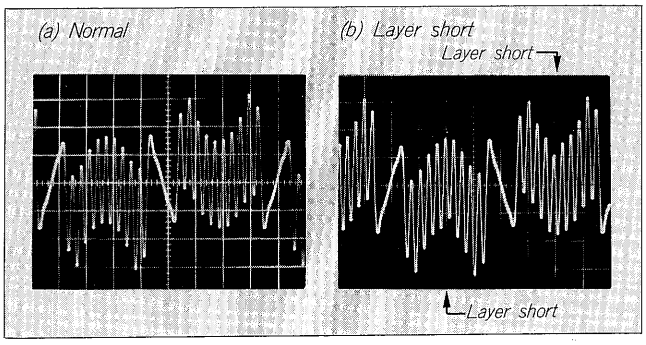


*Fig. 8* Induced voltage waveforms of layer monitor search coil (three-phase short)




The search coil induced voltage waveforms are shown in *Fig. 8*, when the rotor winding is normal and when there is a layer short, in condition of the three-phase short circuit of a generator. When a layer short occurs, since the magnetomotive force of that point is reduced, the flux distribution also becomes small.

**4.4 Brush spark detector**

When the exciting slip ring of a generator becomes rough or the characteristics of the brush holder deteriorate, it is characterized by brush sparking and the slip ring quickly becomes rough and at the same time, abnormal brush wear occurs. Therefore, continuous monitoring of brush sparking is important from the standpoint of preventive maintenance. Detecting the harmonic voltage superimposed on the excitation voltage and detecting noise as an electromagnetic wave are being studied as methods of monitoring this brush sparking. A device that uses the harmonic voltage superimposed on the excitation voltage to monitor brush sparking is under development.

**4.5 Monitor of various filed quanties of generator with brushless exciting system**

With the brushless exciting system, the various field quantities (field voltage, current, ground detection) of the generator cannot be measured directly and a device that uses telemetry to measure these quantities contactlessly was developed.

This device transmits signals corresponding to the magnitude of the field quantities to the fixed section by an FM carrier system. The field voltage is measured by a shunt resistor and the field current is measured by the voltage drop across low resistance-temperature coefficient manganin inserted into the field circuit as a shunt. Ground fault detection is performed by applying a DC voltage between the field winding and shaft. Electric power for measuring circuit is supplied from the fixed side by using a rotating transformer.

A method using an optical sensor was developed to detect rotary rectifier diode protection fuse trouble.

## 5 CONCLUSION

Recent high capacity turbine generator technological advances centered about reliability improvement measures and preventive maintenance technology were described above. The authors will be happy if it serves as reference for all those concerned.