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PROGRESS OF HYDRAULIC TURBINE GENERATOR

Keiichi Hata
Takeo Miyajima
Masayoshi Muraoka

1 FOREWORD

In the hydraulic turbine field, the kinds of turbines is becoming more diversified and the demand for quality and the use of new technology for facilities is raising steadily.

The main themes are:

(1) Development of a high speed and large capacity generator-motor from the standpoint of economy.

(2) Development of a high efficiency generator to deal with the jump in energy costs.

(3) Development of a large capacity bulb turbine generator to deal with development of very low head regions.

(4) Development of a maintenance-free machine to reduce operating costs, etc.

(5) Development of a protection and monitoring system to deal with promotion of unmanned power stations.

Fuji Electric uses its technical strength in the manufacture of all kinds of machines, from horizontal small capacity generators to high speed, large capacity generator-motors, to develop new technology and new products. Examples are used below to describe the main characteristics.

2 LARGE AND MEDIUM CAPACITY VERTICAL GENERATOR AND GENERATOR-MOTOR

At the beginning of 1975, many of the generator ordered and manufactured were medium and low speed machines, such as the four 485 MVA, 112.5 rpm units, the largest ever made by Fuji Electric, for the Revelstoke Power Plant of Canada which began commercial operation in 1984. As shown in *Table 1*, the ratio of high speed machines, represented by the pumped storage generator-motor, has been increasing in recent years. For these high speed machines the long stator core length is to be considered. For example, the ventilation and cooling system must be studied. Fuji Electric realizes optimum ventilation and cooling through ventilation experiments by scale model and/or test results of an actual machine. The strength of the rotating parts, including fatigue and buckling considering the high centrifugal force and starting frequency, must also be studied more than in the past.

Separate from these generator structural problems is the increase in the demand for more efficient generators

Table 1 Vertical hydraulic turbine generator and generator-motor order and manufacturing record

Year	Plant name	Unit	Output (kVA)	Voltage (kV)	Frequency (Hz)	Speed (rpm)	Speed at load rejection ΔN (rpm)	Runaway speed Nr (rpm)	$\frac{\Delta N}{Nr}$	Maximum velocity of rotor (m/s)
1981	Samrangjin	2	(G) 385,889kVA (M) 376,628kW	18.0	60	300	450	420	1.07	145
1981	Pieman	2	136,000	13.8	50	167	242	300	0.81	126
1981	Sultan River	2	60,720	13.8	60	257	321	460	0.7	111
1982	Lower Borpani	2	62,500	11.0	50	500	650	850	0.76	143
1982	Hondozi	1	83,400	11.0	50	273	445	545	0.82	144
1983	Pålmiet	2	(G) 250,000kVA (M) 200,000kW	16.5	50	300	490	497	0.99	176
1984	Hapcheon No.1	2	55,000	13.2	60	257	347	505	0.69	137
1984	Ventanas-Garita	2	54,100	13.8	60	400	600	680	0.88	160
1985	Lucky Peak	2	50,000	13.8	60	257	475	643	0.74	165
1985	Blanda	3	60,000	11.0	50	500	725	850	0.85	143
1985	Upper Indravati	4	166,700	11.0	50	428.6	644	730	0.88	178
1986	King	1	160,000	13.8	50	273	396	500	0.79	168
1986	Anthony	1	94,000	13.8	50	428.6	644	740	0.87	163

accompanying the jump in energy costs. Generator efficiency is more high than that of prime mover, but Fuji Electric has realized higher efficiency than in the past through recent advances in analysis technology and various experiments.

The contents of studies on the strength of rotating parts mentioned above and examples of application to actual machines and technology to get high efficiency and examples of its application to actual machines are introduced below.

2.1 Rotor strength

As shown in *Table 1*, recently, the rotor peripheral speed at the runaway speed of not only pumped storage machines, but also of normal generators has risen to 180 m/s. The ratio ($\Delta N/Nr$) of the speed rise (ΔN) at load rejection and the runaway speed (Nr) is also rising gradually. Because of this trend, rotor strength evaluation requires more reliability based on detailed studies and experiment than in the past.

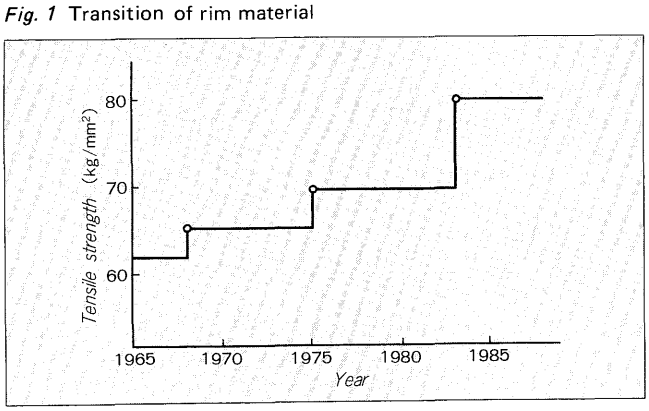
Fig. 1 shows the transition of the tensile strength of the material used with thin plate laminated rim. As shown in this figure, materials having a tensile strength of 80 kg/mm^2 class have recently come into use. What requires special attention when using these high tensile strength materials is the fatigue strength accompanying starting and stopping of the generator and the buckling strength on the thin plate laminated construction.

Concerning the fatigue strength, generally, the fatigue strength of a material does not become high as the tensile strength increases. Therefore, in the design stage, the stress and strain distribution of the stress concentrated part, in particular, are studied by the finite element method and detailed studies based on the results of this study are made on low cycle fatigue.

On the other hand, the permissible buckling load of a thin plate laminated structure is virtually unrelated to the mechanical strength of the material used and is affected considerably by the plate thickness and the dimensions of the structure and the thin plate laminated construction.

When high tensile strength steel is used, since a high stress level is selected, the buckling strength condition is more severe than when ordinary tensile strength steel is used.

Fig. 1 Transition of rim material



Regarding the buckling behavior of a thin laminated construction rim at the point of pole piece attachment, Fuji Electric got the buckling load by experiments with a model of the actual machine size. *Fig. 2* is a photograph of the rotor rim test piece used in the experiments after the buckling test. *Table 2* shows the results of the buckling test of various pole piece construction.

2.2 High efficiency technology

Generator losses are classified into bearing loss, windage loss, core loss, stray load loss, and I^2R loss of stator and rotor winding. These losses are caused by various physical phenomena and differ substantially with the generator speed.

In this section, as an example, efficiency improvement means to the Samrangjin pumped storage power plant generator-motor (386 MVA, 18 kV, 300 rpm) to which amount evaluation of loss is evaluated especially high, is described. A sectional view of this machines is shown in *Fig. 3*.

(1) Core loss

Core loss is mainly generated inside the stator core. However, slot ripple loss generated at the pole core surface and the loss at the core end structure caused by the leakage magnetic flux at the end of the core are also included.

To minimize the loss in the core, 0.35 mm thick highest class low loss silicon steel plate and nonmagnetic stator core spacer were used.

To minimize the slot ripple loss, a 0.5 mm thick field core was used. Electromagnetic analysis of the core end by FEM was also performed and the end loss was minimized

Fig. 2 Example of buckling test of rotor rim

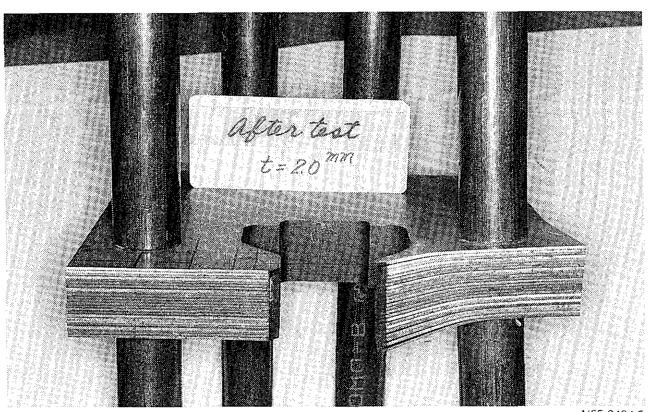


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Table 2 Result of buckling test

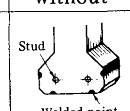
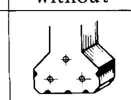
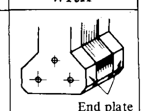
Type	A	B	C
No. of studs	2	3	3
No. of welded point	4	5	5
End plate	without	without	with
Construction			
Buckling stress	100	126	162 min.

Fig. 3 Sectional view of generator-motor for Samrangjin pumped storage power station of Korea

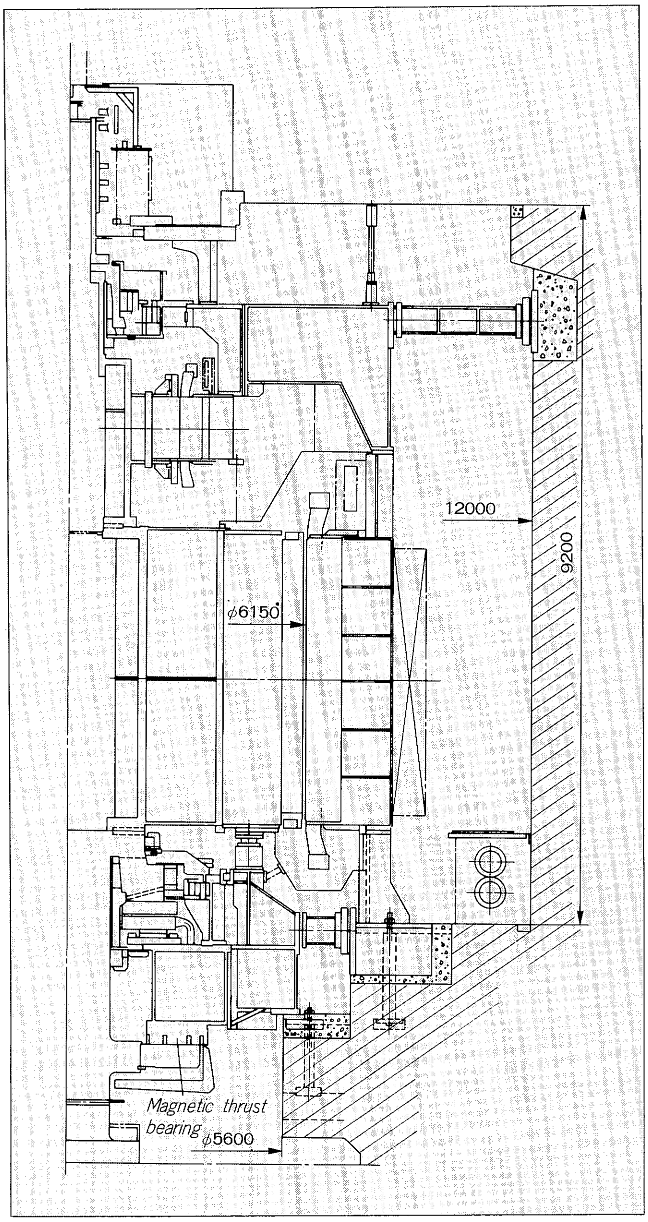
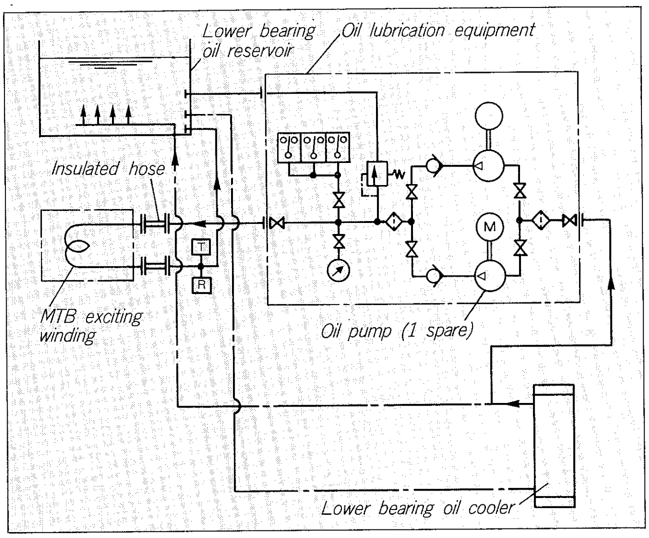


Fig. 4 Oil sequence for MTB (Magnetic thrust bearing)



by the suitable use of nonmagnetic material.

(2) Bearing loss

The bearing loss of this machine was minimized by reducing the load applied to the thrust bearing considerably by using the magnetic thrust bearing that is a special feature of Fuji Electric machines. The magnetic thrust bearing bears approximately 50% of the total thrust load, including the hydraulic thrust load (95% of the generator rotor weight). Therefore, the bearing can be made smaller without a loss of operating reliability. This also minimizes notonly the friction loss, but the rummage loss which occupies about half of the total thrust bearing loss in high speed machines. Reducing the outer diameter of the thrust bearing also minimizes the guide bearing loss by reducing the diameter of the guide bearing.

By cooling the MTB exciting coil directly with the oil inside the bearing oil reservoir, the size of MTB is reduced and improvement of reliability is achieved by minimizing the temperature rise. The MTB oil sequence is shown in *Fig. 4*.

(3) Windage loss

This machine uses rim ventilation (radial ventilation). Rim ventilation is different from conventional forced ventilation in that it minimizes the inequality of the air flow in the axial direction. For this machine, ventilation analysis by computer based on the results of experiments using a scale model were performed and optimum cooling by minimum air flow was realized, so windage loss was minimized. Since the ratio of the rotor rummage loss unrelated to the air flow is high with high speed machines, this loss was minimized by making the rotor surface extremely smooth.

(4) Others

The stray loss of this machine was minimized by making a special transposition at the coil end, in addition to the conventional 360° Reabel transposition, and using a nonmagnetic material at the coil end peripheral structure.

The I^2R loss of the field winding was minimized without increasing the constitution of the machine by inserting the field winding into the space between the poles used for ventilation in the past by using rim ventilation. This machine started commercial operation in June 1986 and is operating favorably.

3 BULB TURBINE GENERATOR

Table 3 lists the bulb turbine generators delivered since 1980.

The ventilation and cooling systems for bulb turbines are mainly a system which uses the outside of the bulb to reliease the loss directly into the river and a system which uses an ordinary air cooler. Of the former cooling system, fin cooling with fins embedded in the inner wall of the bulb is applied to machines having a comparatively large

Table 3 Bulb turbine generator ordered and manufacture record (From 1980)

Year	Power station name	Number of units	Output (kVA)	Voltage (kV)	Frequency (Hz)	Speed (rpm)	Bulb diameter (m)
1980	Merced Main Canal	1	2,830	4.16	60	180	3.45
1980	Futamatase	1	650kW	3.3	60	600	1.15
1981	Western Yamuna Canal	8	10,440	6.6	50	188	3.49
1981	Dawson	1	4,660	4.16	60	120	4.37
1981	Lower Mettur	8	18,333	6.6	50	75	7.2
1982	Itado	1	2,040kW	6.6	50	375	2.1
1982	Shingo No. 2	1	40,900	6.6	50	136	5.9
1983	Chungju No. 2	2	7,060	6.6	60	171	3.75
1983	Main Canal Headworks	1	27,370	6.9	60	113	6.3
1983	Yuda	1	5,750	6.6	60	150	3.88
1985	Eastern Gandak Canal	3	6,112	6.6	50	107	5.15
1986	New Martinsville	2	21,620	6.9	60	64.3	8.4

capacity. Since fin cooling is advantageous in that it is maintenance-free, because it does not use water, and provides inspection space by eliminating the air cooler, its use should be expanded.

On the other hand, very low speed high capacity bulb turbine generators have recently appeared, as shown in *Table 3*. Even though the bulb diameter of these machines is larger than in the past, the air gap is the same. Therefore, to secure a uniform air gap at installation and operation, stator construction studies have become more important than in the past.

This section introduces the contents of research on this fin cooling system and the stator construction of large machines and an example of their application to an actual machine.

3.1 Fin cooling system

In the fin cooling system, the number of fins is selected from welding of the fins in the axial direction in the bulb inner wall and the relation between the fin pitch and bulb diameter. On the other hand, since the area over which the fins are welded cannot be increased in proportional to the generator output, the range over which the fin cooling system can be applied is decided.

Fuji Electric has promoted more compact coolers even for atmospheric pressure machines and improved cooling efficiency and extended the range of the fin cooling system as shown in *Fig. 5* ever since the first fin cooled machine, a 17 MVA unit (delivered in 1981) for the Electric Power Development Co. Sakuma No. 2 power station.

Field testing of a 5750 KVA unit for the Kyushu Electric Power Co. Yuda power station, the largest capacity fin cooled unit in Japan, has been completed. The test results are introduced in *Table 4*. Since the pressure rise

Fig. 5 Fin cooling system application range

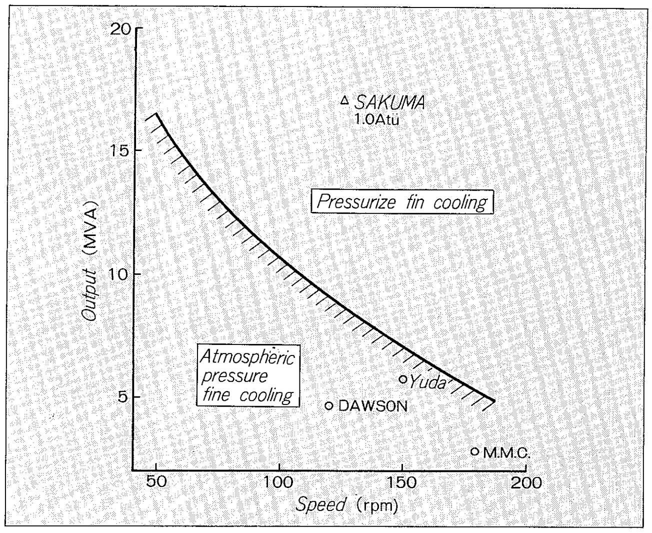


Table 4 Results of field test of 5,750kVA normal pressure fin cooled unit

Test item		Measured value	Guarantee value
Coil temperature rise (°C)	Stator	50	70
	Pole	29	80
Cooling air temperature (°C)	Cooled air	29	50
	Hot air	41	–
Brg. temperature (°C)	Thrust brg.	35.5	65
	Generator guide brg.	38	65
	Turbine guide brg.	32	65
Cooling water temperature (°C)		16	25

type fin cooling system can improve the coefficient of heat radiation considerably, fin cooling can also be used with large capacity units.

3.2 Large machine stator construction

The transition of the bulb diameter of the bulb turbine generators manufactured by Fuji Electric is shown in *Fig. 6*.

The bulb outer diameter of a bulb turbine generator cannot be selected freely like normal vertical and horizontal turbine generators because of water channel conditions restrictions.

Therefore, when the short circuit ratio and other electrical characteristics are assumed to be constant, the pole pitch of a bulb turbine generator is smaller than that of normal generators and becomes an almost constant 200 to-300mm. Therefore, the air gap is within the 7 to 11mm range regardless of the bulb diameter.

On the other hand, since the deformation of the stator in the installed state is proportional to the cube of the bulb diameter, with the stator of a large machine, the ratio of deformation compeared with the air gap becomes large and countermeasures against it have become very important matter.

For a bulb generator, even if the bulb diameter is in-

Fig. 6 Transition of bulb outer diameter of bulb turbine generator

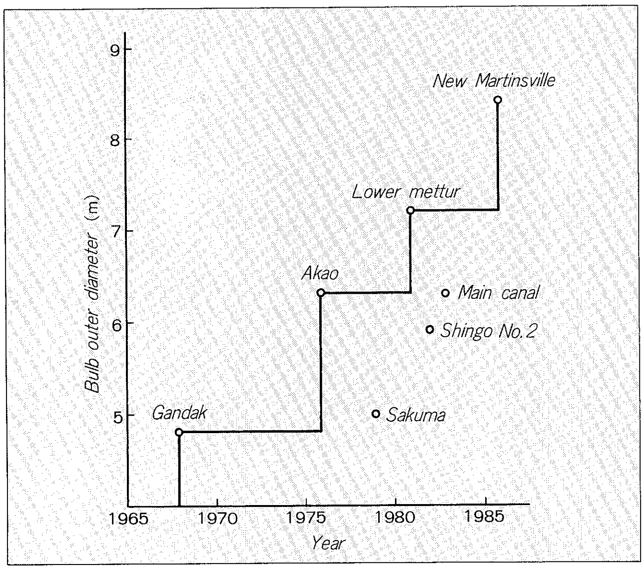
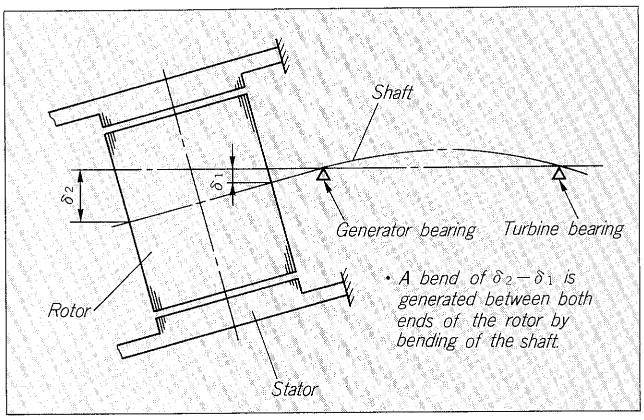


Fig. 7 Stator installation method concept



creased, the space between the stator core outer diameter and stator frame outer diameter, which support the rigidity of the stator itself, cannot be made correspondingly large and special countermeasures are necessary for the stator of large machine.

Therefore, a method which reduces the deformation by providing deformation prevention beams inside the stator are used.

A two bearing support system bulb generator has such merits as short installation period, simple maintenance around the generator bearing, etc. However, because the rotor overhungs, with large machines, the uneveness of the gap in the axial direction due to bending of the shaft by the weight of the rotor is large and has an undesirable affect on vibration during operation and the electrica characteristics.

This problem is solved by us by installing the stator along bend of the rotor as shown in *Fig. 7.*

The stator core tends to expand to the outer diameter side due to the temperature rise during operation. However, if it is restrained by a stator frame cooled by outside water, a large stress is generated in the core and the core buckles. To prevent this, special consideration must be given to the space between the core and stator frame so that thermal expansion of the core is relieved.

4 SMALL CAPACITY TURBINE GENERATORS

This section introduces the technical trend of small capacity turbine generators and Fuji Electric's new technology related to the air cooled bearing that does not use cooling water which has gained attention in recent years.

4.1 Recent technical trends

As a result of the domestic energization promotion policy, hydraulic development of regions which did not see development in the past is proceeding. The average output of the hydroelectric plants of these new developments is 10MW or less. Scrap-and-build of machinery more than several ten years old is also proceeding separately from these new development regions.

Since scale merits cannot be expected from these low capacity power plants, minimizing the initial and operating costs is important.

To minimize the initial cost, the machine is made smaller and the machinery is simplified by:

(1) Adoption of the Class F temperature rise.
(2) Adoption of the natural GD^2 by setting the speed rise at load rejection to the runaways speed.
(3) Adoption of an induction generator, depending on the region and capacity.

To reduce operating costs, the machine is made maintenance free by:

(1) Adoption of a brushless exciter.
(2) Adoption of the air-cooled bearing.

4.2 Air cooling bearing of vertical machine

In recent years, the use of brushless exciter has become popular, simplification of maintenance for medium and small capacity generator has been paid attention to the cooling water system.

At power plants where pollution of the river water and the mixing of leaves and dirt in the flood season are especially bad, even if the performance of the cooling water system strainer is strengthened and the forced rejection of debris by a reverse flow system and other countermeasures are taken, daily maintenance of these devices and piping cannot be neglected and labor saving was a large matters.

Fuji Electric has promoted research, development, and experimentation on an air cooling system which does not require water to cool the bearing lubricating oil ever since the beginning of 1975. The first unit was delivered with (2,800kVA/333rpm) for the Tokyo Electric Power Co., Inc. Otsu Power Station in 1978. Thereafter, it was also used with (7,200kVA/514rpm) for the Mie Prefecture Industry Bureau Yamatodani Power Station. Both systems are operating favorably. The sectional view of an air cooled bearing machine is shown in *Fig. 8.* An exterior view of an

Fig. 8 Sectional view of turbine generator adopting air cooled bearing

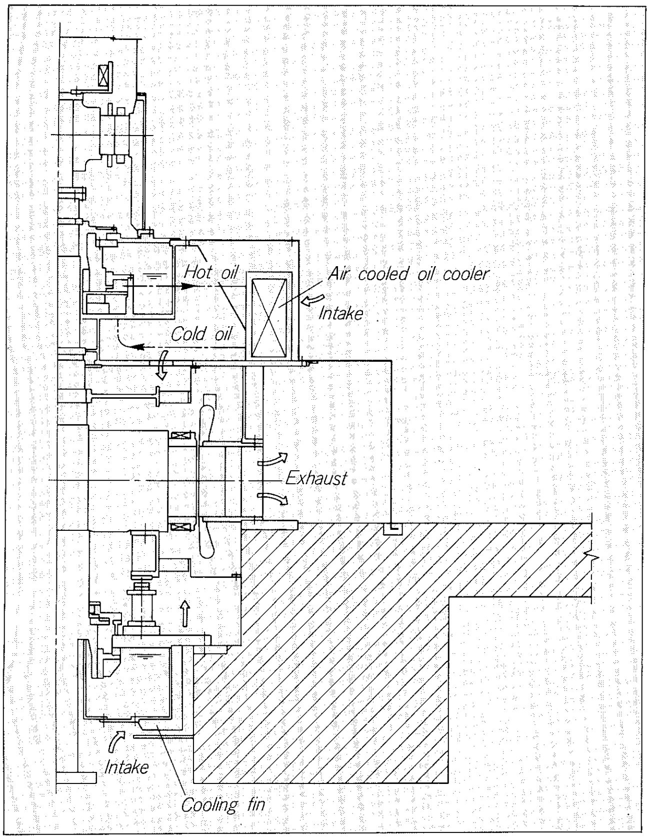
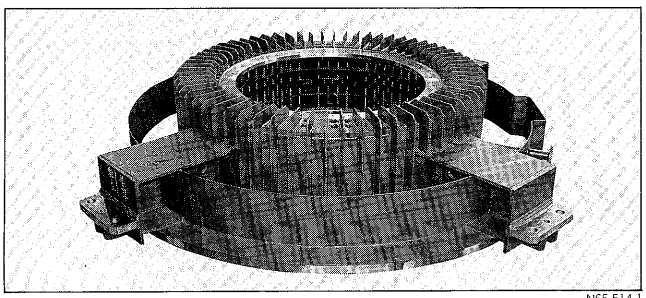


Fig. 9 Exterior view of air cooled bearing oil tank



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air cooled bearing oil tank is shown in *Fig. 9*. As shown in the figure, the thrust bearing is air cooled by an external cooler and the lower bearing is cooled by fins on the oil tank. Since the cooling air temperature is higher and heat transfer rate of an air is smaller than a water, the bearing temperature tends to become high. Therefore, the air cooled bearing application range expansion point is improvement of the heat radiation density of the oil tank surface or air cooler. However, the recent increase in the trend of not using water is accompanied by noticeable progress in the improvement of performance from this standpoint. The construction of the cooling pipe used with recent air cooled oil coolers is shown in *Fig. 10*.

Fig. 11 shows the relationship between the air temperature and bearing temperature from the data measured in the field test with an actual machine. It can be seen from this figure that a temperature of as air cooled bearing

Fig. 10 Shape of cooling pipe of recent air cooled oil cooler

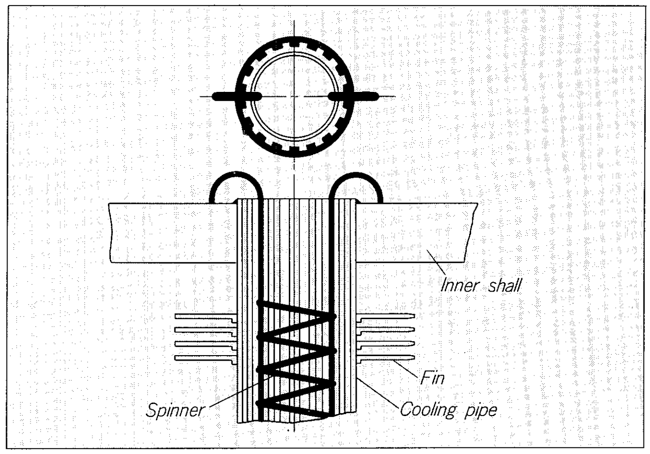
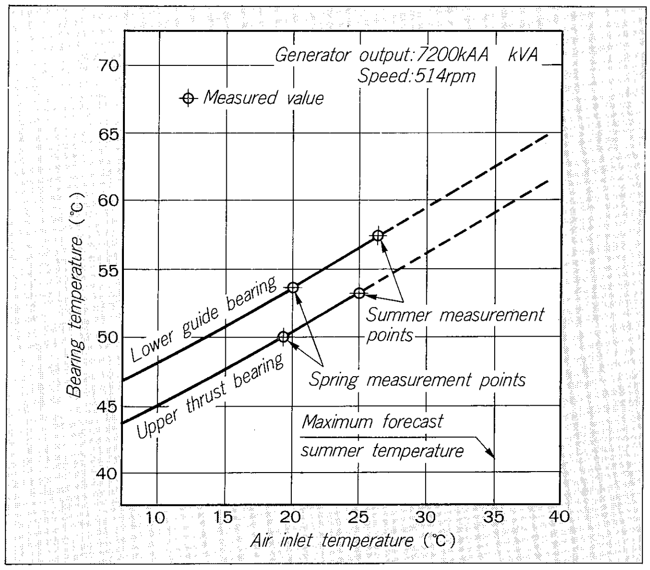


Fig. 11 Field test results of air cooled bearing temperature



is favorable with that of a water cooled bearing compeared.

Together with the above development, and low loss oil tank construction development, if the conditions are established, application of the air cooling system can be forecast to the whole range of small capacity, medium speed machines. The range of application to vertical machines is shown in *Fig. 12*.

The standard conditions and constructions for application of the air cooled bearing are shown below.

(1) Generator is outlet pipe self-ventilated type.
(2) Bearing guaranteed temperature shall be 75°C or less.
(3) The kind of oil used shall be VG46.
(4) Construction Thrust bearing oil tank: Separate oil cooler system
Guide bearing oil tank: Direct cooling by finned oil tank.

The demand for an air cooled bearing for turbine generators has increased suddenly in recent years. Fuji Electric plans to improve its cooling efficiency, expand its application range, and make the system more compact to meet the

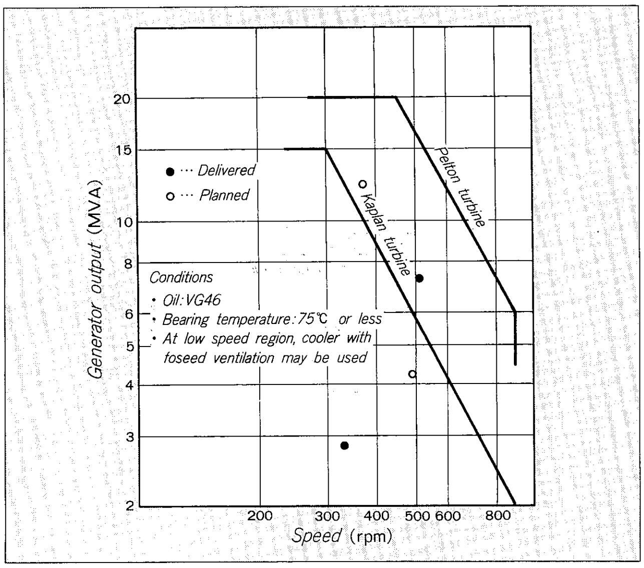


Fig. 12 Vertical machine air cooled bearing application range

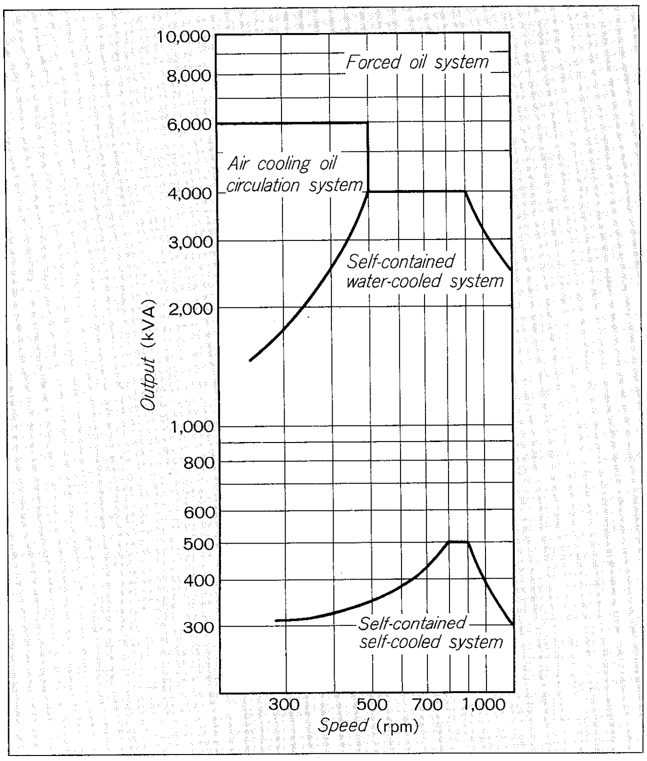


Fig. 13 Horizontal bearing lubrication and cooling systems

demand of users.

4.3 Self-cooling bearing of horizontal machine

The bearing lubrication and cooling system of conventional horizontal machines is generally a forced oil lubrication system with cooling water equipment and gravity tank at the ceiling of the building.

Since most horizontal machines are small capacity machines, development of a turbine generator emphasizing simplification of the equipment and simplification of maintenance eliminating the cooling water system has advanced. Bearing lubrication and cooling systems are classified as shown in Fig. 13 and are one part of elimination of power house equipment, such as elimination of the lubricating oil piping, the cooling water equipment, and both. Application examples are shown in *Table 5.*

Table 5 Application examples of lubrication and cooling system of horizontal machine

Plant name	Output (kVA)	Speed (rpm)	Kind of turbine	Lubrication and cooling system	Bearing temp. (°C)
Water Resources Development Public Corporation Muro Dam	630	900	Cross-flow	Self-ventilation, self-cooling	85
Hokuriku Electric Power Co., Inc., Miko Shimizu	490	900	Francis	"	75
Kochi Prefecture Kirimi	670	900	Cross-flow	"	85
Yamanashi Prefecture Yushima	2,110	750	Pelton	"	85
Tochigi Prefecture Miyama	2,465	300	Pelton	"	85
Chubu Electric Power Co., Inc., Oguro	1,160	600	Pelton	"	75
Chubu Electric Power Co., Inc. Achigawa	920	400	Double current Francis	"	65
Chugoku Electric Power Co., Inc., Katsuyama No. 1	4,000	514	"	"	75
Chugoku Electric Power Co., Inc.,Zoogawa	3,200kW	900	Francis	Self-contained water-cooled	75
Hokuriku Electric Power Co., Inc. Oritate	4,200	450	Double current Francis	"	65
Kyushu Electric Power Co., Inc., Kono	2,200	900	Francis	"	65
Tokyo Electric Power Co., Inc., Michiyabara	1,895	429	S type tube	"	65
Chubu Electric Power Co., Inc., Aohara	2,010	600	Francis	Air cooled oil circulation	70

A new type of bearing using a heat pipe is also being developed. It cools the bearing by sending the heat generated at the bearing to the flowing water around the turbine parts through a heat pipe. This is called a rotating heat pipe. It is a maintenance-free bearing that does not need ancillary devices for bearing lubrication and cooling.

The heat pipe was used to cool the rotor of a totally enclosed induction motor in 1979 and more than ten thousand units have been delivered and are operating without a problem. Development experiments for the new type bearing using a heat pipe are almost completed and it is expected to be applied to an actual machine before long.

The new type bearing using a heat pipe is shown in *Fig. 14.* When the heat generated by the bearing exceeds the heat transfer capacity of the rotating heat pipe, bearing is cooled by using a heat pipe cooler together.

5 TURBINE GENERATOR PROTECTION AND MONITORING SYSTEM

Recently, unmanned or one man controlled power stations have advanced and the demand for remote monitoring of the inspection items checked by patrolling in the past has increased. Fuji Electric is advancing research and development to meet these customer needs. This section introduces the brushless exciter telemetry system and brush spark monitor as example.

5.1 Telemetry system of hydraulic turbine generator with brushless exciter.

This system is being manufactured for use with the 83.4MVA generator for the Tohoku Electric Power Co., Inc. Hondoji Power Station. Its outline is shown in *Fig. 15.* As shown in this figure, the objects of detection are main unit field current and voltage, field earth fault, and diode failure. The figures are converted to low level voltage signals and sent to the outside contactlessly, with FM as the main carrier.

Except for diode failure detection, the detection circuit is the same as the system already used with steam turbine generators. To simplify the transmission system, a new pulse CT secondary output serial addition system was used for diode failure detection. Specifically, when the diodes are normal, the sum of the CT secondary voltages becomes zero as shown in *Fig. 16*, but when a diode has failed, an output is generated and is used as the failure signal. The number of modulation frequencies is reduced by 1/6 by using this system.

5.2 Brush spark detection

Fuji Electric is researching systems that detect the spark frequency by a condenser coupling system and by an antenna system. *Fig. 17* shows the correlation between the brush sparking number and output voltage waveform of each system. In both cases, the brush sparking number and output voltage correlation was good and it was confirmed that remote monitoring of brush spark generation at the slip ring was practical. However, since the former is weak against noise from the controller inserted into the power supply cable and the receiving sensitivity of the latter differs with the construction of the equipment and is not as universal as the former, which system to use must be decided on an ample examination of the environment, etc. at installation. Fuji Electric is continuing research and development to improve the defects of both systems.

Fig. 14 Bearing using heat pipe

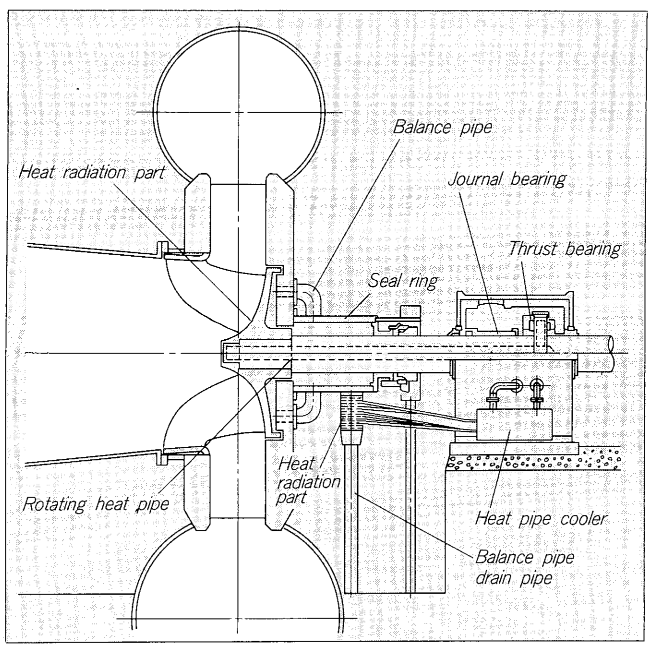


Fig. 15 Concept of telemetry system of hydraulic turbine generator with brushless exciter

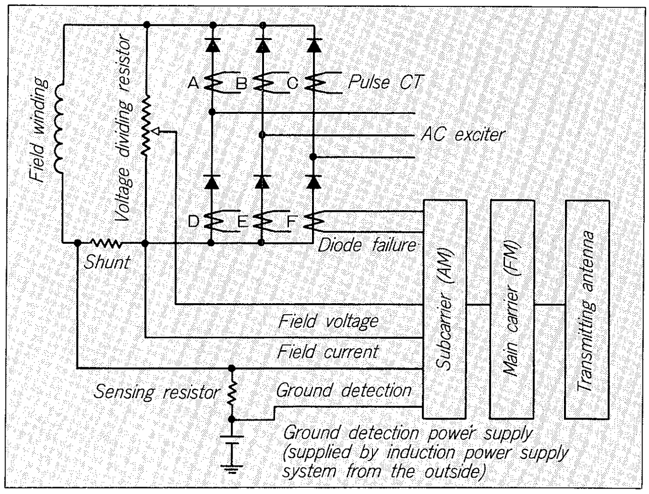
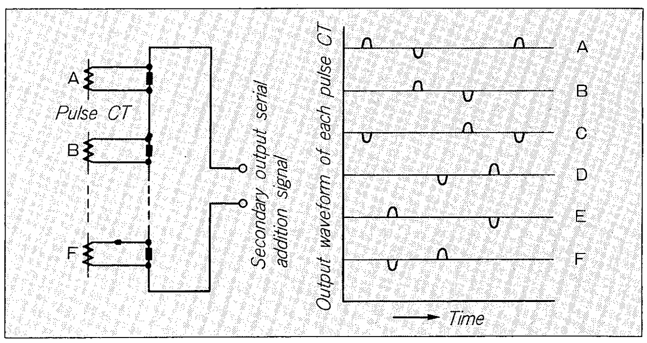


Fig. 16 Pulse CT secondary output addition system



6 RENEWAL TECHNOLOGY

In recent years, reform and modernization of turbine generators for effective use of existing hydraulic turbine generators has been advancing.

The record of reformation and modernization work performed recently is shown in *Fig. 18.* It is recommended that the opportunity be taken from the standpoint of preventive maintenance and shellac insulation stator windings be renewed to epoxy resin insulation windings. Making

Fig. 17 Brush sparking number and output voltage relationship

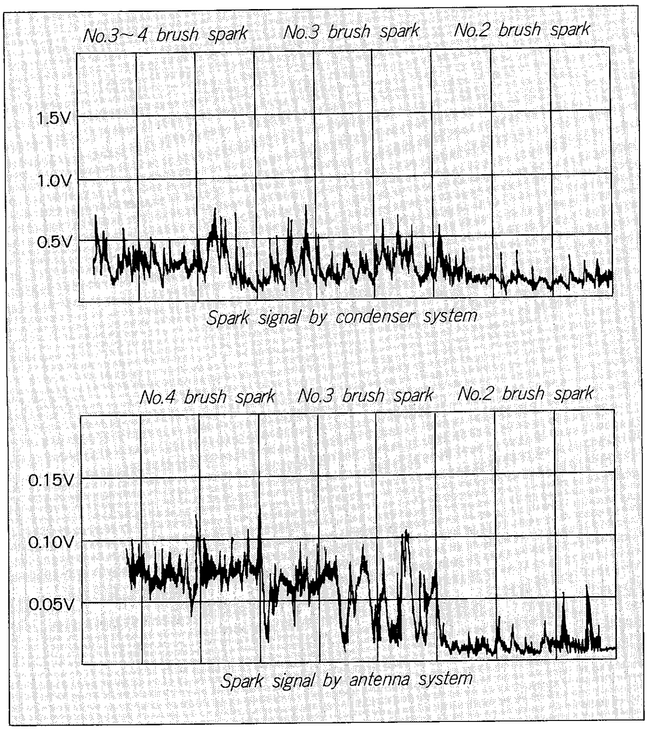
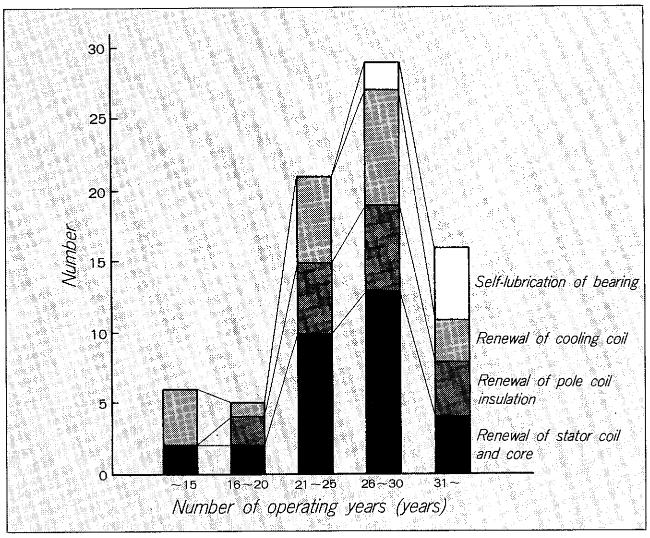


Fig. 18 Record of turbine generator reform and modernization



these reforms and modernizations improves machine reliability and simplifies maintenance and inspection. Renewal of the stator core and coil improves efficiency and reduces the winding temperature rise and improves other performances. As an example, the efficiency of a 12 MVA, 400 rpm machine was improved about 0.3%. Fuji Electric will continue efforts on the reform and modernization desired by users by using the newest technology.

7 CONCLUSION

Fuji Electric's newest hydraulic turbine generator technology was outlined about.

To meet the needs of the diversifying market, we will also undertake.

- development and practicalization of preventive maintenance technology.
- development of high quality and low cost equipment.
- development of new models

and many other themes.