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LARGE CAPACITY GENERATOR-MOTOR

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I. INTRODUCTION

Power demand has been increasing every year in Japan with the expansion of the economy and the improvement in living standards, and the rate of increase has been an average of 10% annually for the last 20 years. This trend will probably continue in the future. Because of this increased power demand, it has become necessary to increase the base load supply capacity in large capacity thermal and nuclear power plants and also to increase the peak load supply capacity by constructing large capacity pumped storage hydroelectric plants.

Fuji Electric is designing and constructing 220MVA/220MW 450rpm generator-motors for the Chongpyong Pumped Storage Power Station of the Korea Electric Co. on the basis of experience gained in the manufacture of a 316MVA generator for the Peace River Power Station in Canada and subsequent technical progress. This article will describe the features in the design of large capacity generator-motor.

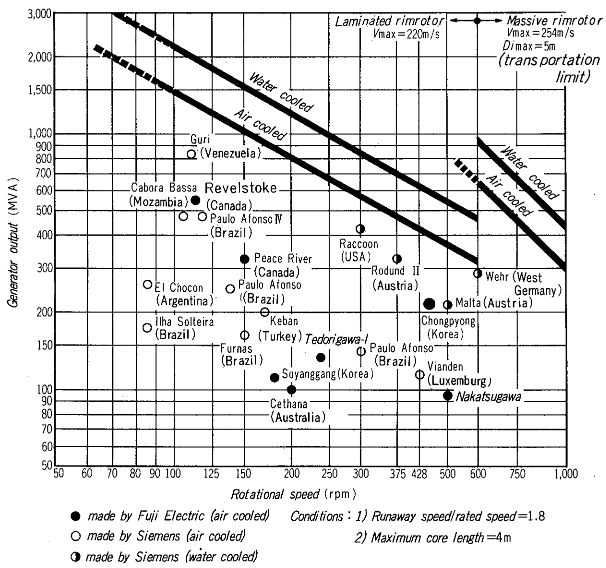

Fig. 1 Manufacturing limit of water-turbine generators

II. MANUFACTURING LIMITATIONS FOR LARGE CAPACITY GENERATOR-MOTOR

Fig. 1 shows records of typical generators and generator-motors manufactured or being manufactured by Fuji Electric and Siemens. The straight lines in the figure indicate what Fuji Electric considers to be its manufacturing limits which are decided mainly in accordance with ventilating techniques and the rotor strength.

The following equation shows the relation between generator output P_s (kVA), and the inner diameter of the stator D (m), core length L (m), rated speed n (rpm), the maximum peripheral speed of the rotor v_m (m/s) and the ratio of the maximum to the rated speed k_m:

$$P_s = CD^2Ln = C\left(\frac{60}{\pi}\frac{v_m}{k_m}\right)^2\frac{L}{n}$$

where C is a machine constant (kVA/rpm·m^3) which expresses the electric and magnetic utility ratio.

The generator output P_s is indicated as the product of the machine constant C and the machine volume D^2L and the speed n. The manufacturing limits are decided in accordance with the limits on these various values.

The magnetic utility ratio is naturally limited since no improvement in the characteristics of the core material is expected. However, the ratio is gradually increasing by means of such measures as correction of the field distribution by a detailed analysis within the flux route by means of the finite element method. The electric utility ratio is limited by winding temperature rises and is increasing in accordance with technical progress resulting from experiments and analysis concerning ventilation, cooling and temperature rises. The utility ratio is also increasing because of a decrease in the insulation thickness and a higher insulation class level in keeping with progress in insulation technology.

One of the measures which has resulted in a remarkable increase in the machine constant C is the use of the direct water cooling method. Since the utility ratio is increased by about 50% above that of ordinary air-cooled equipment in consideration of the suitable exciting capacity and efficiency, the limited output has also increased as shown in *Fig. 1.*

The inner diameter D of the stator core is limited by the rotor strength, especially the rotor rim strength. Because of improvements in design accuracy due to stress

Table 1 Comparison of starting methods

Starting method	Damper winding starting method				Synchronous starting method				Starting motor direct coupled starting method	Remarks
					Starting by special generator			By means of thyristor converter		
	Full voltage	Reduced voltage	Split winding	Low frequency	By same capacity generator	By small capacity generator	MG set			
Applicable capacity range	Small	Medium · Small	Medium · Small	Medium	Large · Medium	Large · Medium	Medium · Small	Large · Medium	Large · Medium	Large: 150MVA or more Medium: 10~150MVA Small: 10MVA or less
Starting capacity (pu)*	4	1	2.4	–	–	–	–	0.06~0.09	0.06~0.09	Shows magnification with respect to main unit output.
Starting time (min)	Short 0.5	Short 1~2	Short 1	Medium 3~5	Medium 2~4	Long 5~8	Long 5~8	Long 5~8	Long 5~8	
Considerations concerning main equipment construction	Heat capacity and thermal stress of damper winding				Nothing special			Rotating position detector	Direct coupling of starting motor	
Disturbance on power system	Large	Medium	Medium	None	None	None	None	None	None	
Accessories	None	Main transformer intermediate taps	None	Special generator for starting			MG set for starting	Thyristor converter	Induction motor for starting, transformer, liquid resistor	Except for things necessary in all cases such as a thrust jack-up device, water depressing device, phase rotation disconnecting switch and a bus switch for starting.
Control and operation	Simple	Main transformer tap changeover	Winding connection changeover	Requires investigation of generator starting speed and excitation ratio	Requires investigation of optimum excitation ratio with no step-out and guide vane opening speed (MG motor torque characteristics)			Regeneration braking possible; large degree of freedom for machinery layout; breakdown recovery easy	Requires investigation of fineness of liquid resistor value changeover	
Applicability	Cheap but limited to applicable range			Few advantages over synchronous starting system	Good in cases of large numbers of equipment but requires investigation to determine if starting is possible or not		Few advantages in comparison with damper winding starting method	Appropriate when there are large numbers of devices	Optimum in of one or two large capacity generators	

Note: * pu means per unit indication.

analyse by the finite element methods and the improvement in material strength, it has been possible to achieve a v_m value of about 220m/s. A 290MVA unit designed and manufactured on the basis of $v_m = 216$m/s is already in operation at the Wehr Power Plant in West Germany. Since a high speed machine utilizes a massive rotor rim, it is possible for v_m to reach about 250m/s and the output limit can also be increased.

Core length L is limited to about 4m by such factors as the vibration, the critical speed, ventilation and thermal expansion in the axial direction of the core, and transport. The previously mentioned 220MVA/220MW machinery now being manufactured is high speed large capacity equipment but it is within the range where an air cooled type is possible.

III. CONSIDERATIONS CONCERNING DESIGN OF GENERATOR-MOTOR

Generator-motor for pumped-storage stations have the following characteristics which differ from those of water power plants only for power generation:

1) Starting for pumping-up operation is required.
2) It is reversible.
3) Starting and stopping frequency is high.
4) The hydraulic exciting force arising in the pump-turbine is high.

The following sections describe various points to be considered in the design in such cases.

1. Starting System

The following three systems can be used during pumping-up operation:

1) Self starting by means of a damper winding
2) Starting by means of a directly coupled motor
3) Synchronized starting system using a frequency variable power source

When selecting the starting system, it is necessary to investigate a wide range of factors from various standpoints including the number of machines to be located in the power plant, the strength of the power supply system and economy. In Fuji Electric, integrated research has been performed on starting systems by cooperative research with Tokyo Electric Power Co. since 1972. *Table 1* shows the main advantages and disadvantages of starting methods, the main applicability, etc.

The self-starting system using the damper winding is the most simple method and has been used for the longest time. Fuji Electric has used this system in the Hatanagi Power Plant of Chubu Electric Power and the Kuromatagawa II Power Plant of Power Supply Development. However, because of limitation of the heat capacity of the damper winding and the effects of the rush current on the power supply system, the application range is limited to around 100,000kW or less.

The system which uses a directly coupled wound-rotor induction motor is effective in cases where there are two or less large capacity machines of the type which can not be used with the self-starting system. This system was used for the Chongpyong Pumped Storage Power Station. The output of the induction motor for starting is decided from the counter torque of the main machine and the starting time and should be 6 ~ 9% of the main machine output. This represents an extremely high output for an induction motor and sufficient caution is necessary concerning the high voltage and large current of the secondary winding and the liquid resistor.

The synchronous starting system has two types: one using a generator as a variable frequency power supply, and the other a thyristor converter. It is best when there are three or more machines and the power supply utilization rate is good. Fuji Electric has used the former system in a generator of the Midono Power Plant of Tokyo Electric Power. The latter system, the thyristor starting system, has been used in the 13,000kW synchronous starter delivered to Kawasaki Steel by Fuji Electric and that manufactured by Siemens for the Raccoon Power Station, which has the world's largest generator-motor. The manufacturing technology has been established for both of these systems.

2. Ventilation and Cooling

In cases where a built-in fan is used for ventilation of a reversible generator-motor, it is necessary to use a type of fan for which the fan action is not decreased in either forward or reverse operation, but with such a limitation, it is impossible to avoid decreases in fan efficiency and ventilation loss also increases.

In large capacity equipment, particularly high speed machines, the core length is long, the core diameter small and the ventilating resistance becomes large. Therefore, it is essential to use a separate fan to assure the necessary quantity of ventilation air. Fuji Electric is investigating the effective distribution of cooling air in each part of the machinery by using a computer for the analysis ventilation and temperature rises, and the optimum design is achieved.

3. Winding and Insulation

Because of the high frequency of starting and stopping in generator-motor for pumped storage power plant, consideration must be given to the heat cycle applied to the windings. For the insulation of the stator winding, F resin/F insulation, which has shown no insulation breakdowns in the 20 years since it first came into use, is used. For this insulation, a test has been performed whereby 70 minute heat cycles are repeated 4,000 times at a temperature difference of about 120°C by inserting a model coil with Reobel transposition with a hollow conductor in a 4m core model and repeating electrical application and direct water cooling. It was found that there was almost no drop in the breakdown voltage and it has been proven that this insulation has sufficient reliability as insulation for generator-motor.

In the case of field windings, particularly in high speed machinery with large centrifugal forces, the thermal expansion of the winding is restricted by friction force due to the centrifugal force. Therefore, silver alloyed copper is used in generator-motor with many heat cycles so that no creep phenomenon will occur. Teflon type slip material is also used between the insulation flange and the winding to reduce the friction restrictive force against the conductor. After 10^4 cycle wear tests, no chages have been found in the lubricating effects from the initial values.

4. Bearings

With the higher speeds and larger capacities, the peripheral speeds and load of thrust bearings have increased and design conditions have become more severe. Especially in the case of generator-motor which require rotation in both directions, there are more difficulties with lubrication than in the case of bearings rotating in one direction only. It has become necessary to increase the number of investigations required to obtained stable characteristics under such conditions as elastic deformation of the pad due to oil film pressure, thermal deformation caused by temperature differences within the pad and oil film thickness during starting after temperature rises. Fuji Electric has established a computer program for the detailed analysis of oil film thickness, pressure distribution and temperature distribution, and optimum design is possible.

The MAGLAGER (magnetic bearing) developed 20 years ago by Fuji Electric and used without accidents, decreases thrust bearing loss caused in reversible thrust bearings and is an effective measure in the realization of high efficiency generator-motors. This MAGLAGER lift up the rotors by electromagnetic force and decreases the thrust load by means of applying direct current to the ring-shaped excitation winding, provided at the bearing bracket. This type of bearing has greatly improved the reliability of thrust bearings by facilitating the establishment of the oil film by strong excitation during starting, decreasing the static friction torque to make smooth starting, etc. It was used in the Chongpyong Power Plant. *Fig. 2* shows a typical characteristics curve giving the relation between the lifting force and exciting current.

5. Vibrations and Rigidity

Since hydraulic exciting force is generated in the pump

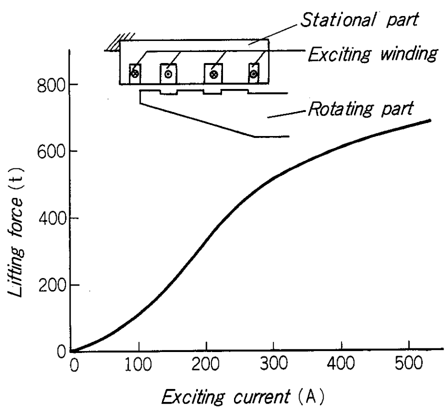

Fig. 2 Characteristics curve of MAGLAGER(magnetic thrust bearing)

turbine runner, it is necessary to take great care concerning vibrations. Fuji Electric has established two methods for the analysis of vibration response: random response analysis and direct response analysis. Using these methods, vibrations in each part and bearing counter forces are analyzed and it is possible to determine the required rigidity in various parts such as the shaft, the top and bottom brackets, the stator frame and the stay beam, and achieve the optimum design. It is impossible to avoid some vibrations in generator-motors in the transient stage and it is necessary to have appropriate supports and reinforcements for not only the main parts but also such parts as motor driven fans, air coolers and covers. Special consideration must also be given to prevention of looseness in the bolts in each part.

6. Fatigue

In generator-motor with high frequency of starting and stopping, careful consideration must be given in strength design to the fatigue phenomenon with respect to repeated centrifugal force and thermal expansion. Fuji Electric employs a sufficient safety factor with respect to the number of repetitions shown below in its design work:

1) 50 times for runaway speed
2) 10^3 times for speed increases during load interruption (more than 50 years at once a month)
3) 10^5 times for starting and stopping (more than 50 years at 4 times a day)

IV. CONSTRUCTION OF THE GENERATOR-MOTOR

As was described in III, the construction of each part is decided in accordance with design based on careful consideration of the characteristics of the generator-motor. The following sections describe the features of the construction and manufacturing method:

1. Construction

The bearing arrangement of generator-motor is generally of the semi-umbrella type in low speed machines but in high speed machines, the diameter of the thrust bearing oil tank is too large with respect to the rotor diameter. Therefore, the height can not always be decreased with the semi-umbrella type and the normal type with the thrust bearing located in the top part of the rotor is better from such standpoints as disassembly and inspection.

Such items as the bearing arrangement, bearing span, shaft diameter and rigidity of each part must be decided on the basis of detailed investigations of the dynamic response of the shaft system to shaft and bearing vibrations due to the exciting force from the pump turbine side and the unbalanced force of the rotating parts, etc.

In the Chongpyong generator-motor, the normal type was used on the basis of the results of detailed vibration and ventilation analysis. A section of this generator-motor is shown in *Fig. 3*.

To shorten bearing span in this generator-motor, the starting motor is placed on top of the upper guide bearing

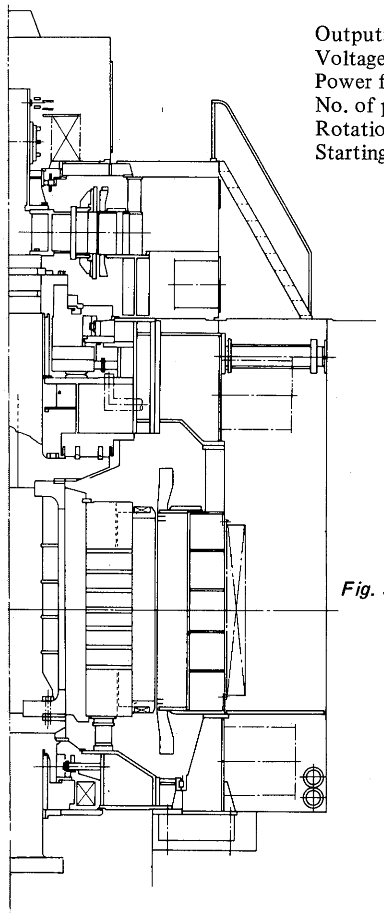

Fig. 3 Section of generator-motor (Chongpyong power plant)

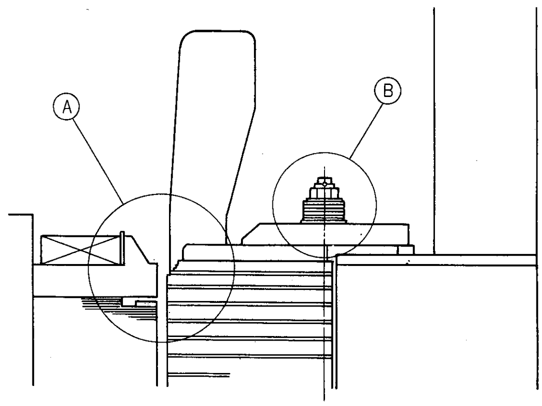

Fig. 4 Detail of stator and rotor core end portion

and the thrust and upper guide bearings are built into the upper bracket oil tank. The magnetic bearing is placed on the bottom side of the upper bracket. A stay beam with a metal spring is attached between the arm of the upper bracket and the foundation to limit vibrations and absorb thermal expansion.

A higher exciting force from the pump turbine side is transferred to the lower bracket which contains the lower guide bearing than to the upper bracket. Therefore, cotters are placed between the lower bracket and the ring base to increase the rigidity with respect to the guide bearing supports.

The forced ventilation system is used for ventilation and cooling, and motor-driven fans are attached between the upper bracket arms and on the outer periphery of the ring base. Cooling air from the air coolers is forced into the machine and a ventilation route is formed between the poles and from the center of the yoke to the stator core.

2. Stator

The stator frame is designed to have sufficient rigidity with respect to vibrations from the pump turbine, thermal expansion of the core and torques during short circuits.

As can be seen in the Ⓐ part of *Fig. 4*, the teeth of the top and bottom ends of the stator core are cutted off and slits are cut in the teeth to prevent local heating in the core because of leakage flux, especially during underexciting operation.

In generator-motor where there is a frequent repetition of heat cycles, careful consideration must be given to vibrations, looseness and buckling in the core. In the stacking of the core, the core is heated to promote rapid cure of the core insulation and Bellville springs are used in the core clamping studs as shown in *Fig. 4* Ⓑ to prevent a decrease in fastening pressure due to the cure. After core stacking, an induction test is performed in which the same magnetic flux as in actual operation is applied to the core to determine if this system has any parts which are resonanz with the vibration frequencies which occur during operation and if there is any local overheating. To prevent axial core vibrations due to leakage flux, core end blocks are bound mutually to the core to increase rigidity of the teeth.

The windings employ the F resin/F insulation coils as mentioned previously. This insulation is especially effective in generator-motor with a long core length and many heat cycles because the coefficient of thermal expansion is nearly equall with the copper. The winding and slot wedges are of the rigid support type so that there will be no drops because of vibrations and heat cycles.

3. Rotor

Since the most stress with respect to fatigue strength should be placed on the magnetic pole attachment part in high speed machinery, the notch effect with respect to dimensions and shapes are confirmed in experiments and the dimensions are decided by high precision calculations of stress and fatigue strength.

The field winding is made of silver alloyed copper, which has little creep, in the upper part. A teflon type slip material is used between the insulation flange and the conductor to prevent creep of the conductor.

The magnetic poles cân of the trapezoid type to eliminate partial forces in the peripheral direction of the field winding or the ordinary parallel type. The selection is made on the basis of overall investigations of the magnetude of the partial forces in the peripheral direction, the relation between the number of coil clamps and ventilation, the ease of coil manufacture, reliability, etc. In Fuji Electric generator-motor, parallel poles are used if there are 16 or more poles and the trapezoid type when there are less than 16 poles.

When the core is long, the overall torque and warp increases and therefore, a special lamination method known as block stacking is used for the magnetic poles so that the poles are manufactured as a unit with good dimensional accuracy.

When it is necessary to disassemble the yoke for transport, a construction in which segmental steel plates are stacked is used. When transport is possible without disassembly, a ring-shaped thick plate lamination construction which has good strength is used. In both cases, a ventilation duct is provided in the axial direction and sufficient cooling air is supplied to the poles and the center of the stator core. Attachment to the rotor hub is by means of a shrinkage fit with interference to a slightly over speed to prevent unbalances during operation. The keys between the yoke and rotor hub are T-shaped keys arranged at equal intervals on the periphery which prevent relative distortion with respect to either forward or rotation.

The brake ring is arranged on the periphery in segments and because of the thermal expansion of the segments during braking in large capacity machinery with frequent starting and stopping, there is the possibility that the fasting bolts will bend and fatigue failure will occur. To prevent this, a special collar is inserted in the fasting bolt holes and tightened so that the fasting bolts will not bend.

4. Bearing

The Fuji thrust bearing is designed on the basis of a detailed calculation of characteristics as described in **III, 4.** It is a reversible Michell bearing with a double plate spring. The slight level difference in the sliding surfaces at the time of installation is easily corrected by elastic deformation of the spring to make the load distribution uniform. No installation adjustments are required.

The oil lifter system is often employed to decrease the frictional torque and protect the bearing at the time of starting, but Fuji Electric employs the oil lifter system and the MAGLAGER to improve efficiency during operation for the bearings of high load reversible machinery operating under severe conditions. Later system also improves the reliability of thrust bearings.

Bearing cooling is performed by the circulation of oil by a built-in pump or by a separate motor-driven pump into an external oil cooler of good efficiency and direct spraying of the oil from the cooler on to the thrust pads. In the case of a built-in pump, experimental results have shown that there is a sudden drop in oil pressure due to mixing with air when the peripheral speed of the collar pump is high. Therefore, in high speed machinery, it is necessary to take measures to prevent the mixing in of air on the intake side and to change the shape of the spray holes on the discharge side.

In the case of the Chongpyong generator-motor, comparative investigations were performed with both systems and the motor driven pump system was used from the standpoint of reliability.

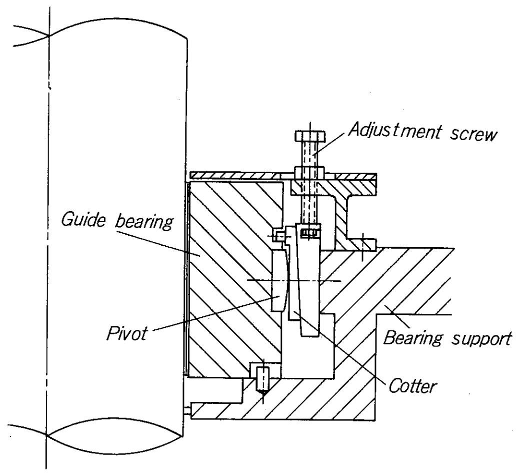

Fig. 5 Holding method of guide bearing

The guide bearing generally employs a segment type pivot system in which gap adjustment is possible. Previously, the rear surfaces of the segments were supported by studs but it was difficult to obtain sufficient rigidity because of dimensional and structural limitations in the screw part of the studs. As shown in *Fig. 5*, a new system in which the pivots are supported by two tapered cotters has recently been used. With this new system, the rigidity of the bearing support part can be much greater than in the former system and this aids in increasing the overall rigidity of the entire bearing support system. To suppress vibrations in the shaft system, it is necessary to make the damping coefficient of the oil film of the guide bearing as high as possible. The length of the bearings in the axial direction must be decided in consideration of not only the bearing load but also the damping capacity.

The shape of the bracket which transfers the bearing load to the base is the main factor in determining the value of the spring constant of the bearing supports. The distance between the center of the bearing and the point of load transfer by the bracket to the base must be as small as possible.

V. CONCLUSION

This article has described the points to be considered in the design and production of large capacity generator-motor and their construction. Fuji Electric has performed detailed investigations of the structure of each part of the generator-motor by means of experiments and computer analysis and it has become possible to manufacture highly reliable machines.