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495MW FRANCIS TURBINE AND GENERATOR FOR COLUMBIA RIVER REVELSTOKE PROJECT

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I. INTRODUCTION

The base design of the Phase I; 495 MW x 4 turbines and generators for the Revelstoke Power Station of the British Columbia Hydro and Power Authority (B.C.H.) of Canada has been completed and the turbines and generators are now under the construction with completion scheduled for 1984.

Fuji Electric has already delivered two 306 MW hydroelectric generating sets to B.C.H. for the Peace River Gordon M. Shrum Power Station and a 183 MW hydraulic turbine for the Jordan River Power Station. The present order was based on the excellent results of an evaluation of the reliability of our machines and technology from the operating records of these machines.

The Revelstoke Power Station is located on the Columbia River in the eastern part of British Columbia Canada's western province. It is the world's largest power station, having a final output of 3,000 MW generated by six generators using the abundant water resources of the Canadian Rockies. Since the unit capacity of the turbines and generators is also one of the world's largest we used the finite element method in all areas of design as well as the conventional design method, we made exhaustive studies of the design and manufacture of these machines to ensure high quality. Various techniques were also introduced for this purpose.

II. OUTLINE OF POWER STATION

Fig. 1 shows the outline of the Revelstoke Power Station. *Fig. 2* shows the construction of the power station and the layout of the equipment.

1. Rating

1) Turbine
Type: Vertical shaft single wheel Francis turbine
Output: 495/467/370 MW
Net head: 130.15/126.8/110m
Rotating speed: 112.5 rpm

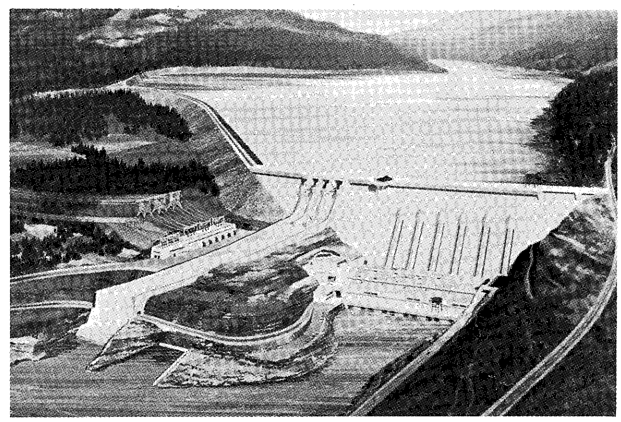

Fig. 1 Outline of power station

Specific speed: 180.6 (m · kW)

2) Generator
Type: Vertical shaft umbrella type synchronous generator
Capacity: 485 MVA (winding temperature: 100°C)
550 MVA (winding temperature: 120°C)
Voltage: 16 kV
Frequency: 60 Hz
Power factor: 0.95 (lagging)
Rotating speed: 112.5 rpm (64 poles)
Direct-axis reactance: $Xdu \leqq 100\%$ (unsaturated value)
Transient reactance: $X'ds \leqq 23\%$ (saturated value)
Flywheel effect: 129,000 t·m^2
Maximum thrust load: 2,050 t

2. Features

1) Turbine

(1) The turbine casing inlet has a diameter of 7m. Our unique parallel stay ring design reduces stress concentration.

(2) The main shaft was made from a mandrel forging to improve quality and reduce the shipping weight.

(3) The runner weighs about 160 t and is constructed in two parts to meet transport limitations. The parts are welded together at the site.

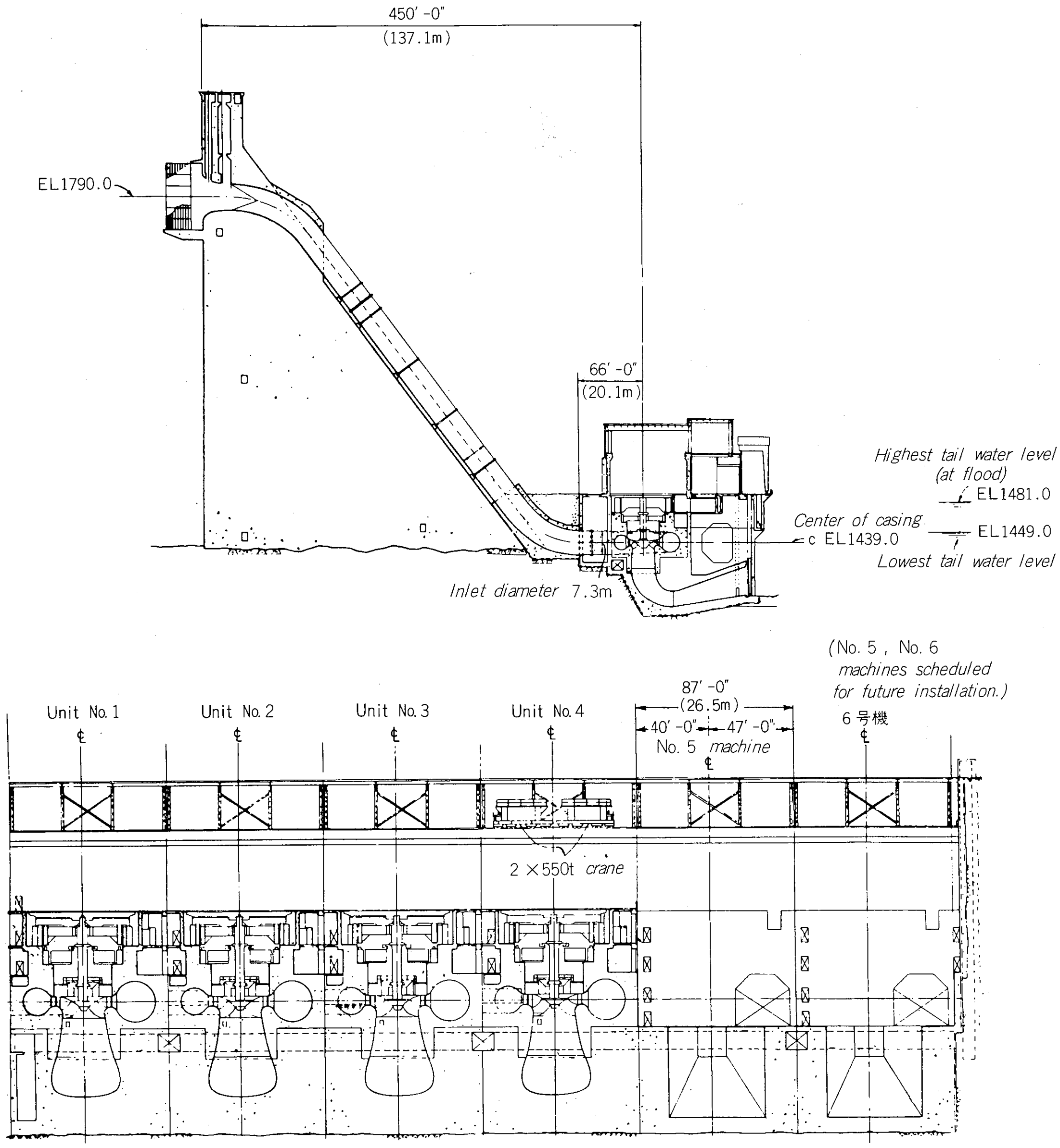

Fig. 2 Sectional view of power station

2) Generator

(1) The generator rotor is a large type having a 13.6m outside diameter.

(2) The thrust bearing is our unique Mitchell type. 2,000t Capacity of thrust bearing is one of the highest in the world.

(3) Stator core lamination stator coil assembly, rotor core lamination and pole assembly are performed at the site.

III. TURBINE

1) Performances

1) Development of runner

The turbine required a high average load efficiency of 93%. The smallest possible runner diameter was also required because of transport limitation. Therefore, a runner featuring good efficiency and caviation characteristics had to be developed.

To improve these characteristics, the runner internal flow was computer analyzed with the RUNFLAS flow analysis program and the blade shape was optimized during the development of this turbine. An increase in the losses was suppressed and an optimum blade shape without any local pressure drop was obtained by reducing the runner diameter resulting in design a runner featuring superior efficiency and cavitation characteristics.

2) Draft tube development

To reduce the amount of concrete required for the power station, the draft tube outlet width is approximate 23.5 m, almost the same value as the main machine spacing, which is determined by the dimensions of the spiral casing. Because of the need for civil engineering strength, two pier noses had to be provided inside the draft tube.

Since the piers inside the draft tube obstruct the smooth circular flow, their effect on the diffuser efficiency is substantial. However, during operation outside the design point, the flow is complex, three-dimensional, and accompanied by swirling, so the performance can not be forecast by numerical analysis.

Therefore, the shape of the draft tube was optimized by comparison tests with a model turbine.

Fig. 3 shows the results of the model tests with a conventional draft tube without piers and a draft tube with two piers. When two piers are provided, the drop in efficiency, especially at the large flow side is noticeable and is about 0.7%. The results of model comparison tests made by changing the various design parameters showed the following:

(1) The effect of the area expansion rate up to pier nose is large.

(2) The effect of the area distribution of the three channels which are divided by the two piers is large.

The optimum parameters were selected and a new draft tube was designed from the above. The broken line in *Fig. 3* shows the results of the model tests. There is no drop in efficiency at the large flow side and the efficiency was improved up to a level equal to that of the draft tube without piers.

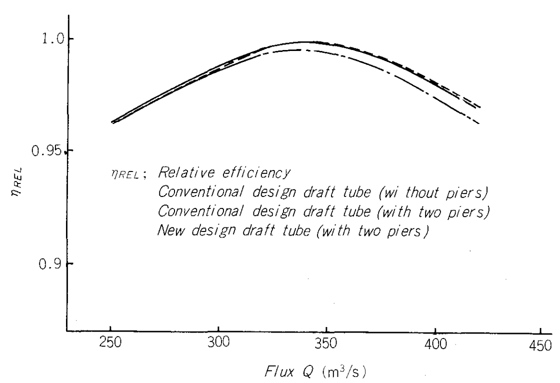

Fig. 3 Effect of draft tube shape in efficiency

3) Model tests

Model tests are extremely important in grasping the wide range of performances of a turbine. Higher measurement accuracy than in the past is especially important in model tests on large high capacity and high efficiency evaluation turbines such as this turbine. Our model test facility is equipped with a computerized automatic measurement system and data processing system and permits extremely accurate performance measurement.

In developing this turbine, we took the opportunity to make comparison experiments with the same model at Swiss Federal Institute of Technology Lausanne of Switzerland, a third party organization, and our test facilities.

Fig. 4 compares the results of the tests conducted at both facilities. The efficiency difference between the results of the two facilities was within about 0.2%. This proved that the measurement accuracy of our model testing facility is on the same level as that of the Lausanne laboratory, a worldwide research organization.

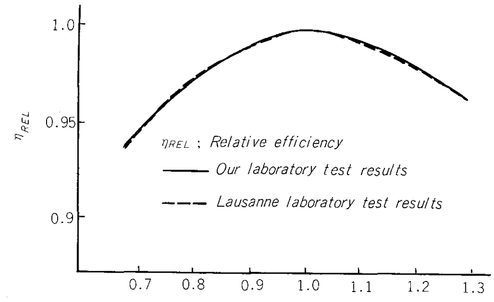

Fig. 4 Comparison of measured model turbine efficiency

The shape of each part of the turbine was optimized from both numerical analysis and model tests and a turbine that amply satisfies the stringent specifications of the actual machine was developed.

2. Construction of turbine

Fig. 5 shows a sectional view of the turbine and generator.

This power station does not have an inlet valve, A flexible coupling and closure section are connected between the penstock and spiral casing.

The flexible coupling consists of a 7,315 mm (24 ft) inside diameter, 1,829 mm (6 ft) long coupling section having a site welded construction and a two part flange welded coupling section. After the site assembly, a 345 psi hydrostatic pressure test is performed.

The closure section is an installed and adjusted 3,658 mm (12 ft) short tube which is divided into four parts for shipment. The spiral casing is embedded in concrete and the flexible coupling is then welded to its inlet.

Since the power station is in an especially cold region, material used for the closure section welding structure is SM50B Modified having a special Charpy impact value of 15 ft-lb or greater at –34°C.

The spiral casing has a 7,315 mm (24 ft) inlet diameter, 11,582 mm (38 ft) long inlet straight pipe section, and 59 mm maximum scroll end section thickness. It is divided into 29 parts for shipment, then assembled and welded into a single unit with the stay ring at the site, after which a 395 psi hydrostatic pressure test is performed.

Because of the large size of the spiral casing and the pressures applied during concrete pouring, casing distortion and embedded effects were analyzed by the finite element method, resulting in a new pipe jack arrangement.

The casing is made of the same weldable structural steel plate (ie SM50B Modified) as the flexible coupling and closure section, with a Charpy impact strength of 15 ft-lb at –18°C.

The stay ring is our unique parallel type design featuring superior performance and strength and a highly reliable rational construction. (This type of stay ring is already in operation in the Peace River Gordon M. Shrum power

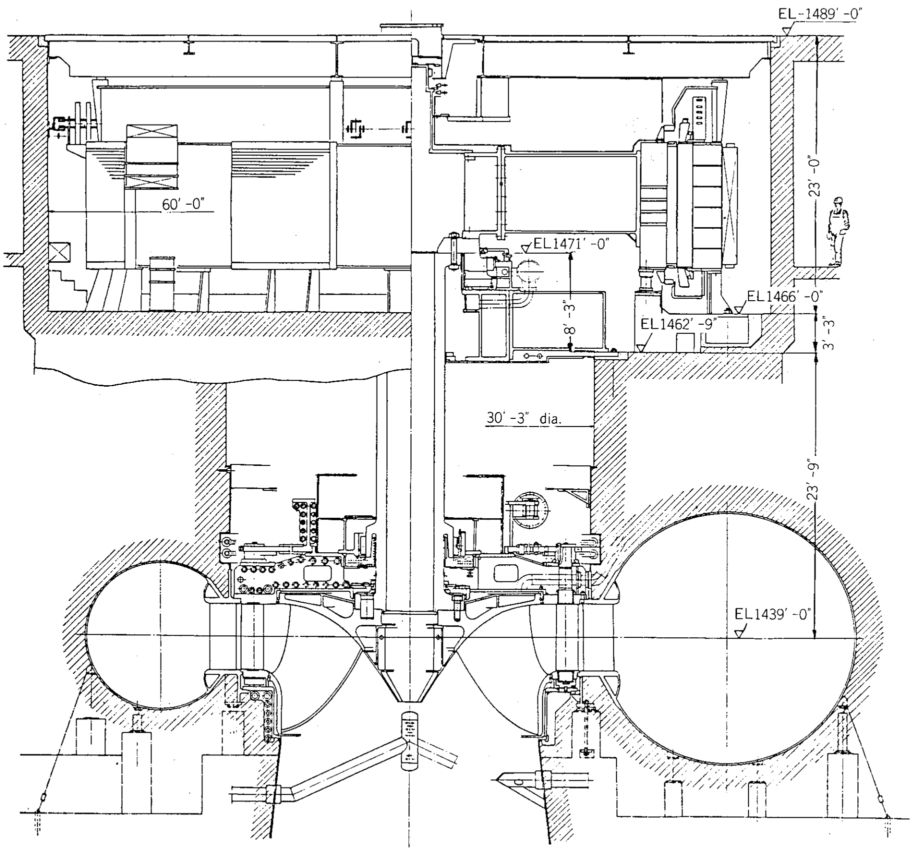

Fig. 5 Sectional view of turbine and generator

station 306 MW turbine, etc. already supplied to the same customer.) The stress and deformation of each part under all operating conditions were analyzed by the finite elements method using symmetrical shaft and three dimension programs. The stay ring consists of four bolted sections. Since it is an extremely large part having an outside diameter of about 11.5 m, height of approximately 3.6 m and a gross weight of about 200 t, special tools are provided to facilitate factory and site work.

Fig. 6 shows the stay ring being manufactured.

The head cover consists of two bolted flanged sections. The coupling flange with the stray ring is made of extremely thick plate to increase its rigidity and simplify its construction. Since the deformation of each part is extremely important from the standpoint of design of structures such as the head cover of a large turbine, the entire turbine was analyzed for each operating condition by the finite element method. The results of these analyses confirmed the head cover, main shaft, and bearing support deformations, runner seal section gap change, bending of the guide vane bearing center line, guide vane top and bottom gap change, guide ring sliding section gap change, radial deformation, runner seal section gap change, bending and other values. Of all the stationary parts of a turbine, the head cover is the heaviest part requiring maintenance. Since its weight exceeds 100 t, special dismantling and reassembly tools are provided.

The bottom cover is bolted to the discharge ring, consists of two bolted flanged sections, and is made of extremely thick plate to increase its rigidity. The discharge

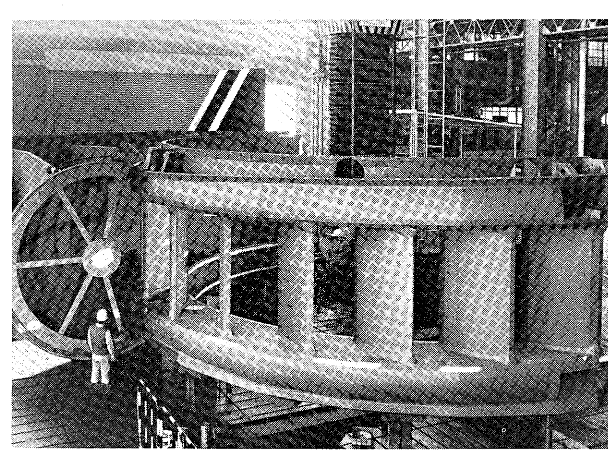

Fig. 6 Stay ring under manufacturing

ring has an 18-8 stainless steel overlay at the face opposite the bottom of the runner band and near the throat that connects to the draft tube. A sheet liner made of 13Cr stainless steel and a bronze gate seal prevent water leakage when the wicket gate is fully closed. The head and bottom cover are provided 13Cr 3.8Ni stainless steel wearing rings at the face opposite the runner seal.

The guide vane is carbon cast steel and uses vanes which can self closed from a 20% opening if the oil pressure fails. Moreover, 18-8 stainless steel is overlayed at the top and bottom surfaces. Solid lubricant sealed embedded type oilless bearings are used for the wicket gate and its operating mechanism.

Four hydraulic opening/closing servomotors are supported by a pin joint at the pit liner section. The wicket gate link mechanism at the bottom can be dismantled by lifting the servomotors with this pin as the support point.

The runner is integrally cost and then split into two sections because of transportation limitations. The crown is bolted together and the sectioned areas of the band and blades are welded at site. Finish marking of the runner periphery and final dynamic balancing of the runner are performed at site by means of special dynamic balancing and cutting machines. The points at which cavitation pitching occurs easily are overlayed with 18-8 stainless steel and the runner liner at both the runner crown and band sides was eliminated. Since the runner dimensions are large and there is not much margin in shipping limits, the runner was shipped on a special shipping frame.

The turbine shaft is integrated with the generator shaft and is made of a mandrel forging. The shaft has a diameter of 1,700 mm, length of about 9,200 mm, and gross weight of 100 t to improve its quality and reduce the shipping weight.

The shaft seal is our unique axial (shaft flange) carbon packing type, featuring superior sealing performance. A compressed air operated maintenance seal is provided at the bottom of the main shaft seal so the carbon packing can be replaced without dewatering the casing.

The draft tube is the elbow type. The 13 m liner and 3,048 mm pier nose sections are made of steel. The other parts are made of concrete. The upper draft is shipped in four sections and the lower draft in eight sections, and are welded at site. The upper draft is welded to the discharge ring at the site. The air supply to the draft tube during partial load operation employs a natural air admission system. An air cylinder operated butterfly valve which operates according to the opening of the wicket gate is provided for air admission.

Synchronous condenser operation of the No. 1 and No. 2 machines is possible. An air compressor is used as the water depression system.

IV. GENERATOR

1. Construction of main parts

Fig. 5 shows the complete umbrella type construction of this machine. Its overall dimensions are 18m x 18m x 8m (height), making it the one of the largest turbine generators in the world.

Stator core dimensions of 13.6m inside diameter and approximately 3.1m length were selected as a result of intensive studies taking into account the $X'ds \leqq 23\%$ transient reactance and winding temperature rise that limit machine design, and the crane capacity limit, including the lifting beam, of 1,000 t when lifting the rotor. The construction of this generator is outlined below.

1) Stator

The stator frame diameter is 16 m and is separated into four parts for shipment. The stator core laminations are completely inter leaved and installed to the stator frame through studs at the site. When the stator expands radially through temperature rise high internal stresses and wave deformation can easily occur in the core. The following measures were taken with this machine to prevent this:

(1) The core is laminated by half lap of the multiple core sectors integrated into a single block and block sector stacking is employed to reduce the internal friction force between the cores.

(2) The stud holes in the core are made elliptical and special studs and welding fitting were used to prevent constriction in the stator frame and core radial direction.

(3) Radial torque pins were used to relieve the thermal expansion constraining force between the stator fram frame and the base.

This construction was also used in the No. 9 and 10 machines (capacity 316 MVA) of the Peace River Gordon M. Shrum Power Plant which were previously manufactured and are operating with good results. However, reliability was increased one full magnitude by adding further improvements.

The stator winding is wave winding of the roebel transposed one turn coil type. Each phase is composed of 8 parallel branches. The main insulation is F resin/F insulation consisting mainly of epoxy resin. The unbalanced current detecting current transformer is installed inside each parallel circuit of this machine to detect short circuit faults between bars and constant monitoring is possible.

2) Rotor

The rotor consists of a thrust block directly coupled on the turbine shaft and rotor spider, thin plate laminated rim, poles, axial fan, and top shaft.

The pole core is installed on the rotor rim by a dovetail groove. A damper winding with interpole connecting bar is provided at the head of the poles. The flux distribution of the pole head is magnetically deflected at the trailing side by operation, and an unbalance is produced due to temperature rise and the electromagnetic force between the damper winding, causing abnormal deformation of the winding, etc. To counter this, asymmetrical type damping windings are used and the windings are made of silver alloy oxygen free copper having reliable hydrogen embrittlement and creep characteristics.

The field winding is a profile copper band which increases the cooling area and reduces the temperature rise. Special consideration has been given to the interpole connections to ensure safe operation against thermal and mechanical displacement of the winding by starting and stopping.

Recently, the need for constant monitoring of the field winding temperature has increased from the standpoints of operation and maintenance. This machine employs a system that constantly monitors the winding temperature. Signals from copper temperature sensors embedded in the winding are transmitted through converters and shaft slip rings to the temperature control system.

When the rotor diameter becomes large, the expansion

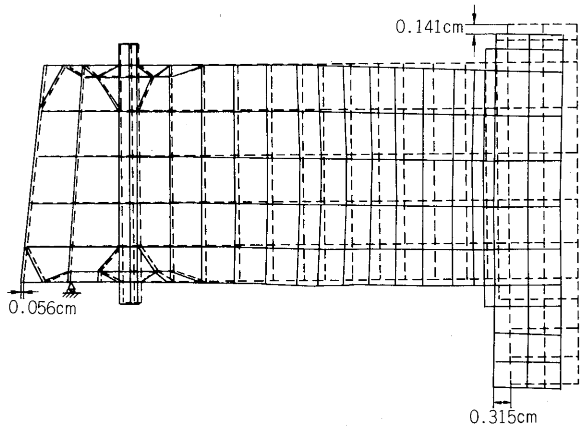

Fig. 7 Deformation of rotor spider after shrink-fitting of rim

of the rotor rim during operation increases so the generator main gap is substantially different when the machine is stopped and when it is running. Therefore, expansion of the rotor and expansion of the stator core caused by temperature rise must be amply studied and the gap value must be set to cover the above mentioned conditions during installation.

In addition to these studies, this machine's constructed so this air gap can be easily adjusted with liners at the poles mounting section. The rotor spider consists of a single ring boss and eight arms. *Fig. 7* shows the results of FEM deformation analysis after shrink fitting.

The spider is constructed so that the rotor rim remains in the pit and only the rotor spider is lifted out when dismantling the turbine.

3) Bearing

The thrust bearing is a Mitchell type bearing which is supported by double disk springs and receives a thrust load of approximately 2,050 t at 14 pads. The oil film thickness, temperature, and pressure distribution on the pads during operation was analyzed by computer, taking the thermal deformation of the pads into account, and were selected to guarantee a bearing temperature of 70°C at the highest cooling water temperature.

An oil lifter supplies high pressure oil to the thrust bearing slideways and facilitates the formation of an oil film during starting and stopping.

The segmental type guide bearing is immersed the thrust oil tank and bearing gap adjustment and transmission of the radial load are performed by a cotter at the rear of the pads.

The bottom bracket is a spider type consisting of six 10 m diameter arms. Four of the arms are removed and shipped as a unit, because of transportation limitations.

A special refinement was used at the base mounting section so the thermal expansion force of the bracket caused by the oil tank oil temperature is not transmitted directly to the foundation.

2. Automatic cooling air temperature controller

This machine is equipped with a device that controls the cooling water flow of the air cooler automatically. Generally, the cooler design water flow is selected so the cooling air temperature is below the specified value at the generator maximum output at the highest cooling water temperature. However, the cooling temperature is maximum only during the short summer period and is fairly low during the remainder of the year. Therefore, the cooling water flow during most of the year is not used.

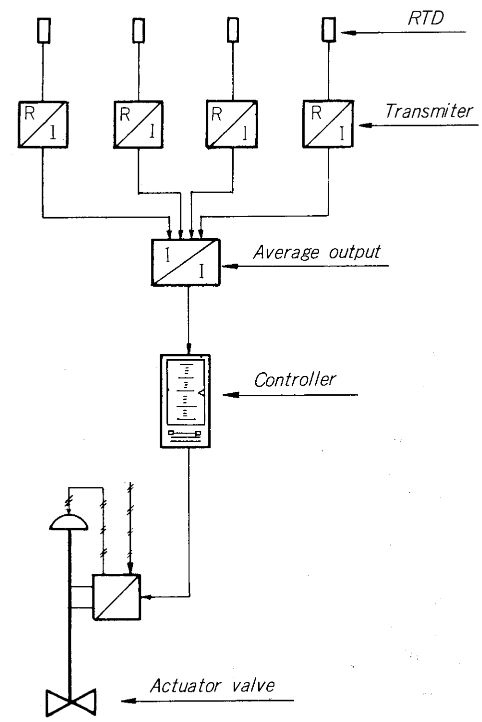

Fig. 8 Cooling air temperature control system

The resistance thermometer and automatic flow regulating valve of this machine adjust the water flow so the mean cooling air temperature remains constant at 25°C. *Fig. 8* shows the block diagram of the cooling air temperature control system.

With this machine, this system can be expected to provide an annual water saving of 1,500,000 tons per generator. This system also reduces the heat change accompanying generator load changes and can also be expected to increase the reliability of the machine.

3. Others

The 19m x 19m top cover which covers the top of the wind passage is an acoustic cover that has been especially processed with a high noise reducing effect matched to the STC45 class (transmission loss effect greater than 45 dB at 500 Hz) stipulated in ASTM-E413. This acoustic treating effect is more than 20 dB better than the conventional cover.

This machine has 16 brake jacks, eight air-operated air louvers for heating air intake during winter period, and a complete spray type fire extinguishing system.