UDC 621. 224. 24+621. 313. 322

LARGE CAPACITY FRANCIS TURBINE AND GENERATOR FOR CETHANA POWER STATION, AUSTRALIA

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I. INTRODUCTION

Fuji Electric has completed a 101,600 kw Francis turbine and 100,000 kva generator for the Cethana Power Station which forms the nucleus of a power development in the Mersey-Forth river basin now being constructed by the Hydro-Electric Commission of Tasmania in Australia. This equipment has already been delivered and is scheduled to put into operation in the early next year. At present the equipment is being installed at the site.

This power station has been planned as a completely underground type and from the viewpoint of economy, it is desirable that the dimensions of the power house be as small as possible and that the period of construction be as short as possible. For this reason, it was most advantageous to manufacture both the turbine and generator in a single manufacturer so that more close tie up is achieved in the design and manufacturing of the equipment which enable the power plant to be economical as well as better in terms of performance and reliability. Exhaustive investigations were carried out and various new techniques were employed in particular so that the required capacity of overhead travelling crane could be reduced, the manufacturing and erection time shortened and maintenance simplified.

The new techniques used by Fuji Electric in this equipment show trends to achieve economy in turbines and generators which will no doubt increase unit capacity in future. The company has also gained considerable confidence in the design and manufacture of large capacity turbines and generators through the successful completion of this equipment.

This article will describe the main features of this equipment, most of which are based on these new techniques.

II. OUTLINE OF THE POWER STATION

The Mersey-Forth Power Development has been planned to supply power in the river bed area of the Mersey and Forth Rivers which are located in the north west part of Tasmania. A total of seven power stations are to be built including the Cethana Power Station introduced in the article, as well as the Lemonthyme (58.2 Mw), Wilmot (32.9 Mw) and Fisher (47.5 Mw) stations to which the main equipment has been delivered by Fuji Electric and which are now in operation or soon will be.

Fig. 1 is an outline of this power scheme. The water from the Mersey River and it tributary, the Fisher River is stored at the Parangana Dam. From there is lead to the Lemonthyme Power Station for about 8 km via very long pressurized underground conduits and penstock. Here the water flows into the Forth River. The water from the Forth's tributary, the Wilmot River, is also led from the Wilmot Dam to the Wilmot Power Station through about 4.6 km long pressurized tunnel and penstock. At this point, it is discharged into the Forth River. These waters and the water of the Forth River itself are stored at the Cethana Dam which is located in about the middle of the Forth River. Directly below the dam is the Cethana Power Station. Water is supplied to this station by means of a vertical shaft covered

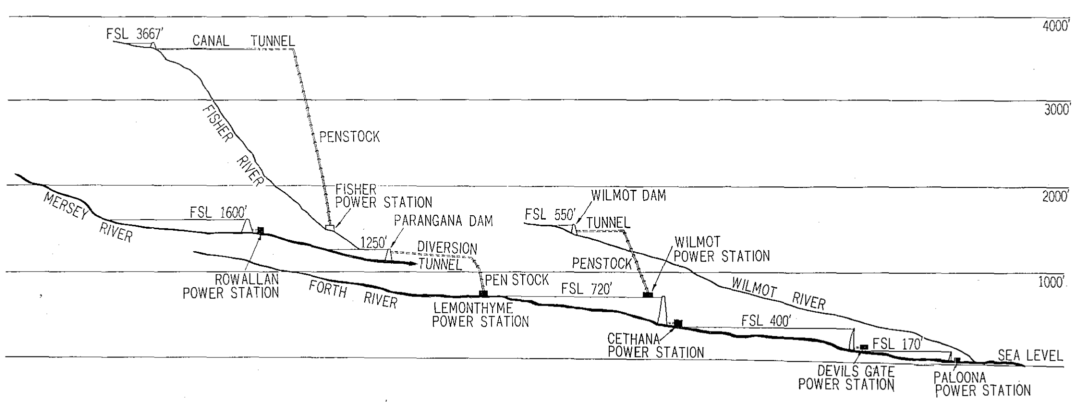
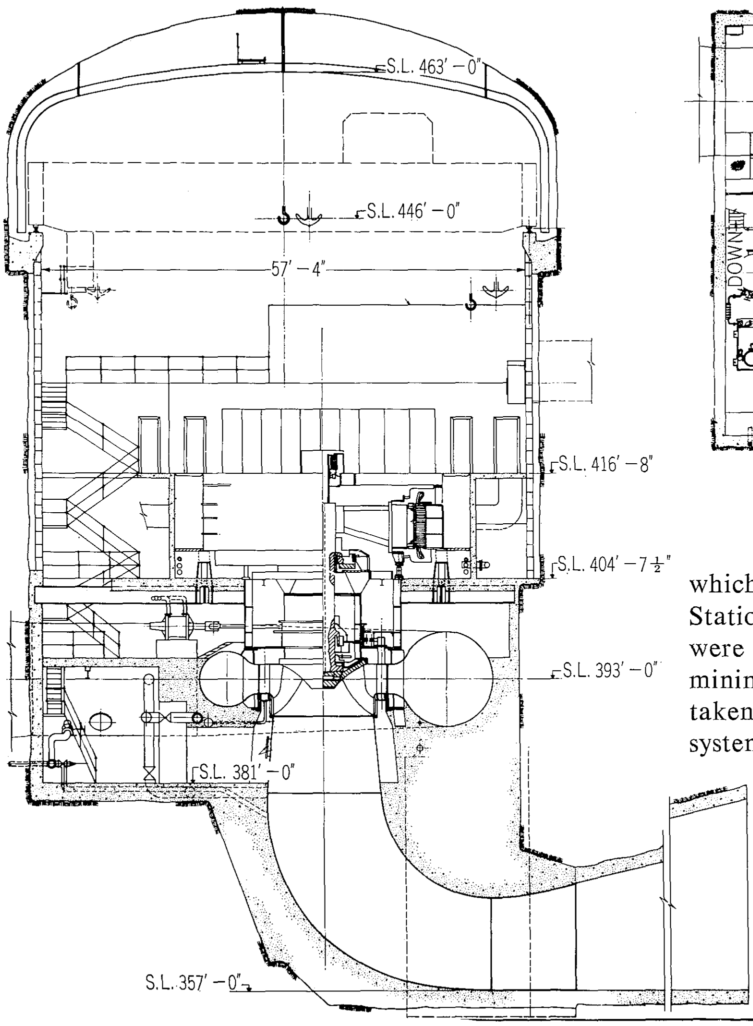
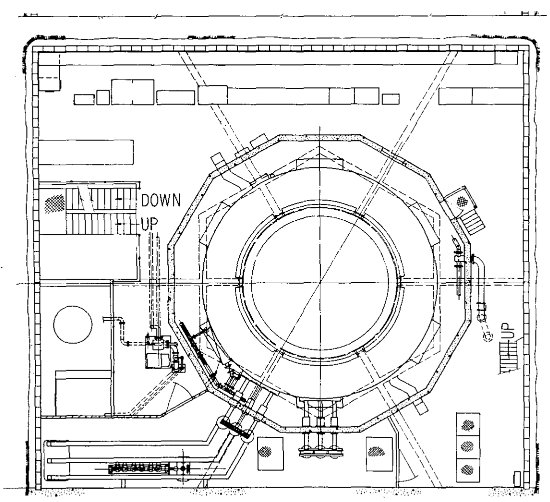


Fig. 1 Schema of Mersey-Forth Power Development



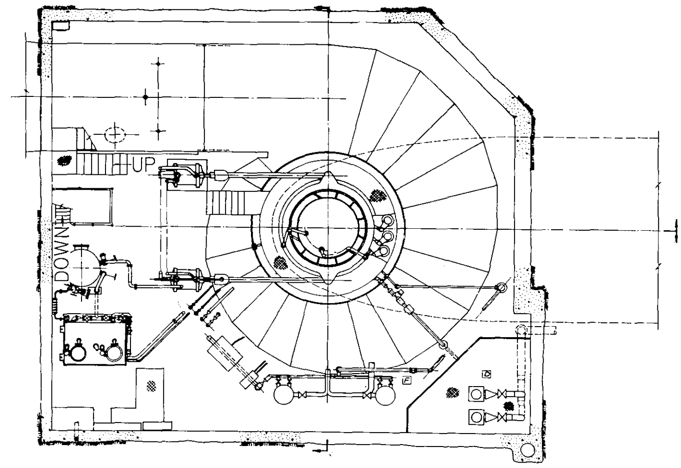
(a) Section power house



(b) Plan of operating floor S.L. 416'-8"

inside with a liner. The water then flows into the Devil's Gate Dam downstream.

This Power Station as well as the other six are designed for fully automatic operation and are remote controlled by means of a power line transmission system from the Sheffield Control Center



(c) Plan of turbine floor S.L. 401'-6"

Fig. 2 Machine hall general arrangement

which is comparatively near the Devil's Gate Power Station. Therefore the power station equipment were required to operate without any attendant for minimum two weeks. Due considerations have been taken of the governor oil, feed-water and lubrication system and also various control equipment.

Since the station is completely underground, the tailrace surge tank is omitted and as a result the length of the tailrace tunnel is about 200 m. Therefore in order to prevent the water column separation phenomena from occurring in the tailrace when the load is rejected, the flow rate in the draft tube is limited to about 2 m/sec and the guide vane closing time was selected as 12 sec, which is a relatively long time. On the other hand, machine inertia parameter of 7.5 sec. or over for generator is selected in respect to the system construction, and consequently a maximum momentary speed rise of 60% is employed. This is rather a very high value in comparison with the conventional machine.

In order to make the machine compact, turbine with record-breaking high specific speed of 206 (m-kw) is used for a head of about 100 m.

When planning and designing the power station equipment, very careful investigations were carried out so as to reduce the power house dimensions i.e. the dimensions of the main equipment, and cut down on construction period so as to lower construction costs. As a result, the following special techniques were incorporated.

1) The upper half of the turbine casing is exposed and only the lower half is embedded in concrete. Therefore the amount of concrete required in reduced and the turbine room's ceiling is lower which means that the overall height of power house.

2) In order to reduce the construction period and also reduce the required volume of concreate the generator is supported by means of a steel barrel.

3) In order to reduce the capacity of the over-head

travelling crane and make the power house construction more economical, a special assembly system was used for the alternator rotor. As a result, the capacity of the crane could be only 25% of that when the rotor complete is lifted as is usual.

4) In order to lower the machine height and simplify assembly, only one common shaft is provided for both the turbine and alternator. The alternator thrust bearing is supported on the top cover of the turbine.

For more details concerning the details of above features as well as the turbine and the alternator, refer to *Fig. 2* and the following sections.

III. TURBINE

1. Turbine Specifications

No. of units	1
Type	Vertical-shaft, single-runner, single discharge spiral-type Francis turbine
Output	At maximum net head: 101,600 kw
	At rated net head: 100,000 kw
	At minimum net head: 90,500 kw
Net head	Maximum: 98.76 m (324 ft)
	Rated: 97.69 m (320.5 ft)
	Minimum: 91.74 m (301 ft)
Speed	200 rpm
Specific speed	206 (m-kw)

2. Turbine Performance

Since power demands increased more than was expected, excavation of the power station was commenced before the tender was issued in order to speed up the start of service operation and the turbine center level was fixed to give a suction head of only −2.1 m. However, noticeable high specific speed turbine is adopted to make the machine size compact, as described above. Since it was necessary to develop a turbine runner with extremely superior cavitation characteristics, several model runners were built and very careful model tests were carried out in respect to cavitation as well as efficiency performance. In this way a runner was developed in which there was almost no cavitation at the plant's cavitation coefficient.

Since there is no tailrace surge tank in spite of the long tailrace conduits of about 200 m, a detailed analysis was made with a computer in considering with the possibility of the water column separation when the load is rejected, and the proper air admission system was established to suppress abnormal negative pressure in the tailrace which may produce water hammer when recombination of the water column occurs. *Fig. 3* shows computed results of the speed increases and water pressure changes in the tailrace and penstock when air is admitted under a full load rejection.

Model test equipment with a tailrace of about 100 m long was also built and the authenticity of the results

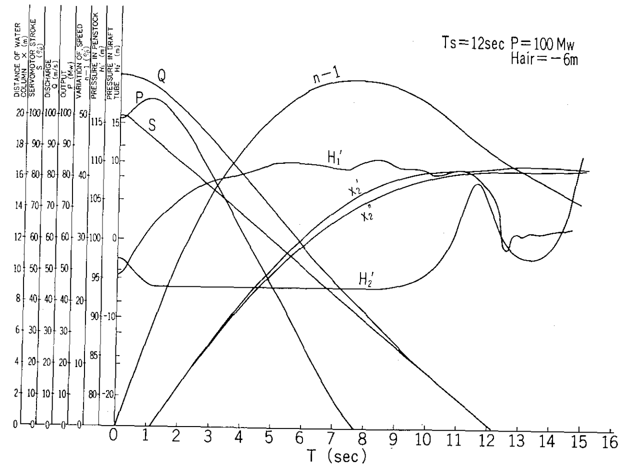


Fig. 3 Computed results of transient phenomena with air admission

from the computers were checked and the detailed research into the water column separation phenomenon was carried out. *Fig. 4* shows an outer view of the test equipment with a tailrace about 100 m long and *Fig. 5* shows actual test results and computed results of transient phenomena during load rejection, including the water column separation in the tailrace. For further details concerning the results of research into the water column separation phenomenon in this type of draft tube, refer to the previous report. (Fuji Electric Journal Vol. 41, No. 11, 1968).

3. Turbine Construction

Fig. 6 shows a section of the water turbine and alternator. The spiral casing is made of high tension steel (tensile strength of 60 kg/cm^2) with a maximum plate thickness of 21 mm. For purposes of transport, it was delivered in 13 sections and at the site it was welded together by the customer under supervision of Fuji Electric engineer. Hydraulic pressure tests were then conducted. The casing was embedded in concrete up to just above the center line of the turbine and the upper half remains exposed. The generator is supported by a steel plate barrel placed on top of the stay ring and six steel reinforced beams located on the underside of the generator floor. The thrust bearing which supports the weights of the rotating parts of the generator

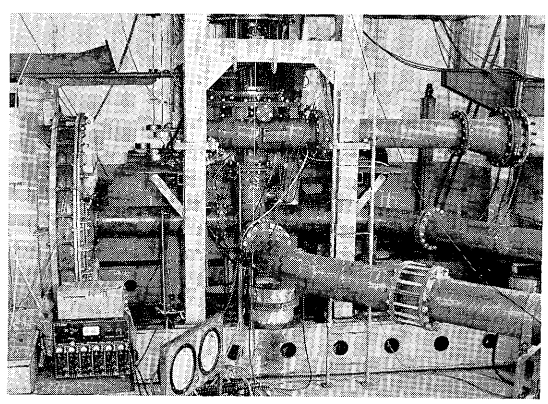


Fig. 4 Test plant

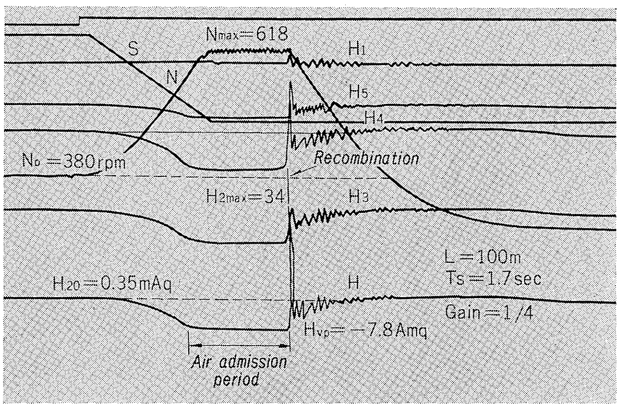


Fig. 5 (a) Results of transient phenomena with water column separation

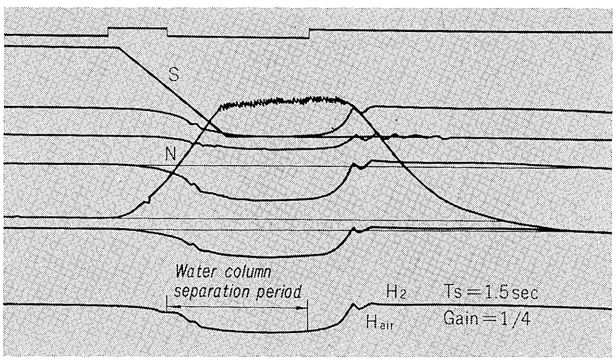


Fig. 5 (b) Results of transient phenomena with air admission

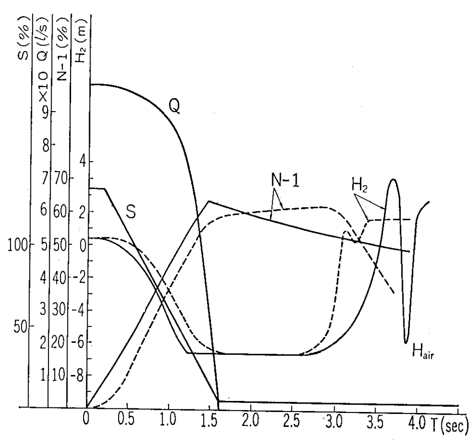


Fig. 5 (c) Computed results of transient phenomena with air admission

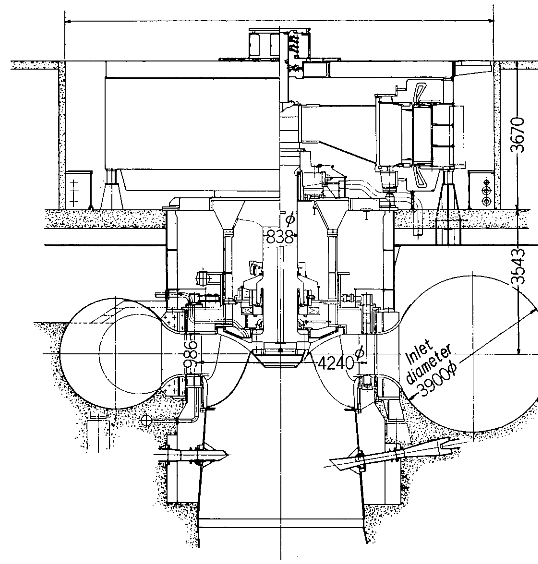


Fig. 6 Section water turbine and alternator

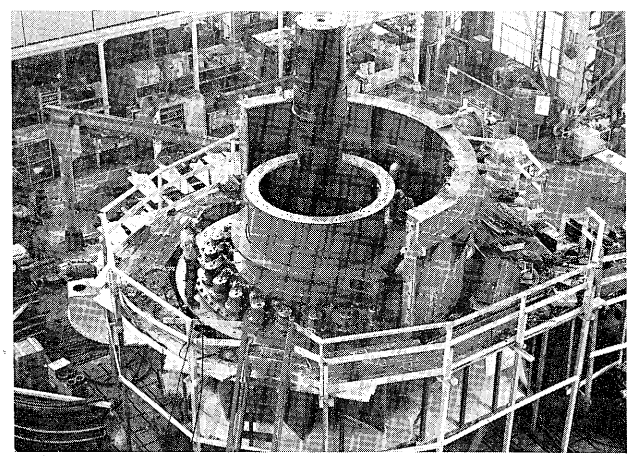


Fig. 7 Water turbine under factory trial assembling

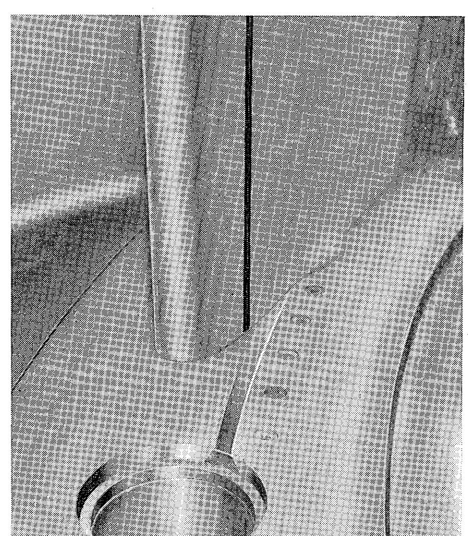


Fig. 8 Guide vane rubber seal

and the turbine are attached to the top of the bearing base on the top cover of the turbine.

The guide vanes are made of 13% chrome cast steel and rubber seals are provided at the clearances between the closing surfaces and the upper and lower facing plates in order to minimize leakage water when the guide vanes are fully closed during synchronous condenser operation. The guide vane bearing employs the nonlubricated type of bearing which was also used in the already completed Lemonthyme and Wilmot power stations. The bearing of link mechanism and of guide ring employ a bearing metal which consists of teflon coated on the surface of porous bronze bearing metal. Absolutely no lubricants are required with this type of bearing and maintenance is very easy because there is no grease

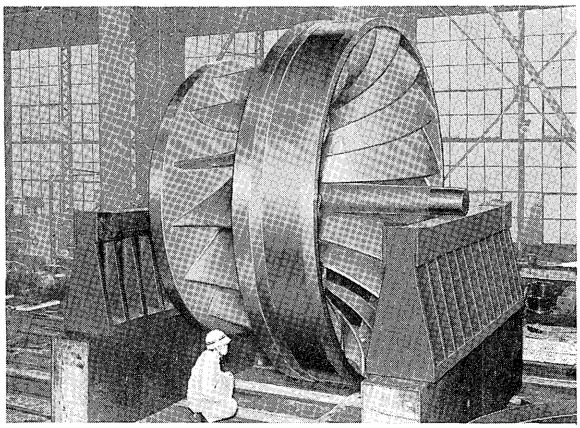


Fig. 9 Turbine runner

lubricating equipment which is always used in ordinary bearings.

The lower guide vane bearings can be dismantled downward through the space around the upper draft tube liner to facilitate maintenance easily. Therefore the upper draft tube liner is exposed and not embedded in concrete.

The runner is made of a single casting of 13% chrome steel. It is connected to the main shaft by means of reamer bolts.

The turbine shaft forms a common shaft with the generator shaft and therefore the overall cost of the turbine and generator is considerably reduced due also

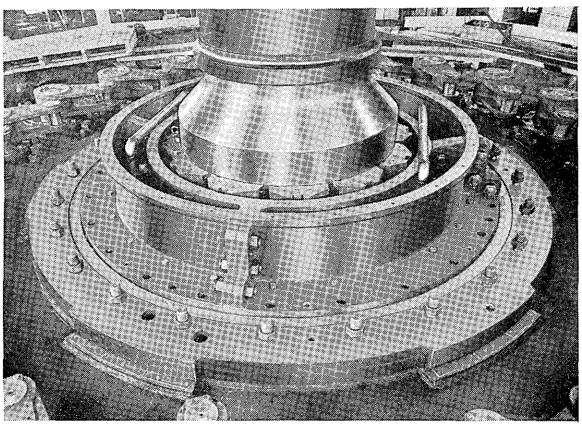


Fig. 10 Turbine guide bearing

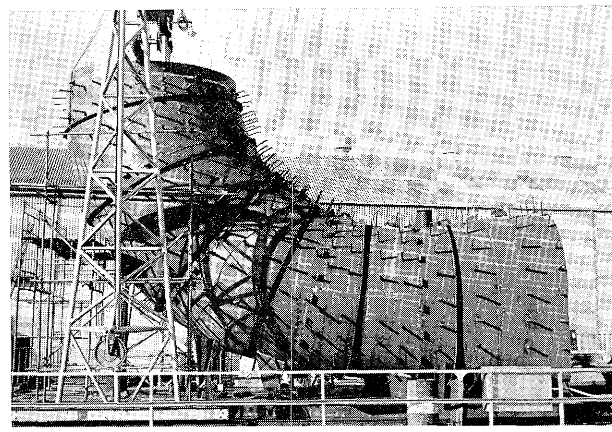


Fig. 11 Draft tube liner

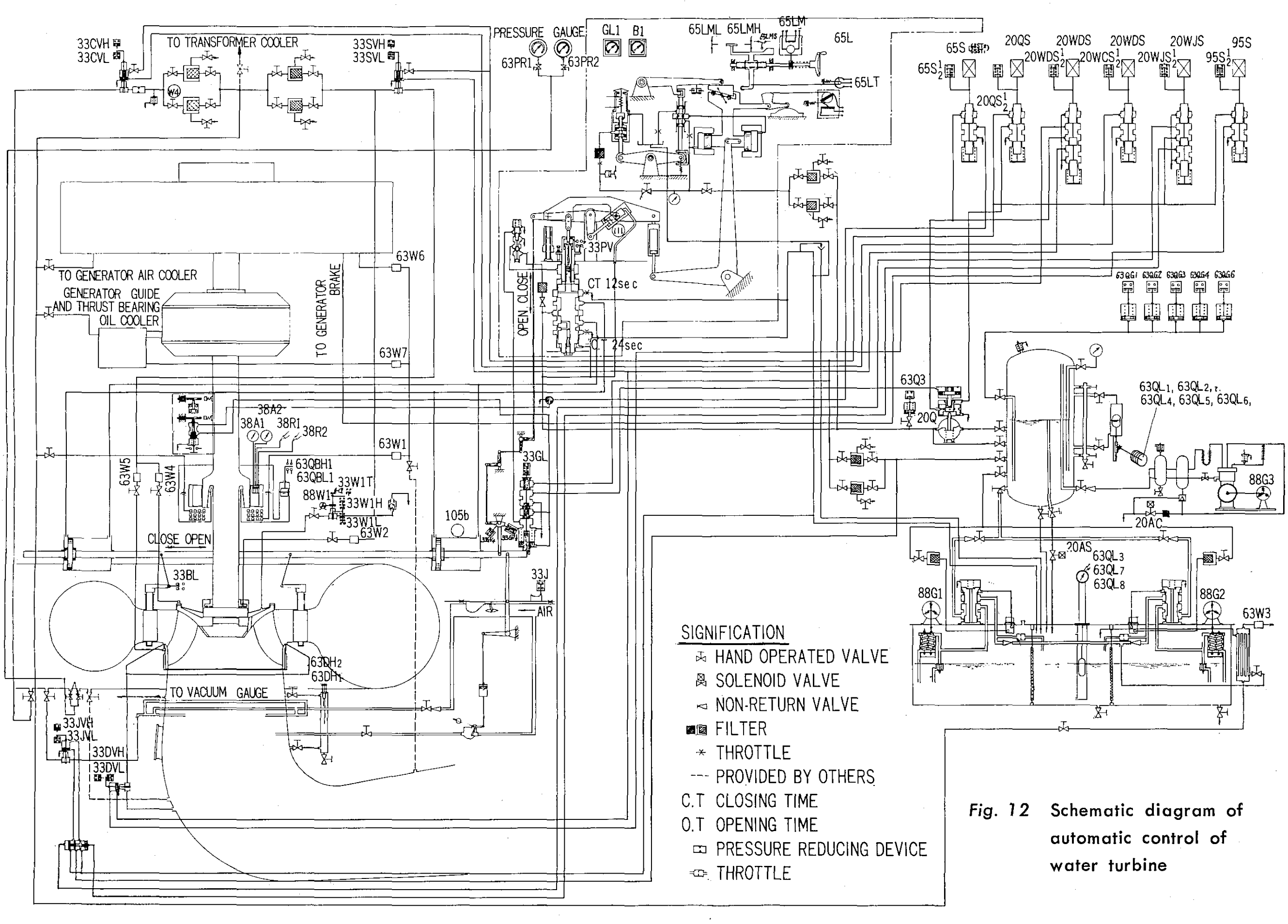


Fig. 12 **Schematic diagram of automatic control of water turbine**

to the generator support system. The turbine bearing is of the segment type.

The main shaft seal equipment employs the carbon packing system unique to Fuji Electric. Since dismantle and assembly of the turbine bearing and main shaft seal must be accomplished via holes in the thrust bearing support, special tools have been developed to facilitate these operations.

The draft tube liner was manufacture in Australia accordance with the design and under the guidance of Fuji Electric. The draft tube liner is almost completely circular so that it can easily withstand the water pressures which arise during water column separation. The outlet of the draft tube liner is shaped like a horse's hoof so that it can be directly connected to the tailrace conduit.

The turbine is designed so that synchronous condenser operation is possible and a jet pump air admission system is used for water depression because it is easy to maintain and less expensive according to the results of investigations comparing conventional air compression devices and the jet pump. This jet pump can also be used for forced air admission when there is a partial load as well as air admission during load rejection. In addition, there is also equipment to supply cooling water to the labyrinth and a valve which exhaust the water leaks from the guide vane into the draft tube are provided.

The governor is of the electro-hydraulic type. Mechanical overspeed protection equipment is provided to close the guide vane in an occasion of turbine overspeeds. Oil level regulation in the oil pressure tank is carried out by means of a special air compressor.

IV. GENERATOR

1. Generator Specifications

Numbe of units	
Type	Vertical shaft totally enclosed closed circuit air cooled synchronous generator
Rated output	100,000 kva
Synch. condenser operation capacity (leading)	85,000 var (at 13.8 kv)
Synch. condenser operation capacity (lagging)	75,000 var (at 13.8 kv)
Rated voltage	13.8 kv
Voltage range at rated output	100 and 105% of rated voltage
Rated power factor	0.85 (lag)
Rated frequency	50 Hz
Speed	200 rpm
Flywheel effect	5990 t-m^2
Standard specifications	British standards
Excitation system	Self-exciting compound type
Excitation capacity	340 kw

2. Features

In addition to the capacity of the self-excited compound type generator of 100,000 kva which is directly connected to the Francis turbine is a record-breaking high, there are many features in respect to construction, specifications etc. These are the results of a concerted effort to design a generator which is both economical and highly efficient. The advantages of a integrated manufacturer who makes both turbines and generators were great and thus all of their requirements could be fulfilled. The following is a description of the basic design of the generator including these features.

1) GD^2 and Δn values

It was necessary that should be provided with the generator for this type machine inertia parameter $T_j \geqq 7.5$ sec which means a $GD^2 \geqq 5990$ t-m^2. This value is almost the natural GD^2 of generators with such an output and speed.

As a result, maximum momentary speed rise of the turbine on load rejection is 60%. In consideration with the speed increases of various auxiliary machines resulting from frequency rises on load rejection, Δn is usually designed to be less than 30～40%, but in this plant, appropriate countermeasures were employed in respect to the auxiliary machines and a Δn of 60% is adopted.

When considering the influence of the increased GD^2 on cost and efficiency, it was necessary to get rid of existing notions about speed rise in order to achieve greater economy and efficiency. The fact that a Δn of 60% was adopted in such large capacity machines will probably serve as a pointer in the future design of large capacity generating plant.

2) Elimination of factory tests requiring complete assembly

When it is necessary to completely assemble and test large scale alternator in the factory, the provisions required entails considerable expense. However, since the customers generally demand a low price and short delivery period and since effective site test methods have been developed, there have been many cases in recent years where trial assembly and tests have been omitted. This was also the case with this generator. Only parts were assembled and tested. The efficiency will be affirmed at the site by means of the calory method.

3) Reduction of crane capacity

Usually, a crane with a capacity of about 200 tons must be provided in order to lift the complete rotor without the shaft. However, this generator is assembled and disassembled with a crane of 50 ton capacity, 1/4th the normal value. As is well known, the capacity of cranes provided in power stations are very large, but they are almost not used except for overhaul and during construction. Since the crane is usually idle, it is necessary that the capacity be as small as possible and the price be cheap. Because of this, economic design of the building construction materials is possible and the overall cost reduction is considerable. For this generator, the heaviest part, the rotor rim is assembled in the generator pit and when the turbine parts are disassembled during overhaul, the rim rests in position supported by jacks and only the rotor center is removed. Then the turbine parts are removed through the inside of the rotor rim. That means, the heaviest part, the complete rotor rim is never lifted by crane. Accordingly it is possible to reduce the crane capacity considerably.

4) Harmonic construction with the turbine

The thrust bearing is installed on the support ring on the top cover of the turbine. This type of construction in which the thrust bearing is attached to the top cover of the turbine is often used in generators directly connected to Kaplan turbines, but used rarely with Francis turbine, because of small diameter of the top cover. However a low head and large capacity Francis turbine like this machine enables to use such a system. As is well known in generators coupled directly with Francis type turbines, bracket is generally located on the bottom of the rotor and the thrust bearing is placed on these brackets. Therefore such a lower bracket will be very heavy so that it must be strong enough to support large thrust loads with a big span of the generator pit. They therefore not only cost a lot but are also high in terms of hight of machine. To prevent this in this equipment, the lower brackets are not necessary and therefore the shaft of the generator and turbine is short. Thus this generator is more lightweight than the usual umbrella types, the generator cost is less and naturally construction fees are greatly reduced.

This equipment uses a system in which the shafts of the turbine and generator are combined in one common shaft. As was described previously the shaft length can also be reduced.

In this generator, such as that described above, the assembly sequence at the site varies somewhat from that of conventional machine and therefore it will be given here.

(1) Insertion of the turbine runner with the crane and attachment of the top cover and thrust bearing support ring.
(2) Insertion of the shaft and couple with runner.
(3) Assembly of the thrust bearing part.
(4) Insertion of the rotor hub with the crane.
(5) Assembly of the rotor rim and shrink fitting on the hub.
(6) Attachment of the poles (except the poles which face to the joint part of stator core)
(7) Assembly of the stator, insertion into the coil of parts connected after assembly and attachment of poles to these parts.
(8) Attachment of top bracket and shield plates.

During disassembly, the rotor rim is unfixed from the center by a special heating method. However, the rim is supported in position by the jacks and need not be hoisted. When the stator coil is necessary to be replaced, only the poles are removed and the work can be done in the space between the rotor rim and the inside of the stator. These are major features.

5) Use of self-excited compound type excitation system

A self-exciting compound type system in which the combined load and no-load excitation component are superimposed by the voltage components rather than the current components as previously was developed and used in this equipment. In this system, the excitation system response is very fast like in the previous self-exciting compound types and voltage control stability is good. And further more, an operating range from low excitation regions to over excitation regions is possible.

6) Cost evaluation of loss

The efficiency of this generator is evaluated by the weighted efficiency and a rather large value is required. When the amount of money per kw is determined in loss evaluation, the increment of the generator investment including its interest as well as amortization cost should be culculated corresponding to decrement of loss, so that it becomes rather large value.

Thus in the design stage, it was difficult to balance the conflict between reducing loss and economical condition. And then there was problem of what were the most appropriate machine from an overall point of view. Each part, therefore, was considered very carefully and efforts were made to select machine which was both highly efficient and economical.

3. Construction of the Various Parts

1) Stator

The stator frame was made of welded steel plates. It was made in three sections for transport. As shown in *Figs. 2* and *6*, the stator is installed on a hexagonal ring base which sets on six beams arranged radially from the generator support ring on the outer rim of the turbine pit. Therefore the weight of the stator is transmitted directly to the generator support ring. During the design stage, strength was investigated by calculating the natural frequency of the foundation and stator system using maximum loads which will take place in sudden short circuit condition.

The stator core is made of high quality silicon steel with a low loss. To further reduce loss, detailed investigations were made concerning end construction of laminated core and the means of attaching the core to the frame. As a result, it was confirmed that construction similar to that used before was best.

The stator winding consists of one turn coils with Fuji F resin (mainly expoxy-resin) insulation which

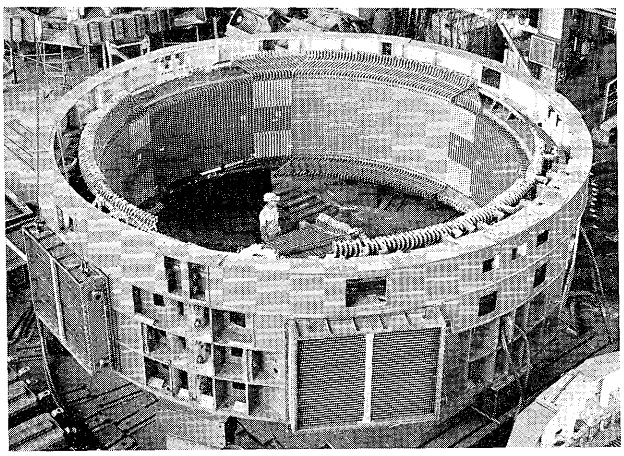


Fig. 13 Stator

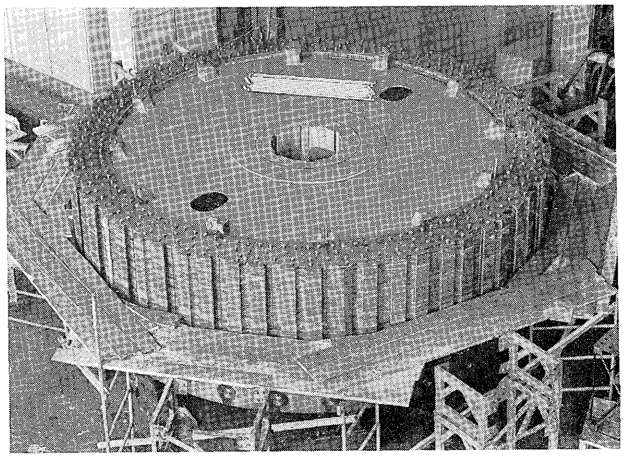


Fig. 14 Rotor rim

is ideal as an insulation system. To reduce stray loss, the stator coils are applied with not only Roebel transposition inside the stator core but also transposition on the connections of the winding ends. The shield cover for the winding ends is made of nonferrous material so as to reduce loss due to leakege flux from the winding.

2) Rotor

The rotor poles are made of stacks of thin plates sandwiched between end plates and welded together by means of several pins which pass through the plates. Special care was taken with the arrangement of the damper winding and the slot ripples in the voltage waveform are minimized. It is necessary to remove or insert the stator coil in the space between the rotor rim and the inside of the stator. For this reason, various measures were adopted to make sure that the poles could be easily attached or removed in order to get the necessary space for assembly of the stator coil.

The rotor rim is made of laminated thin plates of high tension steel held together by reamer bolts. As was described previously this lamination work was carried out in the generator pit at the site.

The rotor hub to which the rotor rim is attached is made of disk type steel plate center according to Fuji Electric's standard system. Its rigidity is increased by means of two disk plates and several stiffeners arranged radially. Since there is nothing to obstruct ventilation air, windage losses are reduced considerably. The rotor hub is divided into two sections. After connected by bolts, the hub was then fitted on the shaft and fixed in position.

The main shaft is made of forged steel and as was explained previously, is common with the turbine shaft. There are no coupling joints and construction is simple. Accordingly there is also no need to worry about bends in coupling joints and reliability is thus very high. The thrust block which is arranged below the rotor is fitted on main shaft by heat shrinkage method. This conveys the thrust load to the thrust bearing.

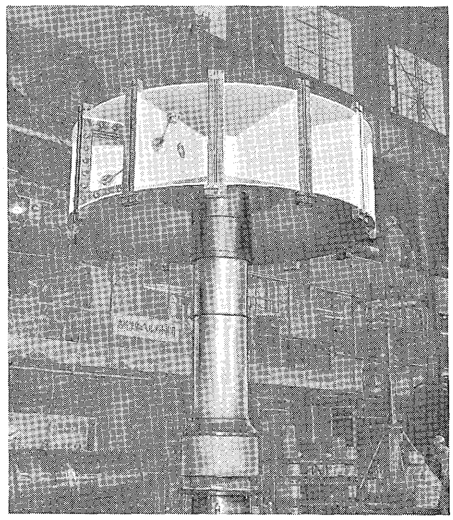


Fig. 15 Rotor hub

3) Bearing

The thrust bearing is a Fuji Michell type bearing which can safely support a thrust load of about 650 tons. The so-called oil lift system is provided with the thrust bearing so as to form oil film on thrust pad by pressurized oil during such slow rotation as centering operation, etc. The oil is injected through holes in the center of the pad by a high pressure oil pump installed outside of the generator. It has a pressure sufficient to support the weight of the rotor. Check valves are provided in the oil injection lines to stop the oil of film from flowing out through the holes during normal operation.

The guide bearing is divided into twelve pads to facilitate easy maintenance. The pads are fixed in the bearing tank and form a full journal bearing.

The thrust bearing and thrust tank are mounted on the thrust bearing bracket. The thrust load is transferred from this brtcket via the thrust bearing support to the top cover of turbine. The radial load which acts on the guide bearing is transferred from the thrust bracket via six arms arranged radially to the foundation.

The bearing is cooled by a separate self-circulating oil cooling system which is standard in all of Fuji's large alternator. The oil is led to the separately installed cooler from the bearing oil tank by means of pump action which is performed by the radially distributed holes in the thrust runner. Cooler maintenance is easy and with the umbrella type construction as used in this machine, the thrust oil tank is small compared with the system of which the cooler is arranged in the oil tank. This means that the guide bearing can be arranged almost in the center of the rotor and the stability of the umbrella type machine can be increased.

4) Other parts

Six air coolers are arranged on periphery of the stator frame. The upper bracket supports the top cover of the alternator enclosure, and in order to avoid transfer of vibrations from the top cover to the foundation, the top cover is insulated from the foundation.

The jacks used to support the rotor can automatically operate during assembly by means of the electric motorized oil pressure equipment.

4. Excitation System

In 1959, Fuji Electric adopted a compound type self-excitation system for water turbine generator for the first time in Japan. After this, more than 80% of Fuji water turbine generator employed this system. The system used up to now employed superimposition of the no-load valtage component and the load current component by means of current from a reactor and current transformer respectively. However, the system developed at this time, employs a combination method in which these two components are superimposed by voltage. As can be seen in *Fig. 16,* the no-load component is obtained from excitation transformer T_r and the load component is obtained from gap current transformer GCT which is connected in series with the transformer T_r. The combined voltages are applied to the rectification circuit and converted into the required field current by AVR control etc.

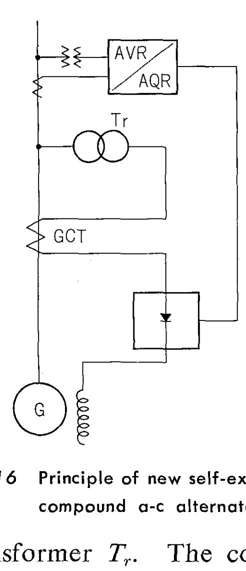


Fig. 16 Principle of new self-excited compound a-c alternator

The features of this system are first that because of adoption of the voltage superimposition system the stability of the control system is excellent; second that excitation current can be obtained even during 3-phase short circuits because of gap current transformer; third the response is almost the same as that of the current superimposition system and lastly stable operation right down to the low excitation regions is possible. For details concerning this system, refer to previous reports. (Fuji Electric Review Vol. 15, No. 3, 1969)

5. Characteristics

The various characteristics of this equipment are follows.

1) Reactances and time constants

x_d	105%		
x_q''	24%		
x_q	74%	T_{d0}'	7.26 sec
x_2	22%	T_d''	0.045 sec
x_d'	29%	T_a	0.173 sec
x_0	10.5%		
x_d''	20%		

2) Operation limit characteristics

Fig. 17 shows the capability curve of this generator. In the low excitation regions, the region of possible operation is narrow for the previous current superimposition system of excitation as can be seen from the dotted line. However, with the voltage superimposition system used in this generator, field current can be controlled stably right down to very low values and therefore the range of operation is greater as can be seen from the figure. During condenser operation, operation with a lagging capacity (low excitation) of 75 Mva and a leading capacity (over-excitation) of 85 Mva is possible.

Recently the necessity of condenser operation has been increasing for water turbine generators, due to system requirements. In such cases, this excitations system is particularly effective.

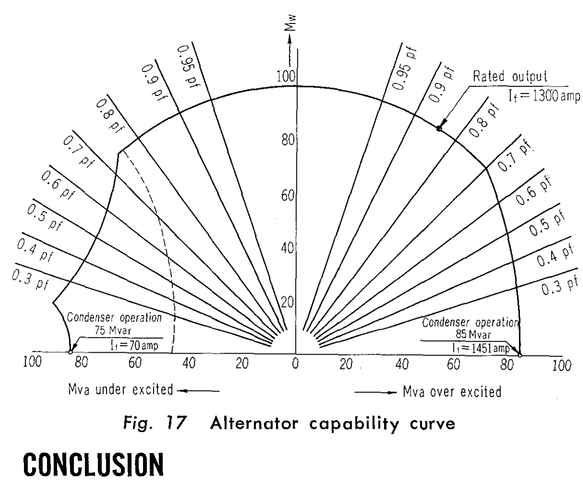


Fig. 17 Alternator capability curve

V. CONCLUSION

By mustering many new techniques, the machine described above was completed and it is hoped that this information will prove useful in the manufacture and design of large capacity turbines and generators in the future. As the demands for cost down of water turbines and generators increase, the new techniques employed in this machine should point the way to greater economy in future machines.

Finally, it is hoped that this article will also serve as some kind of reference in the economical planning of future hydroelectric power stations.