EQUIPMENT OF SUDAGAI UNDERGROUND POWER STATION OF THE TOKYO ELECTRIC POWER COMPANY

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I. INTRODUCTION

The complete equipment of Sudagai power station, the first underground power station in the postwar project, was ordered from our company in September, 1953. It was planned, designed, and built by our engineering staff with its collective effort, and was completed with successful test results at the factory. The primary requisite of the equipment is high reliability, fitness for fully standing the requirement of peek load period, noise and moisture proofness, minimizing the floor area in consideration of peculiar character as an underground installation. Further, simplicity, easy operation and maintenance being taken into account, it was aimed at to be of the most up-to-date design.

Underground power stations have developed in Europe specially in Norway and Sweden, and are reported to be about some 60 installations in the world, all being in successful operation. In Norway, as a particular case, principal power stations are of underground installation, which is partly due to the defensive reasons but mostly for the sake of economy, having ahistory of 30 years. Even in Japan, Uryu power station, the Hokkaido Electric Power Company and Iyogawa Power Station, the Shikoku Electrie Power Company were recorded as underground installations in the past, but Sudagai Power Station is the first undertaking of the kind in the postwar era. In this power station, the switchboard room and the substation equipment are located on the ground for economical reasons. The power station is situated at the diverging point of the main stream of the river Tone and the river Naramata. The generated power is stepped up to 154 kV and transmitted to the territory of Tokyo via Joetsu trunk lines.

II. PARTICULARS OF EQUIPMENT

Machines

1. Water turbine
   2–Vertical single wheel single flow spiral Francis turbines.
   (a) Effective head
   Normal head .....77.0 m
   Max. head .....83.0 m
   Min. head .....58.0 m
   (b) Output
   Max. output .....22,400 kW
   Standard output .....20,800 kW
   At the min. head and full opening .....16,200 kW
   (c) Quantity of flow
   At the max. head .....30 m^3/s
   At the normal head .....30 m^3/s
   At the min. head .....32.5 m^3/s
   (d) Speed ..... 250 R. P. M.
2. Main Generators
   2–Vertical revolving field enclosed and circulated air ventilation type generators
   (a) Output .....24,000 kVA
   (b) Voltage .....11,000 V
   (c) Power Factor 90%
   (d) Frequency .....50∼
   (e) Speed .....250 R.P.M.
   (f) Line Charging capacity .....16,500 kVA
   (g) Direct coupling exciter .....130 kW
3. Main Transformers
   2–Outdoor use nitrogen sealed 3 phase oil immersed self-cooled type
   (a) Rated output .....24,000 kVA
   (b) Voltage
   Primary, rating .....10.5 kV
   Secondary, rating .....154 kV
   Secondary taps .....147, 161 kV
   (c) Frequency .....50∼
   (d) Connection
   Primary; delta
   Secondary; star
4. A-C Circuit Breakers
   4–161 kV Outdoor use insulator type expansion breakers
   (a) Rated current .....800 A
   (b) Rated frequency .....50∼
   (c) Rated rupturing capacity.....2,500 MVA
   4–6.9 kV Indoor use water expansion breakers
   (a) Rated current .....400 A
   (b) Rated frequency .....50∼
   (c) Rated rupturing capacity .....100 MVA
5. Neutral grounding resistor
   1–Outdoor transformer-neutral grounding resistor
   (a) Terminal voltage .....$161/\sqrt{3}$ kV
   (b) Current .....100 A
   (c) Resistance .....930 Ω

(d) Time.....30 sec.

6. Others including 1–3 phase 500 kVA station service transformer, 1–375 kVA reserved electric power source equipment, main switchboards, auxiliary switchboards, instrument transformers, disconnecting switches, condenser type instrument transformers, lightning arresters, cubicles, remote indicators, installation work.

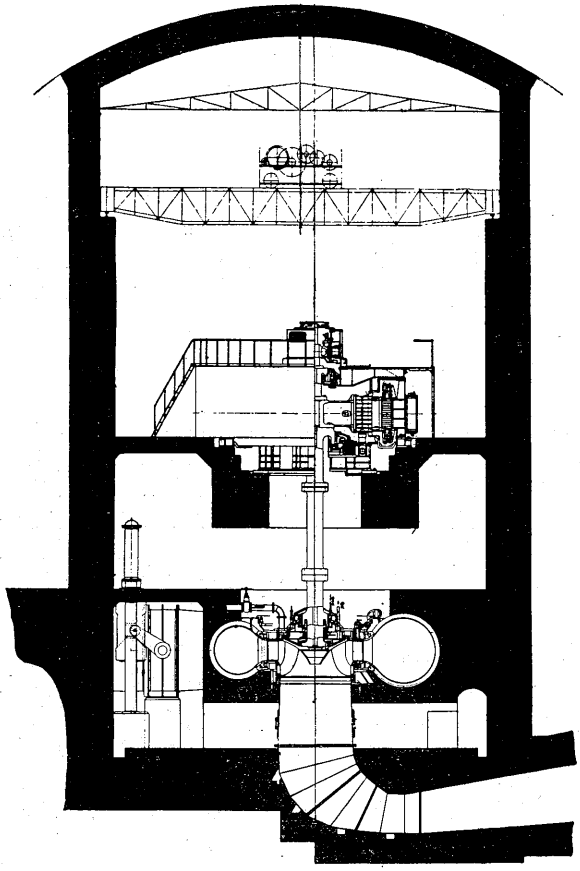

Fig. 1. Sectional elevation of water turbine generator

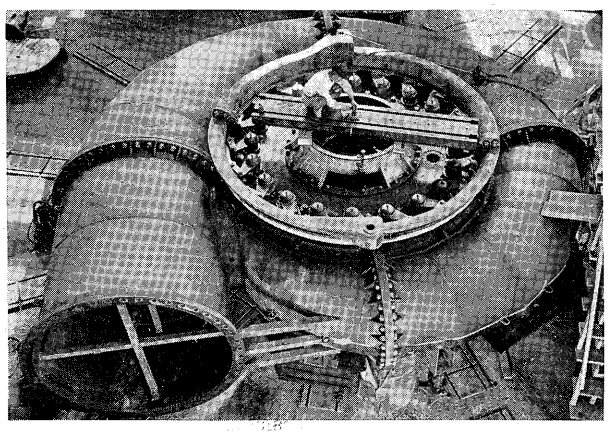

Fig. 2. Main turbine at turbine works

Water turbines

Water turbines are of vertical single wheel single flow Francis turbines having a specific speed of 158 (m–kW) which is good for insuring relatively high efficiency for Francis units. They are of all welded steel plate construction, their upper and lower casings, speed rings being all of steel plates fabricated by welding, too. They have been proved very excellent. In the pressure test of the spiral casing, test pressure of 14.5 kg/cm^2 was applied, but no water leakage at all and elongation 1～0 mm was the result without any troubles. As to the inspection of the welded joint, circumspect X-ray examination was given according to the standards of Swedish Welding Society. The method of drawing-in air to the turbine was in accordance with the latest practise of Voith to insure the best result. The water drains of the water turbine proper resorts to the natural flow to the draft tube. When the tail race level rises, the drainage is made to a drain water pit. Air vents of the turbine is usually a source of big noise and special consideration is given in the piping as an underground power station. The piping, after all, has been made in the water pressure regulating tank on the tail race side. Water sealed bearings employ carbon packings. For grease lubrication is provided an automatic

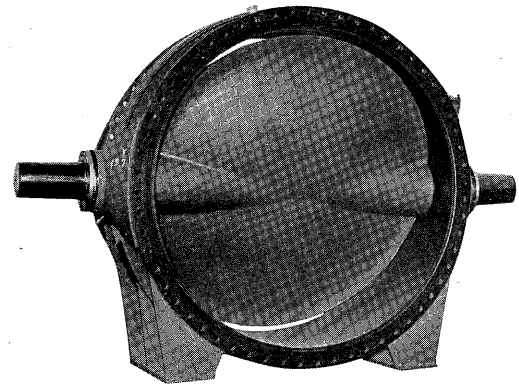

Fig. 3. Main valve (inner dia 2,650 m.m.)

grease lubricating device working once every 12 hours. At the water inlet, one unit of gravity lowering type batterfly valve of the latest design which is capable of interrupting the flow of water is employed for the convenience of required space and also for the reason that our company is fully confident of building perfectly leakage-proof batterfly valves. There is no upper penstock valve. The employment of gravity lowering type inlet valve dispenses with pressure oil at closing the valve, and because of the gravity being the motive force, the reliability at the closing increases considerably and pressure oil mechanism becomes simple, which in turn reduces the capacity of the pressure oil tank. This power station is provided with a pressure oil tank having a capacity of 2,410 l with stop relay operating oil pressure of 12 kg/cm^2, taking

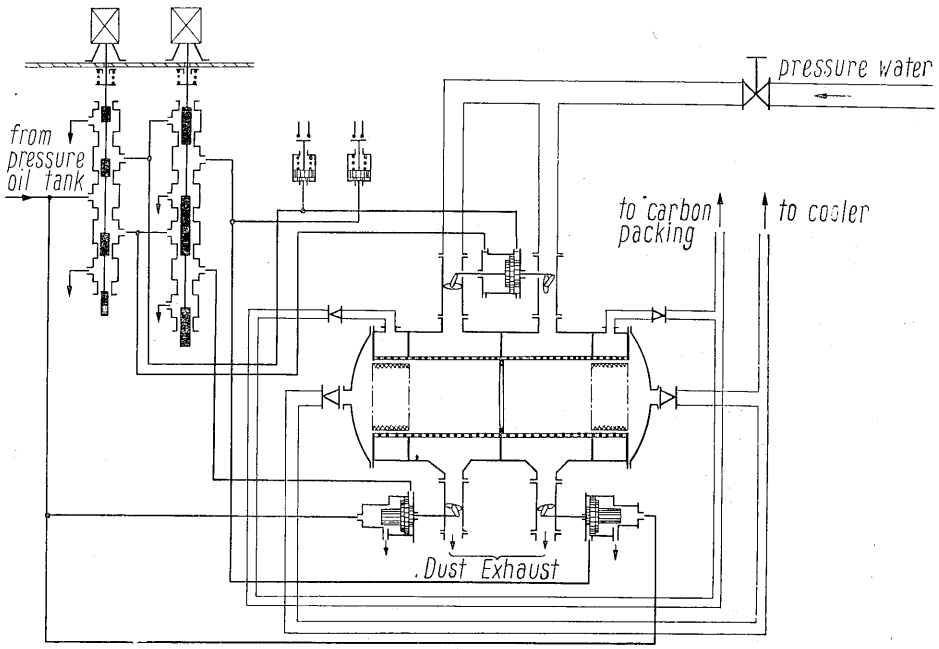

Fig. 4. Automatic strainer

into account of enough margine. If ordinary type inlet valve were in use, this oil pressure would be required stop relay pressure 13.5 kg/cm^2 and capacity 4,000*l*.

Cooling water is supplied directly from the penstock using an automatic water strainer for the convenience of maintenance and having an operation indicator on the main switchboard. This system is designed aiming at absolute no failure. It is provided with one tank, and change-over of strainer is made on condition of reduced water flow to discharge dirt by opening the exhaust valve. After a little while the exhaust valve is closed to complete the change-over operation. Water for the carbon packing and ventilators is taken in through 0.5 mm netting provided in the same tank so as to dispose of the matter with one tank, serving to reduce the required floor space.

For the governor, a cabinet type governor is placed in the water turbine room. This governor is in more advanced design than the conventional one, being capable of controlling the pressure oil pump, grease oil pump and automatic strainer as well and economizing the floor space a great deal. Fig. 7 illustrates a part of controlling mechanism of pressure oil pump and grease pump placed inside the cabinet governor. For the pressure oil pump, a screw type Imo pump of German make is employed to make the size smaller and also to avoid noises, for conventional geared pump is the source of noise besides being large in size. With a confidence that a central system of using one compressor for 2 turbines respectively in the case of pressure oil and of air brake is good for the purpose, compact and simple installation has been successfully made by thus reducing the number. For drainage pumps to operate in the uuderground station, 2–vertical immersion type pump having a capacity of 3 m^3/min. and 2-horizontal centrifugal pumps having a capacity of 3 m^3/min. are provided taking into consideration of leakage water in the station.

All drainage pumps start and stop automatically at a predetermined water level, their operating condition being indicated on the main switchboard room. The control panel for the drain pump is installed together with bearing motor panel in the underground control room, and main and attached apparatus related to the water turbines are controlled from two places.

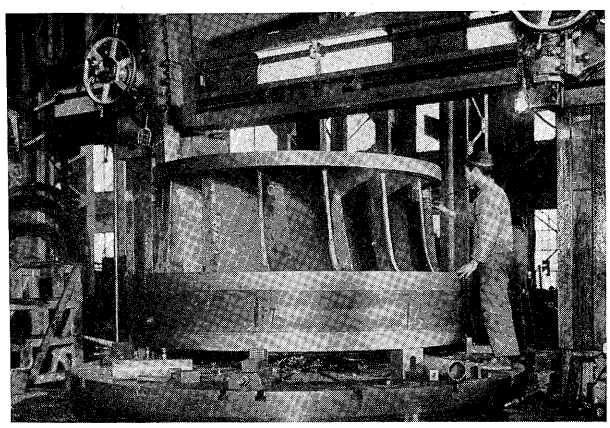

Fig. 5. Francis runner under manufacturing

Model tests were conducted in July, 1954 at the hydraulic power test room of our company, when excellent result above guaranteed efficiency by 1% was obtained. Such a method of guaranteeing efficiency may be said the most proper in present Japan.

For the disassembling of water turbine, it is so designed that the middle shaft is to be lifted out by means of a simple lifting device and the machine is all disassembled in the turbine room.

Generators

The generator are of semi umbrella type vertical revolving field enclosed ventilated by air circulating system having a capacity of 30,000 kVA with a guaranteed overload of 30 minutes. The gitter wind-

ings coils transposed in the slot for the purpose of reducing stray load loss and preventing layer short are in use. They are made one turn for one coil and is entirely free from layer short. The stator is splitted to four parts for the convenience of transportation. Silicon steel plates are given vacuum annealing after punched so as to reduce vacuum loss. A noise prevention method, which is one of important problems of the machine, is applied as follows. Hoods and air passage are made of specially thick iron plates lined with felt. At their joints dampers are provided. As to the stator, it has been successful in reducing the noise to 10 phones by giving special treatment. At the outlet of cooling air of exciters, noise prevension devices are provided.

For automatic voltage regulator ampli-trans

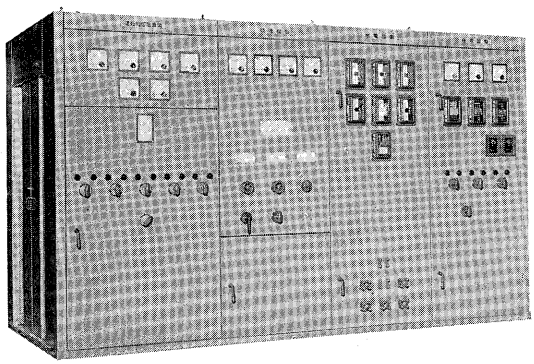

Fig. 6. Front panel of cabinet governor

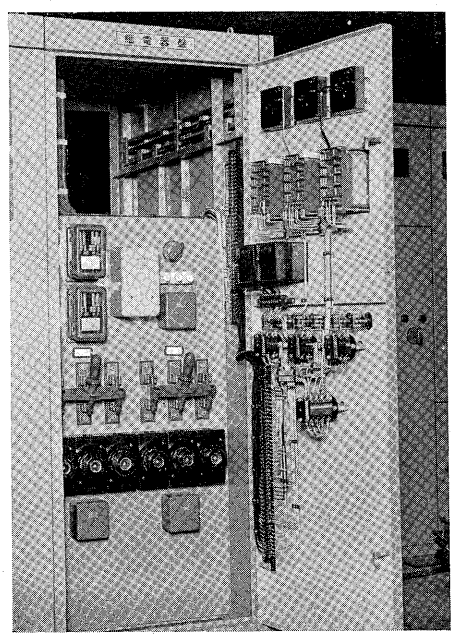

Fig. 7. Control app. of oil pressure pumps and grease pump (inner view of the cabinet governor)

type automatic voltage regulator (magnetic amplifier type) are employed, which insures quick response excitation. Further the machine is made very dependable by flat excitation characteristics

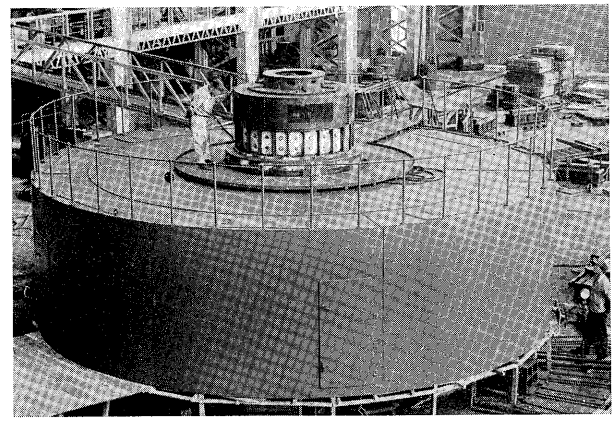

Fig. 8. Main generator at large rotating machine works

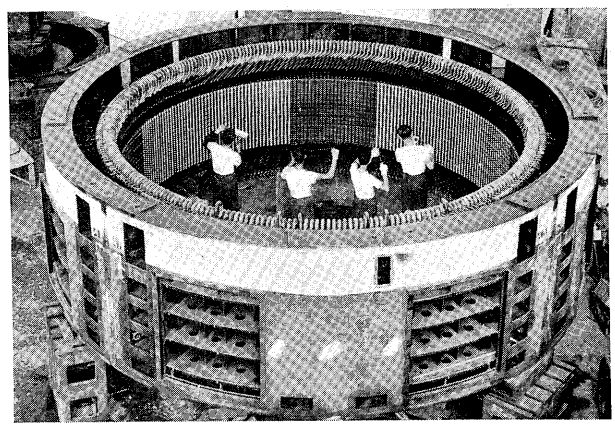

Fig. 9. Stator of main generator

of our unique exciters with Isthmus magnetic poles. This regulator is a two stage push-pull amplifier provided with an automatic *kVA* limit.

This equipment is a two stage push-pull type amplifier with a *kVA* limiting device. As its performance will be explained sometime later, no description is made herein, but its principal advantage of the *kVA* limiting device is briefed as follows.

A limit in the employment of alternating current generators is the limit of *kVA* output determined by the temperature rise. In order to make one

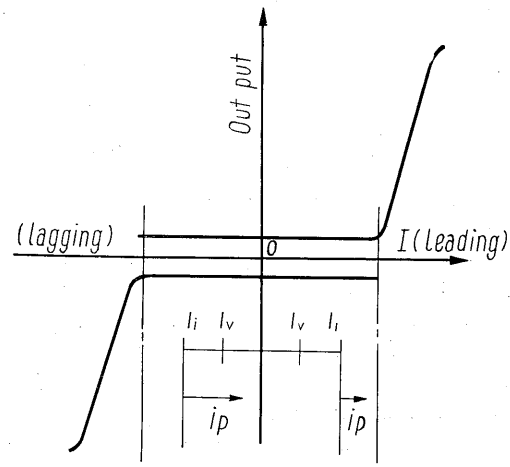

Fig. 10.

hundred per-cent use of generators, therefore, it is desirable to hold the kVA of the machine at a definite value within a predetermined range. This limitation is termed as kVA limit by our company. This is realized by a kVA limiting part which consists of two sets of push-pull type magnetic amplifier. Its characteristic is, unlike the ordinary push-pull type, provided with a bias to a considerable degree, so that it forms a step shaped characteristic as shown in Fig. 10. As inputs to it, three signals of i_v, i_i and i_p are given as shown in Fig. 10, where i_v is D.C. current proportional to output voltage of the generator, i_i is D.C. current proportional to output current of the generator, and i_p a pilot signal to charge its sign whether its phase is leading or lagging. Then, the reason why the kVA limit is feasible is explained as follows.

Limiting kVA is a trial to hold the relation between V and I on a hyperbola of $VI=$const. But, as it is very difficult to execute it perfectly, the curve is replaced by a straight line of $V+I=$ const. which covers approximately a part of $VI=$ const. Therefore, when $(V+I)$ becomes large, it is suppressed to a certain value to execute kVA limiting approximately as shown in Fig. 11.

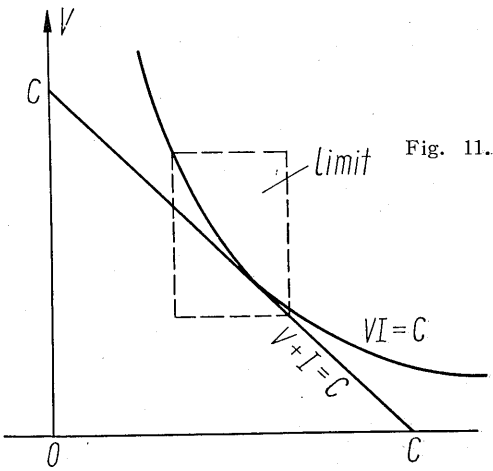

Fig. 11.

The pilot signal i_p under question is as shown by a vector diagram in Fig. 12. That is, if voltage obtained as a resultant of each current of phase R and phase T is added to a midpoint of the voltage between phases R and T, the resultant voltage become two values of $\overline{RN}$ and $\overline{TN}$. In this case, the angle between $\overline{MN}$ and $\overline{RN}$ changes at the rate of the resultant of two currents of phase R and phase T, but $\overline{RN}$ and $\overline{TN}$ become equal in size when $\overline{MN}$ is perpendicular to $\overline{RT}$. Therefore, at a desired power factor—for instance at a unity power factor in the case of this kVA limitation—let $\overline{MN}$ be perpendicular to $\overline{RT}$, and if $\overline{RN}$ and $\overline{TN}$ are compared with after rectification, a plus or minus signal is available according to lagging or leading of the phase. This is made of resistance shown in Fig. 16. This is also a quantity approximately proportional, as shown in Fig. 13, to $2I \sin\theta$.....(where θ is a phase angle between V and I), *i.e.*, a quantity proportional to wattlsse current and is used for preventing cross current.

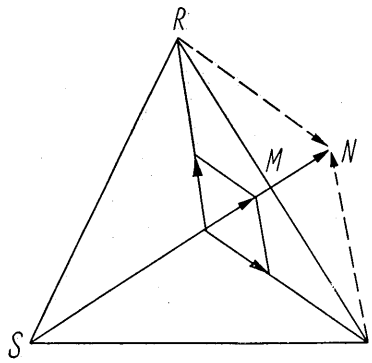

Fig. 12.

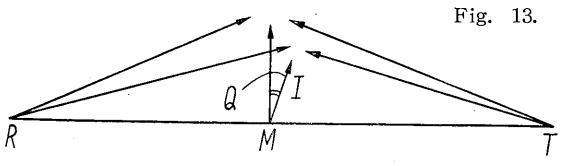

Fig. 13.

As the cross current is a kind of wattless power, limiting it will just answer the purpose of preventing cross current. Then the wattless component of current is superposed on the AVR fundamental current to suppress the wattless current. This is regulated by adjustable resistance R_{11}. That is, if R_{11} is turned in the direction of "small," the change of terminal voltage per unit wattless current becomes large, and accordingly the cross current decreases. But the faculty of holding the voltage at a definite value decreases in proportion. The power factor regulator is the one making this inclination as shown in Fig. 14 dotted line.

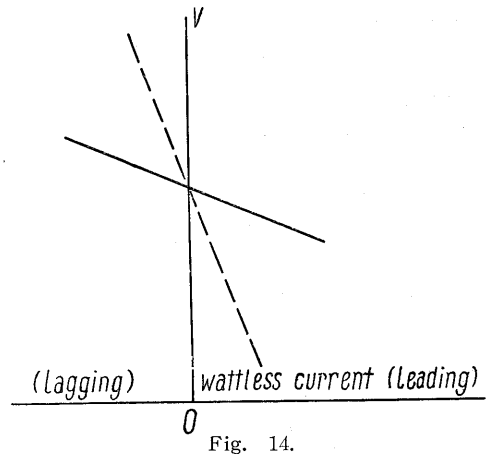

Fig. 14.

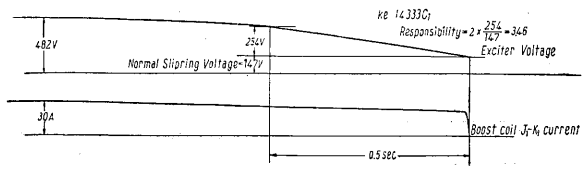

Fig. 15. 130 kW exciter responsibility by A.I.E.E. rule

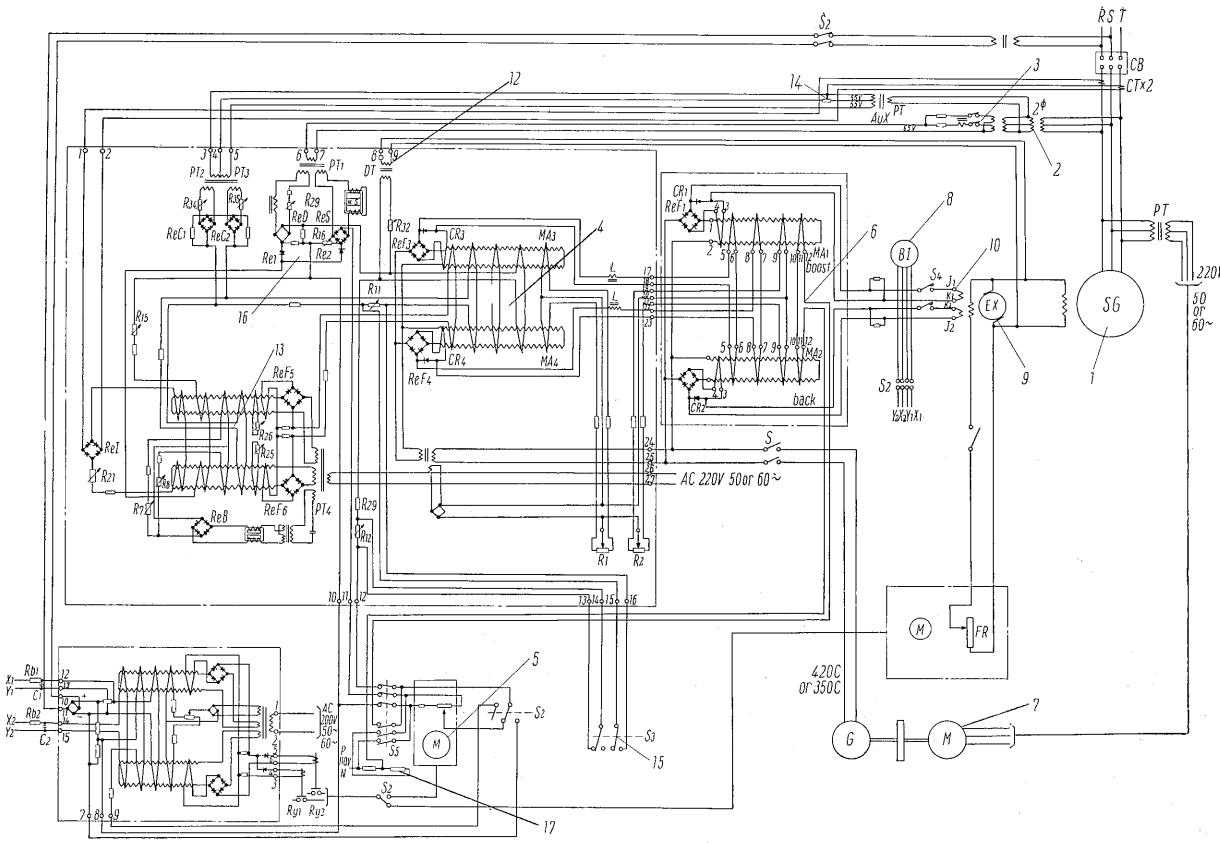

Fig. 16. A Type AVR skeleton diagram

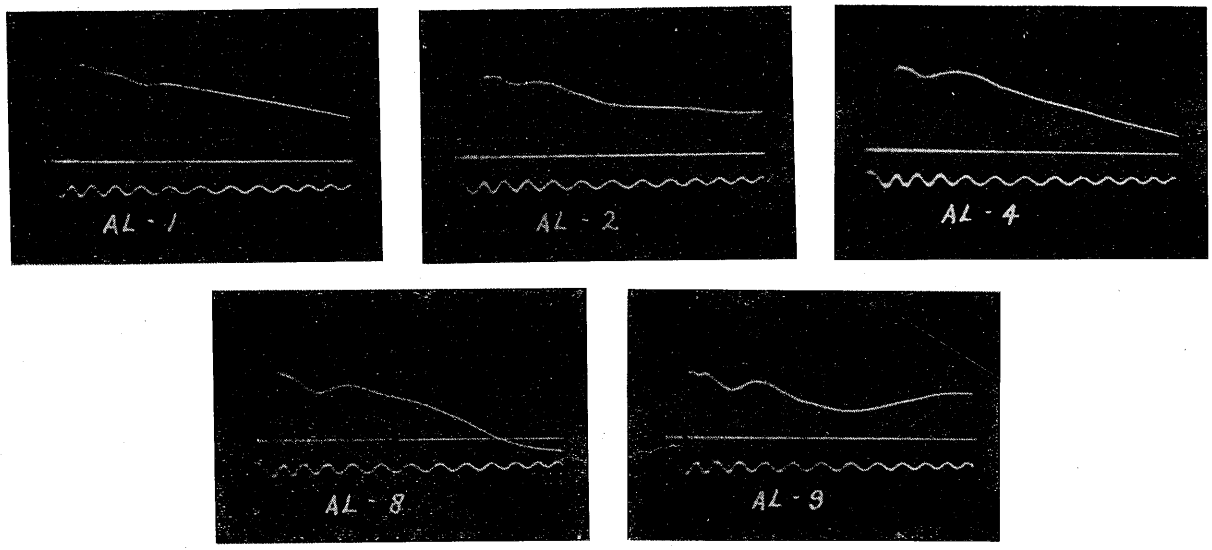

Fig. 17. Analyser test

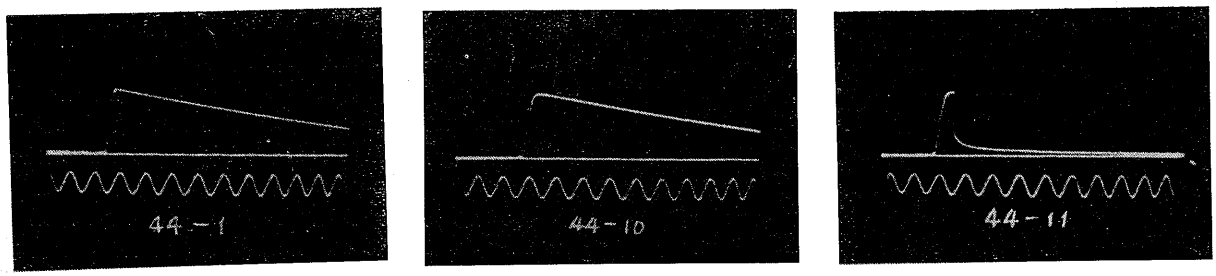

Fig. 18. Break down test results of stator winding

Moreover, being a magnetic amplifier, it is capable of delivering a stable, large output so as to do away with a sub-exciter, the generator is reduced of its height by 400 mm as compared with the ordinary design. Bearings are all made of self oil containing system for the simplicity of mechanism. As for cooling of generators, the cooling water is fed directly from the penstock through a reducing device, which can be adjusted to give the best result after the installation at the site. A fire extinguisher using carbon di-oxide gas is provided. Fig. 17 shows the test results of analyser test.

Fig. 18 shows the test results of insulation breakdown tests on stator coils. Fig. 15 is a result of responsiveness of exciter according to the A.I.E.E. standards.

Transformers

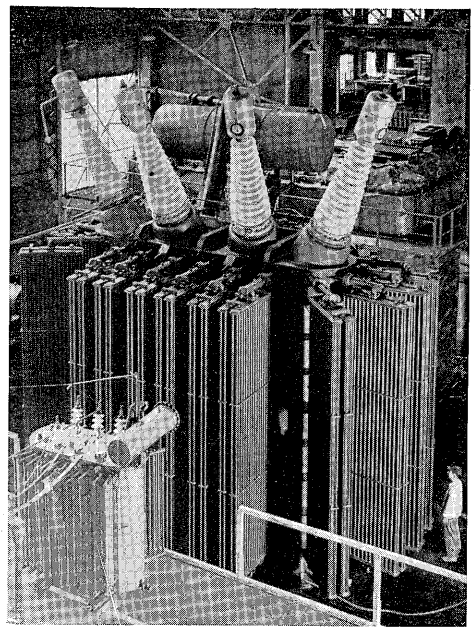

Fig. 19. Main transformer completed at large transformer works

The transformers are of outdoor 3 phase nitrogen sealed oil immersed self cooled type and are also guaranteed for standing overload of 30,000 kVA for 30 min. against the water turbine output at over gate. Their coils are of Einzel-scheiben lightning proof type. The core is made up of T–95 sheet steels carefully selected at the factory piece by piece. For nitrogen sealing, a conservator having two separate chambers, Type FT of our special design, is used. Based on many successful results, it is claimed to be very safe and dependable. To cope with the transportation limit of 15 tons in weight, the transformers are shipped disassembled, and are assembled again at the site. They are attached with special wheels capable of changing their direction by 90 degrees so as not to necessitate a traverser. This was the first design made success in Japan by our company. The test result has proved that the transformers have efficiency 0.1% higher than guaranteed value. The temperature rise of oil is 32°C and other performances are all excellent.

Switchboards and Instruments

Now description is made about switchboards and instruments. The controlling system of this power station adopts, as illustrated in the single line diagram in Fig. 21, a unit system and the machines are paralleled at high voltage, making the arrangement af apparatuses very simple. High voltage circuit breakers on the side of station circuit are omitted. High voltage disconnecting switches rated 11.5 kV 400 A are motor operated and are in such a design as to have enough capacity to interrupt exciting current of 2×500 kVA station service transformers. Fig. 20 shows cubicles for 11.5 KV circuits. In the switchboards are included generator surge absorbers, 11 kV disconnecting switches, a transformer complete with 5 kVA automatic voltage regulators for driving a high frequency generator and instrument transformers. Disconnecting switches on the 11.5 kV circuit are operatable in front of the main switchboard and of this cubicle panel. Besides, there are provided the ampli-trans type voltage regulator and cubicles for field circuits. Fig. 22 shows the arrangement of the apparatuses. The controlling apparatuses for generator are all included herein.

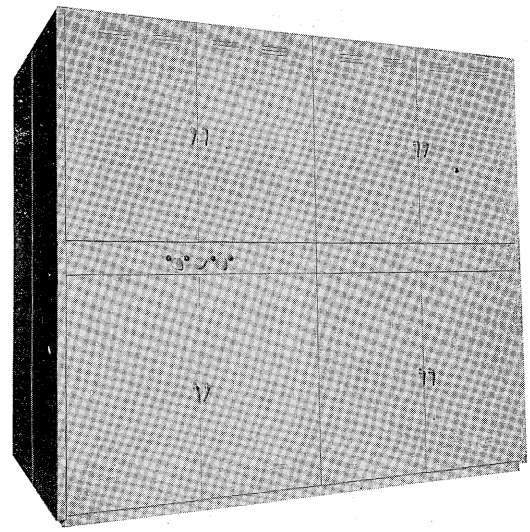

Fig. 20. 11 kV generator circuit cubicle

The circuit breakers for station circuits are all of the water expansion circuit breaker which are regarded as the most proper in the point of fire proof, noise proof and small size. Fig. 23 shows the cubicles of the station circuits. The instru-

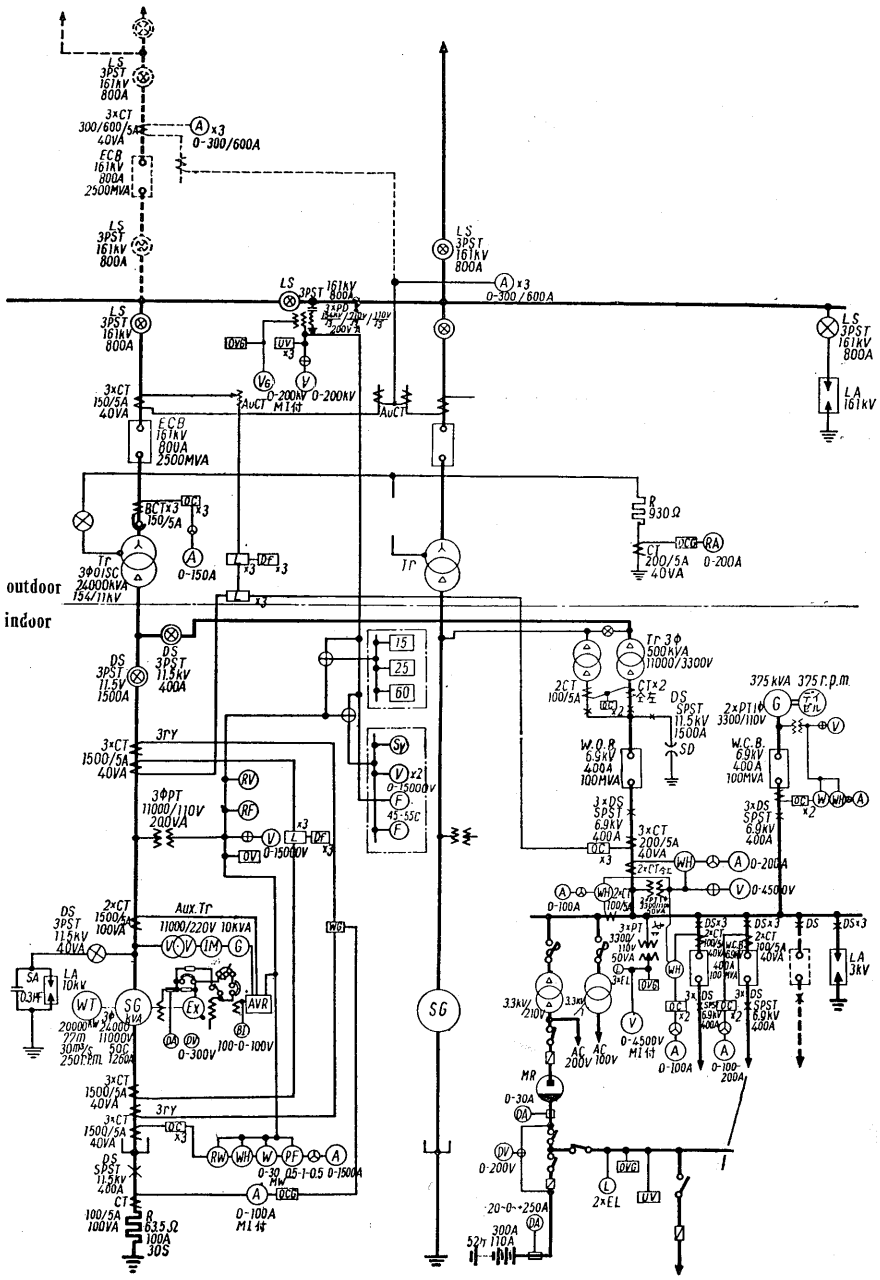

Fig. 21. Skeleton diagram

ment transformers and disconnecting switches for the station circuit are all included in this switchboards with a provision of bus panel in it.

As reserve power source equipment, one 375 kVA, 375 R. P. M. Diesel generator manufactured by the Tateyama Works is employed. Upon failure of station power source, it automatically starts without delay to close the circuit breaker on the output side via a time limit relay.

For those require the remote indication such as the guide vane opening of water turbines, positions of load limit, oil pressure of pressure oil tanks, water level at the dam, tail race water level and other important indications, our unique ring tube remote transmission system operating on D.C. source is used, and the indication is kept available even when the station A.C. source is interrupted. That means, D.C. power is made available through a selenium rectifier from the station A.C. circuit, and upon failure of power D.C. is taken out of the cell. The ring tube transmitting system is the one to short-circuit resistances with mercury, very accurate indication being available. To take warm water for irrigation, it is necessary to take water from the upper part of the dam. For the purpose of giving alarm for low water level at five steps. Type NZ regulator using a ring tube type transmitter of our own make is employed.

On the back of the main switchboard, which is attached with a desk panel, are provided an automatic synchronizing panel, operation control panel and protective relay panel to make the effective use of the panel space and also to keep the appearance neat. In the control of operation, as both regular and spare pressure oil pumps are motor operated, a change-over switch (43 Q) is installed in a cabinet governor for the purpose of simplifying the control at the main control desk, and by operating an operating switch (3 QM) on the desk panel a motor selected by the change-over switch (43 Q) is made to start. As to a power source for emergency stop a means is provided that the interruption of D.C. controlling voltage does not affect on the operation of the main machine under the ordinary running condition. But, taking into account the case where even a means of full stop fails, an emergency source directly rectified from the generator output voltage is provided. To the master switch (1) is provided "preparatory step" and it is made a step to start the grease pump and the AVR power

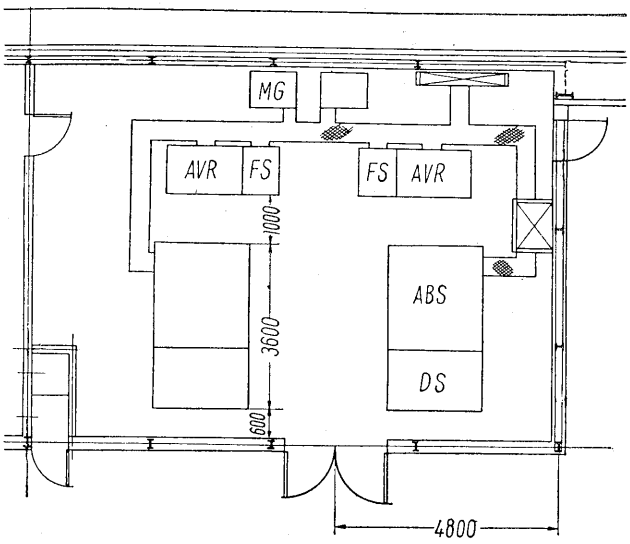

Fig. 22. Generator circuit app. room

source. The automatic synchronizing device adopts our relay scheme of established reputation. In closing a circuit breaker (52) for automatic synchronizing throw-in, an auxiliary P. T. is provided between 10 kV side and 150 kV side to adjust a phase lag due to the transformer, as it is high voltage synchronizing. Further, a condenser type instrument transformer is provided on a 150 kV bus. On the brake control-circuit two voltage relays, (14) and (14 Y) are provided and are made to operate at 50 and 20% of the rated voltage. In a certain time limit after the operation of (14),

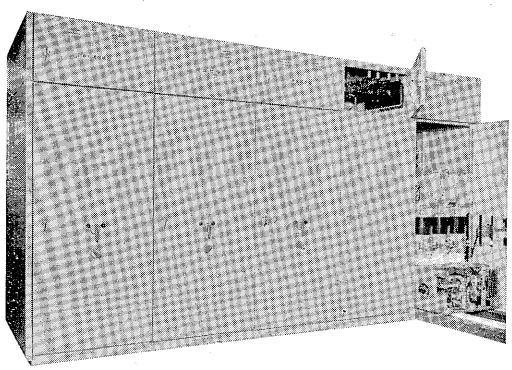

Fig. 23. 3 kV Station service cubicle

if (14 Y) does not function, the brake is to operate so as to avoid false operation due to the interruption of the circuit of permanent magnet generator. It is, however, needless to mention that a guide vane locking device (74 L) and A.C. circuit breaker (52 b) are counted in the brake operation. In addition, to the thorough investigation of inter locking circuits of all the machines, a standard "**one man control system**" is adopted. Moreover, every auxiliary apparatus is arranged to make automatic restarting without hand reset of relays in case of power failure of the station circuit.

The 161 kV circuit breakers are of expansion breaking system using three interrupting points. Besides a self arc breaking chamber, and the other worked by other force is provided to expect perfect interruption of small current, too. The free tripping system is of pneumatic and electric operation. The concrete stand for circuit breakers is made in the shape of compartment, in which a air compressor apparatuses, control panel and secondary air reservoir to reduce the floor area of main control room. The building is double walled, lined with acoustic slates and al-tiles. An air conditioner of having a capacity of 50 ton refrigerator is installed to make a change of air four times a day.

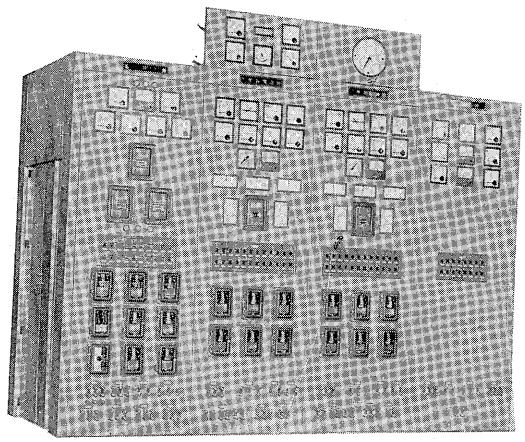

Fig. 24. Main board (with desk board)

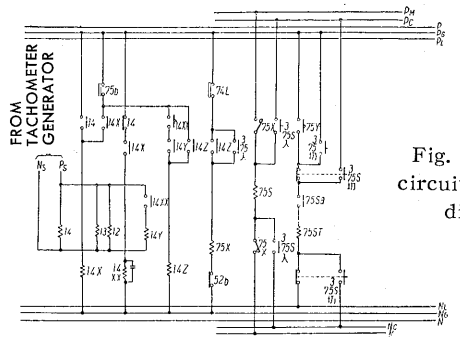

Fig. 25. Brake circuit sequence diagram

III. CONCLUSION

The above is a brief explanation of the main apparatuses of our own make. Description is chiefly made on the construction of the main apparatuses and not much on the performance of each unit, because the writers intention is to make this article as reference to those who will design underground power stations in future. The construction of Sudagai Powor Station, he considers, is to be of some interest as one standard type of future power stations in Japan. At present the installation and wiring of the machines was finished by our hand according to the additional contract. In concluding the article, the writer express his cordial thanks to all the officers of Tokyo Electric Power Company who gave him valuable guidance.