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74,200 KVA GENERATOR FOR SHIMOTAKI POWER STATION, TOKYO ELECTRIC POWER CO., Inc.

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I. PREFACE

The Shimotaki Power Station utilizing the abundant water resources of the Kinu River, a branch of the Tone River, is a peak load station having an output of 138,000 kw. This recently developed water turbine is of a large capacity high speed type whose output approaches the limit, which has been increasing from year to year, for high speed machines. The economic output limit as compared to the manufacturing limit, which is essentially based on manufacturing techniques and the materials used, is naturally lower. The present generator, shown in *Fig. 1*, posseses many superior features over the conventional large capacity, high speed type of machine. Special consideration has been given to the mechnical construction and strength, heating, cooling, lubrication, ventilation, repeated starting and stopping operation, etc., because of its use as a peak power station. The outstanding features of this generator will be explained.

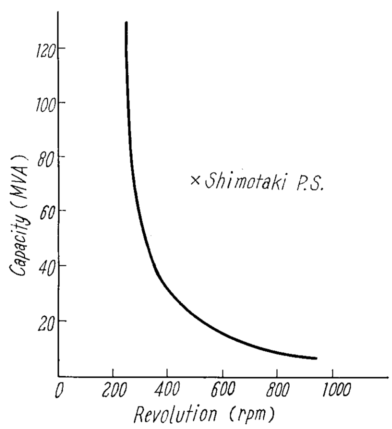

Fig. 1 Relation between output and speed of water turbine generator built in Japan

II. OUTLINE OF GENERATOR

For generators of comparatively small capacity and supplying power to variable loads such as winches, this point has been studied pretty thoroughly and it seems that the basis for calculating the rated output is already established. For a large capacity generator, however, a rated output that would take an overloaded operation under a normal service condition into account was rarely considered. But recently, from the standpoint of economy, the instances in which both the rated and maximum outputs are specified, each requiring a different temperature rise limit, are increasing. Because of AFC operation, this power station is often operated at under one-half load.

Generator Ratings
- Number of unit: 2
- Type and frame construction:
  Vertical shaft; Salient pole; Revolving field; Totally enclosed; Closed air circulation with a water-cooled air cooler.
- Output : 74,200 kva
- Voltage : 13,200 volt
- Current : 3245 amp
- Frequency : 50 cycle
- Power factor : 0.91
- Revolution : 500 rpm
- GD^2 : 640 tm^2

Exciter ratings
- Output : 250 kw
- Voltage : 440 volt
- Revolution: 500 rpm
- Ceiling voltage : 800 volt

Guaranteed performance
Efficiency

Output (%)	100	75	50	25
p. f. = 1.0	97.8	97.3	96.3	93.2
p. f.=0.91	97.5	97.0	95.9	92.5

Temperature rise (cooling water 25°C)

Output	74,200 kva
Stator winding (by thermometer method)	70°C
Field winding (resistance method)	70°C
Bearing temperature (Embedded-detector method)	65°C

Voltage regulation
at p.f. = 1.0 25%
at p.f. = 0.91 35%
Short-circuit ratio 1.0
Over speed test 850 rpm for 1 min.

III. CONSTRUCTION OUTLINE

The generator is a large-output, high speed type of machine with a rated output of 74,200 kva at 500 rpm, one of the most outstanding generators in Japan. A peripheral speed of about 75 m/sec was long used as a limiting condition to determine rotor diameter, efficiency, vibration, noise, economical operation, maintenance problems, etc. It follows from this condition that as the ratio of core length to pole pitch becomes greater the temperature gradient, in the shaft direction, of the iron core and winding increases due to the difficulty encountered in providing adequate air ventilation which in turn results in a considerable temperature rise at the core center. Active research into ventilation systems, windage loss, low vibration and noise construction have so advanced that the required inertia constant has increased to the point where a recent generator was manufactured with a peripheral speed exceeding 75 m/sec. Windage loss effects on this machine could not be ignored because of the long periods of light load operation that were encountered.

Because of the large value of the inertia constant required, 6.6 seconds, and our confidence in being able to minimize windage loss, vibration and noise, we boldly decided on a diameter having a peripheral speed of 84 m/sec. Performance was better than our expectations. Actual running tests resulted in better efficiency, quieter operation, and more uniform cooling, thus giving us confidence in our design and manufacturing techniques of high speed machines and also giving rise to the prospect of increasing the peripheral speed limit to a still higher value. Bearings are of a normal type and are arranged so that each guide bearing is on the upper and lower side of the rotor with the thrust bearing and upper guide bearing installed within an oil tank which is bracketed above the rotor. *Fig. 2* shows a sectional drawing of this generator.

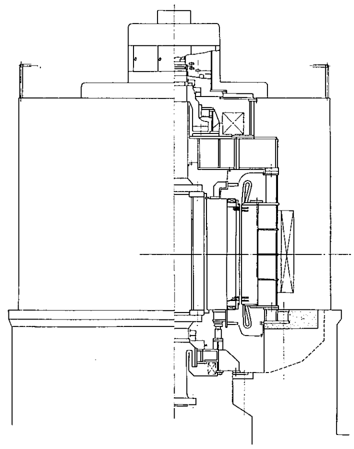

Fig. 2 Section of 74,200 kva generator

At this power station site, due to the proximity of a tourist resort, particular attention was paid to the generator's appearance.

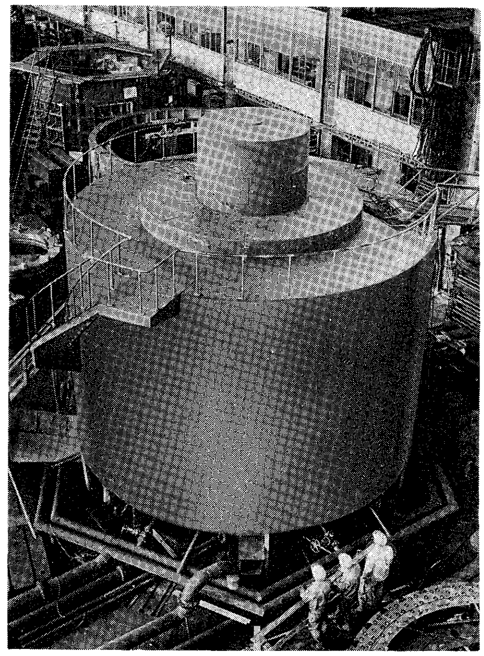

Fig. 3 74,200 kva generator

As a large output high speed machine many conditions had to be changed in construction design so as to meet a 15 ton transportation weight restriction which forced us to use an uneconomical design in which the stator was divided into six sections, the rotor into three sections (upper, middle, and lower shafts), and the rotor yoke into four sections in the directions of the shaft. However, because of our traditionally superior techniques in function and weight-saving design, we succeeded in minimizing the weight to within the permissible limits.

1. Stator

The stator frame is of welded steel construction

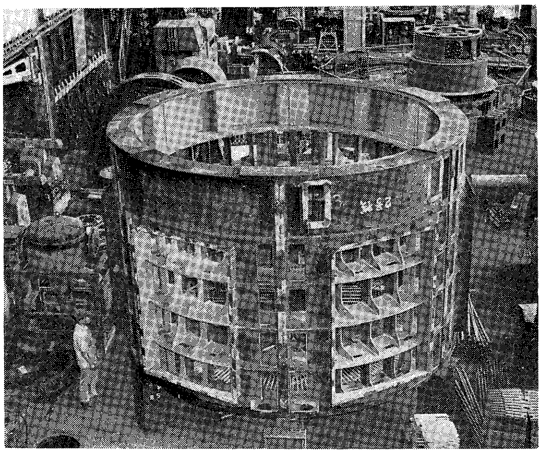

Fig. 4 Stator frame

utilizing pipe frames as much as possible so as to minimize the weight and is divided into six sections having an outer diameter of 5 meters and a height of 3.3 meters. The outer appearance of the stator frame is shown in *Fig. 4*.

Following strain correction by annealing, the surface joints and inner diameter of the welded frame are precisely machined. Throughout the entire process induction tests were carried out in order to determine the resonant frequency so as to insure that it did not fall at the source frequency or multiples thereof and also to check on the welds so that no abnomal vibration would result due to resonance after completion.

0.35 mm S-class silicon steel was used for the stator core which after being punched was annealed to relieve strain and minimize core loss. The silicon steel plates were baked on both sides with a thin uniform film of a special varnish which did not change in thickness after aging or long years of operation and were then laminated in a ½ over-lap pattern. Occasionally during the operation of a high speed machine having long core length the coils are damaged from vibration caused by the iron core becoming loose. During the time the core for this machine was being laminated, the divided sections were tightened temporarily and finally after they being heated and dried were given several additional tightenings.

The stator winding is composed of one turn Gitter coils. The coil insulation of a machine of high voltage and large capacity controls the life and function of the machine. Because of the light to heavy load cycle that is encountered in a peak load power station, which in turn causes a cooling-heating cycle within the generator, coils are liable to break down because of the great difference in expansion coefficients between copper and the insulating material.

Compared to present high potential insulating materials the F-resin coil has a relatively small coefficient of expansion difference. Strain between the conductor and insulating material is at a minimum as has been proven through forced aging tests. In a machine of this type where there are a small number of poles and long coils of low reactance, which will allow a large short-circuit current to flow, coil support becomes a very difficult problem.

To determine F-resin resistance against mechanical impact due to a short-circuit current, besides basic experiments, a test model, inserted in the iron core, was used to carry out the experiments; a current that is equivalent to short-circuit current was applied to the resin coil at an ambient temperature of -5°C and the variation of the insulation test values aginst the tanδ corona pulse, etc., at before and after the test were checked. Also, at one point of the coil winding, a bending stress was applied repeatedly, insulation tests were made and the results were compared. Thus we obtained the data necessary for perfect maintenance of an F-resin coil winding.

2. Rotor

Careful consideration was given to the rotor construction design so as to provide a 1.5 safty factor against material failure due to the large amount of stress that would be present at the turbine run-away speed of 850 rpm. Thermal stress and bearing temperature were also given special attention. *Fig. 5* pictures the rotor.

The magnetic pole core is made from 1.6 mm high strength steel plates laminated together by a hydraulic press into a thickness of about 2.5 m and formed by special steel end plates. In order to equalize the centrifugal force in the shaft direction when the iron core is joined together, reinforcing plates are welded to both sides of the core plates. The iron core,

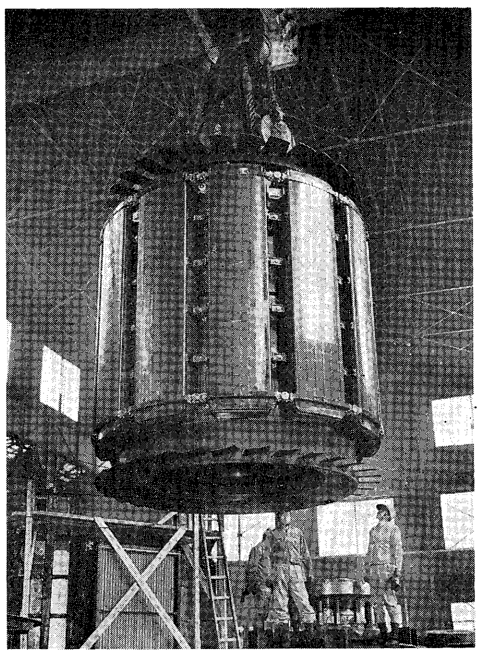

Fig. 5 Complete rotor of generator

after considerable discussion, was fixed on the yoke by a dove tail key.

The field winding, the same as the stator winding, was constructed from F-resin insulated coils. During periods of stoppage or overhaul under conditions of high humidity as is found in underground power stations, insulation resistance is not lowered thereby making this type of insulation most suitable for use in generators of this kind. The winding are wound around the iron core drum through the mica baked on the core and they are fixed closely to the poles by compression and heating using the pressure and temperature determined by consideration of the temperature difference between the windings and poles and centrifugal force during operation. Round steel rods are fixed at several positions along the full length of the iron core to prevent the windings from enlarging due to thermal expansion or centrifugal force at the run-away speed. The dimensions for the copper plates used in the field coil are determined by the exciting voltage and the magnetic pole air gap construction. However, with a machine of high speed and large capacity as this one, besides the above, expansion due to the centrifugal force, etc., must be considered to determine the width and thickness. Expansion and deviation due to the peripheral component of the centrifugal force are affected in a most complicated way by the temperature difference of the copper plates and iron core, method of holding the coils between poles, method of holding the coils to the iron core and friction between the copper plates, etc. For this reason, each manufacture used his own construction method based on his own experience.

Our past experience assures us that this method of winding support will provide a satisfactory margin in the operation of this machine. Some layers of the windings are equipped with suitable cooling fins to aid in the over-all cooling process. Pole winding connections always present a difficult problem in the design of high speed machines. The connecting bars must be designed to withstand centrifugal force and thermal expansion. In this case they are protected against centrifugal force by round steel supports but constructed to act freely against thermal expansion but still maintain adequate contact. Round copper damper windings are inserted on the head of the magnetic pole and silver-brazed to sector type end rings. Each end ring sector is then joined together by connectors to form a complete ring. The end rings of the damper windings in this machine are placed between the pole core and the terminal plate so as to minimize the stress on the damper bars whose yield point was lowered due to heating at the time of silver-brazing.

The fitting portion that supports the short bar with the terminal plate is constructed so that the bar's free movement in the axial direction due to thermal expansion during operation is not hindered. At the same time, the short bar is of a special cross section to prevent creation of extra stress at the fitting portion by an unbalanced centrifugal force.

The end ring connectors are constructed of flexible laminated steel plates containing a large center curvature as protection against thermal expansion and are supported by steel rods to counteract centrifugal force. Because of the transportation weight restrictions, the rotor yoke was made in 4 sections divided in the axial direction. Special high tensile strength forged steel was used so that sufficient rigidity was present while still allowing for the design of a large internal diameter thus minimizing the weight. The main shaft was divided into 3 sections (upper, middle, and lower) and connected together utilizing round pins in a radial direction and strongly bolted flanges. Due to the long iron core length and the distance between the shaft support bearings, the middle section demanded a high rigidity characteristic to withstand the stress forces that would be encountered at or above the turbine run-away speed. The section was fabricated of welded steel in a logical box type, so-called skin stress design which gave a 44% weight saving over the conventional one body forged steel shaft. The recent progress in welding techniques has made the use of this type of shaft construction for high speed machines highly reliable and was used in this case without reservation. The main shaft was designed with a 150% safety factor based on the run-away speed. It is essential that when the divided shaft units are joined they fall into perfect alignment to prevent vibration. Total shaft deflection was checked in our testing shop (see *Fig. 6*), by combining the shaft sections and trial testing on a lathe.

3. Other parts

The upper bracket, too, was forced to be divided into sections because of transportation limitations. The bearing section oil tank, as it was required to enclose the cooling tubes to minimize the power

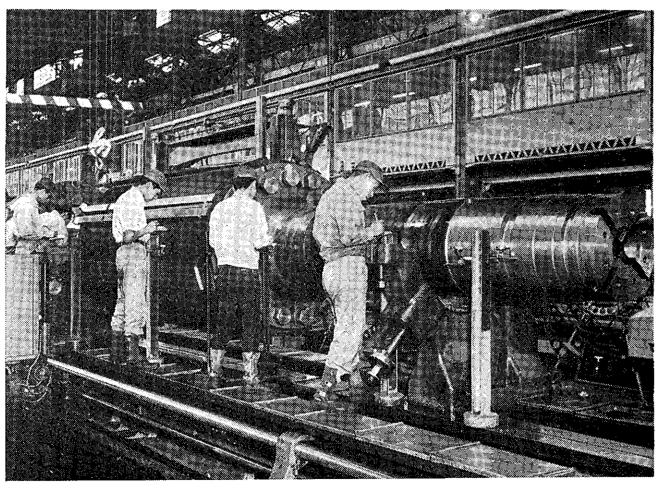

Fig. 6 Alignment checks of main shaft

loss of the bearings, had to be very large; the central oil tank and its outer walls were constructed detachable for transportation purpose. Six arms also were constructed to be removable. To prevent oil leakage, the joining section of the central oil tank and outer wall is precisely finished and provided with a suitable packing.

Frequent starting and stopping operations are encountered in peak load power stations. The life and function of the brake lining, therefore, becomes an important aspect of future maintenance. Comparison tests on several kinds of materials were carried out to determine the proper combination for the brake ring and lining. As a result of the tests, carbon steel was used in the construction of the brake ring and an asbestos resin-mold product, pressed and heat treated, was used for the lining.

4. Construction of Auxiliaries

The exciter and other auxiliaries in a conventional water turbine generator are usually of an open type. Because this generator is housed completely underground the auxiliaries were totally enclosed to provide protection from the high humidity and to decrease the noise level inside the narrow building. A combination single air cooler was installed to provide cooling to the auxiliaries as well as the main generator. Noise tests conducted in our testing shop indicated a noise level of 85 phon increasing to 90 phon when the inspection door was opened, which we felt was quite good for such a large generator. The resistance of the exciter windings is sometimes lowered due to the waste powder resulting from the wear between the commutator brushes and the slip-rings. To prevent this, the brushes were arranged in front of the exhaust fan so that the loose powder does not come into contact with the winding. An air filter is installed in the air duct to remove the powder and to prevent it from entering the main generator.

IV. AIR VENTILATION COOLING

In a machine having a long core length compared with core diameter, the air ventilation cooling becomes important; the cooling air must be distributed so as to maintain a uniform temperature throughout the machine.

The ventilating circuit is designed to obtain a uniform temperature distribution by allotting the cooling air with consideration for the loss and thermal resistance and heat radiation constant of each part; however, if the ratio of the core length to the pole spacing becomes too large, sending of required amount of air to the central part becomes difficult. In this machine, since the acceleration constant required was large and the core diameter became large out of necessity, the ratio of the core length to pole spacing is less than 3. When the ratio is below 3, local center heating may be disregarded; however, air quantity to the center was increased as much as possible to act as a safety factor.

A greater part of the windage loss in a high speed machine is due to other factors than the fan loss. Additional ventilation due to the rotor fan effect, must combine with the forced ventilation system in such a manner as to reduce eddy-current losses to a minimum. These losses occasionally are as high as 20% when not matched. When operated at light load the mechanical loss in this machine accounts for 56% of the total loss. It becomes apparent, therefore, that eddy-current losses must be held to a minimum. Because of mutual interference with the rotor blade action, an accurate designing a proper fan for rotary machine is rather difficult. Fuji Electric, because of its mass of measurement records and experiment results, is able to make a fairly accurate estimate of the external resistance of the rotor blade and air cooling devices, etc., and it believes that a considerable accuracy can be expected of its fan designs. Since this machine was designed to be a record-making generator, an axial fan capable of regulating blade angle freely was adopted to secure the needed air quantity at a minimum windage loss. The most suitable blade angle position was set from tests conducted at the factory. *Fig. 7* compares

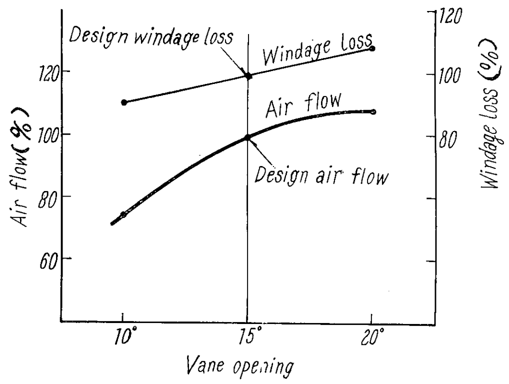

Fig. 7 Cooling air quantity and windage loss due to various pitch of blade

blade angle values to air flow and windage loss. A 15° blade angle was finally decided upon and as such coincided with the assumed design values.

As to the effective distribution of the cooling air, as can be seen in the measurement results of air flow distribution in the core duct of the stator of this machine, *Fig. 8*, the air flow is distributed uniformly over the entire core length with properly adjusted air resistance of the ventilation circuit parts. When the metallic fan guide of an axial fan approaches the stator winding, a large eddy-current loss is sometimes realized due to flux leakage from the stator end coils. Therefore, a glass-polyester fan shield was used instead of the usual metal type. The 6 air coolers are arranged equidistantly around the stator periphery. The cooling pipes were made from

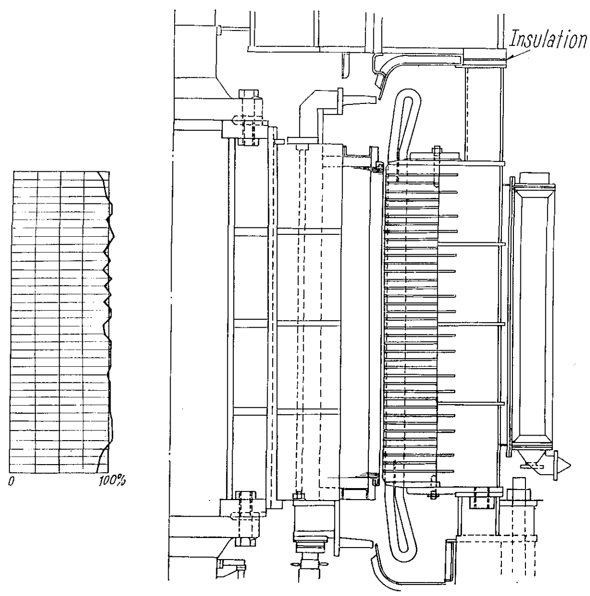

Fig. 8 Distribution diagram of cooling air

a well known anti-corrosive material called " ever-brass pipe " to which copper wire U-fins, in the form of a coil, were soldered to the outside.
Resonance frequency measurements had to be made because of the extremely long length of the cooling pipes so that proper support could be provided to prevent the failure of the junction joints from resonance. An expansion type method was adopted for the connection joints between the pipe and pipe plates to provide adequate binding and eliminate water leakage and corrosion.

V. LUBRICATION

The upper guide bearing is mounted inside the upper bracket oil tank and is cooled by the common oil cooling pipe. The bearing diameter is 1.2 m with a high peripheral speed of 31.5 m/sec at the rated generator speed. This presented many problems relating to lubrication, temperature, etc. Discussions were held and comparisons of various design conditions were made between the present machine and actual operation results from our test equipment using a vertical shaft short-circuit generator with a peripheral speed of 52.4 m/sec. A solid cylindrical type steel plate fabrication was adopted and considered suitable from the standpoint of oil groove construction, bearing clearance, etc. This type of construction is advantageous during assembly and disassembly operations requiring very little labor to center the bearing and no adjustment is necessary to set the bearing clearance and yet always being able to maintain the initial set position. Bearing loss increases with speed ; moreover, air mixes easily with the oil because of stirring and forms bubbles lowering the lubricant delivering efficiency of the oil pumping holes in the bearing collar. This hinders the proper lubrication of the bearing's sliding surface and, at the same time, lowers thermal conduction efficiency of the cooling water pipes, resulting in possible burning due to high temperature. To prevent the above harmful effects, special construction was used to minimize oil agitation caused by the collar rotation and to reduce the contact between the stirred oil and the air. Successful results were obtained in our shop holding the bearing temperature to 48.5°C with a water temperature of 20.5°C and considerably lower than the guaranteed value of 65°C, and at the same time, we were able to obtain valuable data on extension of application range of unified type cylindrical bearing and construction of high speed bearing. The lower guide bearing was constructed the same as the upper except that it was divided. A Mitchell type thrust bearing was used with metallic springs as supports. When assembling the thrust bearing the load must be balanced between each segment. The usual complicated adjustment necessary when using a screw adjusting system was avoided by utilizing the metal spring design. Minor errors in manufacturing such as height of the metal spring, height of the segment, etc. are easily compensated for by this type of support. After manufacturing, the spring constant for each metal spring is checked for uniformity under an actual load. Because of the excellent construction of the bearing and superior erection techniques with regard to leveling and upper bracket deflection, no adjustment was necessary, thereby speeding up the erection process and yet giving high performance dependability.

VI. CHARACTERISTIC AND TEST RESULTS OF GENERATOR

1. Wave Form

This machine is designed for fractional slot, not skewed, but there is practically no slot harmonics.

To simplify the connection of the coil ends and coil end supports, a wave winding was used with a special short pitch connection to eliminate specified higher harmonics. Wave form distortion has always been measured according to JEC 114 ; however, T. I. F. is used in the U. S. A. to emphasize inductance interference. Last year the I. E. C. decided on a standard T. H. F. measured by changing weight dependent upon the frequency of each higher harmonic. The no-load induced voltage of this machine in the following table is based on the above mentioned standards.

	THF	TIF (Balance)	Deviation factor of wave form
Measured value	0.461%	18.4	1.2%
Standard value	Below 1.5%	Below 50	Below 10% (Guaranteed value below 5%)

As can be seen, all the standards have been met.

2. Exciting System

The ratio of exciting capacity to the rated output is small in a high speed machine, therefore, the exciter and time constant for the field circuit and armature circuit may also be kept small. A d-c one stage amplifying system directly connected to an OH type self exciting d-c machine (exciter) was adopted. Since the exciter is provided with an isthmus pole it is capable of controlling to a low voltage by self excitation manual operation. The generator must be operated on a transmission line of 140 kv, 25 km for an initial line change.

In this case, the generator voltage is gradually increased from zero to the rated voltage; with the exciter connected as self-excitation, a stabilized operation of the generator to near the zero voltage is possible by controlling the field resistance. Since this exciter has only one field winding, the armature and field winding terminals of this exciter are disconnected during normal operation and the exciter functions as a completely separated exciter.

The exciter's magnetic circuit is constructed with a specially designed laminated iron core so as to minimize time lag. Tests indicated a voltage build-up rate of 4860 volts/sec with a ceiling voltage of 800 volts. The response of an OH exciting device is decreased very little by the d-c amplifier stage and, therefore, is said to serve almost the same function as an OH exciting device.

3. Reactance

Field and damper winding leakage reactance decreases in a machine with a small number of poles. Even in machines with the same short-circuit ratio, reactance decreases proportionally to the cube root of the number of poles.

The measured reactance values for this machine, as shown in *Table 1*, are much smaller than that of a low speed machine. Transient stability must be taken into consideration when determining maximum rated output and dimension of a large output machine.

In the present machine the reactance is small so that it is possible to design without consideration of transient stability.

Table 1 **Test result of reactance and time constant**

Xd	98%	Xq	59.0%
Xd′	25.3%	—	—
Xd″	19.2%	Xq″	18.7%
X_2	19.0%	X_0	11.5%
Ta	0.2 sec	Td_0'	8.38 sec
Td′	2 sec	Td″	0.079 sec

4. Nominal Efficiency

Fig. 9 shows the nominal efficiency that may be expected as calculated from factory tests of a 1.0 p. f. and the rated p. f.

Test records indicate higher values than those guaranteed and do not show low values even at partial loads. This proves that the mechanical loss has been successfully reduced to a minimum value by the rational air ventilation and lubrication.

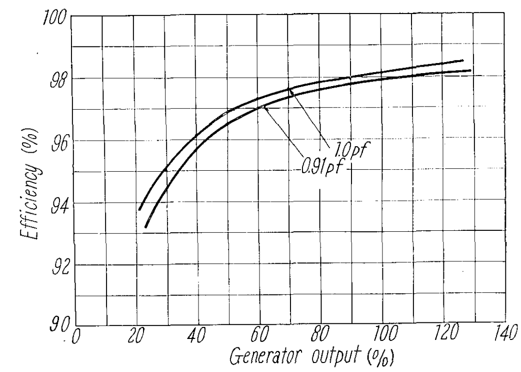

Fig. 9 Efficiency curves

5. Temperature Rise Test

Temperature rise tests were conducted in conditions approaching those of normal operation as nearly as possible utilizing air coolers and cooling water. The results are shown in *Table 2* and confirm that sufficient allowances have been included. Uniform cooling was checked by both the search coil and resistance methods. Bearing cooling also indicated a sufficient design allowance when tested under actual conditions at the site. We are now confident in our design and manufacture of bearings for high speed machines.

Table 2 **Test result of heat-run test**

Output		74,200 kva
Stator coil	Search coil method	59.5°C
	Resistance method	53.5°C
Rotor coil	Resistance method	45.7°C
Bearing temperature (Water temp. 20.5°C)	Thrust bearing	48.5°C
	Upper guide	48.5°C
	Lower guide	50°C

VII. CONCLUSION

We have outlined the generator at the Shimotaki Power Station. Hydro-electric turbines throughout the world have departed from the conventional manufacturing methods raising the old speed and output limits and still remaining within accepted economical limits. This generator is an up-to-date machine in which severe design and manufacturing specifications were met under difficult conditions peculiar to our country such as a peak load power station, transportation restrictions, etc. Test results have proved that our expectations were achieved. We hope that these techniques will not stop at this plant but will continue to be developed to aid in future progress in the design and manufacturing of high speed machines.