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5-NOZZLE PELTON TURBINE GENERATOR DELIVERED TO BAMBAJIMA POWER STATION OF HOKURIKU ELECTRIC POWER CO., INC.

By Atsuo Imanishi and
Takashi Konota

Second Power Techinical Sect., Central Technical Dep't.

I. PREFACE

After World War II in our country vertical shaft Pelton turbines have been constructed one after the other.

Though there are many actual examples in foreign countries also, at present where many model turbine tests for 4-, 5- & 6-nozzle ones have been finished, the model tests show that the Pelton turbines in running are not always most economical and high efficiency.

If other number of nozzles and speed were designed for the turbines, many machines would be more economical and have higher efficiency.

When considered from historical standpoint, at first in order to make turbine generator economical, high speed was taken and number of nozzles increased (for instance 4, 5—only rare—, 6 nozzles), but at present high specific speed runners have been developed for 5-nozzle and for under 5-nozzle ones and specific speed of $Ns=20$ (m-kW) is the most suitable and also for about $Ns=22$ (m-kW) efficiency does not drop much. However, with 6 nozzles, because angle with adjacent nozzles will be 60°, with present techniques unless specific speed is under $Ns=18$ (m-kW) at most, interference of jet water will occur. Consequently, even by adopting 6 nozzles, it would not be possible to make it economical by raising speed. Therefore, range of applying 5-nozzle turbine will become larger. *Fig. 1* shows possibility of how widely 5-nozzle turbine can be adopted, (it is intended to introduce this in detail on another occasion).

In installations with high head and large output, because speed of generator cannot be taken high, it will be more advantageous to adopt 4, 3, 2 nozzles. 6-nozzle turbine remains in *Fig. 1* in a small degree. When effective head becomes greater than about 800 m, Ns cannot be taken large whatever number of nozzles is adopted and with 1,000 m, it will become about 16. That is to say, when effective head becomes great, because there is a limit to specific speed, 6-nozzle turbine will not necessarily become disadvantageous but on this account this can be considered in only a few zone as *Fig. 1*. Also with range for 5-nozzle turbine, from relation with generator synchronous speed, it can be considered from this point that speed will not differ much to 4-nozzle turbine and that even with a slight drop of efficiency it will be better to take 4-nozzle but theoretically it is considered that 5-nozzle turbine will be adopted in a very wide range in the future. However, as hitherto actual results as far as we know, there are only about 4 installations in the world including Bambajima Power Station (all others are mostly 4-nozzle or 6-nozzle even within the range of 5-nozzle in *Fig. 1*).

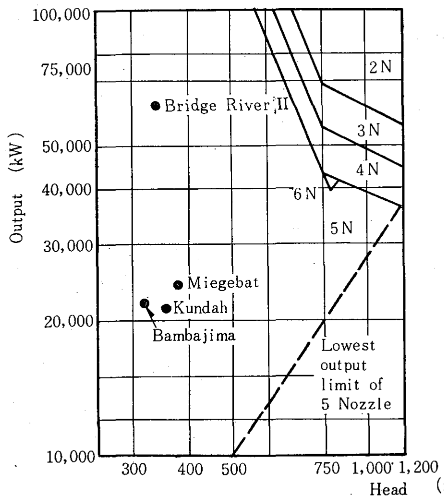

Fig. 1 Suitable zone of 5-nozzle Pelton turbine

5-nozzle turbine has an odd number of nozzles and because development of its model was retarded, it seems that this was not widely adopted. However, at present where all model tests have been completed and researches advanced, we consider that this should be more and more adopted.

II. TURBINE AND GENERATOR SPECIFICATION

1. Course till Decision was made for 5-Nozzle

In the case of Bambajima Power Station, for the conditions effective head 319 m, turbine output 22,000 kW, frequency 60 c/s, of generator no difficulty would be felt in manufacture of generator for any

Table 1 **Manufacturing example of 5-nozzle Pelton turbine**

Name of power station	Country	Head (m)	Quantity of flow (m^3/s)	Output (kW)	Speed (rpm)	Maker
Bridge River II	British Columbia	340	20.2	60,000	300	Neyrpic
Miegebat	France	380	7.05	23,900	428	Neyrpic
Bambajima	Japan	319	7.9	22,000	450	Fuji
Kundah	India	360		21,600		Dominion Engineering

Table 2 **Comparison table of each plan**

Number of nozzles	4	4	5	5	5	6	6
Speed (rpm)	400	450	400	450	514	400	450
Specific speed (m-kW)	22.0	24.8	19.7	22.1	25.3	18.0	20.5
Turbine max. efficiency (%)	88.3	*2	88.7	88.3	*3	*4	*5
Generator max. efficiency (%) (P.F. 0.9)	97.5		97.5	97.5			
Generator exciting capacity (%)	109		109	100			
Crane lifting capacity (%)	108		108	100			
Turbine weight (%)*1	105		107	100			
Generator weight (%)*1	76		76	72			
Turbine generator total weight (%)*1	181		183	172			

*1 Comparison of turbine and generator weight are for weight of 5-nozzle 450 rpm turbine taken as 100%.
*2 Specific speed is too great and turbine efficiency is too bad.
*3 Not only is specific speed too great but jet from next nozzle makes interference with each other inside bucket and makes efficiency drop and there is so-called danger of interferenc of jet.
*4 Because speed does not increase even when made 6-nozzle and so it is not at all economical.
*5 There is danger of interference of jet and at same time speed does not rise even when made 6-nozzle.

speed. It would suffice to determine number of nozzles and speed from the standpoint of hydraulics. Various plans that were studied at the time of planning were as shown in *Table 2*.

However, 4-nozzle 450 rpm plan, 5-nozzle 514 rpm plan, 6-nozzle 400 rpm plan and 6-nozzle 450 rpm plan were eliminated on account of the reasons shown in *Table 2*. Accordingly, that remained for the final comparison object were 4-nozzle 400 rpm plan, 5-nozzle 400 rpm plan and 5-nozzle 450 rpm plan. Of these 3 plans, 4-nozzle 400 rpm plan was inferior to 5-nozzle 400 rpm plan and 5-nozzle 450 rpm plan on points of turbine efficiency and turbine generator economy. Next, when comparison is made between 5-nozzle 400 rpm plan and 5-nozzle 450 rpm plan, 450 rpm plan though turbine efficiency will be somewhat less, will be much lighter in turbine and generator weight and on this account will be cheaper in equipment cost. After carefully considering generated power quantity accompanying drop of efficiency in relation to equipment cost carefully, it was decided to adopt the 5-nozzle 450 rpm plan.

2. Turbine

1) Specification
No. of units: 1

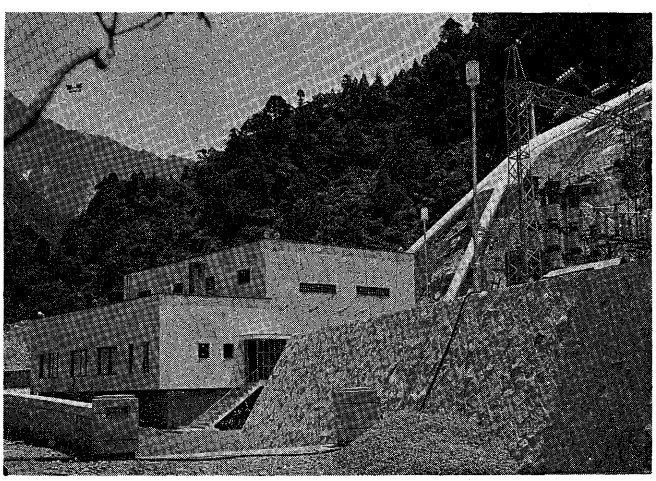

Fig. 2 View of Bambajima P.S.

Type : Vertical shaft, single runner, 5-nozzle Pelton turbine
Output : 22,000 kW
Effective head : 319 m
Quantity of flow : 7.9 m^3/s
Speed : 450 rpm
Specific speed : 22.1 m-kW
(Regarding efficiency see *Fig. 3*)

2) Turbine Construction

Fig. 4 shows sectional view of turbine proper. As seen in the drawing, nearly all parts, upper head cover and housing to begin with are made of welded steel plate and parts contacting with running water inside have the most suitable curvature so that water coming out from bucket will not interfere again with runner and jet.

Housing is made as the most economical single-wall construction and lower part is made as 10-angle polygon from consideration to simplify manufacture. Casing is composed of bend pipe, branch pipe and flow-in bend pipe of which branch pipe and flow-in pipe are of cast steel and bend pipe is made of welded steel plate with flange only of cast steel. For type of nozzle, as shown in *Fig. 8*, servo-motor inside contained system is adopted whereby building is made smaller and dismantling and inspection made easy.

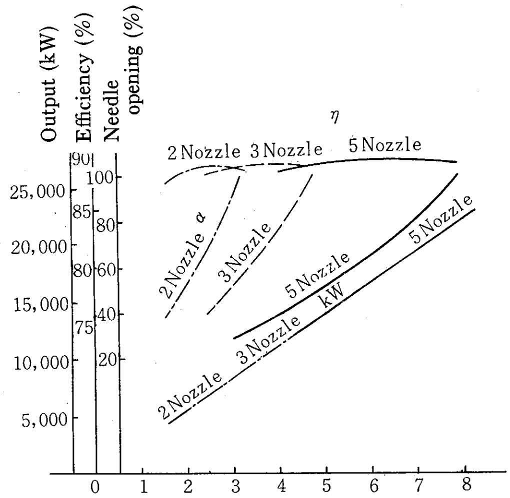

Fig. 3 Efficiency curves of water turbine

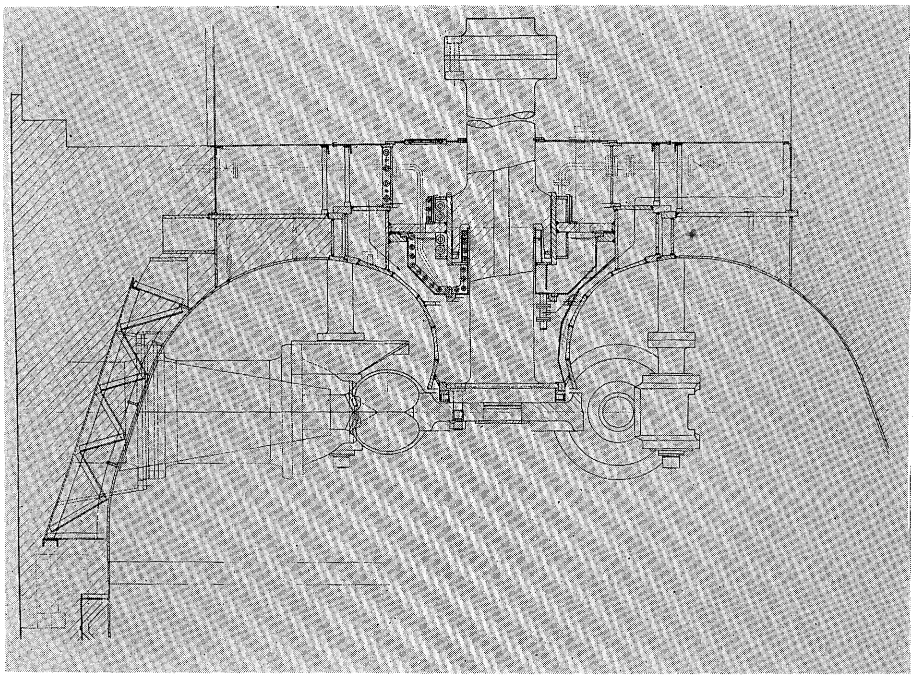
Fig. 4 Sectional view of turbine

With hitherto nozzle system of Pelton turbine, that is, with types that control needle by penetrating needle rod into casing inside, even if number of nozzles are increased and speed raised, there were many cases where for dismantling needle, dimensions of building because larger. Contrary to this, when this nozzle type contained inside servo-motor is adopted, even if number of nozzles is increased, because area of building will not increase, it is a very effective system especially for cases where number of nozzles become many.

This system is the first of its kind as domestic production but is being already adopted in Kurobe-gawa No. 4 Power Station of Kansai Electric Power Co., Inc. (output 95,800 kW, head 580 m, quantity of flow 18.65 m^3/s, speed 360 rpm, J.M. Voith GmbH made) which has needle operating servo-motor contained inside nozzle pipe and construction is such that for disassembling nozzle, it can be done by keeping inside nozzle and servo-motor mechanism as one body and lowering this into pit and because no

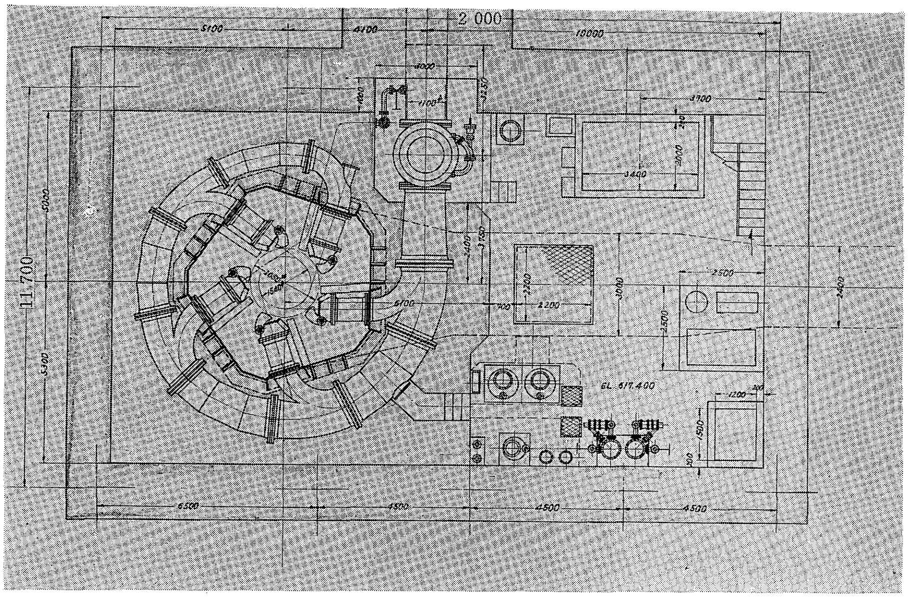

Fig. 5 Arrangement of machine (plane)

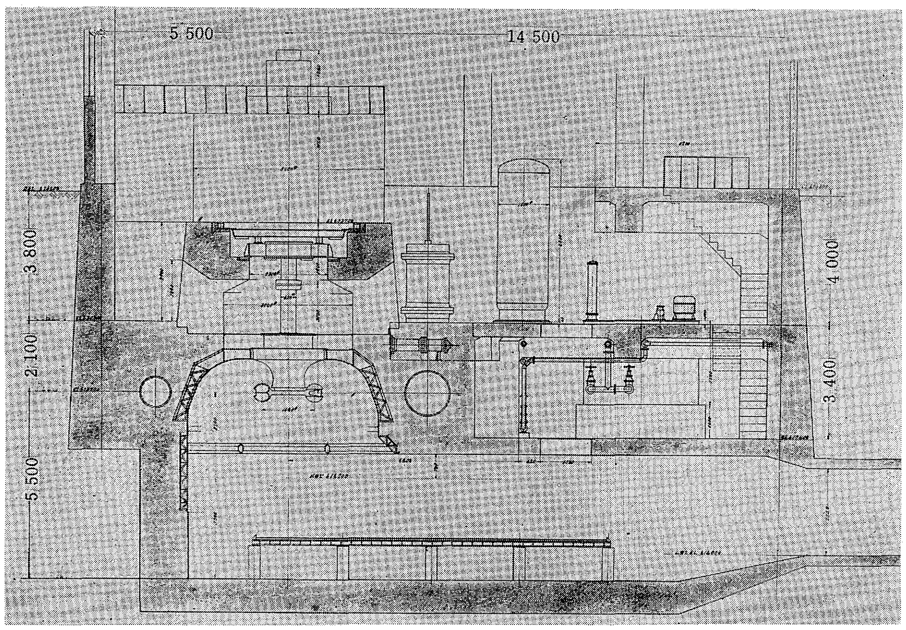

Fig. 6 Arrangement of machine (section)

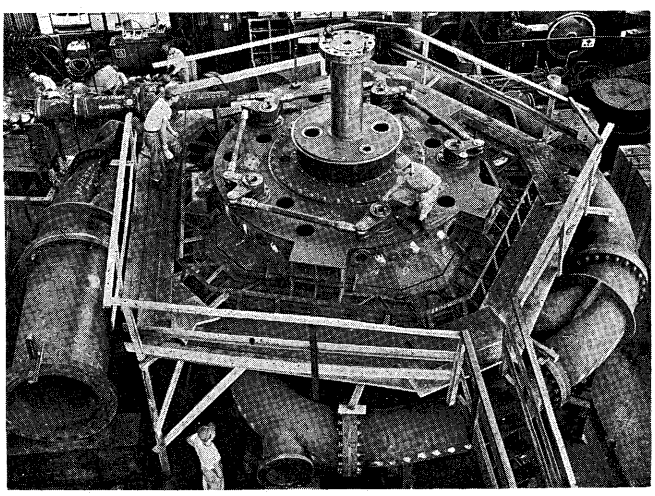

Fig. 7 Assembled turbine

space will be required for disassembly outside the casing, building construction and civil construction work will become exceedingly simple.

Arrangement drawing with all these points considered together is as shown in *Fig. 5* and *Fig. 6*.

Casing and nozzle part are subjected to water pressure test with 51 kg/cm^2 all in combined state and checked to see everything is in order.

Runner is made of 13% Chrome cast steel as one body, number of bucket 17, max. external diameter 2,050 mm, weight about 4 ton for which satisfactory results have been obtained in casted state and processing state.

Main bearing adopts self-circulated type provided with water jacket and carrying out cooling by passing water and the construction is such that operation can be safely done by 1-nozzle operation

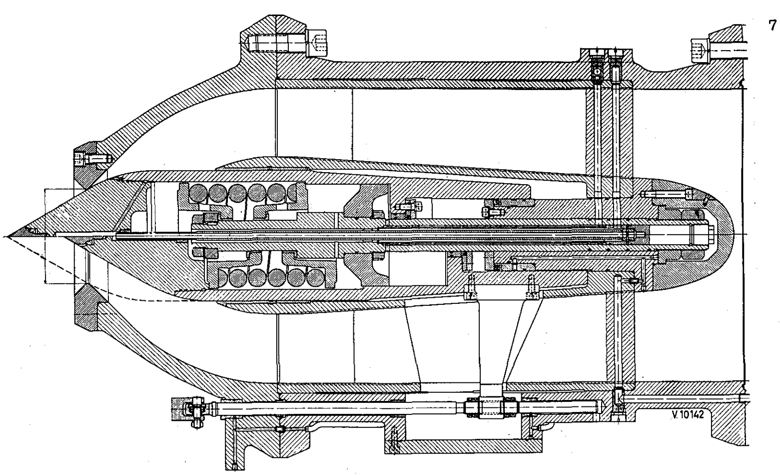

Fig. 8 Explanation section drawing of inside controlled nozzle

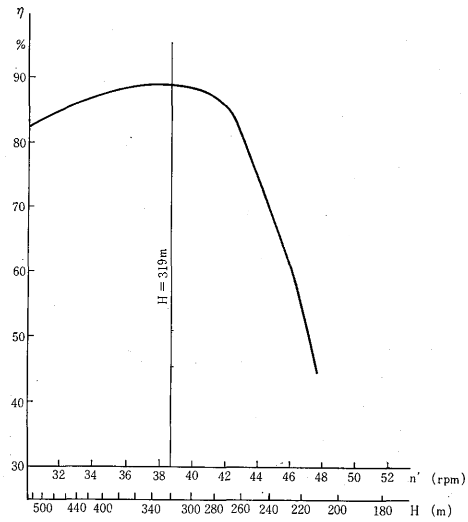

Fig. 11 Efficiency curve of model turbine

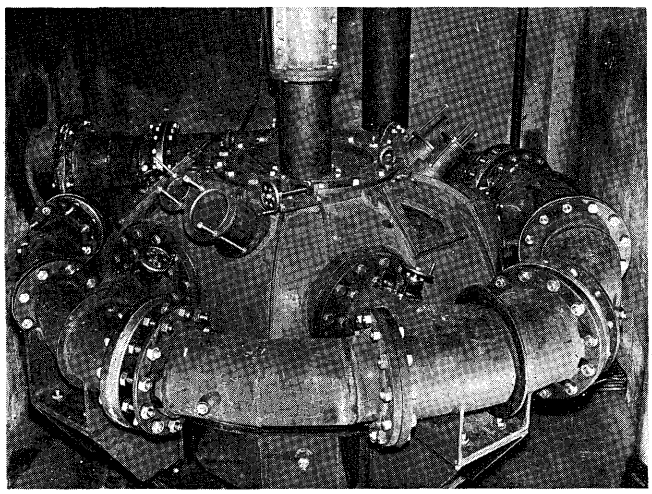

Fig. 9 Model turbine

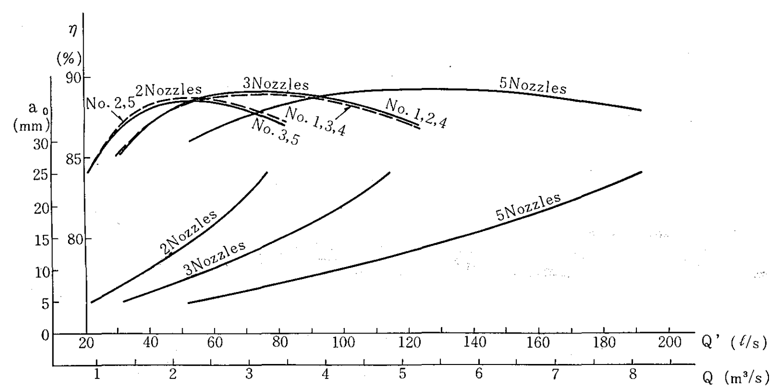

Fig. 10 Efficiency curves of model turbine

to begin with and for all combinations of number of nozzles.

In 5-nozzle Pelton water turbines, there may be anxiety that strain will be produced to bearings, etc. on account of unbalance of force due to jet during 2- or 3-nozzle operation, but from the beginning, bearings and other construction parts are normally designed to be able to operate safely even in 1-nozzle operation where conditions are worst. Consequently, even if 5-nozzle is adopted, there is no necessity to make considerations specially from point of strength and so price of machine will not become high.

In 5-nozzle water turbines, in order to carry out high efficiency operation, change-over operation to 2-, 3- and 5-nozzle is done and this system is as stated below. That is, during starting 3-nozzle (A-group) is done, and when load becomes above about 60%, the other 2 nozzles (B-group) begin to open and operation will become 5-nozzle. In the case where load sinks, when load becomes under about 55%, B group will close and operation will be done by A-group (3 nozzles) only and further when load still decreases and becomes about under 40%, now B-group begins to open and A-group closes being designed so that 2-nozzle operation will be carried out. These change-over obtain conditions by limit switch attached to needle and limiting relay, and are so made that they will be carried out automatically and reliably. In such a way, number of nozzles in 5-nozzle Pelton turbine can be controlled in 3 steps 5-, 3- and 2-, in contrast to which, in 4-nozzle turbine, it can ordinarily be controlled only in 2 steps, 4- and 2- and therefore 5-nozzle water turbine has better efficiency at low loads.

3) Model Test

As manufacturing of 5-nozzle turbine was the first experience for us, we executed many model tests. A part of them are introduced in the following lines. The model test of servo-motor inside contained system construction was also conducted.

At 400 mm pitch diameter, the highest efficiency of the model is 89.2%. This value is excellent as the specific speed of 22.1 m-kW. *Fig. 10* shows efficiency curves in case of 5, 3 and 2 nozzles respectively.

As the turbine is 5-nozzle high specific speed one, tests of efficiency down and interference of jet under

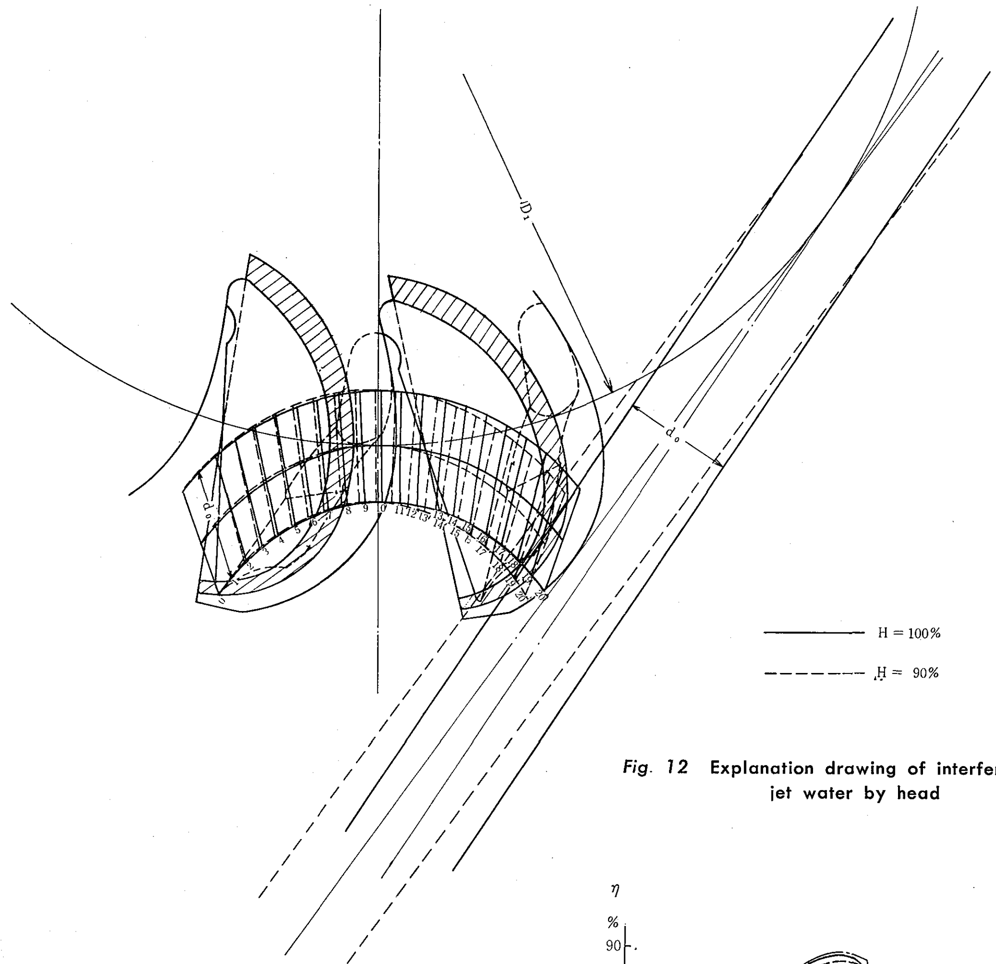

Fig. 12 **Explanation drawing of interference of jet water by head**

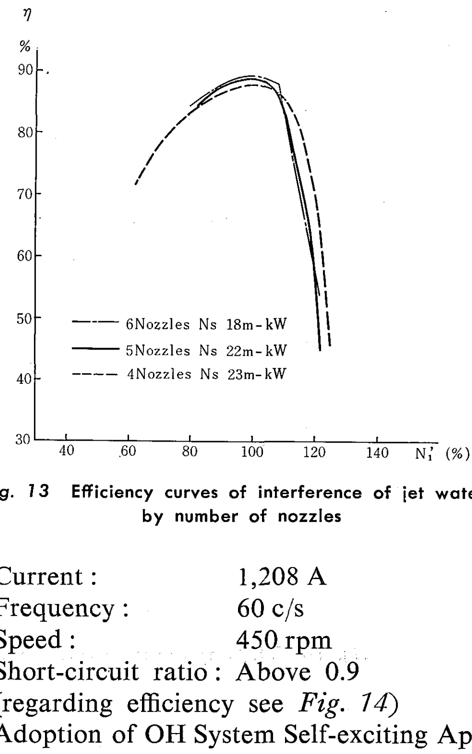

Fig. 13 **Efficiency curves of interference of jet water by number of nozzles**

head variation were executed. It is understood that interference of jet occured at less than 90% head. Interferences of jet at 100% and 90% heads (in this power station almost no variation) calculated from relative speed drawing are shown in *Fig. 12.* It is seen that, when water drip of 0 position hit at the bottom of bucket, at 100% head next jet does not enter but at 90% head interference has occured.

Comparison between interference of jet at 4-nozzle ($Ns=23$), 6-nozzle ($Ns=18$) and interference at 5-nozzle ($Ns=22.1$) is shown in *Fig. 13.*

6-nozzle one makes intereference of jet at 90% head inspite of $Ns=18$, and inferior to 5-nozzle $Ns=22.1$ one.

In case of 4-nozzle ($Ns=23$) one, interference of jet does not occur at 90% head and no interference until 80% head. However the max. efficiency of 4-nozzle $Ns=23$ is worst among all.

3. Generator

1) Specification

No. of units:	1
Type:	Enclosed wind duct ventilated type AC synchronous generator
Output:	23,000 kVA
Voltage:	11,000 V
Current:	1,208 A
Frequency:	60 c/s
Speed:	450 rpm
Short-circuit ratio:	Above 0.9

(regarding efficiency see *Fig. 14*)

2) Adoption of OH System Self-exciting Apparatus and Short-circuit Ratio

In Bambajima Power Station, so-called OH system self-exciting apparatus composed of power source transformer, current transformer, saturable reactor, silicon rectifier, etc. This exciting apparatus, since delivery to Ōbari Power Station (former name Tazawa) of Tōhoku Electric Power Co., Inc. (8,500 kVA

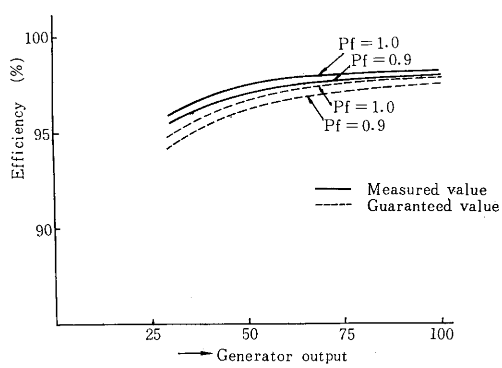

Fig. 14 **Efficiency curves of generator**

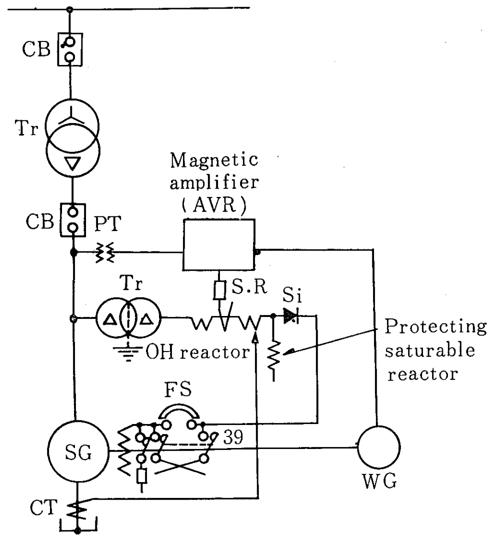

Fig. 15 **Single-line connection diagram of self excited AC generator**

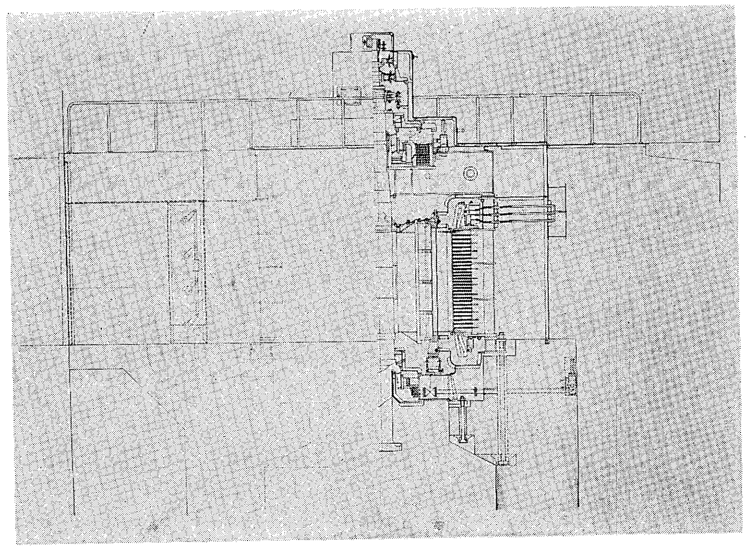

Fig. 16 **Section view of generator**

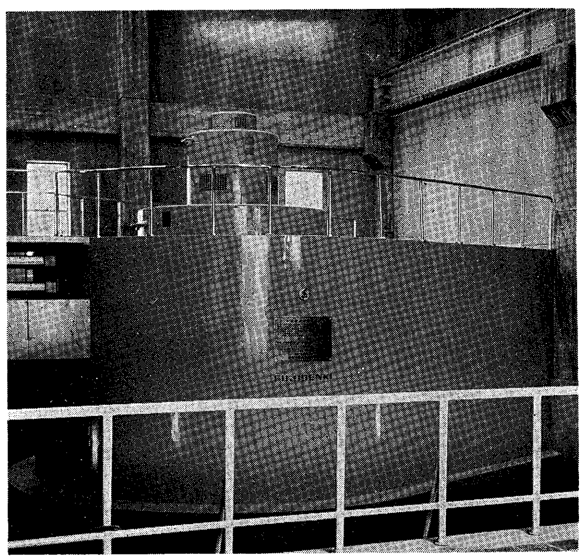

Fig. 17 **23,000 kVA generator**

6.6 kV 333 rpm 50 c/s) has attained actual results of 10-plus installations for only turbine generators.

In our Company, at the Ohari Power Station site, various experiments were carried out through which, compared with hither (rototing type exciter+continuous action type automatic voltage regulator) system, it was confirmed that it was very effective for control of voltage rise during sudden load variation, increase of normal state stability and increase of transient stability and conclusive evidence has been obtained that short-circuit ratio of generator can be made smaller than hitherto. (see Fuji Electric Journal Vol. 33, No. 6)

If short-circuit ratio of generator is decreased, generator becomes economical and raise of efficiency also can be hoped for. In Bambajima Power Station, short-circuit ratio 0.9 has been adopted and efficiency is 0.1~0.2% higher than ordinary cases where 1.0 is adopted. Also, self-excited AC generator with short-circuit 0.9 is not inferior whatever to generator using rotating type exciter with short-circuit ratio 1.0 in characteristics.

3) Construction of Generator

As shown in *Fig. 16*, generator has ordinary construction and to upper part of generator, a permanent magnet generator (0.7 kVA 110 V 60 c/s) for frequency detection and speed governor power source and self-exciting generator (10 kVA 220 V 60 c/s) for automatic voltage regulator power source are direct coupled.

For this generator also, welded construction based upon latest welding techniques is fully taken in and efforts to reduce weight is carefully paid.

Stator frame is made as steel plate welded construction and for transportation is split into 3 sections. To lower parts of this, base formed of 6 blocks is attached. Stator winding is made as 1-turn gitter coil and is transposed inside slot and for insulation, latest system of F resin insulation of our Company is adopted. This F resin coil is insulated with F resin impregnation having epoxy lineage resin as main ingredient which possesses such merits as

(1) No gap whatever is present in insulation

(2) Superiority in withstanding oil and moisture

(3) Superiority in electrical characteristics as for tan δ, etc.

tan δ-voltage characteristics of generator stator winding is shown in *Fig. 18*.

Rotor spider is made as hollow box form welded construction having 6 arms and fixed to main shaft by shrinkage fit. Yoke is formed of 4 wrought steel thick plates and magnet poles are mounted on

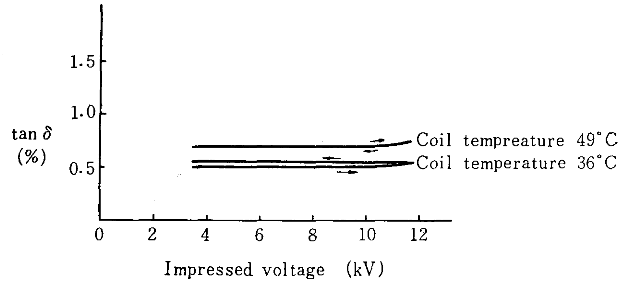

Fig. 18 tan δ vs. voltage characteristics

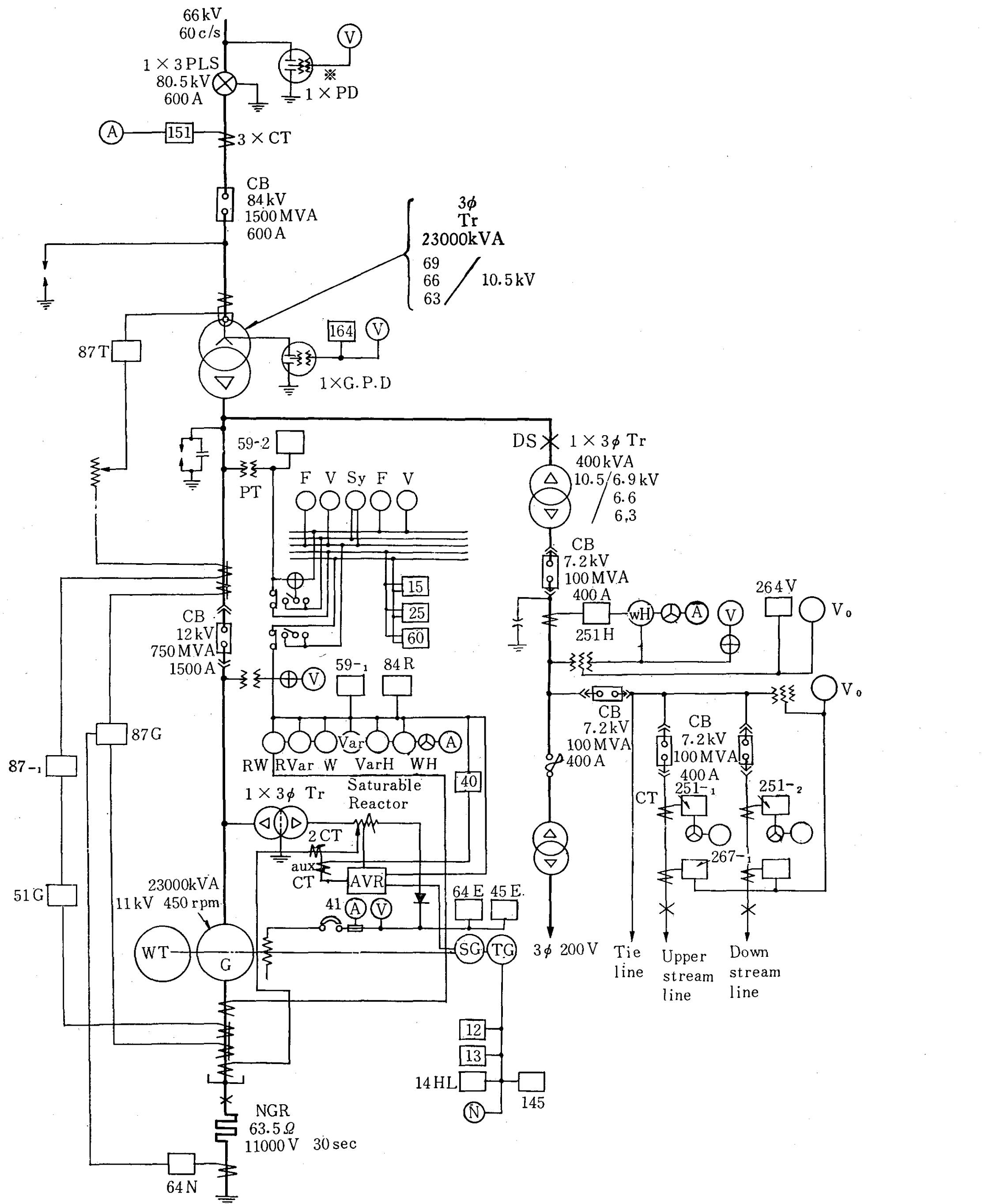

Fig. 19 Single-line connection diagram of Bambajima P.S.

this yoke by dove-tail form key. Magnet pole winding same as stator winding adopts F resin for ensuring perfect insulation.

For thrust bearing, Michell type is adopted and both lower and upper bearings are self-circulated types using cooling pipe and also water jacket.

Air duct is enclosed ventilated type and suction side air duct and exhaust side air duct are separated inside one air duct, air suction being carried out from power station building outside and air suction side inlet is provided with air filter so that dust and dirt are completely removed. Air that has been freed from dust and dirt enters generator inside from between suction inlet and upper bracket provided on generator bed and cooling iron core, windings, etc. and is exhausted to power station outside.

In exhaust side air duct, a door is provided to heat generator room by using warm air that has cooled generator in winter and moreover by providing air damper, the construction is made such that it will automatically close in the case of generator faults. Consequently, because it does not suck air in from generator room as is so with ordinary ventilated types, noise is little and also due to air filter provided at air suction side inlet, dust and dirt will be removed and generator interior will not become unclean which makes it have no difference with air circulating types.

III. TRANSFORMER, ETC.

Single-line connection diagram of Bambajima P.S. is as shown in *Fig. 19*. Main transformer on account of transportation limitations (15 t, No. 2 limit of Japanese National Railway) is made as outdoor-use nitrogen filled type special 3-phase transformer (23,000 kVA, 10.5/69–66(R)–63(F) kV 60 c/s) and it is considered so that each phase can be transported to site completely assembled as it is. Also, 84 kV circuit breaker is Fuji expansion circuit breaker, 12 kV and 7.2 kV circuit breakers are Fuji water circuit breakers and all other switches and switch panels are Fuji made ones.

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