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SMALL HYDROPOWER PLANTS, THE METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA, U.S.A.

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I. FOREWORD

The Metropolitan Water District of Southern California established a program of constructing small hydropower plants at 14 locations by 1984. The plants will have a capacity of 77.2 MW when they are all on line. Work has been completed on 7 of the plants and the remaining seven are in design or construction stages.

Metropolitan Water District is one of the largest wholesalers of water in the world, serving a population of nearly 13 million people in an area that covers about 5,100 square miles. Major cities in Metropolitan's service area include Los Angeles, San Diego, Pasadena and Long Beach.

The district receives water from the Sacramento River through the California State Water Project and from the district's own Colorado River Aqueduct. Water from the Colorado is pumped up about 410 meters through five pumping plants to get the water over mountain ranges in the desert. Water from the State Water Project is lifted about 700 meters before it reaches the Southern California basin.

The Colorado distribution system extends some 380km from the intake plant on the Colorado River to the district's terminal reservoir in Riverside County east of Los Angeles. From this terminal reservoir the water enters the district's local distribution lines. Similarly, water from the State Water Project arrives at two terminal reservoirs in Southern California–one to the east and the other to west–before entering the local distribution system.

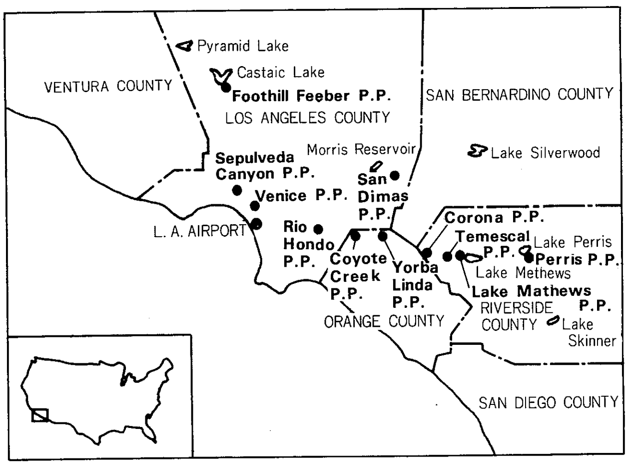

Fig. 1 Locations of hydropower plants

There are many other reservoirs and regulating ponds

Table 1 Ratings of turbines and generators

Plant Name \ Item	No. of Unit	Turbine					Generator			
		Output (kw)	Head (m)	Discharge (m^3/s)	Speed (rpm)	Type	Output	Voltage (kV)	Frequency (Hz)	Type
Lake Mathews	1	5,070	32.30	17.70	327.3	VF	4,900kW	4.16	60	IG
Foothill Feeder	2	4,670	62.80	8.50	600	VF	4,516kW	4.16	60	IG
San Dimas*	1	10,149	136.20	8.50	200	VP	9,924kVA	4.16	60	SG
Yorba Linda*	1	5,117	61.36	9.60	120	VP	5,089kVA	4.16	60	SG
Sepulveda Canyon*	1	8,808	111.56	13.45	120	VP	8,540kVA	4.16	60	SG
Venice*	1	10,376	111.25	13.45	600	VF	10,120kVA	4.16	60	SG
Temescal	1	2,948	44.20	8.50	600	HF	2,850kW	4.16	60	IG
Corona	1	2,948	44.20	8.50	600	HF	2,850kW	4.16	60	IG
Perris*	1	8,160	54.25	18.42	514	VF	7,940kVA	4.16	60	SG
Rio Hondo	1	1,960	71.02	3.12	1,200	HF	1,910kW	4.16	60	IG
Coyote Creek	1	3,230	72.54	4.96	900	HF	3,125kW	4.16	60	IG

* Outdoor type hydropower plant

in the system. Since there is a significant head difference in these distribution systems, either pressure reducing stations or discharge control stations are provided in some ten locations, thus controlling preasure and discharge of supply water by means of valve controls.

Following the energy crises that began a few years ago, the district determined that the differences in head in its system could be used to economically produced hydroelectric enrgy. The plants are located where pressure-reducing valves once dissipated the energy in the water.

Fig. 1 shows the locations of construction sites of the hydropower plants for which the Fuji Electric Co., Ltd. supplied turbines and generators. This table also shows the rations of the supplied turbines and generators. The small hydropower plants shown in *Table 1* have many features. This paper will describe those features, since an understanding of Metropolitan's program could serve as a reference for the current and future applications of using water distribution lines to generate hydropower.

II. PLANNING

1. Characteristics of a Distribution System

Water that travels through a long pipeline system is held in reservoirs and regulating ponds at various locations and is supplied to each user through the supply pipelines.

A control valve station is located immediately in front of each regulating pond controlling discharge according to the water level of the regulating pond. Also, control valve stations are installed in pipelines and is constantly controlling discharge pressure according to the needs of downstream users.

Aside from the length of pipelines, the elevation difference is significantly large and thus much energy is being reduced at each control station. The project has been planned to substitute the control valve with a hydropower facility. Features of the hydropower plants at such locations as follows.

1) Large Pipeline Loss

Since the pipeline is very long, the pipeline loss against discharge is significantly large. Thus, the available power potential in each pipeline is as shown in *Fig. 2*. As seen from the curves in *Fig. 2*, the net head is high when the discharge is small while the net head lowers when the discharge is large. The avilable power becomes maximum at intermediate discharge.

2) Relatively Large Variations of Discharge

Since this water supply project is based on estimated increase for water supply demand in the next 15 years, it is necessary to consider the present discharge and the discharge for which future plans have been taken into account. Also, it is a matter of course that consideration is required concerning seasonal variations of discharge as in the case of an ordinary water supply.

3) Low Pressure Rise

Since the pipeline extents a long distance, it is necessary to give sufficient consideration to pressure rise. As the pipeline extends as long as a maximum of 25 km, it is necessary to consider the characteristics at the time of a high-speed operaton of the turbine, as well as closing of the closing time of the turbine.

2. Application of Turbine

Some power generating points are located immediately before a regulating pond before the water enters a pipeline. In the case of a power plant located immediately before a regulating pond, the water used for power generation is discharged into a pond of free discharge level. In the case of a power plant located in pipeline, it is necessary to discharge the water used for power generation with sufficient residual pressure so that a proper discharge pressure can be maintained.

In the latter case, a reaction turbine should be employed. In the former case, however, the turbine to be employed can be either an impulse turbine or a reaction turbine.

1) Turbine for Holding Water Pressure Rise to Minimum

Generally, water pressure rise can be lowered if the closing time of the guide vane is extended. However, as in this project, if a water pressure rise needs to be controlled in a 15- to 60- minute time period (inconceivable in a conventional system) it is necessary to take additional conditions into consideration.

If the generator trips, the speed of the turbine and the generator will increase. In the case of a Pelton turbine, speed increase can be controlled by bending the direction

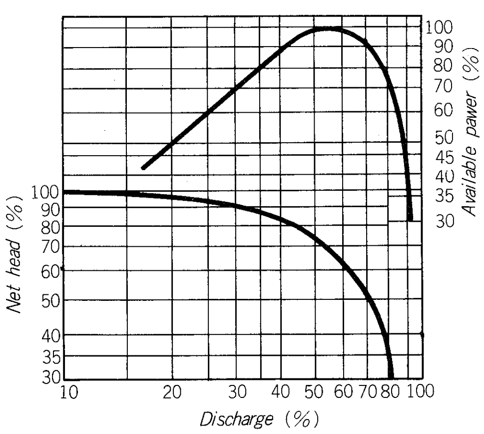

Fig. 2 Available power of pipe line

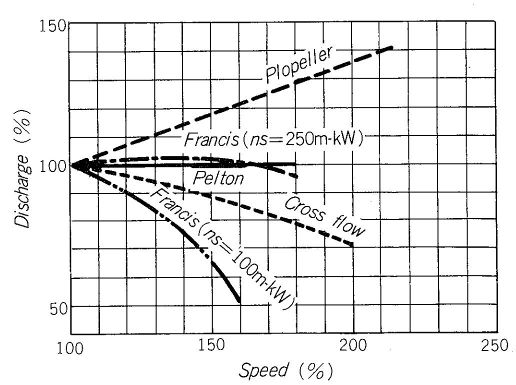

Fig. 3 Discharge characteristics at runaway speed

of water flow by controlling the deflector irrespective of opening and closing the needles. However, in the case of a Francis turbine, it reaches a runaway speed every time the generator trips.

In the case of a Pelton turbine, even if its speed has reached a runaway speed, discharge of the turbine remains unchanged unless the opening of the needles does not change. However, in the case of a reaction turbine, such as a Fransic turbine, discharge of the turbine changes along with a change of the speed of the turbine. Since the speed reaches runaway speed within several seconds, the flow of water in the pipe is changed by the difference between the discharge at the time of the rated speed and the discharge at the time of a runaway speed. Thus, the objective to reduce discharge variation by lengthening the closing time cannot be accomplished.

For the reasons cited above, it is desirable to employ such a turbine which allows less variation in discharge even if the speed of the furbine has increased. Therefore, it is appropriate to employ either a Pelton turbine or a Francis turbine of which specific speed (ns) is about 250 (m · kW) as shown in *Fig. 3* below.

(1) Francis Turbine

Normally, a Francis turbine having specific speed (ns) of about 250 (m · kW) is employed in a net head range of less than 75 m. However, if the location to install the turbine is determined only for prevention of cavitation in a case where variation of the net head or variation of discharge level is significant, aeration to the draft pipe sometimes becomes disabled when the discharge level has increased and, as a result, surging at a partial load operation cannot be prevented. On the other hand, if a draft height (hs) of −10 m is provided, or, in other words, if residual pressure of more than 1 atm is provided at the draft pipe outlet, surging does not occur. Therefore, when a Francis turbine is to be employed, a draft height of more than −2 m should be provided or residual pressure of more than 10 m should be provided for proper aeration to the draft pipe. In the case where residual pressure is high, a Francis turbine can be used even if the net head is high.

For the above reasons, a Francis turbine having specific speed (ns) of about 250 (m · kW) is used at a power plant installed in pipeline because the residual pressure there is high.

(2) Pelton Turbine

At a hydropower plant installed immediately in front of a regulating pond, there are many cases where a Pelton turbine is used (at a sacrifice of some loss in the net head) instead of employing a Francis turbine by taking more excavation for the power plant. The net head varies with the locations at which a hydropower plant exists. Generally, the applicable net head of a Francis turbine ranges from 61 m to 136 m, but a Pelton turbine is employed in a more extended lower range of net head.

Explanations have been given so far about the types of turbines employed and the reasons for using such turbines. In a case where the pipeline is extended very long and the pressure rise is somewhat limited by various kinds of existing conditions, it is inevitable that a system different from a conventional system must be employed, which, in turn, will be one of the prerequisite conditions for development of a small hydropower plant system.

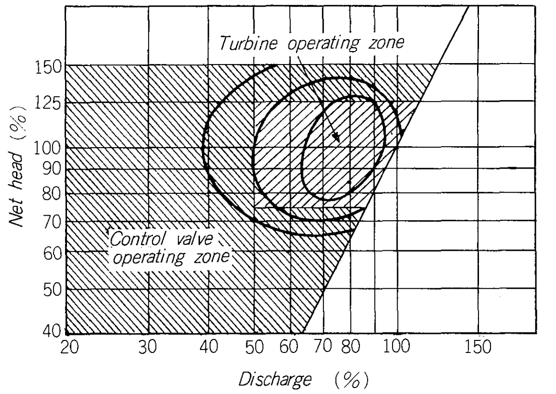

Fig. 4 Operating range of turbine and by-pass regulating valve

2) Variations of Net Head and Discharge

To meet the requirements of a water supply project in which the pipeline extends very long and for which future demand for water supply has been taken into account, a system operation of a relatively wide range is required. However, with respect to variations of net head and discharge, it is necessary to limit the operating range because of cavitation, vibration, noise, and lowering of operating efficiency. In this program, the water supply project has been planned in such a way that the existing discharge control valves can be applied to a normal operation as well as to an operation in a case where the turbine and the generator have stopped operating.

Fig. 4 shows the operating range at a plant where a Francis turbine is being employed. In this case, discharge of less than 50% are controlled by the bypass regulating valve. Even at a high net head and at a low net head, all discharge is controlled by the bypass regulating valve at a range in which the operation is difficult due to the characteristics of the turbine.

III. APPLICATION OF EACH PLANT

1. Hydropower Plant in Front of Regulating Pond

The water introduced to the system from the reservoirs is reserved in regulating ponds at various locations and is distribued to downstream users. *Fig. 5* shows a hydropower plant constructed in front of a regulating pond. In this hydropower plant, a vertical Francis turbine is being used. The draft height (Hs) at the casing center is −2 m.

Fig. 6 also shows a hydropower plant constructed in front of a regulating pond. Due to the location of the existing pressure reducing valve station, the tailrace is a free discharging level and a vertical Pelton turbine is being employed in this power plant. In other words, the center of the turbine is located above the tailrace level.

2. Hydropower Plant in Pipeline

As seen from *Fig. 7*, the tailrace is directly connected

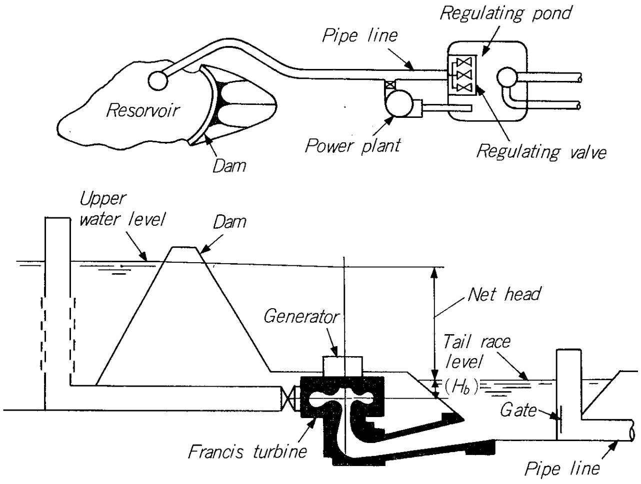

Fig. 5 Discharge below open water surface

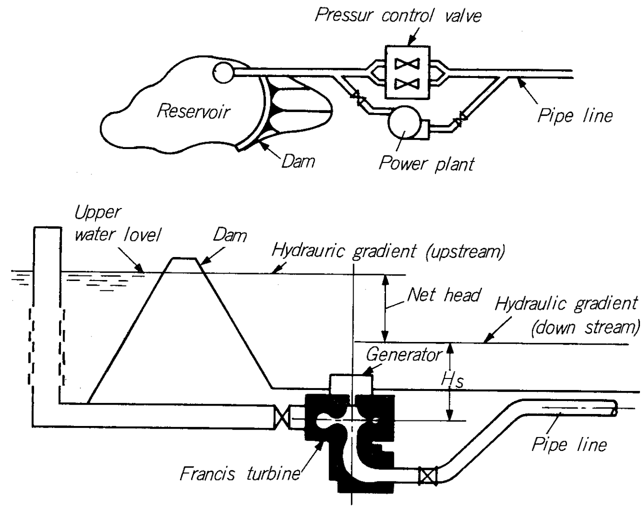

Fig. 7 Hydropower plant in pipe line

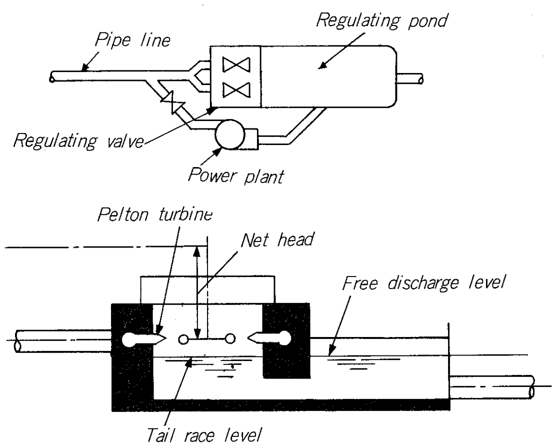

Fig. 6 Discharge above downstream water surface

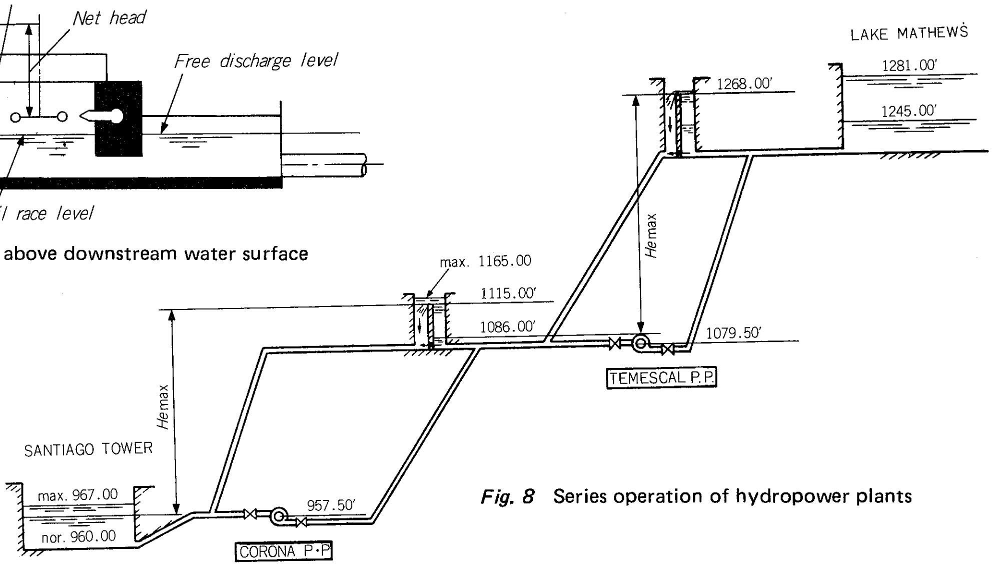

Fig. 8 Series operation of hydropower plants

to the downstream distribution system. In this hydropower plant, either vertical or horizontal francis turbine is employed, and the center of the turbine is located lower than the tailrace level. In this arrangement, it is necessary to provide a valve at the draft tube outlet for checking the operation of the turbine.

3. Series Operation of Power Plants

Basically, a Francis turbine is employed in a hydropower plant in pipeline.

Fig. 8 shows the piping system diagram at both Temescal Power Plant and Corona Power Plant. In this piping system, the head of the upper pond and the lower pond is divided into two. Since the discharge at both power plants is the same, the ratings of the turbines and the generator are exactly the same, and these two plants are being operated in series. Since two turbines installed in series cannot be controlled to the same head and the same discharge, a head-sustaining structure and a bypass circuit equipped with a regulating gate are provided. This bypass circuit is to be used in case the turbines have stopped operating or discharge has increased.

IV. FEATURES OF TURBINES

1. Operating System of Guide Vane and Needle

Since distribution system pressure rise is not allowed for, as has been explained previously, the opening and closing time of the guide vane and needle ranges from 15 to 60 minutes which is 0.02 to 0.06 mm/s at the speed of the

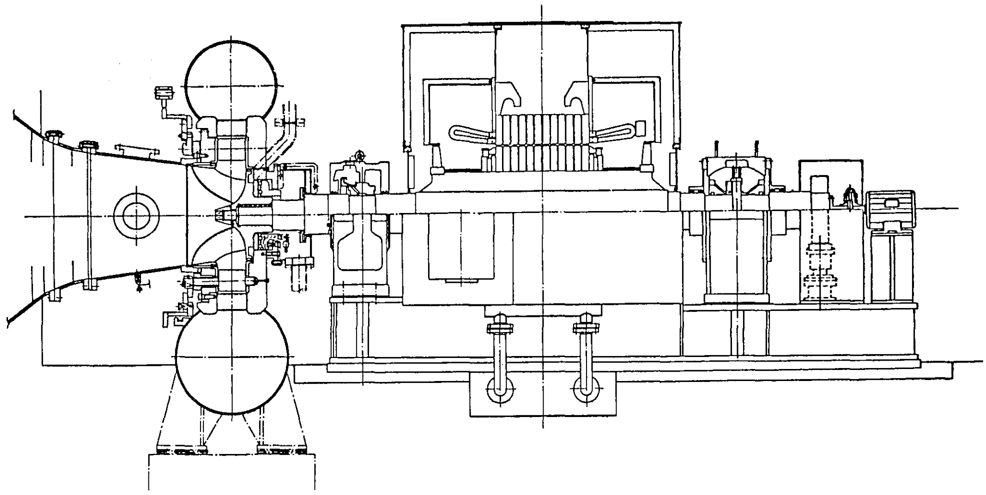

Fig. 9 Sectional drawing of horizontal Francis turbine and generator

servomotor. This closing time is extremely long, inconceivable in the case of a conventional turbine.

Because of difficulty in controlling such an extremely slow servomotor speed by means of an oil pressure system, a motor-driven system is employed for operation of the guide vane and the needle. This motor-driven system is a servomotor using ball screws, and is operated by both AC and DC power sources. Only in the case of an emergency stoppage is the DC motor is used. In the case of a motor-driven system, mechanical portions of the actuator and an oil pressure system are not required, and thus, the auxiliary units are simplified and maintenance can be performed with ease. Therefore, it is anticipated that the motor-driven system, will become the control system of small hydropower plants.

2. Francis Turbine

From a viewpoint of structure, the Francis turbine for this project is the smae as any existing Francis turbines. But this turbine is required to have the capability of withstanding a runaway speed operation for long periods of time. Generally, in the case of a high-speed turbine, it is difficult to secure the space for installing an oil tank and a cooling system required to retain bearing temperature within the allowable range of values at the time of a runaway speed operation. For this reason, a cooling system is externally installed to secure required amount of oil and to increase cooling efficiency. The lubricating oil is self-circulating by means of pumping action.

As seen from *Fig. 9*, the runner of a horizontal type turbine overhang to the generator shaft, and the guide vane and its operating mechanism are provided at the draft pipe side to facilitate disassemble and assembly.

For the shaft seal, the carbone ring system of the end-seal type is used. At each power plant, the draft height (Hs) is as high as −20 to −60m, and the maximum draft height reaches as high as −180m. For this reason, special consideration has been given to the shaft seal so that it can withstand high pressure.

3. Vertical Pelton Turbine

The structure of the Pelton turbine for this project is the same as that of a general Pelton turbine. However, an entirely new system is being employed for the operating system of the needle and the deflector. To begin with, the needle is part of motor-driven system, and the needle operating shafts thrusted into the turbine pit through the head cover (mutually connected) by means of connecting rods. With this arrangement, four or five needles are concurrently operated by one operating unit. *Fig. 10* is a plane view of the vertical Pelton turbine pit, showing the motor-driven system for needles and the connections by the connecting rods. The deflector is opened by oil pressure and is closed by spring action. The oil pressure servomotor

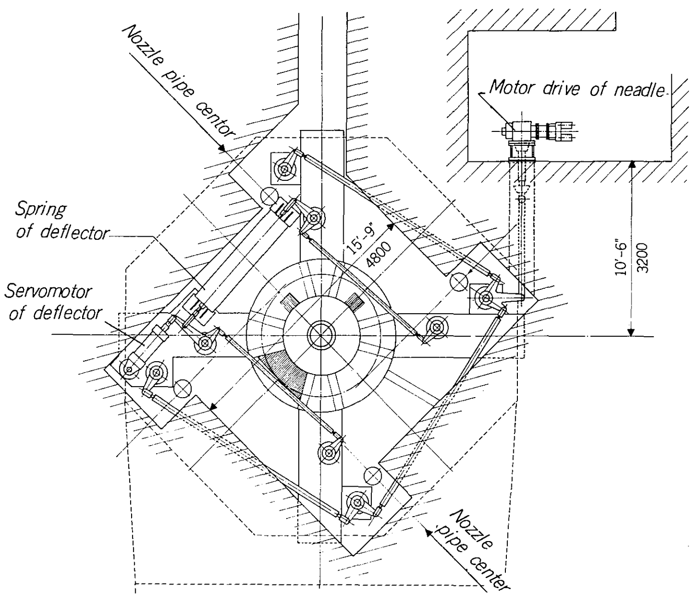

Fig. 10 Plan view of vertical Pelton turbine pit

is on-off controlled by means of a solenoid valve. A bladder-type accumulator is used as the oil pressure system for the deflector servomotor, thus simplifying the oil pressure system. An air compressor is not provided. The turbine installed in San Dimas Power Plant is designed in such a way that it can be equipped with the shaft seal to meet futuer operations when tailrace levels might be depressed.

V. FEATURES OF GENERATORS

1. Features Related to Generating Facility

As has been described previously, the closing time of the guide vane of the Francis turbine is very long and, thus it is impossible to avoid a runaway speed operation. Therefore, the inherent flywheel effect (GD^2) of the generator is used as the flywheel effect (GD^2) so that the generator can withstand a runaway speed operation for 30 to 90 minutes. With respect to cooling capability of the bearing, rigidity of the bearing supports, and the fitting and strength of the rotating section, sufficient considerations have been given so that they can withstand a long-time runaway speed operation. For the rotor, after it was manufactured at the factory, dynamic balance has been provided by means of a large balancing machine. Further, the rotor shows a good results in the runaway speed test conducted at the installation site.

Basically, the main objective of the generator using the pipeline lies in maintaining the discharge to the downstream and thus, the contribution to the system with respect to frequency regulation is relatively small. Therfore, if only power supply to the system is condidered, a generator not equipped with governor is sufficient to serve the purpose. For this project, induction generators have been employed as the generators for output of up to 4.9 MW. The cage rotor can be shipped incorporated in the generator. Therefore, in planning a small hydropower plant in the future, greater system economy can be expected if employment of an induction generator is considered according to the purpose for the turbine.

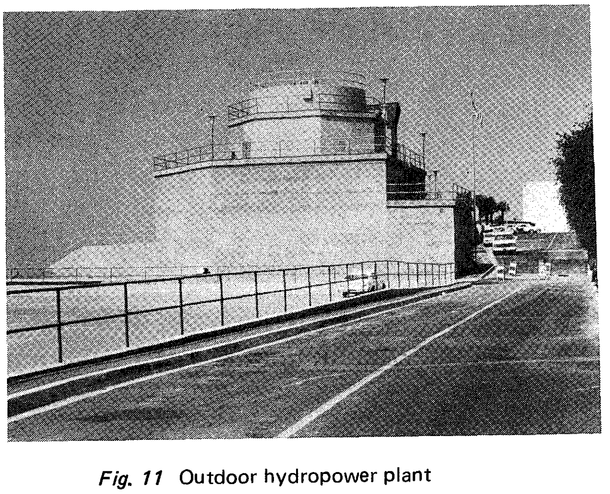

Fig. 11 Outdoor hydropower plant

On the other hand, from the fact that there is little rainfall in southern California, an outdoor-type generator without power plant house is employed, and its assembly is performed using a motorized crane instead of using an installation-type crane. Further, because the surface temperature of the outer cover of the generator reaches a ıximum of 75°C during summer and considerating noise reduction because the generator is an out-door-type generator, an adiabator is provided on the inner surface of the outer cover. *Fig. 11* shows a photograph of an outdoor hydropower plant.

2. Vertical Synchronous Generator

Fig. 12 is a sectional drawing of vertical Pelton turbine and generator. For the generator directly connected with a Francis turbine, an ordinary structure has been employed in which a thrust bearing is equipped at the top of the rotor. On the other hand, for the generator directly connected with a low-speed Pelton turbine, a bevel structure has been employed in which thrust bearing is equipped at the bottom of the rotor. As seen from *Fig. 12*, a simple shape of thick steel plate structure has been specially selected for the rotor center of the bevel structure. For the rotor center, deformation and strain at the time of a runaway speed operation has been analyzed by means of the finite element method. Also, as a result of a runaway speed test conducted at the site, it has been verified that the rotor center is completely free from any problem with respect to operations. Further, the thrust bearing and the guide bearing are of such a structure that allows disassembly and maintenance check without lifting the rotor.

3. Vertical Induction Generator

Fig. 13 is a section drawing of vertical Francis turbine

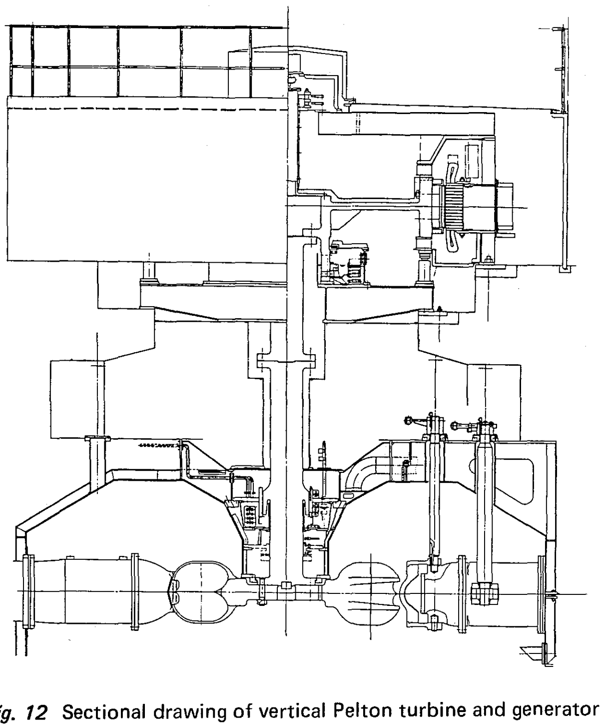

Fig. 12 Sectional drawing of vertical Pelton turbine and generator

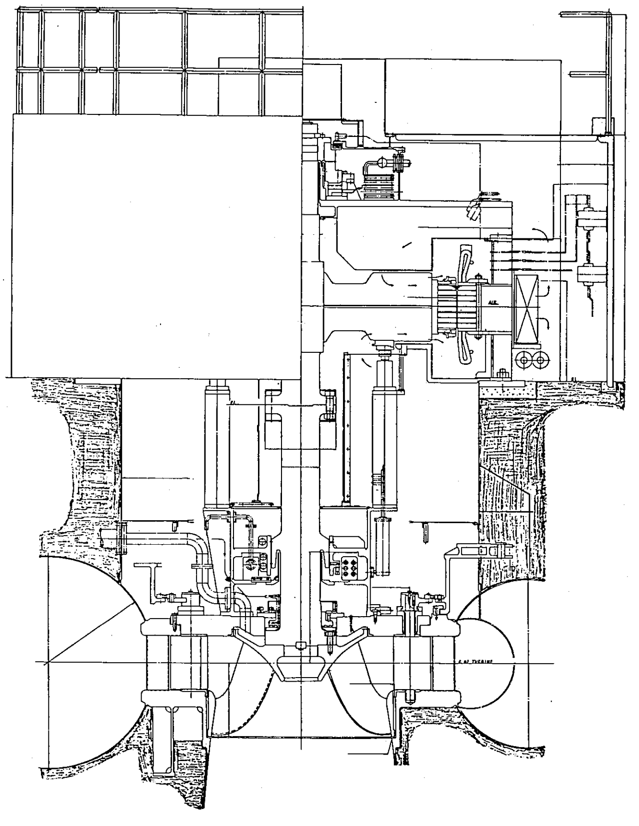

Fig. 13 Sectional drawing of vertical Francis turbine and generator

and generator. For the turbine and generator, so-called monoblock structure has been employed in which the lower guide bearing and bracket of the generator have been omitted, thus aiming at improvemed economy of the housing and machine. As one each guide bearing is provided at the top of the generator and at the turbine side, the rotor center arm is welded to the shaft taking an increase of critical speed into account, thus enhancing the ridigity of the shaft. It is another feature that the center arm welded to the shaft also functions as the ventilating fan. The brake of the generator is provided at the turbine shaft support.

4. Horizontal Induction Generator

As seen from *Fig. 9*, the rotor shaft is of one-shaft structure in which the turbine runner is overhanding. The bearing is of a pedestal structure, and the thrust bearing is provided at the opposite side of the turbine. These devices are installed on the common stand together with the stator, and can be shipped in a state equipped with the cooler and the outer cover, thus facilitating the installation work at the site.

VI. AFTERWORD

In the foregoing have been described various features of small hydropower plants using a water distribution system. The main contents of the description can be summarized as follows: The Fransio turbine has been designed considering that the turbine always operates at a runaway speed at the time of load shut-off; the Pelton turbine has been employed for the purpose of avoiding pressure rise in the pipeline and is being used by lowering the applicable head to a low head zone.

At present, the small hydropower plants are already in service at 7 sites, and the shipping of the power plants for the remaining sites has been completed and installation of each of the delivered power plants is in progress at the site concerned.