STANDARDS/MANUALS/ GUIDELINES FOR SMALL HYDRO DEVELOPMENT

3.1
Electro-Mechanical–
Selection of Turbine and Governing System

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Lead Organization:

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PREAMBLE

There are series of standards, guidelines and manuals on electrical, electromechanical aspects of moving machines and hydro power from Bureau of Indian Standards (BIS), Rural Electrification Corporation Ltd (REC), Central Electricity Authority (CEA), Central Board of Irrigation & Power (CBIP), International Electromechanical Commission (IEC), International Electrical and Electronics Engineers (IEEE), American Society of Mechanical Engineers (ASME) and others. Most of these have been developed keeping in view the large water resources/ hydropower projects. Use of the standards/guidelines/manuals is voluntary at the moment. Small scale hydropower projects are to be developed in a cost effective manner with quality and reliability. Therefore a need to develop and make available the standards and guidelines specifically developed for small scale projects was felt.

Alternate Hydro Energy Centre, Indian Institute of Technology, Roorkee initiated an exercise of developing series of standards/guidelines/manuals specifically for small scale hydropower projects with the sponsorship of Ministry of New and Renewable Energy, Government of India in 2006. The available relevant standards / guidelines / manuals were revisited to adapt suitably for small scale hydro projects. These have been prepared by the experts in respective fields. Wide consultations were held with all stake holders covering government agencies, government and private developers, equipment manufacturers, consultants, financial institutions, regulators and others through web, mail and meetings. After taking into consideration the comments received and discussions held with the lead experts, the series of standards/guidelines/manuals are prepared and presented in this publication.

The experts have drawn some text and figures from existing standards, manuals, publications and reports. Attempts have been made to give suitable reference and credit. However, the possibility of some omission due to oversight cannot be ruled out. These can be incorporated in our subsequent editions.

This series of standards / manuals / guidelines are the first edition. We request users to send their views / comments on the contents and utilization to enable us to review for further upgradation.

Standards/ Manuals/Guidelines series for Small Hydropower Development

General	
1.1	Small hydropower definitions and glossary of terms, list and scope of different Indian and international standards/guidelines/manuals
1.2 Part I	Planning of the projects on existing dams, Barrages, Weirs
1.2 Part II	Planning of the Projects on Canal falls and Lock Structures.
1.2 Part III	Planning of the Run-of-River Projects
1.3	Project hydrology and installed capacity
1.4	Reports preparation: reconnaissance, pre-feasibility, feasibility, detailed project report, as built report
1.5	Project cost estimation
1.6	Economic & Financial Analysis and Tariff Determination
1.7	Model Contract for Execution and Supplies of Civil and E&M Works
1.8	Project Management of Small Hydroelectric Projects
1.9	Environment Impact Assessment
1.10	Performance evaluation of Small Hydro Power plants
1.11	Renovation, modernization and uprating
1.12	Site Investigations
Civil works	
2.1	Layouts of SHP projects
2.2	Hydraulic design
2.3	Structural design
2.4	Maintenance of civil works (including hydro-mechanical)
2.5	Technical specifications for Hydro Mechanical Works
Electro Mechanical works	
3.1	Selection of Turbine and Governing System
3.2	Selection of Generators and Excitation Systems
3.3	Design of Switchyard and Selection of Equipment, Main SLD and Layout
3.4	Monitoring, control, protection and automation
3.5	Design of Auxiliary Systems and Selection of Equipments
3.6	Technical Specifications for Procurement of Generating Equipment
3.7	Technical Specifications for Procurement of Auxiliaries
3.8	Technical Specifications for Procurement and Installation of Switchyard Equipment
3.9	Technical Specifications for monitoring, control and protection
3.10	Power Evacuation and Inter connection with Grid
3.11	operation and maintenance of power plant
3.12	Erection Testing and Commissioning

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ANNEXURE

SELECTION OF TURBINE AND GOVERNING SYSTEM

1.0 OVERVIEW

Selecting the type, kind, (within type) configuration, (horizontal or vertical) size, and number of turbine units that best suit a project is a detailed process. This involves technical, environmental, financial, and other considerations. The most inexpensive turbine may not be the best solution to the available head and flow. For small hydro up to 5 MW unit size, selection on the basis of typical turbine data furnished by manufacturers is recommended. For units above 5 MW size information exchange with turbine manufacturers is recommended for selection of turbine at project stage.

The selection procedure is prepared for selection of turbine based on the techno economic considerations to permit rapid selection of proper turbine unit, estimation of its major dimensions and prediction of its performance.

1.1 Scope

This guideline covers selection procedure based on techno-economic considerations of turbines and governing systems for unit capacity up to 25 MW .

1.2 Purpose

The purpose of this guideline is to provide guidance for selection of turbines and governing systems by developers, manufacturers, consultants, regulators and others. The guideline includes, planning, investigation, design and execution as well as manufacturing of equipment and testing at work.

1.3 References

The guidelines shall be used in conjunction with the following standards, publications with latest edition.

(R1). IS: 12800 (Part 3) – 1991, Guidelines for selection of hydraulic turbine, preliminary dimensioning and layout of surface hydroelectric powerhouses.

(R2). IS: 12837 – 1989, Hydraulic turbines for medium and large power houses – guidelines for selection

(R3). IEC: 61116 – 1992, Electro-mechanical equipment guide for small hydroelectric installations.

(R4). IEC: 60041 – 1991, Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines

(R5). IEC: 60193 – 1965, International code for model acceptance tests of hydraulic turbines.

(R6). IEC: 60308 – 2005, International code for testing of speed governing system for hydraulic turbines.

(R7). IEC: 60545 – 1976, Guide for commissioning, operation and maintenance of hydraulic turbines.

(R8). IEC: 60609 – 2004, Cavitation pitting evaluation in hydraulic turbines, storage pumps and pump-turbines.

(R9). IEEE: 1207 – 2004, Guide for the application of turbine governing system for hydroelectric generating units.

(R10). IEEE: 125 – 1996, Recommended practice for preparation of equipment specifications for speed governing of hydraulic turbines intended to drive electric generators

(R11). USBR- Selecting Hydraulic Reaction Turbine, Engineering Monograph No. 20,

(R12). CBIP-Publication No. 175 - 1985, Small Hydro Stations Standardization

(R13). CBIP-Publication No. 305 – 2009, Manual on Planning and Design of Small Hydroelectric Schemes

(R14). AHEC, IITR- Micro Hydro Quality Standards – 2005

(R15). ASME – 1996, Guide to Hydropower Mechanical Design (Book)

(R16). Vinogg, L., and Elstad, I. (2003). Mechanical Equipment. Norwegian University of Science and Technology, Trondheim, Norway, 130 pp.

(R17). Guthrie and Brown “Hydro Electric Engineering Practice Vol. 2. CBS Publishedrs & Distributors Delhi in agreement with Blackie & Sons Ltd., London

Abbreviations:

IS : Indian Standards
IEC : International Electrotechnical Commission
IEEE : Institute of Electrical and Electronic Engineers
ASME : American Society of Mechanical Engineers
USBR : United States Bureau of Reclamation
CBIP : Central Board of Irrigation and Power
AHEC IITR : Alternate Hydro Energy Centre, Indian Institute of Technology, Roorkee

2.0 PLANT CAPACITY, UNIT CAPACITY AND SPARE CAPACITY

Techno-economic (optimization) studies for plant capacity, unit capacity and spare capacity are required to be carried out for optimum utilization of energy resource to determine power plant capacity and unit size.

Maximum utilization of available potential energy from the energy resource is required depending upon present economic viability. Accordingly energy remaining unutilized and efficiency of operating equipment is an important consideration in deciding the number, size and type of generating units. Further, rising cost of energy demands provision to be made for further capacity addition to utilize unutilized energy during seasonal excess water periods. In case of unit size above 5 MW, plant capacity and unit size may also be determined on the basis of capacity as peaking station.

2.1 Power Equation

Power can be developed from water whenever there is available flow, which may be utilized through a fall in water level. The potential power of the water in terms of flow and head can be calculated with the following equation.

$$kW = 9.804 \cdot Q \cdot H \cdot \eta$$

where :

- Q is quantity of water flowing through the hydraulic turbine in cubic meters per second.
- H is available head in meters
- η is the overall efficiency (Product of turbine efficiency and generator efficiency)

2.2 Plant and Unit Capacity

Plant Rating -Water power studies determine the ultimate plant capacity and indicate the head at which that capacity should be developed. Techno-economic (optimization) studies are required to be carried out to determine optimum size and number of units to be installed. Considerations involved in determining generating capacity to be installed and optimum number and size of units to be selected at the site are as follows:

(a) Maximum utilization of energy resource.
(b) Maximum size of units for the net head available.
(c) Operating criteria.
(d) Spare capacity
(e) Optimum energy generation and cost of generation per unit.
(f) Part load operation
(g) Worldwide and local experience.
(h) Future provision

The generating capacity of a hydro power plant is expressed in kilo Watt (kW) or Mega Watts (MW) and is selected based on a careful evaluation of several important parameters i.e. head, discharge and head flow combination.

Capacity optimization flow chart is given in figure 1

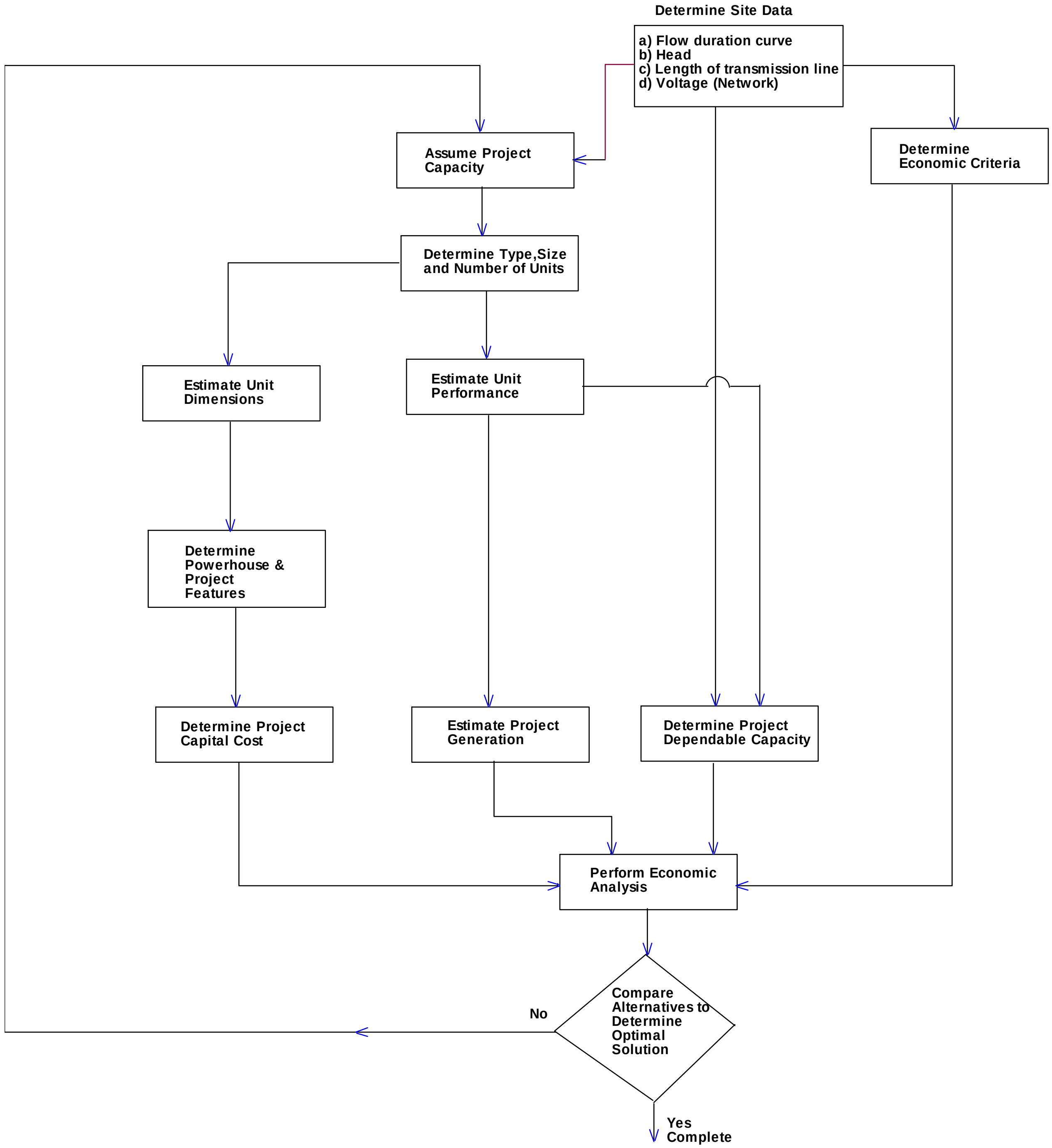


Fig. 1: Plant Capacity, Unit Capacity and Number Optimisation Flow Chart

(Source: ASME-1995-The guide to Hydropower Mechanical Design)

3.0 SITE DATA

After techno-economic studies carried out (para 2) to determine plant capacity and unit size etc., selection of turbine may be made as per guidelines provided here. Departure from these guidelines may be necessary to meet the special requirements and conditions of individual sites.

3.1 Net Head

The effective head available to the turbine unit for power production is called the net head. Selection of rated and design head requires special attention. Definitions of these heads are given in Para 3.2 and shown in figure 2. The turbine rating is given at rated head.

Determination of rated head, design head and maximum and minimum net head is important. Permissible departure from design head for reaction turbines for optimum efficiency and cavitation characteristics based on experience data is given in table 1.

Table 1: Permissible departure from design head for reaction turbines for optimum efficiency and cavitation characteristics

Type of turbine	**Head (%of design head)**	
	Maximum	**Minimum**
Francis	125	65
Propeller – fixed blade turbine	110	90
Kaplan – Adjustable blade propeller turbine	125	65

3.2 Definition of Head

Gross Head (H_g) – is the difference in elevation between the water levels of the forebay impoundment and the tail water level at the out let.

Effective Head (Net Head) - The effective head is the net head available to the turbine unit for power production. This head is the static gross head, the difference between the level of water in the Forebay/impoundment and the tail water level at the outlet, less the hydraulic losses of the water passage as shown in Fig. 2. The effective head must be used for all power calculations. The hydraulic losses in closed conduit can be calculated using the principles set out in general hydraulic textbooks. In addition to conduit losses, an allowance for a loss through the intake structure should also be included. In general a hydraulic loss of one velocity head (velocity squared divided by 2 x acceleration due to gravity) or greater would not be uncommon for intake structure. The hydraulic losses through the turbine and draft tube are accounted for in the turbine efficiency.

Rated head (h_r) – is the net head at which the full-gate output of the turbine produce the generator rated output in kilo Watts. The turbine nameplate rating usually is given at this head. Selection of this head requires foresight and deliberation.

Permissible range of head for reaction turbines for optimum efficiency and cavitations characteristics based on experience data is given in table 2.

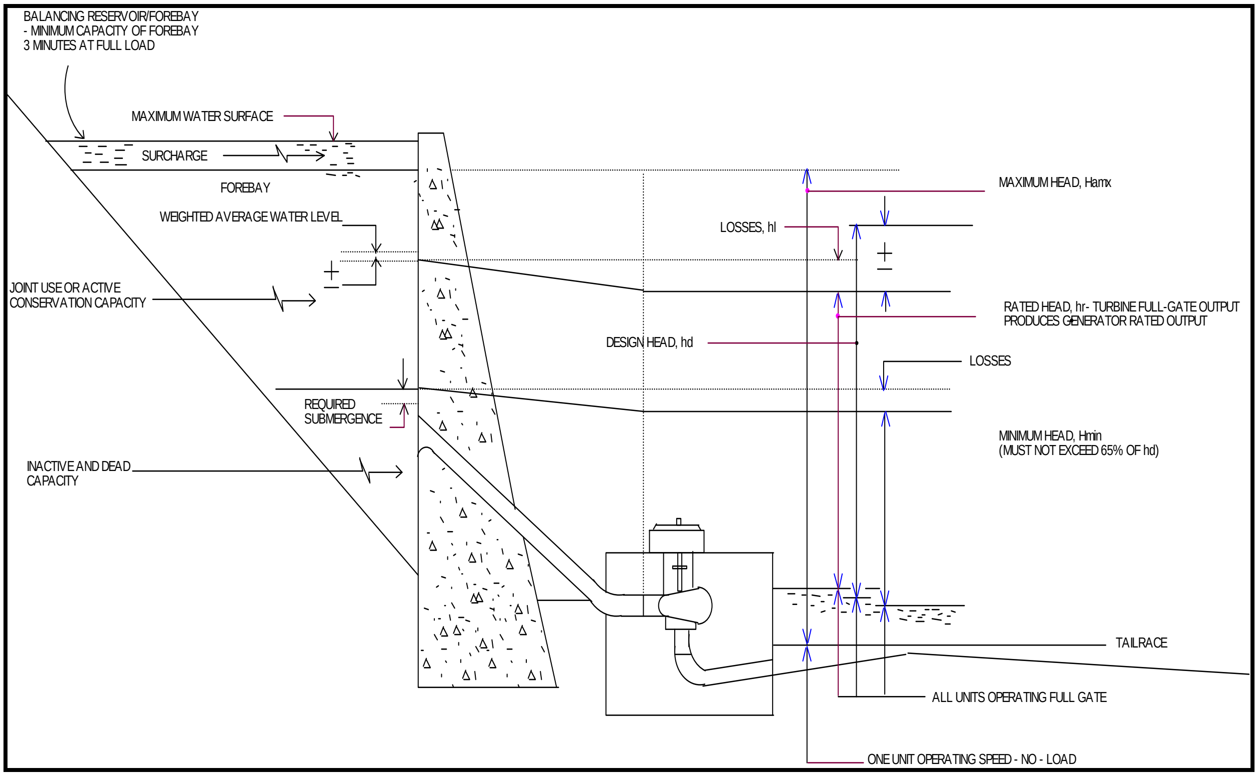


Fig. 2 : Definition of Head in Reaction Turbines
(Source : USBR Design Monograph no. 20)

Maximum Head (H_{max}) – is the gross head resulting from the difference in elevation between the maximum forebay level without surcharge and the tailrace level without spillway discharge, and with one unit operating at speed no-load (turbine discharge of approximately 5% of rated flow). Under this condition, hydraulic losses are negligible and nay be disregarded.

Minimum Head (H_{min}) – is the net head resulting from the difference in elevation between the minimum forebay level and the maximum tailrace level minus losses with all turbines operating at full gate.

Weighted Average Head - is the net head determined from reservoir operation calculations which will produce the same amount of energy in kilowatt-hours between that head and maximum head as is developed between that same head and minimum head.

Design Head (h_d) – is the net head at which peak efficiency is desired. This head should preferably approximate the weighted average head, but must be so selected that the maximum and minimum heads are not beyond the permissible operating range of the turbine. This is the head which determines the basic dimensions of the turbine and therefore of the power plant.

4.0 CLASSIFICATION AND TYPES OF TURBINES

Turbines can be either reaction or impulse types. The turbines type indicates the manner in which the water causes the turbine runner to rotate. Reaction turbine operates with their runners fully flooded and develops torque because of the reaction of water pressure against runner blades. Impulse turbines operate with their runner in air and convert the water's pressure energy into kinetic energy of a jet that impinges onto the runner buckets to develop torque.

Reaction turbines are classified as Francis (mixed flow) or axial flow. Axial flow turbines are available with both fixed blades (Propeller) and variable pitch blades (Kaplan). Both axial flow (Propeller & Kaplan) and Francis turbines may be mounted either horizontally or vertically. Additionally, Propeller turbines may be slant mounted.

4.1 Francis Turbines

A Francis turbine have a runner with fixed blades (vanes), usually nine or more, to which the water enters the turbine in a radial direction, with respect to the shaft, and is discharged in an axial direction. Principal components consist of the runner, a water supply casing to convey the water to the runner, wicket gates to control the quantity of water and distribute it equally to the runner and a draft tube to convey the water away from the turbines.

A Francis turbine may be operated over a range of flows approximately 40 to 110% of rated discharge. Below 40% rated discharge, there can be an area of operation where vibration and/or power surges occur. The upper limit generally corresponds to the maximum generator rating. The approximate head range for operation is from 65% to 125% of design head. In general, peak efficiency of Francis turbines, within the capacity range of 25 MW, with modern design tool like CFD (computational fluid dynamics) have enabled to achieve in the range of 94 to 95%.

The conventional Francis turbine is provided with a wicket gate assembly to permit placing the unit on line at synchronous speed, to regulate electric load and speed, and to shutdown the unit. The mechanisms of large units are actuated by hydraulic servomotors. Small units may be actuated by electric motor gate operations. It permits operation of the turbine over the full range of flows. In special cases, where the flow rate is constant, Francis turbines without wicket gate mechanisms may be used. These units operate in case of generating units in Micro hydro range (upto 100 kW) with electronic load controller or shunt load governors. Start up and shut down of turbines without a wicket gate is normally accomplished using the shut off valve at the turbine inlet. Synchronising is done by manual load control to adjust speed.

Francis turbines may be installed with vertical or horizontal shafts. Vertical installation allows a smaller plan area and requires a deeper setting of the turbine with respect to tailwater elevation locating the turbine below tailwater. Turbine costs for vertical units are higher than for horizontal units because of the need for a larger thrust bearing. However, the savings on construction costs for medium and large units generally offset this equipment cost increase. Horizontal units are more economical for smaller sets up to 8 MW with higher speed applications where standard horizontal generators are available.

The water supply casing is generally fabricated from steel plate. However open flume and concrete cases may be used for heads below 15 meters for vertical units.

Francis turbines are generally provided with a 90-degree elbow draft tube, which has a venturi design to minimize head loss. Conical draft tubes are also available, however the head loss will be higher and excavation may be more costly.

Provision for removing runner from below through an access gallery after removal of bottom cover for quick repair of excessive pitting, metal erosion, corrosion in case of presence of injurious elements in water is made sometimes.

Typical horizontal axis turbine installed at a project is shown in figure 3.

4.2 Axial Flow Turbines

Axial flow turbines are those in which flow through the runner is aligned with the axis of rotation. Axial flow hydraulic turbines have been used for net heads up to 60 meters with power output up to 25 MW. However, they are generally used in head applications below 35 meters Tubular turbine (S-type) are used below 30 meters head and 8 MW capacity. Bulb units can be used for low head if runner diameter is more than 1 meter. Specific mechanical designs, civil constructions and economic factors must be given full consideration when selecting among these three axial flow turbine arrangements.

A propeller turbine is one having a runner with four, five or six blades in which the water passes through the runner in an axial direction with respect to the shaft. The pitch of the blades may be fixed or movable. Principal components consist of a water supply case, wicket gates, a runner and a draft tube.

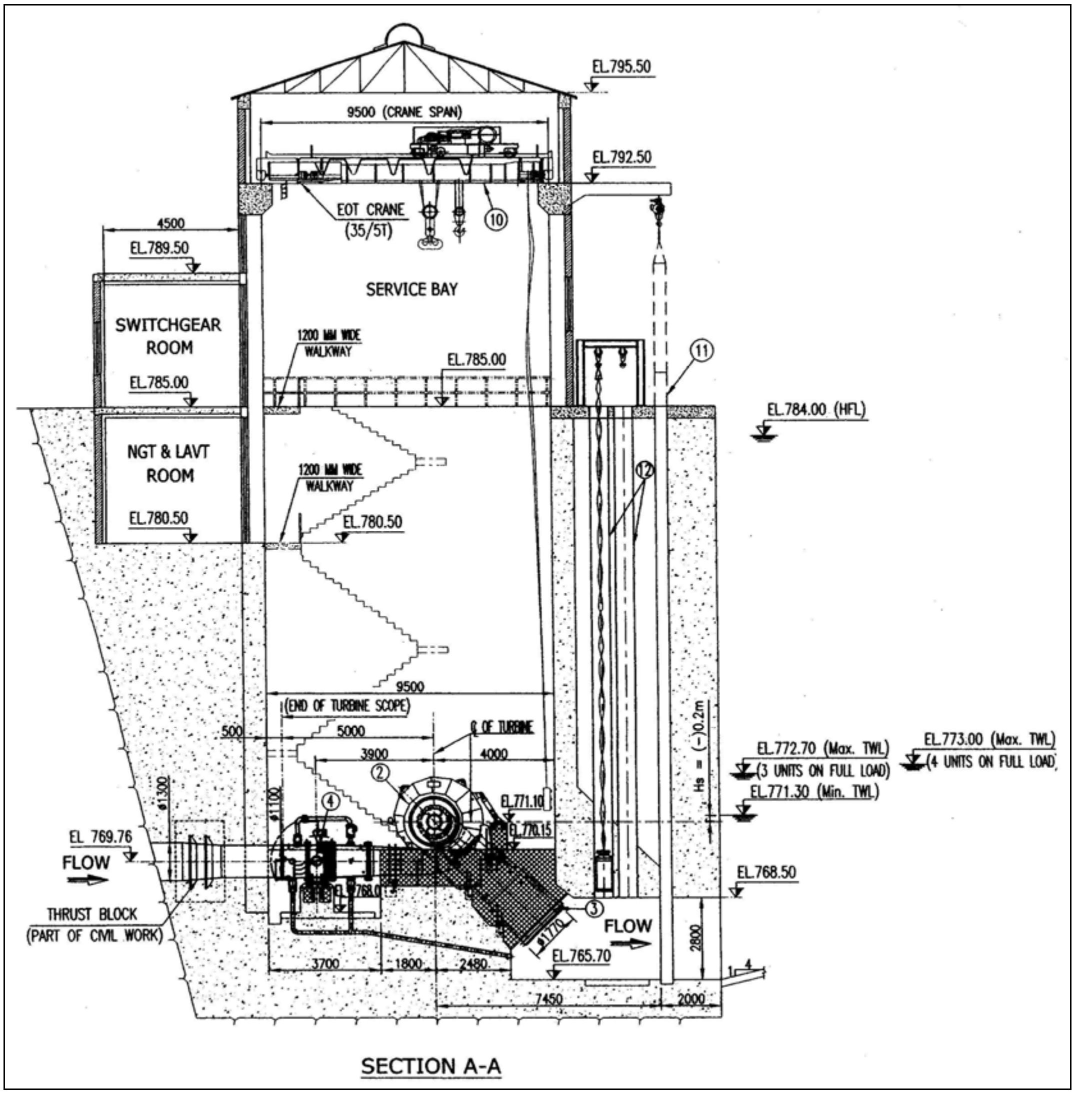
The efficiency curve of a typical fixed blade propeller turbine forms a sharp peak, more abrupt than a Francis turbine curve. For variable pitch blade units the peak efficiency occurs at different outputs depending on the blade setting. An envelope of the efficiency curves cover the range of blade pitch settings forms the variable pitch efficiency curve. This efficiency curve is broad and flat. Fixed blade units are less costly than variable pitch blade turbines; however, the power operating ranges are more limited.

In general, peak efficiencies are approximately the same as for Francis turbines.

Propeller turbines may be operated at power outputs with flow from 40-120% of the rated flow. Discharge rates above 105% may be obtained; however, the higher rates are generally above the turbine and generator manufacturers' guarantees. Many units are in satisfactorily operation at heads from 60 to 140% of design head. Efficiency loss at higher heads drops 2 to 5% points below peak efficiency at the design head and as much as 15% points at lower heads.

The conventional propeller or Kaplan (variable pitch blade) turbines are mounted with a vertical shaft. Horizontal and slant settings will be discussed separately. The vertical units are equipped with a wicket gate assembly to permit placing the unit on line at synchronous speed, to regulate speed and load, and to shutdown the unit. The wicket gate mechanism is actuated by hydraulic servomotors. Small units may be actuated by electric motor gate operators. Variable pitch units are equipped with a cam mechanism to coordinate the pitch of the blade with gate position and head. Digital control envisages control of wicket gates and blade angle by independent servomotors coordinated by digital control. The special condition of constant flow, as previously discussed for Francis turbines, can be applied to propeller turbines. For this case, elimination of the wicket gate assembly may be acceptable. Variable pitch propeller turbines without wicket gates are called semi Kaplan turbine.

The draft tube designs discussed for Francis turbines apply also to propeller turbines.



Rated head	:	103.345 m
Runner diameter	:	856 mm
Type of turbine	:	Horizontal Francis
Rated turbine/generator speed	:	750 RPM
Butterfly valve	:	Ø 1100

Fig. 3: Horizontal Francis Turbine (4 x 4000 kW) of a typical Project

4.2.1 Tubular Turbines (S-Type)

Tubular or tube turbines are horizontal or slant mounted units with propeller runners. The generators are located outside of the water passageway. Tube turbines are available equipped with fixed or variable pitch runners and with or without wicket gate assemblies.

Performance characteristics of a tube turbine are similar to the performance characteristics discussed for propeller turbines. The efficiency of a tube turbine will be one to two % higher than for a vertical propeller turbine of the same size since the water passageway has less change in direction.

The performance range of the tube turbine with variable pitch blade and without wicket gates is greater than for a fixed blade propeller turbine but less than for a Kaplan turbine. The water flow through the turbine is controlled by changing the pitch of the runner blades.

When it is not required to regulate turbine discharge and power output, a fixed blade runner may be used. This results in a lower cost of both the turbine and governor system. To estimate the performance of the fixed blade runner, use the maximum rated power and discharge for the appropriate net head on the variable pitch blade performance curves.

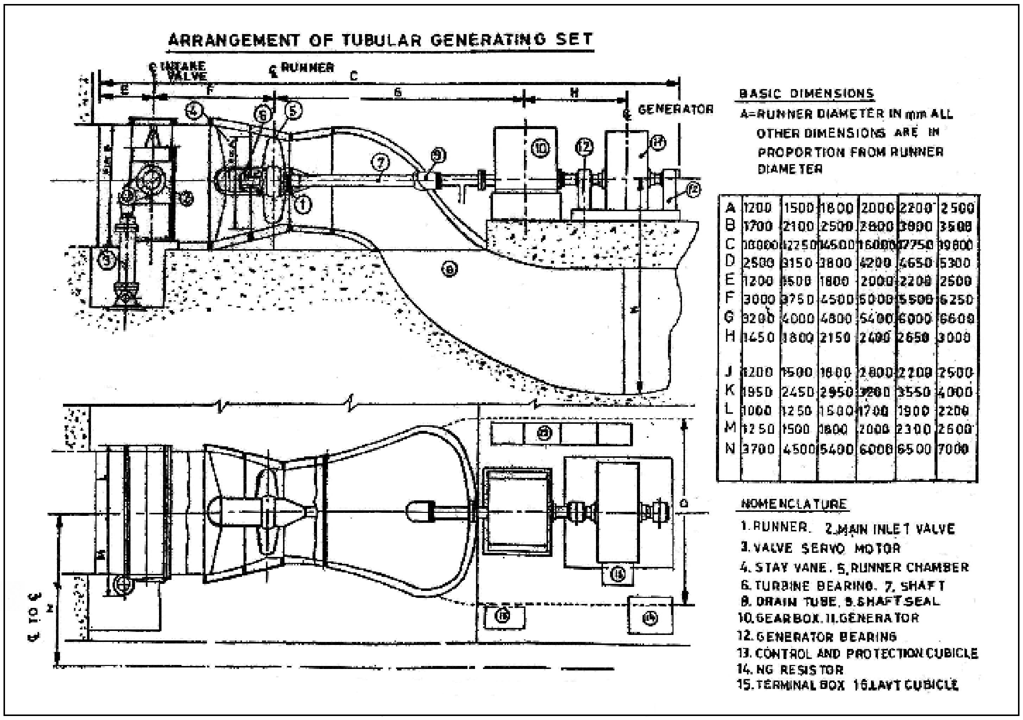
Several items of auxiliary equipments are often necessary for the operation of tube turbines. All tube turbines without wicket gates should be equipped with a shut off valve automatically operated to provide shut-off and start-up functions.

Tube turbines can be connected either directly to the generator or through a speed increaser. The speed increaser would allow the use of a higher speed generator, typically 750 or 1000 r/min, instead of a generator operating at turbine speed. The choice to utilize a speed increaser is an economic decision. Speed increasers lower the overall plant efficiency by about 1% for a single gear increaser and about 2% for double gear increaser. (The manufacturer can supply exact data regarding the efficiency of speed increasers). This loss of efficiency and the cost of the speed increaser must be compared to the reduction in cost for the smaller generator. It is recommended that speed increaser option should not be used for unit sizes above 5 MW capacity.

The required civil features are different for horizontal units than for vertical units. Horizontally mounted tube turbines require more floor area than vertically mounted units. The area required may be lessened by slant mounting, however, additional turbine costs are incurred as a large axial thrust bearing is required. Excavation and powerhouse height for a horizontal unit is less than that required for a vertical unit. Typical Tube turbines based on runner diameter is shown in Figure 4.

4.2.2 Bulb Turbines

Bulb Turbines are horizontal, which have propeller runners directly connected to the generator. The generator is enclosed in a water-tight enclosure (bulb) located in the turbine water passageway. The bulb turbine is available with fixed or variable pitch blades and with or without a wicket gate mechanism. Performance characteristic are similar to the vertical and Tube type turbines previously discussed. The bulb turbine will have an improved efficiency of approximately 2% over a vertical unit and 1% over a tube unit because of the straight water passageway.



A	1200	1500	1800	2000	2200	2500
B	1700	2100	2500	2800	3000	3500
C	10000	12250	14500	16000	17750	19800
D	2500	3150	3800	4200	4650	5300
E	1200	1500	1800	2000	2200	2500
F	3000	3750	4500	5000	5500	6250
G	3200	4000	4800	5400	6000	6600
H	1450	1800	2150	2400	2650	3000
J	1200	1500	1800	2800	2200	2500
K	1950	2450	2950	3200	3550	4000
L	1000	1250	1500	1700	1900	2200
M	1250	1500	1800	2000	2300	2600
N	3700	4500	5400	6000	6500	7000

Fig. 4 Typical Dimension of Tube Turbine based on runner dia.
(Source: IS: 12800(Part-3)1997)

Due to the compact design, powerhouse floor space and height for Bulb turbine installations are minimized. Maintenance time due to accessibility, however, may be greater than for either the vertical or the tube type turbines. Figure 5 shows longitudinal section of bulb turbine installation of a typical 2 x 9 MW SHP having rated and design head 8.23 m.

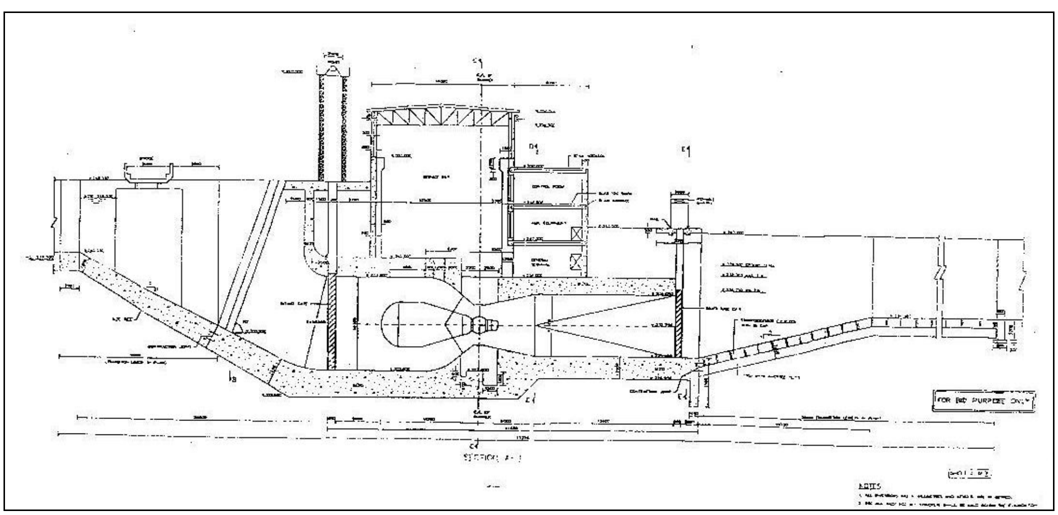


Fig. 5 Bulb Turbine of a typical 2 x 9 MW SHP

4.2.3 Vertical Semi-Kaplan Turbine with Syphon Intake

Low specific speed Vertical semi-Kaplan turbine set above maximum tailrace level with syphon intake with adjustable runner blade and fixed guide vane. As the name suggests, the vertical turbine with syphon intake operation on the syphon principle i.e. the intake flume chamber valve is closed and made water tight and vacuum is created by a vacuum pump which enables water to enter flume chamber and energise the runner. Shut down is brought about by following the reverse procedure i.e. by breaking vacuum. Since turbine operates on a syphon principle, it is not necessary to have Intake and Draft gates thereby reducing the cost. The syphon intake semi kaplan vertical turbine part load efficiency at about 30% load is about 76%. Turbine is suitable for variable head also. Dewatering and drainage arrangements are also not required.

This type of turbine has been found to be most economical for canal drop falls (upto 3-4 m head). The turbine is set above maximum tailwater level and hence lower specific speed. A typical installation is shown in fig. 6.

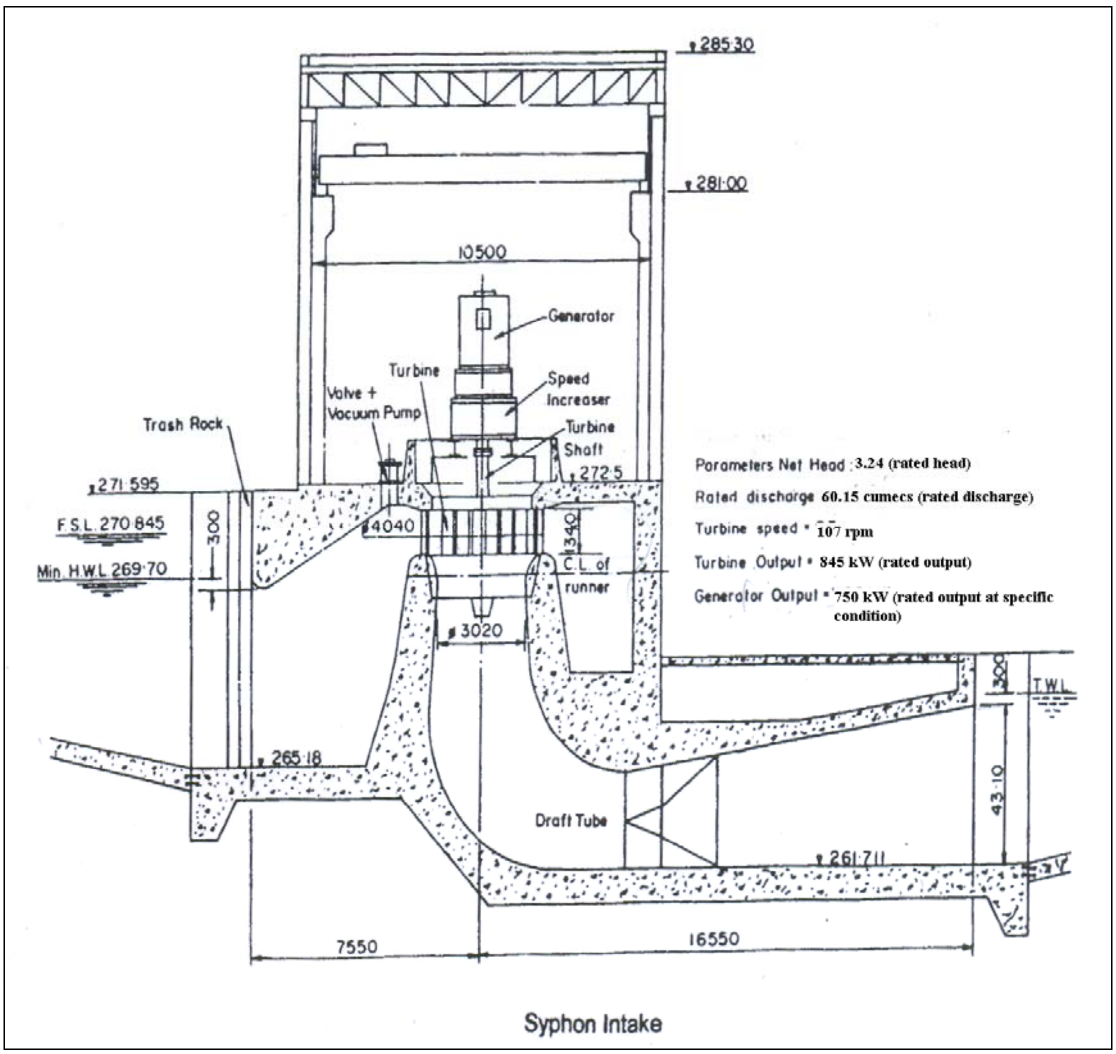


Fig. 6 Syphon Intake of a typical Project

Control of the turbine is maintained by hydraulically operated needle nozzles in each jet. In addition, a jet deflector is provided for emergency shutdown. The deflector diverts the water jet from the buckets to the wall of the pit liner. This feature provides surge protection for the penstock without the need for a pressure valve because load can be rapidly removed from the generator without changing the flow rate.

Control of the turbine may also be accomplished by the deflector alone. On these units the needle nozzle is manually operated and the deflector diverts a portion of the jet for lower loads. This method is less efficient and normally used for speed regulation of the turbine under constant load. Pit type turbine has been shown in Fig. 7(a) & 7(b).

Runners on the modern impulse turbine are a one-piece casting. Runners with individually attached buckets have proved to be les dependable and, on occasion, have broken away from the wheel causing severe damage to powerhouse. Integral cast runners are difficult to cast, costly and require long delivery times. However, maintenance costs for an impulse turbine are less than for a reaction turbine as they are free of cavitation problems. Excessive silt or sand in the water however, will cause more wear on the runner of an impulse turbine than on the runner of most reaction turbines.

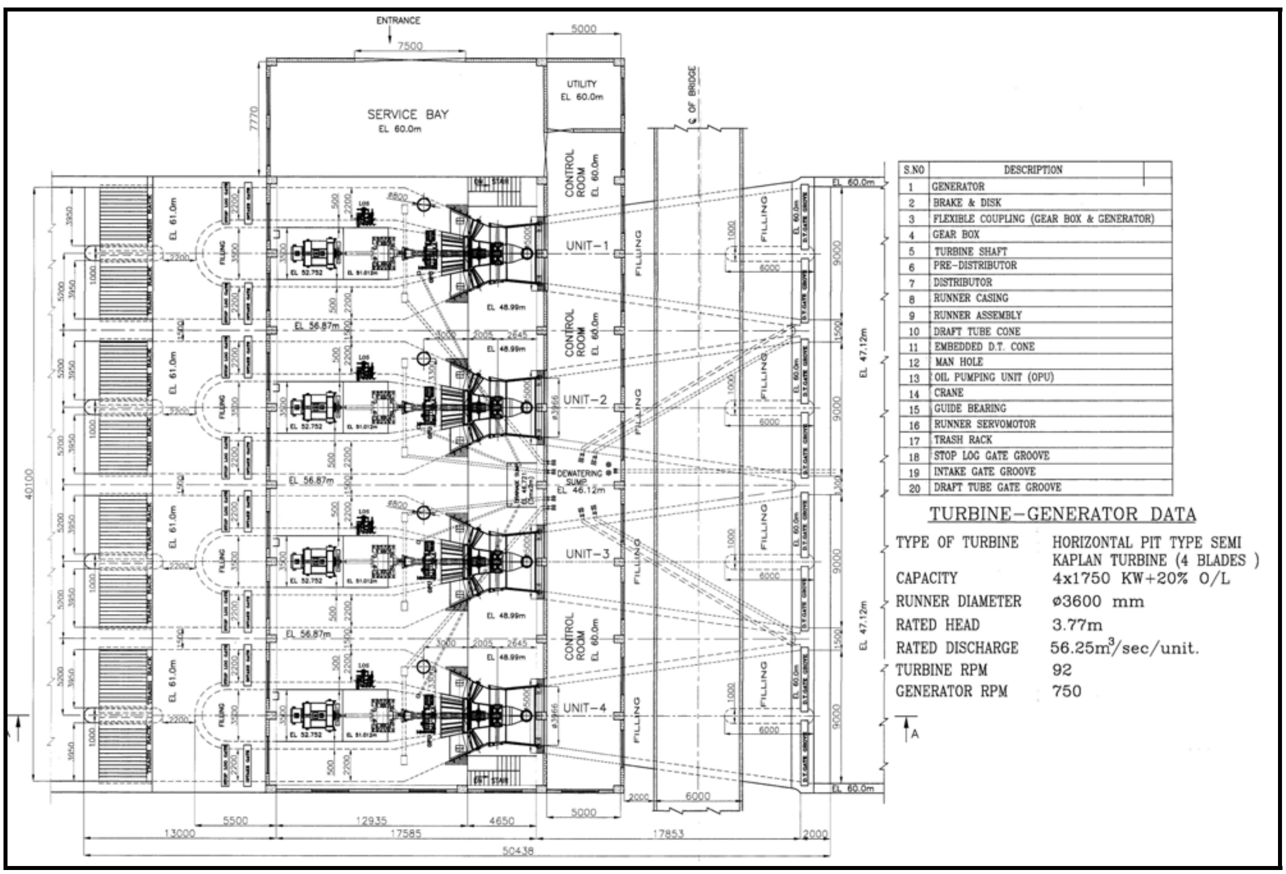


Fig. 7 (a): Plan of Pit Turbine

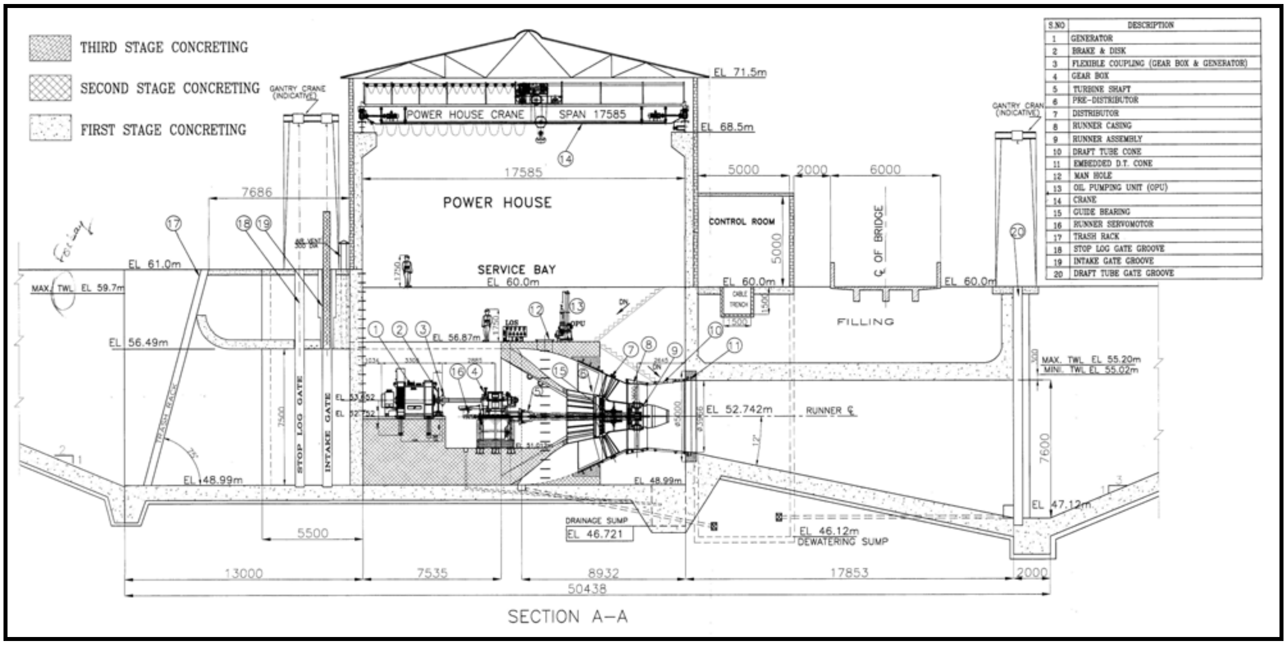


Fig. 7 (b): Longitidunal Section of Pit Turbine

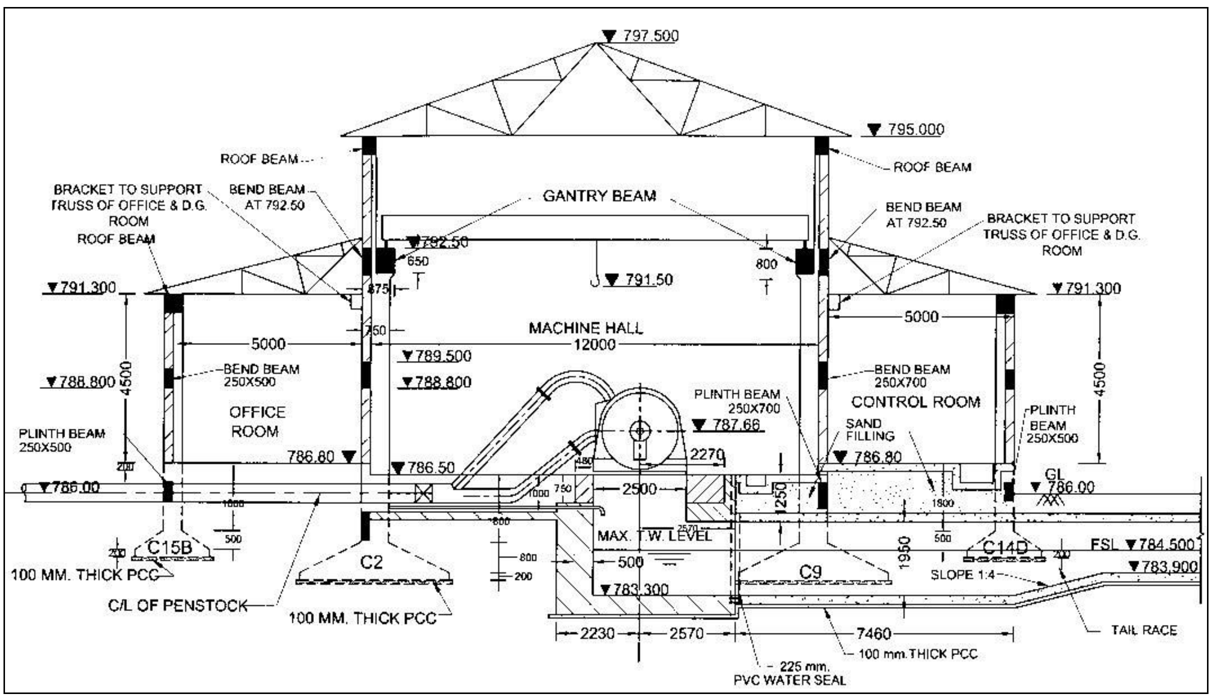


Fig. 8 Impulse Turbine for a typical 1500 kW Project

The runner must be located above maximum tail water to permit operation at atmospheric pressure. This requirement exacts an additional head loss for an impulse turbine not required by a reaction turbine.

Impulse turbines may be mounted horizontally or vertically. The additional floor space required for the horizontal setting can be compensated for by lower generator costs on single nozzle units in the lower capacity sizes. Vertical units require less floor space and are often used for large capacity multi-nozzle units.

Horizontal shaft turbines are suitable for small hydro applications that have less water available.

Multi-jet turbines are slightly more costly than single jet turbines; however, the more rapid accumulation of stress cycle alternations justifies a more conservative runner design. Abrasive martial entrained in the water will erode the buckets of a multi-jet turbine more rapidly than in the case of a single jet per runner.

For the same rated head and flow conditions, increasing the number of jets results in a smaller runner and a higher operating speed. Therefore, whether vertical or horizontal, multi-jet turbines tend to be less costly for comparable outputs because the cost of the runner represents up to 20% of the cost of the entire turbine.

A deflector is normally used to cut into the jet when rapid power reductions are required such as a complete loss of connected-load. The deflector is mounted close to the runner on the nozzle assembly and typically is provided with its own servomotor. Cross section of 2 jet pelton turbine of a typical project is at figure 8.

4.3 Turgo Impulse Turbines

Another type of impulse turbine is the turgo impulse. This turbine is higher in specific speed than the Pelton turbine. The difference between Pelton and turgo is that, on a turgo unit, the jet strikes one side of the runner and exits the other side. The turgo unit operates at a higher specific speed, which means for the same runner diameter as a Pelton runner, the rotational speed can be higher. The application head range for a turgo unit is 15 meters to 300 meters. Turgo units have been used for application up to 7,500 kW. Efficiency of turgo impulse turbine is about 82 to 83 %.Fig 9 shows typical turgo runner and spear.

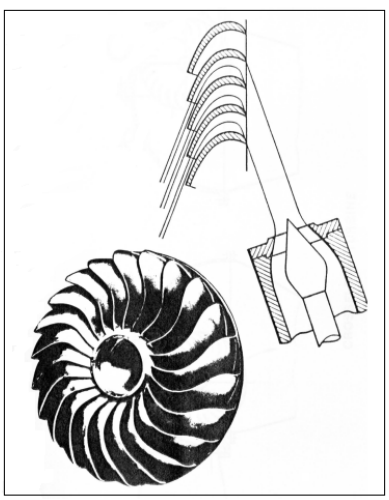


Fig 9 Typical turgo runner and spear

4.4 Cross Flow Turbines

A cross flow turbine is an impulse type turbine with partial air admission. Performance characteristics of this turbine are similar to a Pelton turbine, and consist of a flat efficiency curve over a wide range of flow and head conditions.

Peak efficiency of the cross flow turbine is less than that of other impulse turbine types previously discussed. Guaranteed maximum efficiency of indigenous available cross flow turbines is about 60-65%.

Floor space requirements are more than for the other turbine types, but a less complex structure is required and a savings in cost might be realized. Typical view and cross section of cross flow turbine is at figure 10 & 11.

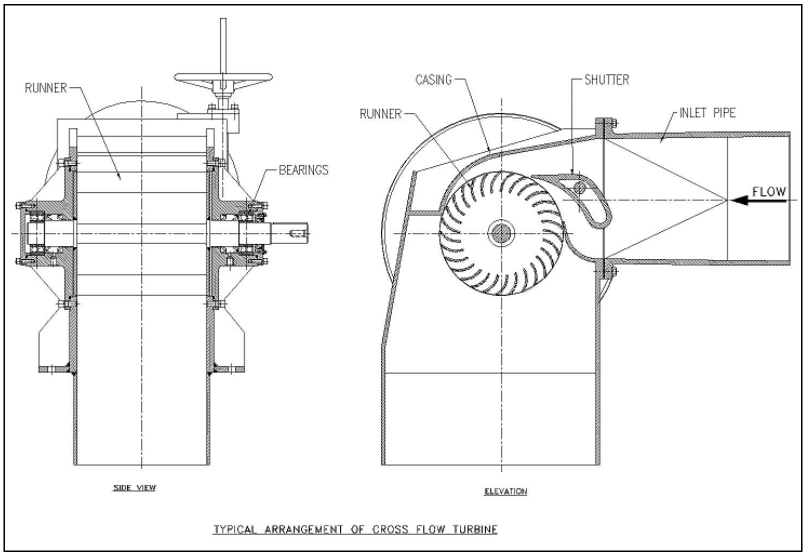


Fig 10 : Typical view of Cross Flow turbine

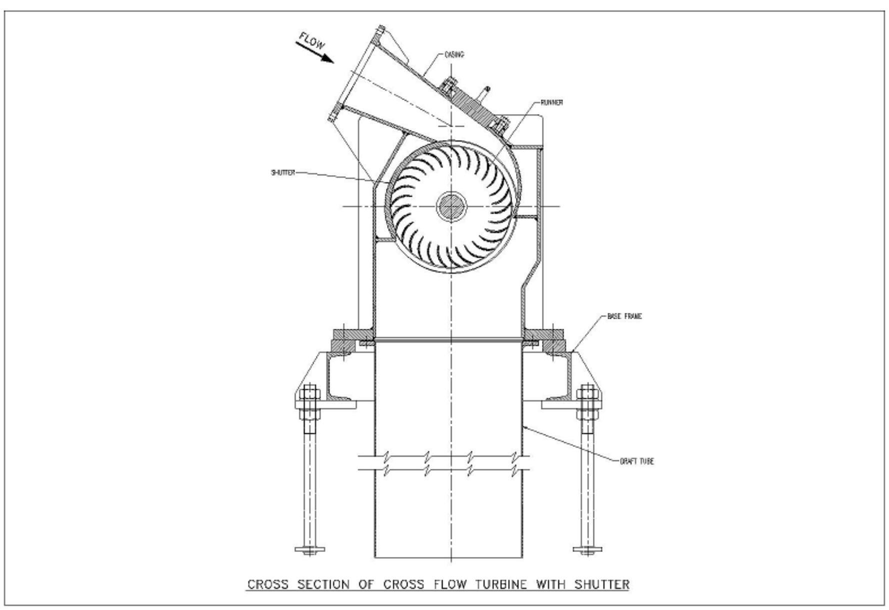


Fig 11 : Cross section of Cross Flow Turbine

5.0 SELECTION OF HYDRAULIC TURBINE

General – The net head available to the turbine dictates the selection of type of turbine suitable for use at a particular site. The rate of flow determines the capacity of the turbine. The term specific speed is generally used in classifying types of turbines and characteristics within type as shown in figure 12. This figure is based on ASME guide to design of hydropower mechanical design 1996 and modified by Indian Projects data attached as Annexure-1. Exact definition of specific speed is given para 5.1. Impulse turbines have application in high head hydropower installations. Application of impulse turbine in low head range is limited to very small size units.

Application range of the three types of turbine is overlapping as shown in figure 12. Description & Application of important turbine types is as follows:

Various types of turbines have already been explained in Para 4.0. Selection criteria of hydraulic turbine up to 5 MW units size (including micro hydro) is generally based on using standard turbines. Hydraulic turbine above 5 MW unit size are generally tailor made and selection criteria is more specific.

Specification requires that the manufacturer be responsible for the mechanical design and hydraulic efficiency of the turbine. Objective of these guidelines is to prepare designs and specification so as to obtain a turbine that result in the most economical combination of turbine, related water passages, and structures. Competitive bidding for the least expensive turbine that will meet specifications is required. In evaluating the efficiency of a proposed turbine, the performance is estimated on the basis of experience rather than theoretical turbine design. Relative efficiency of turbine types is shown in figure 13 and 14. The peak efficiency point of a Francis turbine is established at 94% of the rated capacity of the turbine. In turn, the peak efficiency at 65% of rated head will drop to near 75%.

To develop a given power at a specified head for the lowest possible first cost, the turbine and generator unit should have the highest speed practicable. However, the speed may be limited by mechanical design, cavitation tendency, vibration, drop in peak efficiency, or loss of overall efficiency because the best efficiency range of the power efficiency curve is narrowed. The greater speed also reduces the head range under which the turbine will satisfactory operate.

The selection of speed and setting described in these guidelines is satisfactory for conditions normally found at most sites and will usually result in a balance of factors that will produce power at the least cost.

5.1 Specific Speed (Ns)

The term specific speed used in classifying types of turbines and characteristics of turbines within types is generally the basis of selection procedure. This term is specified as the speed in revolutions per minute at which the given turbine would rotate, if reduced homologically in size, so that it would develop one metric horse power at full gate opening under one meter head. Low specific speeds are associated with high heads and high specific speeds are associated with low heads. Moreover, there is a wide range of specific speeds which may be suitable for a given head.

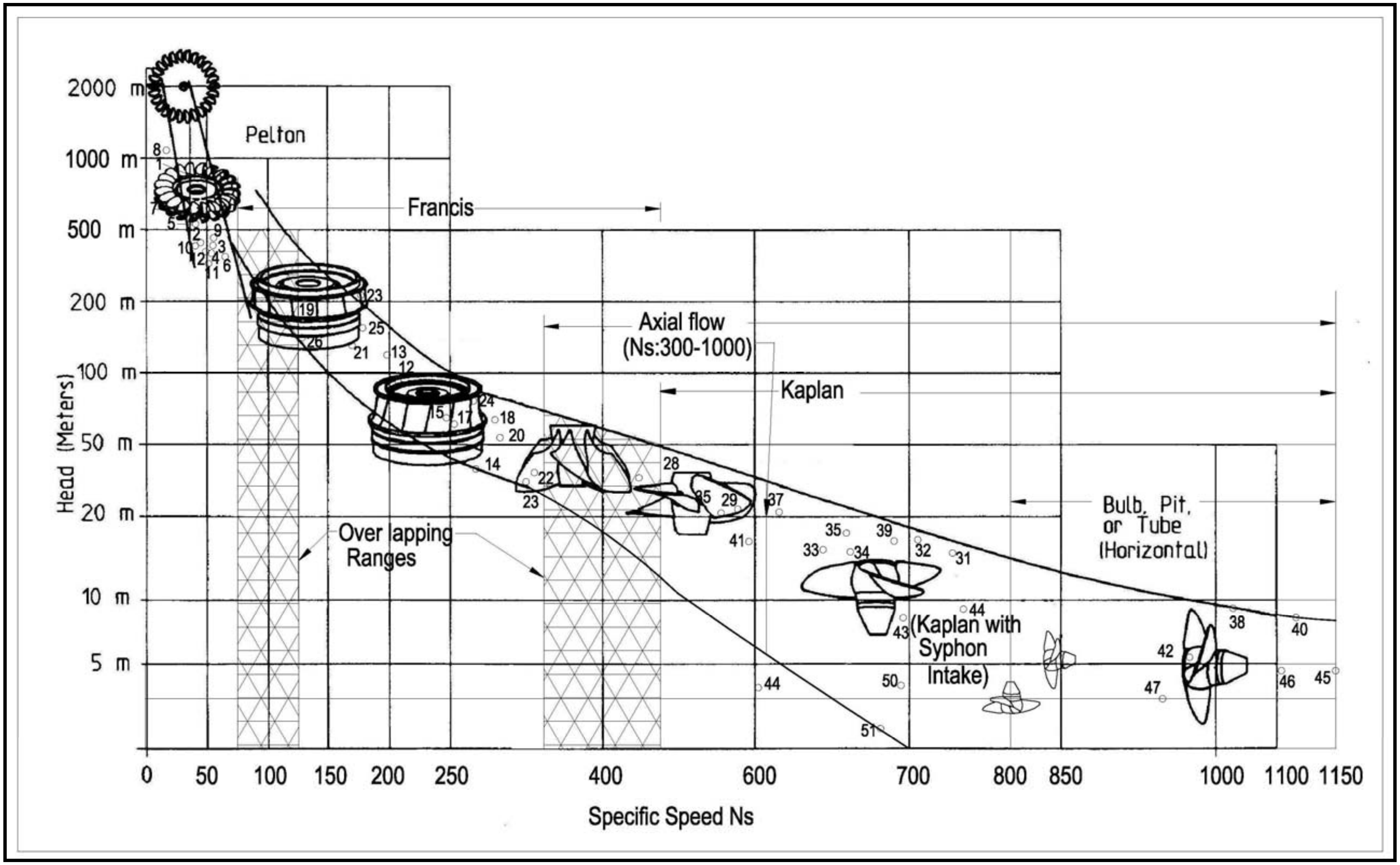


Fig. 12: Ns versus Head. *This figure shows the various turbine type as a function of specific speed (Ns) and head. This figure should be used a guideline, as there is overlap between the various turbine types with respect to their operating ranges*

Note: *Details of SHP are attached as Annexure-1* (Adapted from ASME–Guide to Hydropower Mechanical Design)

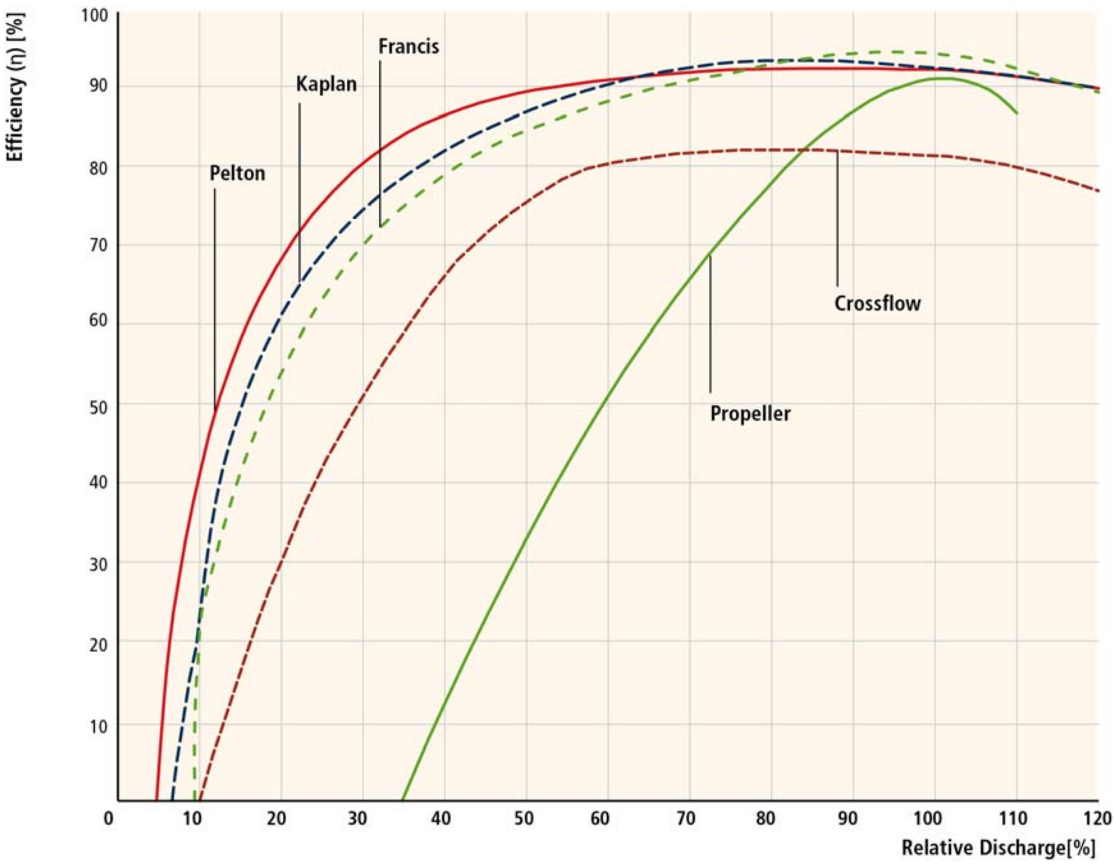


Fig.13: Typical efficiency curves for different types of Hydropower turbines (Source: Vinogg, L. and Elstad, I. (2003).

Selection of a high specific speed for a given head will result in a smaller turbine and generator, with savings in capital cost. However, the reaction turbine will have to be placed lower, for which the cost may offset the savings. The values of electrical energy, plant factor, interest rate, and period of analysis enter into the selection of an economic specific speed. Commonly used mathematically expression in India for specific speed is power based (English System) is as follows:

$$Ns = \frac{Nr\sqrt{Pr}}{Hr^{(5/4)}}$$

Where

Nr = revolutions per Minute

Pr = power in metric horse power at full gate opening (1 kW = 0.86 metric hp)

Hr =rated head in m

The specific speed value defines the approximate head range application for each turbine type and size. Low head units tend to have a high specific speed, and high-head units to have a low specific speed. Figure 12 may be seen.

Ns, kW Units = 0.86 Ns metric horse power unit

Flow based metric system for specific speed (Nq) used in Europe is given by equitation below.

$$Nq = \frac{NQ^{0.5}}{H^{0.75}}$$

Where

Nq	=	Specific Speed
N	=	Speed in rpm
Q	=	Flow in cubic meters/second
H	=	Net Head in meters

Specific speed (metric HP units) range of different types of turbines is as follows:

Fixed blade propeller turbines	–	300 – 1000
Adjustable blade Kaplan turbines	–	300 – 1000
Francis turbines	–	65 – 445
Impulse turbines	–	

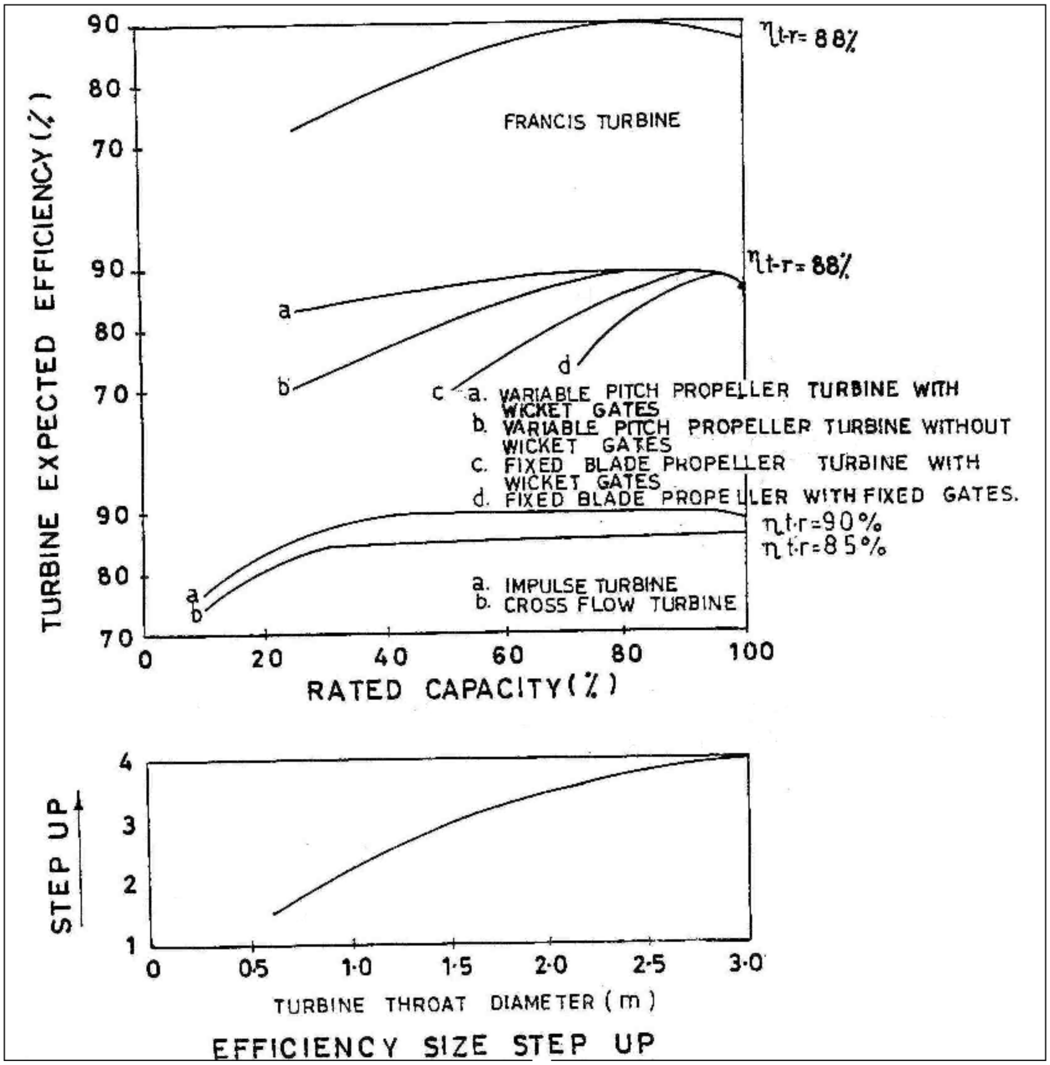
i)	Pelton Turbine per jet	16-20 per jet for multiple jets the power is proportionally increased
ii)	Cross flow turbine	12-80

5.2 Turbine Efficiency

Typical efficiency curves of the various types of turbines are shown for comparison in Fig 13. These curves are shown to illustrate the variation in efficiency of the turbine through the load range of the design head. Performances of the various types of turbines when operated at heads above and below design head are discussed. Approximate efficiency at rated capacity for the reaction turbines are shown for a turbine with a throat diameter of 300 mm in fig. 14. Rated efficiency will increase as the size of the turbine increases. The bottom curve shows the relationship of efficiency to throat diameter. The rated efficiency for turbines with throat diameters larger than 300 mm may be calculated in accordance with this curve. This curve was developed from model test comparison to apply the step-up value throughout the operating range. The efficiency curves shown are typical expected efficiencies. Actual efficiencies vary with manufacturer and design.

5.2.1 Turbine Performance Curves

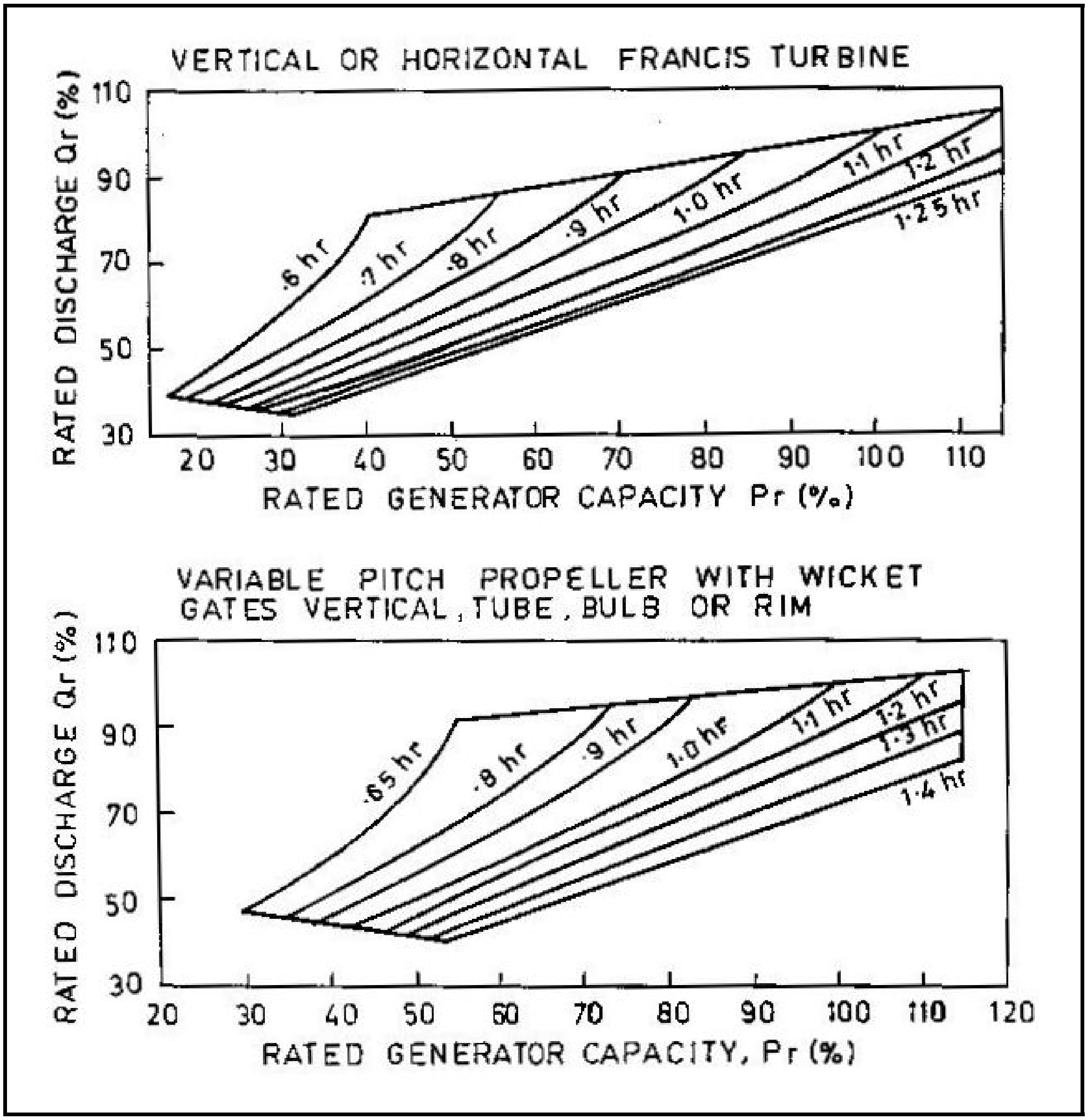
Figures 15 and 16 show performance characteristics for Francis and Kaplan (variable pitch blade propeller with wicket gates) as well as for propeller (fixed blades with wicket gates) and Tube (variable pitch blades without wicket gates) type turbines respectively. These curves were developed from typical performance curves of the turbines of a special speed that was average for the head range considered in the guidelines. Comparison of performance curves of various specific speed runners were made and the average performance values were used. The maximum error occurs at the lowest Pr and was approximately three percent. These curves may be used to determine the power output of the turbine and generator when the flow rates and heads are known. The curves show percent turbine discharge, percent Qr versus percent generator rating, percent Pr throughout the range of operating heads for the turbine.



NOTES:

1. η_{tr} =Turbine Efficiency at rated output (Pr) and head (hr)
2. The values shown are typical for a turbine with 300 mm diameter runner. The values shown in the size set up curve may be added to the η_{tr} values for large units. Values apply for Francis, fixed and variable pitch propeller, tube, bulb and rim turbine.
3. Efficiency of indigenous cross flow turbine is about 60 - 65%.
4. Peak efficiency at design head and rated output is about 2-5% higher.
5.

Fig. 14 : Turbine Efficiency Curves (Source IS: 12800 (Part-3) 1997

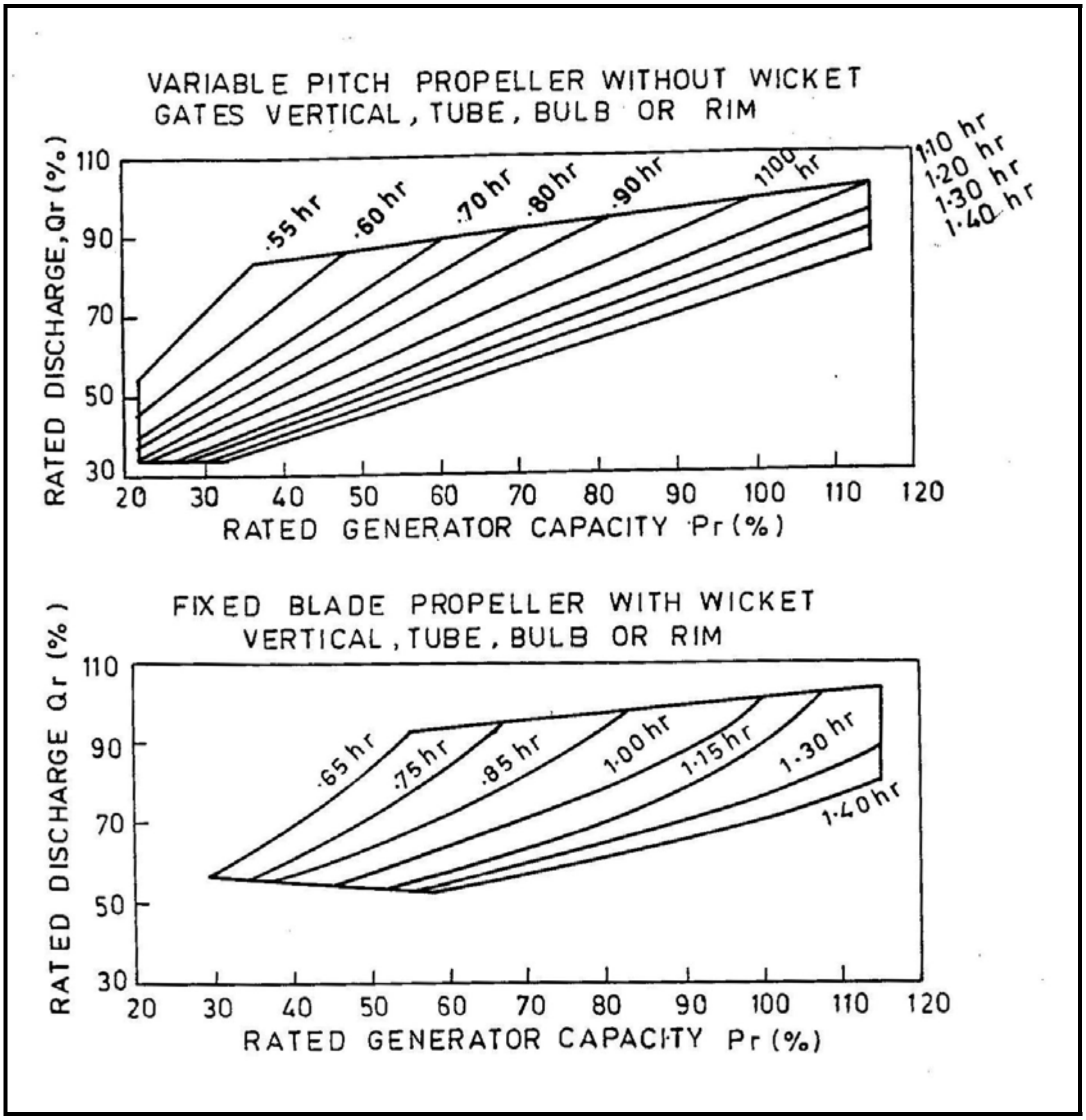


$Pr = \gamma_w . Hr. Q r. \eta_{tr.} \eta_g$ (kW)

Where,

Pr = Rated capacity at Hr
Hr = Selected Design Head
Qr = Turbine Discharge at Hr ε Pr
η_{tr} = Turbine efficiency at Hr ε Pr(%)
η_g = Generator efficiency (%)
γ_w = Specific density of water in N/m^2 and may be taken 9.804

Fig. 15 : Francis and Kaplan performance curves (Source IS: 12800 part 3)



$Pr = \gamma_w . Hr. Q r. \eta_{tr.} \eta_g$ (kW)

Where,

Pr = Rated capacity at Hr
Hr = Selected Design Head
Qr = Turbine Discharge at Hr ε Pr
η_{tr} = Turbine efficiency at Hr ε Pr
η_g = Generator efficiency (%)
γ_w = Specific density of water in N/m^2 and may be taken 9.804

Fig. 16 : Propeller turbine performance curves (Source IS: 12800 part 3)

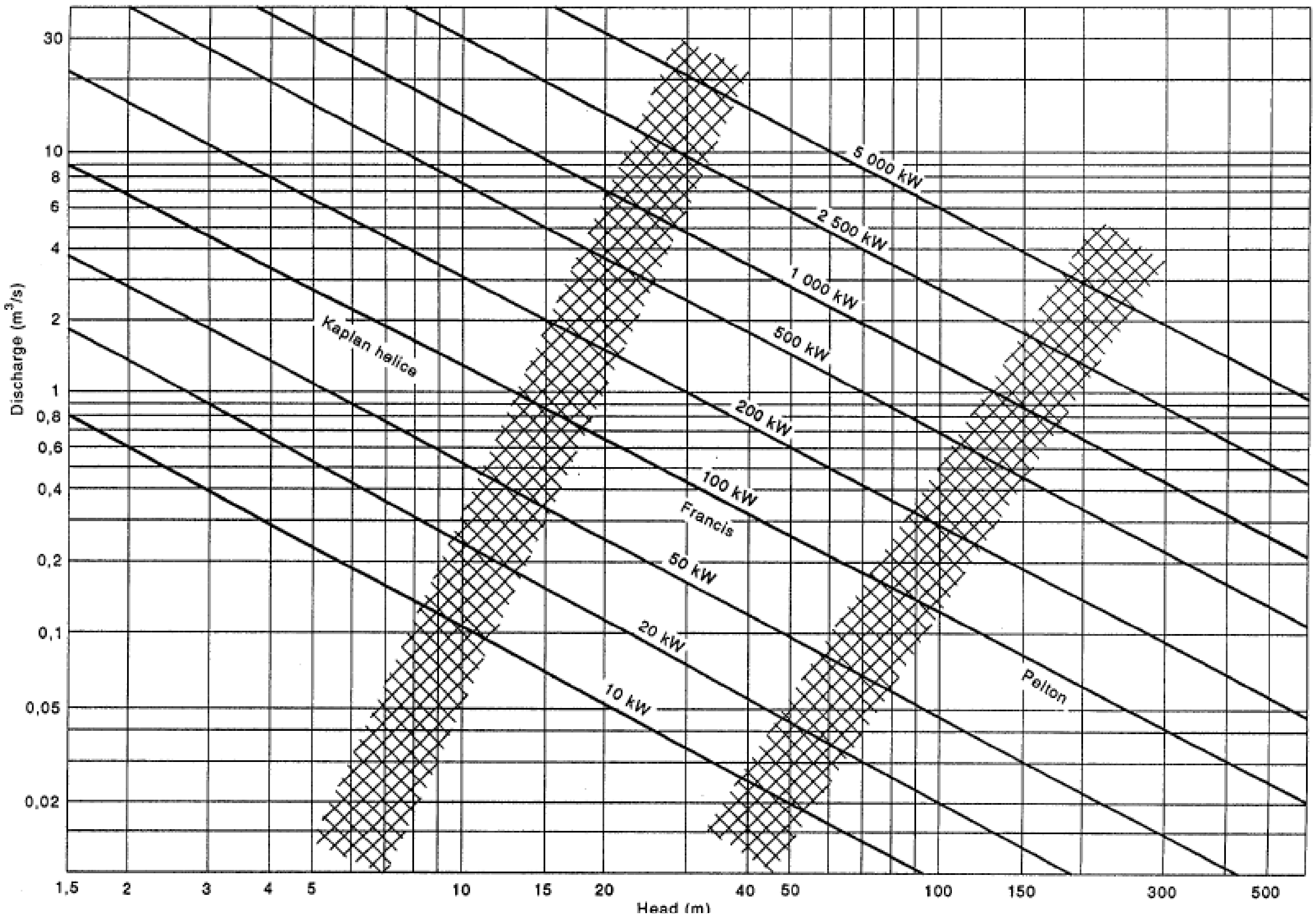


Fig. 17 : Turbine Operating Regimes (Based on IEC: 61116)

5.3 Selection Procedure for Small Hydro up to 3 MW Unit Size

5.3.1 General

Selection procedure for small hydro (SHP) including micro hydro power stations unit size is determined from techno-economic consideration as per Para 2.

Preliminary selection for type of small hydro turbine can be made from figure 17 (IEC – 61116 – 1992. Kind (within type) and configuration (horizontal or vertical) may be based on economic consideration including cost of civil works, efficiency etc.

Runner diameter may be used for preliminary layout of the turbine as pre IS 12800 part (3) for economic evaluation. Relative efficiency is given in figure 13. Type and configuration is given in Para 4.

5.3.2 Micro Hydro Range (up to 100 kW)

A large number of micro hydro in remote hilly areas are being installed to supply power to remote villages.

- Electricity for lighting and appliances (fan, radio, TV, computer, etc), in homes and public buildings such as schools and clinics
- Electrical or mechanical power for local service and cottage industries
- Electrical or mechanical power for agricultural value-adding industries and labour saving activities
- Electricity for lighting and general uses in public spaces and for collective events

The electricity provided is in the form of 415/240-volt AC line connections to users, with 11 kV sub transmission, if required.

These are generally high head schemes. A typical micro hydro scheme is shown in figure 17. Selected turbine efficiency and speed is of paramount importance for cost effective installation as illustrated below:

5.3.2.1 Cost Elements in small and micro hydro power projects as per National Consultants recommendations UNDP – GEF Hilly Projects is shown in figure 18.

These cost elements are for type of micro hydro in remote hilly area. Efficiency of indigenous turbines in the micro hydro range is approx. as follows:

Pelton	-	90%
Turgo Impulse	-	80%
Cross flow	-	85% (60% - 65% Indigenous Unit)
Francis	-	90% (Peak Efficiency at 90%)

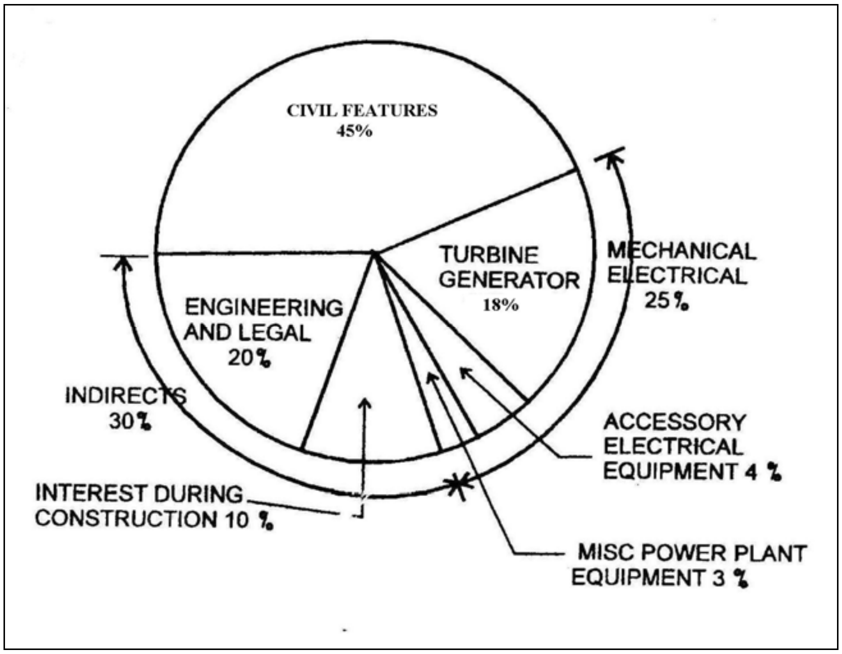
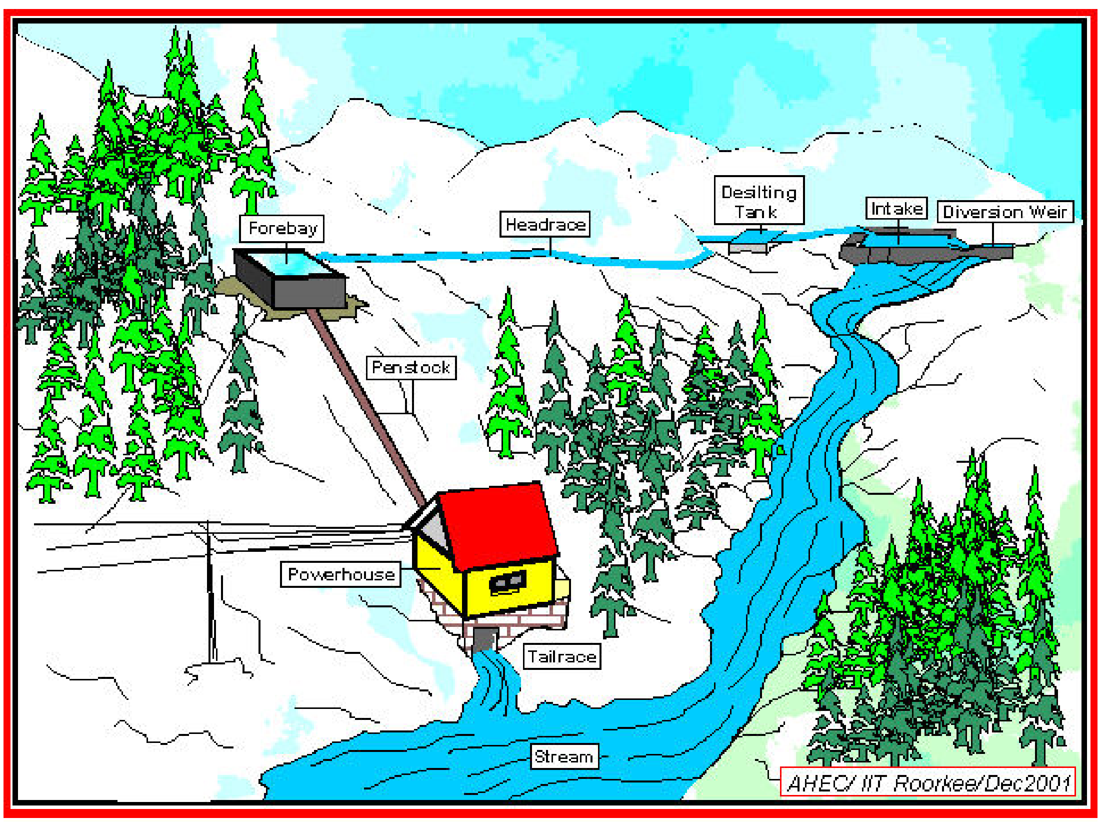


Fig. 18 : Maximum Civil Features Cost (High Head Scheme)



Typical Arrangement of Small Hydro Power Station

Fig. 19

Minimum weighted average efficiency of turbine and generator set (η_{Tv}) 0.50x η_{T100}+ 0.5 η_{T50} specified in Micro Hydro standard issued by AHEC (extracts at Annexure 1). Accordingly weighted average efficiency of different category (size) of micro hydro is as follows:-

Category A	Category B	Category C
Up to 10 –45 kW	Up to 50 kW	Up to 100 kW
45%	50%	60%

5.3.2.2 Step by step procedure for selection of turbine is detailed below:

1) Obtain Field Data as follows:
   a) Discharge data - Q cumecs
   b) Head - H head in meter
   c) Voltage Net work (415 volts or 11 kV)
   d) Nearest grid sub-station (optional) – kV and length of interconnecting line
2) **Compute kW capacity** (P) with available data from site P = Q x H x 9.804 x 0.8
3) Fix unit size, number and installed capacity based on data collected and requirement.
4) Using kW; H and Q per unit select usable turbine from figure 17
5) In case of turbine in overlapping range determine speed and specific speed relation and determine synchronous speed based on applicable range of specific as per Para 5.1. Higher speed machine is cost effective.

5.3.2.3 Cost/kW Comparison of 100 kW 60 m head, Run of the river scheme using different type of turbine based on cost element as per figure 18 is given in table 2.

The civil works i.e. intake weir, settling tank, canal, penstock and power house costs is dependant upon quantity of water required for generation i.e. proportional to efficiency. Rough cost comparison between cross flow; Turgo Impulse and Pelton/Francis turbine is based on indigenous available turbines.

Table 2 : Cost/kW comparison of 100 kW, 60 m head, run of the river scheme using different turbines

Item	Cross flow	Turgo Impulse	Francis	Remarks
Civil works 45% (For Francis turbine)	35100	29700	27000	
Electro-mechanical				1000/1500 rpm generator for Francis and turgo impulse and 750 rpm gen. For cross flow
i) Turbine	3940	4320	4800	
ii) Generator } iii)Equipment }	11220	10200	10200	
Direct cost	50260	44220	42000	
Engineering and Indirect cost	21540	18950	18000	
Total cost/kW	71800	63170	60000	

Francis turbines costs although higher by 20% reduce cost/kW by 20%.

5.3.2.6 Examples of Turbine Selection (micro hydro range)

Typical example-I:

Site Data	Q	=	0.674 cumecs
	H	=	62 m
	P	=	9.80 x 0.674 x 62 x 0.80
		=	327.61 kW

Installation proposed (based on load survey) = 2 x 100 kW

<u>Turbine selection</u> (with following particulars)

Power (P)	=	100 kW
Head	=	62 m

i) As per IEC 61116- (Fig. 17), Francis turbine requiring a discharge of 0.2 cumec per turbine is feasible. Peak efficiency of Francis turbine as per figure 14 is 90% (at 90% gate opening).

Accordingly Francis turbine requiring a discharge of 0.2 cumec per turbine and 0.4 cumec for 2 turbines are selected.
Civil work may be designed for 0.45 cumec (10% + 5% margin).
Pumps as turbine (mixed flow) can also be used.
Check for part load efficiency.

5.3.2.7 Typical example-II:

Site Data

Q	=	0.441 cumec
H	=	51.0 m
Power required	=	50 kW
Available power	=	9.80 x 0.441 x 51 x 0.8
	=	176.32 kW

Installation Proposed –1 x 50 kW

<u>Turbine Selection</u> (with following particulars)

Power (P)	=	50 kW
Head	=	51 m

i) As per IEC 61116- (Fig. 17), Francis Turbine requiring a discharge of 0.1 cumec per turbine is feasible. Peak efficiency of Francis turbine as per figure 14 is 90% (at 90% gate opening).

Accordingly Francis turbine requiring a discharge of 0.1 cumec per turbine.
Civil work may be designed for 0.25 cumec (10% + 5% margin) for two turbine (one for future).
Check for part load efficiency.

5.3.3 Mini Hydro in the Range 0.1 MW to 5 MW

Selection Procedure

1) Field Data Required

   a) Discharge data - Q cumec
   b) Head - H head in meter
   c) Voltage Net work (415 volts or 11 kV)
   d) Nearest grid sub-station (optional) – kV and length of interconnecting line

2) **Compute kW capacity (P)** available from site

   P = Q . H . 9.804 . 0.8

3) Fix unit size, number and installed capacity based on data collected.
4) Using kW; H and Q per unit select usable turbine from figure 12 or 17.
5) In case of turbine in overlapping range determine speed and specific speed relation and determine synchronous speed based on applicable range of specific speed as per Para 5.1. Higher speed machine is cost effective.

5.3.3.1 Example of turbine selection (mini hydro range)
High Head Power House
Site Data

A common penstock bifurcating at the powerhouse into a wye branch for each power unit is proposed. The length of the penstock system including Y-branch length is 340 meters.

Details of hydraulic system and basic data for design of turbine as extracted from the specifications is given below:

(1)	Full reservoir/max. Forebay level (m)	1935
(2)	Minimum draw down level (m)	1934
(3)	Maximum gross head (static) (m)	198
(4)	Maximum net head (m)	185
(5)	Minimum net head (m)	184
(6)	Rated head (m)	185
(7)	Elevation of centre line (m)	1737
(8)	Maximum tail race level (m)	1734
(9)	Diameter of each penstock (m)	1200
(10)	Length of penstock (m)	340
(11)	Permissible speed rise	45%
(12)	Permissible pressure rise	20%

Discharge Data

Stream discharges available for diversion for generation of power at a typical site are given in Table 3. There is no storage. Inter connection of power plant implies utilisation of entire power generated for feeding into the grid besides supplying local loads . Accordingly, power generation based on minimum in flows and loading of turbine as percentage of installed capacity is shown in Table-4. It is clear that at no time the part load operation is below 67%. Average plant factor during water shortage critical months (December-April) is about 73%.

Table – 3 : Discharges (m^3/sec) data of a typical site

S. No.	Month	1978	1981	1982	1983	1986	1987
1.	January	3.00		3.13	3.49	-	3.10
2.	February			3.08		-	3.05
3.	March			3.00	3.17	-	2.77 2.85
4.	April	4.21		4.16		-	3.16
5.	May	5.19		4.50		-	>5.0
6.	June	9.48				-	>5.0
7.	July		24.00			-	9.10 8.25
8.	August			13.65		11.35	11.90
9.	September			8.00		~ ≥.8	12.10
10.	October			6.20		7.71	7.90 8.00
11.	November			5.20		≥.4.8	7.05
12.	December			3.10		3.40	5.67

Inter connection and load characteristics

The powerhouse is proposed to be interconnected by a 33 kV lines to another power plant with a ring main for interconnection with Grid sub-station.

Table – 4 : Part Load Operation of Units

Installation = 2 x3 MW; Rated Head = 185 m

S. No.	Month	Discharge (Cumecs)		Minimum available Power = 9.81 x Q.HE kW	Average plant factor during month
		Average	Minimum		
1.	January	3.18	3.00	4356	71%
2.	February	3.06	3.05	4428	73.8%
3.	March	3.00	2.77	4022	67%
4.	April	3.84	3.16	4588	76.4%
5.	May	4.89	4.50	6533	100%
6.	June	7.00	5.00	7259	100%

7.	July	9.00	8.25	6000	100%
8.	August	12.30	11.35	6000	100%
9.	September	9.30	8.00	6000	100%
10.	October	7.27	6.20	6000	100%
11.	November	5.68	4.80	6969	100%
12.	December	4.05	3.10	4501	75%

NOTE: Overall Efficiency assumed 80%

A small 250 kVA transformer to feed local loads at power station site is also proposed.

Accordingly, it is considered essential to design the turbines for stand alone isolated operation as well as for parallel operation with grid.

Turbine Selection

Rated Head (H) = 185 m
Rated Power (P) per unit = 3000 kW

As per IEC 61116- (Fig. 17) it is seen that either an Impulse or Francis Turbine may be suitable.

Specific speed (n_s) is related to rotational speed (n) by specific speed $n_s = n\sqrt{P}/H^{5/4}$

$$n_s = n\sqrt{P}/H^{5/4}$$
$$= n\sqrt{3000}/(185)^{5/4}$$
$$n = 12.45\ n_s$$

Setting of runner was calculated as per Para 6.

Table – 5 : Comparision of Runner diameter and speed for various values of specific speed

S. No.	**Type of Turbine**	**N_s (metric)**	**n(r.p.m.) =12.4 n_s**	**Runner dia (m)**	**Setting of runner above tailrace**	**Remarks**
A.	Single Jet Pelton	10 15 20	125 187.5 250	4.11 2.74 2.06	Above maximum T.W. level	Speed nearest Synchronous
B.	Double Jet Pelton	15 20 30	187.5 250 375	2.74 2.06 1.30		
C.	Francis	80 100	1000 1250	0.54	+3.2 m	Nearest Synchronous Speed Not Possible
		120	1500	0.4	–1.4 m	Speed nearest Synchronous

Runner diameter (D) and speed for various possible values of n_s are computed and compared in Table 5.

For Pelton Turbine upper practical limit of jet diameter D_j and runner diameter ratio $D_j/D = 0.1$, then D is 2.1 m which corresponds to a unit with specific speed $n_s = 21$ for single jet pelton and about 30 for two jet turbine. Accordingly, synchronous speed of 375 RPM pelton 2 jet turbine having runner dia of about 1.3 m is possible in case Pelton turbines are used.

Pelton turbines can be coupled directly to 375 r.p.m. (16 pole) generator or 750 r.p.m. (8 pole) generator through speed increasing gears.

For Francis turbine a 6 pole machine 1000 r.p.m. can be set 2.7 m above minimum tailwater and may be economical to use. Four pole, 1500 r.p.m. generators coupled to 120 (n_s) turbines are also feasible and are cavitation free but not recommended due to high speed low inertia in generators and lower setting.

5.3.3.2 Comparison of 375 r.p.m. Pelton Turbine and 1000 r.p.m. Francis Turbine

1. Cost of directly coupled Pelton turbine generator set will be more (about 2.5 times that of Francis Turbine coupled generators) and those coupled through speed increasers by about 1.5 – 2 times.
2. Selection of low specific speed Francis turbine (1000 r.p.m.) with a setting of 0.7 m above minimum tail water level is possible and is liable to be cavitation free.
3. Excessive silt or sand in the water will cause more wear on the runner of an impulse turbine than on the runners of most reaction turbines.
4. Powerhouse size is liable to be bigger by about 70% for Pelton units. Thereby increasing Civil Engineering cost.
5. Setting for Pelton turbine nozzle center line is proposed at EL 1737 m and maximum tail water E.L. is 1734 m. Accordingly, if Francis turbine is used, a minimum increase in head of 3 meters is possible. Available head will be further increased during water shortage winter months when tail water is at lower level.
6. Peak efficiency of Pelton turbine is slightly lower than peak efficiency of Francis turbine but part load efficiencies of Pelton turbines are higher. The units do not run below 70% load (Annexure-I) and 80% of the time the units are running above 80-90% load. Accordingly, it is considered that Francis units will generate more energy.
7. Penstock length (L) is 340 meter and head (H) is 185 m. According L/H ratio is about 1.8 indicating no water hammer problem for stable speed regulation for Francis turbines and no special advantage for Pelton turbines.

5.3.3.3 Conclusion & Recommendations

Proposed Pelton turbines were replaced by Francis turbines and large economies in cost (25-30%) were made.

5.3.4 Low Head Range – Canal power Houses

Cost element in a low head project such as in canal fall projects is shown in figure 20. Accordingly equipment cost predominates. Cost of generators is reduced by providing speed increasing gears and accordingly selection of turbine in important for cost affective installation. Accordingly only high specific speed (Axial flow) is possible. Selection procedure is therefore is to select type and configuration of axial flow turbine as clarified in example. Low Head canal fall Schemes. Most of the canal falls in the country are below 4 to 5 meter head. Canal schemes in the range lower that 3 meters are designed as ultra low head schemes.

5.3.4.1 Example of Turbine Selection

a)A typical example

Site Data

Discharge Q	=	61.05 cubic meters/sec
Net head H	=	3.46 meters
Power P	=	9.80 x 61.05 x 3.46 x 0.85
	=	1759 kW
Installation	=	2 x 750 kW

Efficiency SHP range of turbine and generator has been taken as 0.85

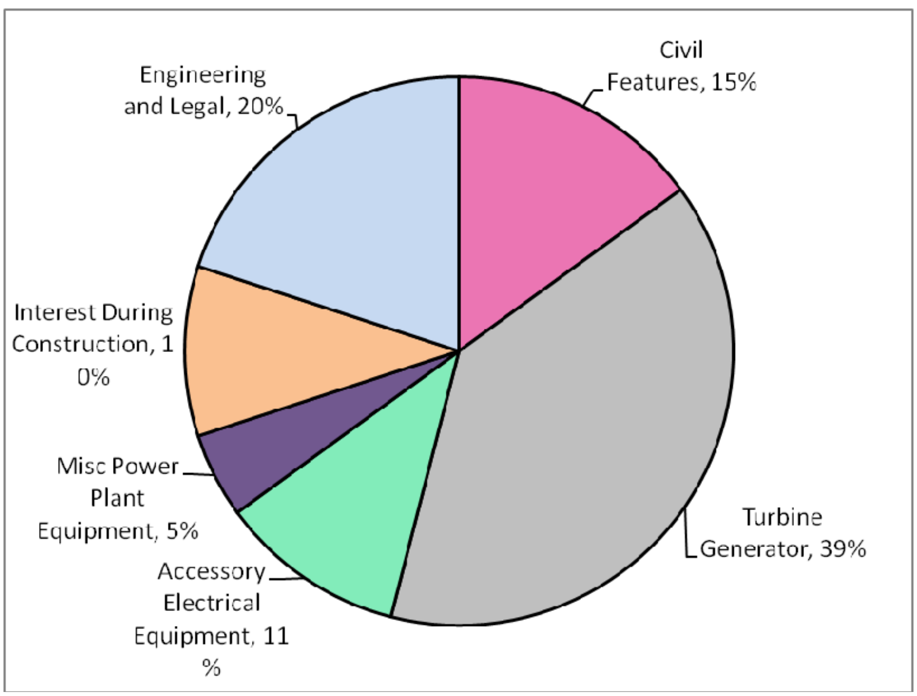


Fig. 20 – Minimum Civil Feature (Low Head Scheme)

Turbine Selection

As per IEC -61116 (Fig. 17) only Kaplan Axial flow turbine is feasible.

Available standard turbine is Tubular turbine S type (Full Kaplan) or Semi Kaplan turbine with runners dia. about 2.200 meter is feasible (Fig. 4). This type of turbines requires intake valve for shut off (emergency) as well as draft tube gates for dewatering. It also requires dewatering and drainage arrangement.

Semi Kaplan vertical turbines with siphon intake as shown in fig. 6 was selected as cheapest and cost effective alternatives (efficient) which does not require intake and draft gates and dewatering arrangements. Detailed comparison of S type tubular turbine with vertical syphon intake turbine is given in table 6.

Table 6 : Comparison of Tubular type and vertical axis siphon intake for ultra low head (below 3 meter head)

S. No.		Tubular turbine (semi Kaplan)	Vertical axis Siphon intake	Remarks
1.	Inlet valve	Required	Not required	
2.	Draft tube gate	Required	Not required	
3.	Drainage pump	Required	Not required as setting is above maximum tailrace	
4.	Dewatering pump	Required	Not required as setting is Above tailrace	
5.	Cost of civil Work	High (setting is low)	Low	
6.	Efficiency	Tubular turbine efficiency is 1% higher		

5.3.4.2 Guaranteed technical Particulars of a typical Mini HP

Turbines ordered is as follows:
Type of turbine – vertical semi Kaplan with siphon intake

Rated Head (H) = 3.24 m
Rated discharge (P) = 845 kW (10% overload)
Rated discharge (Q) = 30.075 cumecs
(for rated output generator terminal)
Efficiency at rated Head & output = 88.92 %
Synchronous Generator Efficiency at rated output = 96.4 %

5.3.5 Selection procedure for Turbines above 5 MW Unit Size

For a small/medium low head power units reaction turbine are used. For high head multiple jet Pelton turbine are used. Selection of turbine type is based on specific speed criteria.

5.3.5.1 Criteria for selection of hydraulic turbine

Criteria for selection of hydraulic turbine based on specific speed as per Indian standard IS:12837 (N_{sp}) is given in table 7.

Table: 7 : **Criteria for selection of hydraulic turbine based on specific speed as per Indian standard IS: 12837**

Type of machine	Head variation % of rated head	Load variation % of rated output	Specific speed (m-mhp)	Peak efficiency in %
Pelton	120 to 80	50 to 100	15 to 065	90
Francis	125 to 65	50 to 100	60 to 400	93
Deriaz	125 to 65	50 to 100	200 to 400	92
Kaplan	125 to 65	40 to 100	300 to 800	92
Propeller	110 to 90	90 to 100	300 to 800	92
Bulb	125 to 65	40 to 100	600 to 1200	92

5.3.5.2 Selection of Reaction Turbines as per USBR Monograph No. 20 Criteria

1. Trial Specific speed, n'_s

Select trial specific speed from figure 5.1 or from economic analysis. Except for unusual circumstances, the selecting specific speeds is near $\left(2334/\sqrt{h_d}\, metric\right)$.

2. Trial Speed, n':

$$n' = \frac{n'_s (h_d)^{5/4}}{(P_d)^{1/2}} \; or \; \frac{n'_s h_d}{\left(\frac{P_d}{h_d^{1/2}}\right)^{1/2}}$$

where

n' = trial rotational speed,
n'_s = trial specific speed,
h_d = design head, and
P_d = turbine full gate capacity at h_d

3. Rotational speed or design speed, n :

The rotational speed nearest the design speed is selected subject to the following considerations:

a. A multiple of four poles is preferred, but standard generators are available in some multiples of two poles.
b. If the head is expected to vary less than 10% from design head, the next greater speed may be chosen. A head varying in excess of 10% from design head suggests the next lower speed.

Rotational speed, $n = \frac{120.\,frequency}{number\,of\ poles}$

$$n = \frac{6000}{number\,of\ pole}\,at\,50Hz$$

4. Design specific speed, n_s:

$$n_s = \frac{n(P_d)^{1/2}}{(h_d)^{5/4}}\ or\ \frac{n\left(\frac{P_d}{h_d^{1/2}}\right)^{1/2}}{h_d}$$

The design specific speed is the basic parameter to which most other factors of the selection are made.

5.3.5.3 Example of Turbine Selection above 5 MW Unit Size

1. Turbine Basic Data

I.	Rated design head	:	57.75 m
II.	Rated Turbine Discharge	:	41.57 cumecs
III.	Total discharge	:	124.72 cumecs
IV.	Maximum tailrace level	:	468.25 m
V.	Rated output at rated head and rated discharge (at generator terminals)	:	20 MW

Net design head (h_d) = 57.75 m

Turbine full gate capacity at rated load (10% over load on generator 96% generator efficiency and 5% margin.

Generator rated o/p = 20,000 kW
(10% overload capacity) = 22,000 kW

Turbine rated o/p required = $\frac{20000 \times 1.10 \times 1.05}{0.96 \times 0.86}$ = 27980 MHP

Trial Specific Speed (n_s') = $\frac{2334}{\sqrt{h_d}}$ (metric)

$$= \frac{2334}{\sqrt{57.75}} = 307 \text{ (fig. 12 shows } n_s = 250)$$

Trial Rotational Speed (n') $= \dfrac{n'_s \times (h_d)^{5/4}}{\sqrt{P_d}}$

$$= \frac{307 \times (57.75)^{5/4}}{\sqrt{27980}} = 292.2 \cong 300 \text{ or } 250$$

Design Speed

Head is expected to vary less than 10% from design head and hence the next greater speed may be chosen.

Accordingly 10 pole (5 pair pole) generator with design speed of 300 rpm is optimum choice.

Design Specific Speed (n_s)

$$n_s = \frac{n\sqrt{P_d}}{(h_d)^{5/4}}$$

$$= \frac{300\sqrt{27980}}{(57.75)^{5/4}} = 315.21$$

$$= 315$$

Discharge Diameter (D_3)

Velocity ratio (ϕ) $= 0.0211\,(n_s)^{2/3}$

$$= 0.0211\,(315)^{2/3} = 0.9768$$

$$D_3 = \frac{84.47 \times \Phi \times \sqrt{h_d}}{n}$$

$$= \frac{84.47 \times 0.9768 \times \sqrt{81.37}}{300}$$

$$= 2.09 \text{ m}$$

Manufacturer

Manufacturer intimated following parameters for the turbine of a typical project

Design head	=	57.75 m
Turbine output	=	20000 kW (without 10% overloads)
Rated speed	=	300 rpm
Runner dia.	=	2.08 m
With 10% overload speed	=	272.7 rpm

6.0 SETTING AND CAVITATION OF REACTION TURBINE

Highest sped practicable at specified head is required for lowest possible cost. In addition greater speed requires the reaction turbine (Francis and Propeller/Kaplan) to be placed lower with respect to the tailwater to avoid cavitation. This generally increases excavation and structural costs.

Cavitation results from sub-atmospheric pressure at places on runner and runner chamber. To minimize this problem the turbine runner is set at depths below the minimum tail water to obtain a countering pressure. The appropriate value of the depth of setting for runner of different specific speed is computed using a characteristic 'cavitation coefficient' for the particular specific speed, as follows (IS: 12800):

$$Z = (H_a - H_v) - \sigma H$$

Where,

Z = Depth of centre line of runner below minimum level of tail water
H_a = Atmospheric pressure in meter water column at plant elevation
H_v = Vapour pressure in meters at plant location temperature
H = head on turbine, meters
σ = Plant sigma or cavitation coefficient for the turbine specific speed
The value for σ may be found from the expression which is as follows:

$$\sigma = \frac{(n_s)^{1.64}}{50327}$$

The value of σ can also be taken from the curves relating n_s and σ shown in fig. 21.

The value of σ for Francis turbines are lower than those for Propeller of Kaplan turbines. The setting level for the latter is consequently lower than for Francis turbine. Many low n_s Francis turbines will yield setting levels above minimum tail water level and same may be the case with Kaplan/ Propeller turbines of very low heads Pelton turbines are set above the maximum tail water level.

Lower setting (below tail water) results in higher speed and hence smaller runner diameter fig. 22 & 23 shows correlation runner diameter and settling for Francis and propeller turbines.

7.0 TURBINE PERFORMANCE

Turbine performance characteristics (pressure and speed regulation) required to be provided considerably impact on design and cost of hydro stations. These characteristics depend upon design of associated water passage from fore bay to tailrace and WR^2 of the rotating masses of the unit.. Head loss in penstock and pressure water system affects direct power loss and optimized by determining economic diameter of penstock and design of bends etc. Pressure and speed regulating characteristics of turbine are required to be provided according to performance requirement of the hydroelectric stations by optimizing pressure water system design and generator inertia WR^2/ GD^2.

7.1 Pressure Regulation

With normal operation i.e. with load accepted or rejected either slowly as the system requires or rapidly during faults, pressure water system follow slow surge phenomena and depends upon the rate of closing the guide vanes/nozzle. The wicket gate closing time is always kept much greater than critical closure time (Tc) i.e. the time of reflection of the pressure wave, this time, Tc $= \frac{2l}{a}$ where l is the length of the pressure water system from tailrace to fore bay/ surge tank and a is the velocity of the sound in water (wave velocity).

Pressure water column inertia is expressed as starting up time (Tw) of water column,

$$Tw = \frac{\sum LV}{gh}$$

Where Tw = starting up time of the water column in seconds

$\sum LV = L_1 V_1 + L_2 V_2 + \ldots\ldots\ldots L_n V_n + L_d V_d$

L_n = length of penstock in which the velocity is uniform

V_n = velocity in section L_n at rated turbine capacity,

L_d = draft tube developed length

V_d = average velocity through the draft tube,

h = rated head of the turbine

g = gravitation constant

During preliminary stage of planning simple and short methods of calculating the pressure regulation as given in references R 11 and R 12 be adopted.

Allievies formula for pressure variation in decimals is given by

$$\frac{\Delta H}{H} = \frac{n}{2}\left\{n \pm \sqrt{n^2 \div 4}\right\}$$

Where n = $\frac{LV}{gHT}$ = $\frac{Tw}{T}$ or in case of uniform penstock dia.

L - length of penstock + ½ the length if the spiral casing

H – head in meter

T – governor closing time in seconds

V – velocity in m./sec.

This formula is sufficiently accurate only if T > $\frac{4L}{a}$ where a is the wave velocity.

Note – Use plus for pressure rise and minus for pressure drop.

Pressure rise in percentage is also given by

$$\frac{\Delta H}{H} = \frac{L \times HP \times 54}{D^2 \times H^2 \times T}$$

Where T, L & H are same as above;

D – diameter of penstock in meter

HP – rated metric Horsepower

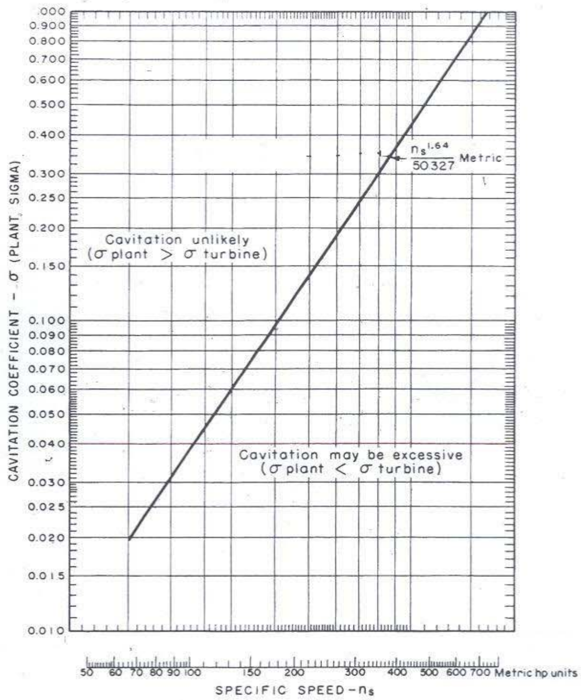
UNIT SELECTION 23

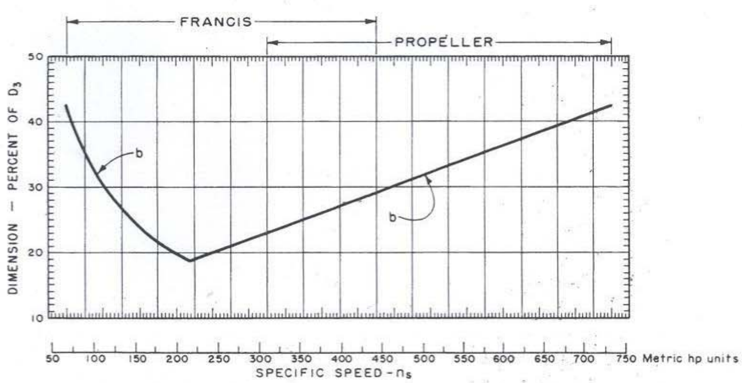
Atmospheric Pressure		Water Properties	
Altitude Metres	H_a M of H_2O	Temp ^0C	H_v Metres
0	10.351	5	0.089
500	9.751	10	0.125
1000	9.180	15	0.174
1500	8.637	20	0.239
2000	8.120	25	0.324
2500	7.628		
3000	7.160		
3500	6.716		
4000	6.295		

H_a = Atmospheric pressure for altitude, (m).

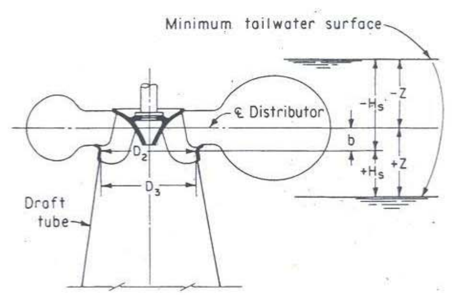
H_v = Vapor pressure of water, use highest expected temperature, (m).

$H_b = H_a - H_v$, Atmospheric pressure minus vapor pressure, (m)





D_2 at shrouding = Least diameter through shroud, (m).
D_3 = Discharge diameter of runner, (m)
b = Distance from D_2 to ℄ of distributor, (m).
(estimated from curve % D_3 vs n_s).
n_s = Specific speed of turbine.



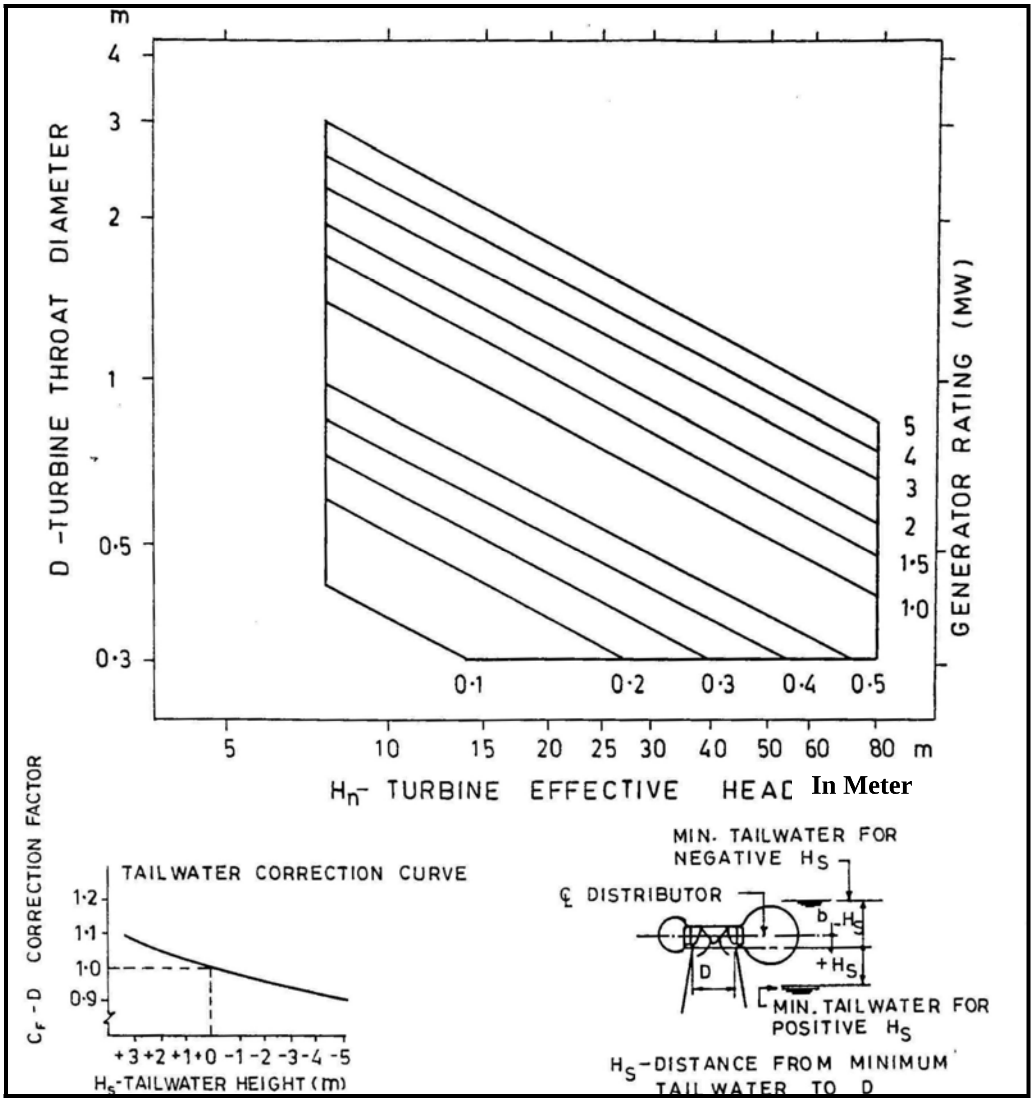
h_{cr} = Critical head, (m).
H_s = Distance from D_2 to minimum tailwater (one unit operating at full gate), (m).
$H_s = H_b - \sigma h_{cr}$ or $\sigma = (H_b - H_s) / h_{cr}$, (m).

Z = ℄ Distributor to minimum tailwater = H_s + b (Total draft head), (m).

Note: Place ℄ of distributor at next lowest full foot elevation, (0.30 m).

Fig. 21 Reaction Turbine

(Source: USBR Engineering Monograph No. 20)



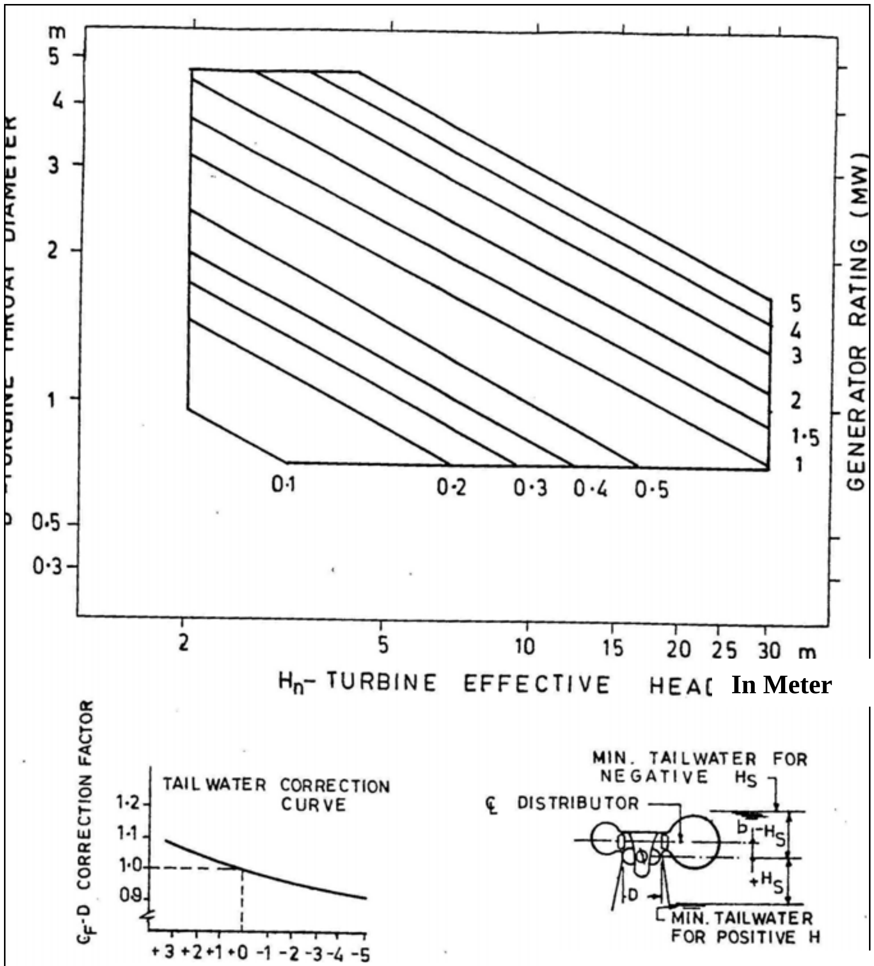
NOTES:

1 Estimated turbine runner diameters D are based upon a plant elevation of 600 m. and a tailwater height (Hs) of zero. Where Hs = distance between minimum tail water level and exit of runner blades.

2 The estimated runner diameters may be used for both vertical and horizontal Francis turbines.

3 For plant elevations higher then 600 m add 1% to D for each 300 m. Subtract 1% from D for each 300 m. slower then the 600 m plant elevation.

Figure 22 Francis turbine runner diameters
(Source: IS 12800 part3)



H_s Tailwater Height (m)

H_s Distance from minimum Tailwater to D

NOTES:

1 Estimated turbine runner diameters D are based upon a plant elevation of 600 m. and a tailwater height (Hs) of zero. Where Hs = distance between minimum tail water level and exit of runner blades.

2 The estimated runner diameters may be used for both vertical and horizontal Francis turbines.

3 For plant elevations higher then 600 m add 1% to D for each 300 m. Subtract 1% from D for each 300 m. lower then the 600 m plant elevation.

Figure 23: Propeller turbine runner diameters
(Source: IS 12800 Part 3)

7.2 Speed Regulation

The speed regulation or stability of a hydro-electric unit may be defined as its inherent property to ensure that changes in external conditions as well as in the turbine and governing equipment result an a periodic or rapidly damped, periodic return to the new steady state. Stability over the normal operating range with the machine connected to the system and stability after disconnection can be considered independently. Most hydro-electric stations are interconnected and as such their satiability is assisted. The more important factors upon which the stability of interconnected units depend are the flywheel effect of the unit, the hydraulic design of the water passages and speed and capacity of the unit. The GD^2 should be sufficient to insure prompt response to power demands and to restrict speed rise following loss of load. But generator GD^2 should be restricted to avoid excessive power swings. Additional GD^2 built into the generator increases the cost, size and weight of the machines and increasing GD^2 more than 50 percent above normal decreases the efficiency.

Flywheel effect is expressed as starting up time of the unit (Tm). This is the time in seconds for torque to accelerate the rotating masses from 0 to rotational speed

$$Tm = \frac{GD^2 \times n^2}{3.6 \times 10^5 \times P} \text{ (metric units)}$$

Where GD^2 = Product of weight of rotating parts and square of the diameter

n = rotational speed rpm
P = Turbine full gate capacity in metric horse power

Governor is the main controller and discussed in Para 8.

Permissible pressure rise and speed rise for various turbines as pre IS: 12837 are given shown in table 8.

Table 8 : Possible Pressure ris & speed rise

Type of Turbine	Pressure Rise (%)	Speed Raise (%)
Pelton	15 to 30	20 to 45
Francis	30 to 35	35 to 55
Kaplan/Bulb and Propeller	30 to 50	30 to 65
Deriaz	20 to 45	35 to 65

7.3 Speed Rise

Sudden dropping of load from a unit through opening of the main breaker will cause a unit to achieve considerable speed rise before the governor can close the gates to the speed-no-load position. The time required to attain a given over speed is a function of the flywheel effect and penstock system. The values of speed rise for full load rejection under governor control is considered an index of speed regulating capability of the unit. Normally adopted range is from 30 to 60 percent, the former applies to isolated units, where changes of frequency may be important when sections of distributed load are rejected by electrical faults. Values from 35 to 60 percent are generally adopted for grid connected hydro station. Generally units for which length of the penstock is less than five times the head can be make suitable for stable frequency regulation of the interconnected system. Also units for which $Tm \geq (Tw)^2$ can be expected to have good regulating capacity. This test should be applied over the entire head range. Plants in which more than one turbine are served from one penstock should be analyzed to determine proper governor settings and appropriate operating practices. Such plants may be unable to contribute to system transient speed regulation but adverse effects upon the system may be avoided by specifying the number of units which may be allowed to operate on free governor (unblocked) at any one time.

The turbine and generator are designed to withstand runaway speed, but at excessive speed severe vibrations sometimes develop which snap the shear pins of the gate mechanism. To minimize vibration, a speed rise not to exceed 60% can be permitted in contrast to the 35 to 45% desired for satisfactory regulation of independently operated units.

7.3.1 Small Hydro (Grid Connected)

Small hydro if grid connected (with no isolated and or islanding provision) cannot take part in frequency control. Accordingly these should be designed for upto 60% speed rise on full load rejection. In canal fall or similar units, speed control is required only during synchronizing. Generator loading should be controlled by level i.e. non speed control governors can be used and loading on the units is controlled by upstream canal water level. These are called non speed control governors.

7.3.2 Small Hydro (Isolated Grid Operation)

These should be designed as frequency control units for the criteria that speed rise on full load rejection does not exceed 35%.

7.4 Pressure Rise and Speed Rise Calculation

The penstock pressure rise and unit speed rise may be calculated from the references given in Para 7.1 entitled ‘pressure regulation’. These could also be calculated as follows, which is based on USBR design monograph no. 20 referred in Para 7.1. Economic studies required to be carried out to determine whether more than normal GD^2, a larger penstock, a surge tank or a pressure regulator is required. Some examples follow:

7.5 Method for Computing Speed Rise

Notation :-

T_f = Servomotor minimum closing time, sec.

P_r	=	Turbine full gate capacity of hr, kW
h_r	=	Rated head, metre
n	=	Rotational speed: design, r/min.
n_s	=	Design specific speed, metric kW unit
GD^2	=	Flywheel effect of revolving parts; kgm^2
L	=	Equivalent length of water conduit, m
A	=	Equivalent area of water conduit, m^2
g	=	Gravitational constant (acceleration), m/s^2
Q_r	=	$\frac{P}{h_r \text{ x } 9.804 \text{ x } 0.8}$ = Turbine full gate discharge, m^3/s
V_r	=	$\frac{Q_r}{A}$ = Conduit water velocity for full gate at hr, m/s
T_m	=	Mechanical startup time
T_w	=	Water startup time

To obtain the speed rise for full load rejection, determine the following values :-

(a) T_K = $0.25 + T_f$, full closing time of servomotor(s)

(b) $$T_m = \frac{GD^2 \text{ x } n^2}{3.6 \text{ x } 10^5 \text{ x } P_r}$$

(c) $$\frac{T_K}{T_m}$$

(d) $n_s = \frac{n(p_r)^{1/2}}{(h_r)^{5/4}}$ At rated cond^n, metric kW unit

(e) Determine S_R from fig. 24 using n_s & $\frac{T_K}{T_m}$

Where,

S_R is speed rise in percent of rotational speed,

n_1 for full gate load rejection to zero, excluding effect of water hammer.

(f) $T_W = \frac{\sum LV_r}{ghr}$ (water start up time)

(g) $K = \frac{T_W}{T_f}$

(h) $S^1{}_R = S_R (1 + K)$, speed rise in percent of rotational speed n_r for full gate load rejection to zero, including effect of water hammer.

Example-1

Given :-

$T_f = 5$ sec, $P_r = 29851$ kW, $h_r = 24.38$ metre

$N_{sr} = 94.7, \quad GD^2 = \frac{1}{6} WR^2 = 8873333.34 \text{ kgm}^2$

$V_r = 4.199 \approx 4.2$ metre/sec

L = 103.63 metre

(a) T_K = 0.25 + 5 sec (0.25 in dead time
= 5.25 sec

(b) $$T_m = \frac{GD^2 \text{ x } n^2}{3.6 \text{ x } 10^5 \text{ x } P_r} = \frac{8873333.34 \text{ x } (94.7)^2}{3.6 \text{ x } 10^5 \text{ x } 29851} = \frac{7.957685199 \text{ x } 10^{10}}{1.074636 \text{ x } 10^{10}}$$

= 7.40

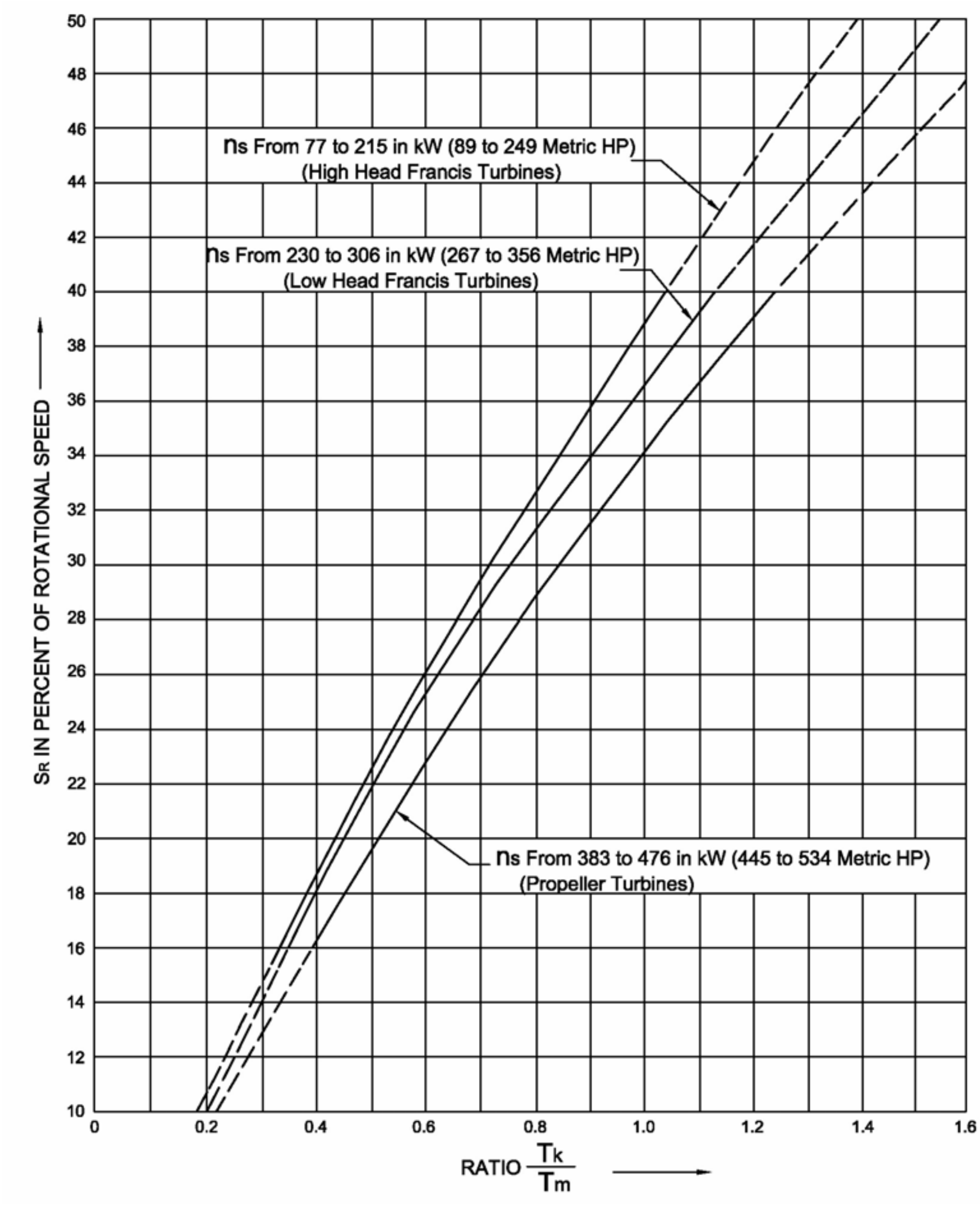


Fig. 24 – Turbine Performance
(Source : USBR Design Monograph no. 20)

(c) $\frac{T_K}{T_m} = \frac{5.25}{7.40} = 0.709$

(d) $n_{sr} = \frac{n\sqrt{P_r}}{(n_r)^{5/4}} = \frac{(94.7)\sqrt{29851\ \text{kW}}}{(24.38)^{5/4}} = 302.02$

$= 302$ MkW

(e) $S_R = 28.1\%$ from Figure 24

(f) $T_w = \frac{103.63 \text{ x } (4.2)}{9.81 \text{ x } 24.38} = 1.8198$

Tw = 1.82

(g) $K = \frac{T_w}{T_f} = \frac{1.82}{5} = 0.364$

(h) $S^1_R = (28.1)\ (1 + 0.364) = 38.32$

Example-2

Data

Length of Penstock (L)	=	153.5 m
Penstock Dia (D)	=	1.289 m
Penstock thickness	=	0.00889 m = 8.89 mm
Rated unit output (full gate)	=	1750 kW (including 10% over load capacity)
Rated Head (H) (full gate)	=	46.634 m
Maximum pressure rise in penstock	=	30%

First Step:- Fix closing time for 30% speed rise

Assuming governor closing time of 4 seconds

Rated Discharge (Q_r) = $\frac{P}{h_r \times 9.804 \times 0.8}$

= $\frac{1750}{46.63 \times 9.804 \times 0.8}$

= 4.78 cumec

Velocity of water (V_r)= Q/A (A – cross sectional area of penstock)

$$= \frac{4.78}{\pi/4 \times (1.289)^2} = \frac{4.78}{0.7854 \times 1.661521}$$

$$= 3.662 \text{ m/sec.}$$

Governor closing time (assumed) = 4 second

Guide vane closing time assuming (t_0) = 4 + 0.25 = 4.25 second
(0.25 sec. as dead time)

Gravitational Constant (g) = 9.81 m/sec^2

Water starting up time (Tw) = $\frac{LV}{gH}$

$$= \frac{153.5 \times 3.66}{9.81 \times 46.63}$$

$$= 1.228 \text{ second}$$

Pressure rise on full load rejection using Alliivies formula

$$\frac{\Delta H}{H} = \frac{T_w}{2}\left\{T_w + \sqrt{T_w^{\ 2} + 4}\right\}$$

Where $T_w = \frac{LV}{gHT} = \frac{1.2287}{4.25} = 0.2894 = 0.29$

L = Length of penstock + Length of Spiral Casing = 153.5

H = Head in meter = 46.63

T = Governor closing time 4 seconds

V = Velocity in meter/second = 3.66 m/s
g = 9.81 m/s^2

$$\frac{\Delta H}{H} = \frac{0.29}{2}\left\{0.29 + \sqrt{0.29^2 + 4}\right\}$$

$$= 33.50\%$$

Speed Rise and WR^2
Normal WR^2 of Gen. & Turbine 42000 lb/ft^2 (GD^2 = 7 Tm^2)

Mechanical starting up time Tm = $\frac{GD^2 \times n^2}{3.6 \times 10^2 \times P_r} = \frac{7 \times 10^3 \times 750^2}{3.6 \times 10^5 \times 1750}$ = 6.25 seconds

Closing time of servo motor T_k = 4 seconds (full closing time of servomotor)

$$\frac{T_k}{T_m} = \frac{4}{6.2} = 0.645$$

Specific speed $n_{sr} = \frac{n\sqrt{P}}{h^{5/4}} = \frac{750\sqrt{1750}}{46.63^{5/4}} = \frac{31374.751}{121.48} = 257.48 = 258$ (m units)

Speed rise S_r = 26.5% (from figure 24)

T_w = 1.23

$$k = \frac{T_w}{T_f} = \frac{1.23}{4} = 0.3075$$

S'_R = (26.6) (1 + 0.3075)

= 34.779 = 34.78%

8.0 HYDRO-TURBINE GOVERNING SYSTEM

8.1 Introduction

Governor control system for Hydro Turbines is basically a feed back control system which senses the speed and power of the generating unit or the water level of the fore bay of the hydroelectric installation etc. and takes control action for operating the discharge/load controlling devices in accordance with the deviation of actual set point from the reference point.

Governor control system of all units suitable for isolated operation are a feed back control system that controls the speed and power output of the hydroelectric turbine. Water level controllers can be used for grid connected units. Governing system comprises of following sections.

a) Control section

b) Mechanical hydraulic Actuation section

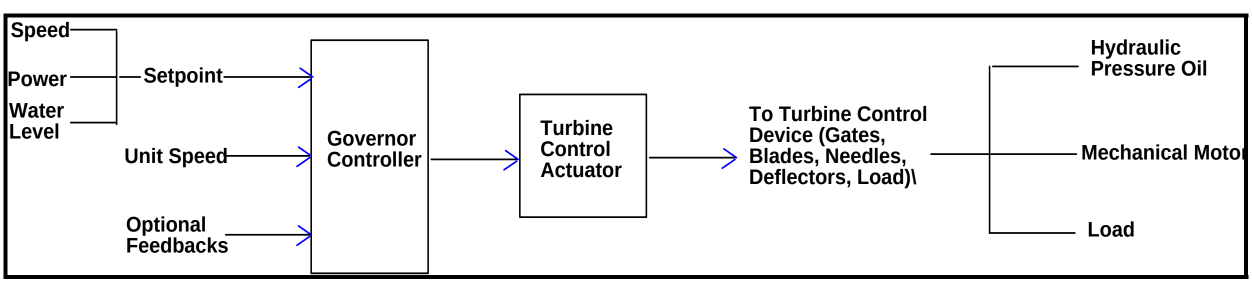


Fig. 25 – Basic Governor Control System

The control section may be mechanical; analogue electronic or digital. Actuator can be hydraulic controlled, mechanical (motor) or load actuator. Load actuator is used in micro hydel range; mechanical (motor operated) may be used say upto 1000 kW unit size. Hydraulic actuators are commonly used. (Fig. 25).

8.2 Type of Governor Control Section

8.2.1 Mechanical Controller

By the middle of 20th century, mechanical governors directly driven by prime movers through belt were used for small machines. The speed of rotation was sensed by fly-ball type pendulum. In second-generation mechanical governors, permanent magnet generator and pendulum motor were utilized for sensing the speed of the machine. The isodrome settings were achieved through mechanical dashpot and droop setting by link mechanism. These mechanical governors were fully capable of controlling the speed and output of the generating unit in stable manner. In case of faulty pendulum, manual control of the units was possible with handles and knobs. This was PI type controller.

8.2.2 Electro-Hydraulic Governor – Analogue Electronics

Next came the third generation Electro-Hydraulic Governors where speed sensing, speed/output setting and stabilizing parameters were controlled electrically and the use of mechanical components was reduced considerably. They increased the reliability, stability and life of the equipment and facilitated more functional requirements. The design of electrical part of the governors kept changing based on the advancement in electronics and development work by individual manufacturers. In this type of governor analogue circuitry is used to develop set point signal that is used to position the control actuators of hydroelectric units. An electro hydraulic interface is used to connect the electronic set point signal into a hydraulic oil flow from a hydraulic servo valve system which determine the position of the turbine control actuators. This is a PID controller.

8.2.3 Electro Hydraulic Governor – Digital Governors

In digital governor, digital controller is used in turbine governing system. This is also PID controller. Digital control hardware running an application programme accomplishes the required control function with this system. Digital controller used for turbine governing system are very flexible and can be used for functions not directly related to the turbine governing control function.

Present day trend is to use digital governing control system in hydroelectric units. The major advantages of microprocessor based system over the earlier analogue governors (based on solid state electronic circuitry) are higher reliability, self diagnostic feature, modular design, flexibility of changing control functions via software, stability of set parameters, reduced wiring and easy remote control through optical fibre cables. Microprocessor based governor control system are capable of carrying out the following control functions in addition to speed control during idle run , operating in isolated grid; interconnected operation and islanding operation.

- Control the power output depending on variation in grid frequency i.e. load frequency control
- Joint power control of a number of generating units in a power station
- Power control as per water levels in Fore-bay and/or Tail-race
- Automatic Starting / Stopping by single command
- Fast response to transient conditions

- Control from remote place Supervisory Control And Data Acquisition (SCADA)

8.3 Turbine Control Actuator System

Actuator system compares the desired turbine actuator position command with the actual actuator position. In most of the hydroelectric units it requires positioning of wicket gates in reaction turbines, spear in Pelton turbines and turbine blades in Kaplan turbines. In load actuators, shunt load bank is adjusted. Pressure oil system with oil servomotor is most commonly used actuator.

8.3.1 Governor Capacity (oil servomotor)

The size, type, and cost of governors vary with their capacity to perform work which is measured in (meter-kilograms). Mechanical governor having a capacity of more that 8300 m kg. are of cabinet actuator type. Those having a capacity less than 7000 m kg. are gate shaft type.

The capacity is the product of the following factors: turbine gates servomotor area, governor minimum rated oil pressure, and turbine gates servomotor stroke. For gate shaft governors, the turbine gates servomotor area is the net area obtained by subtracting the piston rod area from the gross piston area. For governors controlling two servomotors mounted directly on the turbine, the effective area is the sum of the net area of the two servomotors.

Servomotor capacity can be estimated by the formulas:

1. Wicket gates servomotor capacity.

$$FY_M = 34\,(h_{wh}\, D_g.M)^{1.14} \text{(metric)}$$

Where

M = wicket gate height
h_{wh} = maximum head, including water hammer, and
D_g = wicket gate circle diameter

2. Blade servomotor capacity (adjustable blade propeller turbine). - The blade servomotor capacity also varies among manufacturers. This can be roughly estimated by the formula:

$$FY_b = \frac{6.17\,P_{max}(n_s)^{1/4}}{(H_{max})^{1/2}} \text{ metrics}$$

Where

H_{max} = maximum head,
n_s = design specific speed, and
P_{max} = turbine full-gate capacity at $H_{max.}$

8.4 Small Hydro Governor Selection Consideration

Actuator and Control systems for small hydro units especially in developing countries have to be selected keeping in view the following:

(a) Traditional flow control governor with mechanical hydraulic actuator is complex demanding maintenance and high first cost. Further performance requirements of stability and sensitivity i.e. dead band, dead time and dashpot time especially for interconnected units may not be met by mechanical governors.

(b) Electronic and Digital flow control governors can take up plant control functions.

(c) Cost of speed control and automation with currently installed analog flow governors, unit control and protection systems is high. These systems require attended operation and are mostly based on large capacity hydro units. This is making most of the units very costly and uneconomical to operate.

(d) The manpower as available is unskilled and further adequate supervision is not feasible.

(e) Load factors for stand-alone micro hydels are usually low affecting economic viability.

(f) Flow Control Turbine Governors are expensive and not recommended for small hydro units in micro hydel range. Electronic load control governing system with water cooled hot water tanks as ballast loads for unit size upto 100 kW are cost effective. This will make a saving of about 40% on capital cost. The generator flywheel is not required. If the thyristor control (ELC) is used then the alternator needs to be oversized upto 20% on kVA to cope with the higher circulating current induced. Accordingly, in case of small units upto 100-150 kW size elimination of flow control governors using load actuator with digital speed controller make these units economically viable and properly designed will eliminate continuous attendance requirement.

(g) Data storage function can be added to the Digital Governors control system with hard disk (i.e. PC).

(h) The dummy loads in the Shunt Load Governors (ELC) can be useful load system or can be used for supplying domestic energy needs.

(i) Digital generation controllers were evolved to take care of speed control, unit control and automation, unit protection and every generation scheduling and have been successfully in operation for over ten years.

(j) Programmable logic control (PLC) based systems are with automation by personal computers are reliable and have been in operation in India.

(k) Dedicated PC based systems for complete generation control can be easily adopted for data acquisition and storage at a nominal cost and can also be adopted to SCADA system.

(l) Manual back up and or redundant control system are provided.

8.4.1 Application of Governor Control System to SHP

Selection of the type of controller to be used in SHP may be based on the recommendations of the American, European and Indian consultants for the UNDP-GEF project for Himalayan range. These recommendations are given in table 9 with following aspects.

(a) Ease of adoption
(b) Sustainability
(c) Cost saving potential
(d) Over all rating

8.5 Personnel Computers (PC) /Programmable Logic Controller (PLC) based Digital Governors

Modern control schemes also utilise personal computers (PCs) in conjunction with PLC control systems. The PCs are utilized with man-machine interface (MMI) software for control display graphics, historical data and trend displays, computerized maintenance management systems (CMMS), and remote communication and control. In addition, the PLC programming software is usually resident on the PC, eliminating the need for a separate programming terminal implement or change the PLC software coding.

A PC also can be used for graphical displays of plant data, greatly enhancing operational control. Standard Microsoft-based graphical display software packages are available for installation on a standard PC. The software package can be utilized on the PC to create specific powerhouse graphical displays based upon real-time PLC inputs. These displays typically include control displays with select-before-execute logical, informational displays for plant RTD temperatures, or historical trending plots of headwater, tail water, and flow data.

Modems with both dial-out and dial-in capabilities can be located in either the PC, the PLC, or both to provide off-site access to plant information. These modems may also be utilised to control the plant operation from a remote location.

Programmable Logic Controller (PLC) type plant controllers with a manually operated back up system combined with PC based SCADA system are used as Governors and for Plant control and data acquisition. This makes the system costly but reliability is stated to be good and can be used for small hydro generation control. It is considered that dedicated digital control systems which is digital P.C. based can perform all functions of governing, unit control and protection as well as for data storage and can be more economical, dependable and are being manufactured in U.S.A., Europe, India and other countries. These dedicated systems with back up manual control facility of speed control in emergency by dedicated semi automatic digital controllers can be an option and is also recommended for UNDP-GEF projects in India.

Monitoring and control and data acquisition system (SCADA system) can be a part of the P.C. based digital governor and generation control equipment. Provision of data storage of one month with 16 MB of Ram memory and a 540 to 850 MB Hard Drive as part of the PC based governing and control system should be provided. This data could be retrieved on a floppy data stick after one month for examination. As the communication links develop the data can also be transmitted via a modem to a remote point for examination and supervisory control.

Auxiliary control normally forms a part of digital governor. It is further recommended that water jet diverters of emergency closure of inlet valves be provided to avoid overspeeding to runaway in case of governor failure emergency.

Table 9 shows comparision of different types of control system.

Table 9 : Governors, Controls and Monitoring Systems, Technology

Rating by MHPG (European Consultant)					Comments		
Concept	**Ease of adoption**	**Sustainability**	**Cost saving potential**	**Overall rating**	**MHPG**	**Mead & Hunt**	**AHEC**
Load Control	3	2	3	2.7	Most useful on non-grid connect sites, upto 500 kW. Could save more than 20% due to spin effects.	Not considered	Most useful on unit size upto 200 kW on both grid & non grid connected.
Analogue integrated governor and plant control.	3	2	2	2.3	Low cost solution for upto 500 kW grid connect.	Not considered	Not recommended cost high.
Digital integrated governor and plant controller	3	2	2	2.3	Preferred solution for large grid connect schemes. Savings where optimisation or complex operation needed.	Not considered	Preferred solution for schemes with unit size above 250 kW.
PLC controller	3	2	1	2	Useful for larger schemes with separate governors.	Recommended	Recommended
Data Logger	3	3	2	2.7	Available in India, suitable for isolated schemes using analogue or flow control governing.	Data storage and retrieval recommended by P.C.	Data storage and retrieval as part of Digital Gov. system.

8.6 Governing System used in India

Basically there is no difference in governors used for large generating units and small units except for sizes, operating pressure and control features as per requirement of individual project. Also for smaller units, hydro-mechanical part of governor is built on the sump of oil pressure plant for compactness. Higher operating pressure is used to reduce sizes of control elements and pipelines. Nitrogen cylinders are used in place of pressure air to avoid use of high-pressure air compressors. Oil pipelines of sizes upto 50 mm are used in stainless steel with ermeto (dismantlable) couplings to reduce welding and maintain cleanliness.

Following types of governing system are used:

Micro Hydro - (up to 100 kW)	Digital speed control system with load actuator is used.
Small Hydro - Up to 3 MW	Flow control governing system with hydraulic actuator and digital PID speed and power control system. Mechanical motor type actuator have also been, used upto 1000 kW unit size with microprocessor based level control PI Controller
Small Hydro - Above 3 MW	Flow control PID governor with hydraulic actuator

8.7 U.S. Practice Regarding Governor and Control

Type of Scheme

Two basic control schemes utilized for small and medium hydro stations are (1) a single PLC with a manually operated back-up system, and (2) a redundant.PLC system. There are various modifications of these two basic schemes, which depend upon the individual plant requirements and owner preference. The single PLC offers the advantages of low cost and simplicity, and is typically based up by a hardwired system. With a redundant PLC system, backup control and memory are provided by a second PLC. Advantages and disadvantages of the two schemes are summarized in Table 10 and 11.

Table 10: Advantages and Disadvantages of the Redundant PLC Control Scheme

Advantages	Disadvantages
• 100 percent backup for the central processing unit (CPU). The CPU includes the processor, system memory, and system power supply.	• Cost. The cost of a second PLC exceeds the cost of a manual backup system.
• Continued automatic control of the unit under headwater level or discharge control with one PLC out of service. This ability allows continued maximizing unit revenue when a PLC fails.	• Complexity. Most small hydro plant operators are not technically trained for troubleshooting PLCs (some of this complexity is offset by the PLC and I/O card self-diagnostics now available.)

Advantages	Disadvantages
• Uniform spare parts. Only one set of I/O cards needs to be maintained. Items such as spare relays and control switches associated with a hard-wired system are not required.	• Failure of both systems simultaneously. Although redundant PLCs do enhance system reliability, they can be prone to simultaneous failure caused by surge. Owners should insist on good surge protection engineering. • Software problems. If software is non-standard, software problems will be common to both PLCs.

Table 11 : Advantages and Disadvantages of a Single PLC with Manually Operated Backup System

Advantages	Disadvantages
• Less expensive than a redundant PLC system.	• Headwater level or discharge control (if performed by the PLC) is disabled whenever the PLC is disabled. When utilizing the manually.
• Less chance of a common mode failure because the hardwired system is less prone to surge-induced failures and more tolerant of inadequate grounds.	• Operated backup system for control, the unit's output is set at the operator's discretion. An operator will usually allow a safety margin of approximately 10 percent in headwater or discharge level to avoid problems such as drawing air into the penstock. As a result, maximum possible revenue for the unit is usually not realized during manual operation.
• Operator familiarity with trouble shooting hardwired relay systems.	• Non-uniform spare parts. Spare parts would have to provided for both the PLC system and the manually operated backup system. However, it should be noted that relatively few spare parts would be needed for the manual backup system, due to its simplicity.

In either unit control scheme, all unit protective relays should be independent from the programmable controllers. This independence will allow the protective relays to function even if the PLC fails, ensuring the safety of unit equipment and personnel. For the single PLC scheme with a manually operated back-up system, it is usually best to have an independent resistance temperature detector (RTD) monitor and annunicator panel functionally operative during manual operation of the unit. These additional panels will provide the operator vital information which will facilitate operation of the plant in the manual mode.

8.8 Examples of Typical Governing Systems

i) 2 x 30 kW Micro hydro with Synchronizing, (isolated operation) – Fig. 26

Digital controller and load actuator (Electronic Load Controller)

ii) 2 x 500 kW –SHP project - (Fig. 27)

Electronic Digital Level Controller with induction generator – grid connected

iii) 2 x 1000 kW –SHP project -(Fig. 28)

Electronic Digital Level Controller with synchronous generator – grid connected with motor operated mechanical actuator, for peak load operation with a limited storage pool

iv) 2 x 3000 kW –SHP project [Fig. 29(a) & 29 (b)]

PC based a digital PID controller with oil pressure servomotor actuator with synchronous generator suitable for isolated/grid connected operation with back up manual control and integrated plant control and off site control facility -

v) 2 x 9 MW –Canal Fall SHP project (Fig. 30)

PLC Digital PID Controller with oil pressure servomotor actuator with Synchronous Bulb generator – grid connected with redundancy and redundant PC based automation

9.0 MAIN INLET VALVE

Inlet valves for closure on shut off are provided on long penstock and where single penstock headers are branched near powerhouse for individual units..

Turbine inlet valves normally operate under zero flow condition and have byepass piping for equalizing pressure before opening and during closing. These are generally operated fully open and fully closed position. Throttling of these valves for flow control should not be allowed. Design pressure rating should include the effects of water hammer for capability for emergency closing on full load rejection.

Hydraulic servomotor usually operates inlet valves. In small hydro the practice is to have a common pressure oil system for closure of turbine wicket gate and inlet valve. These valve especially in SHP are held in open position by oil pressure and closed by weight on release of oil pressure.

9.1 Butterfly Valves

Butterfly valve is most commonly used inlet valves because of rugged; compact, simple design and low cost. Small butterfly valves have been used upto 300 meters head.

9.2 Spherical Valves

These valves are used up to 1200 meters and diameter up to 4.5 meter.

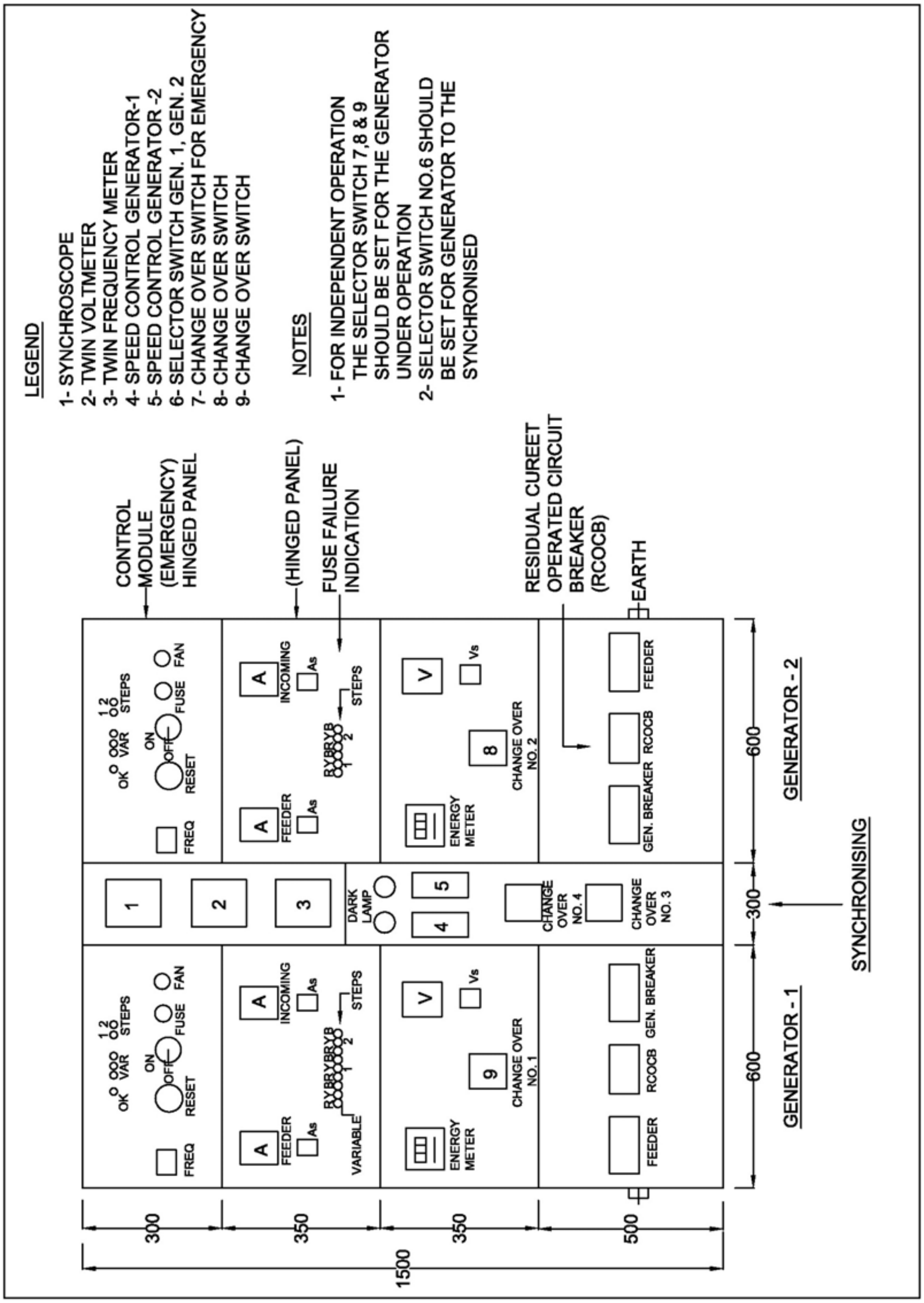


Fig. 26 Digital controller and load actuator (Electronic Load Controller)

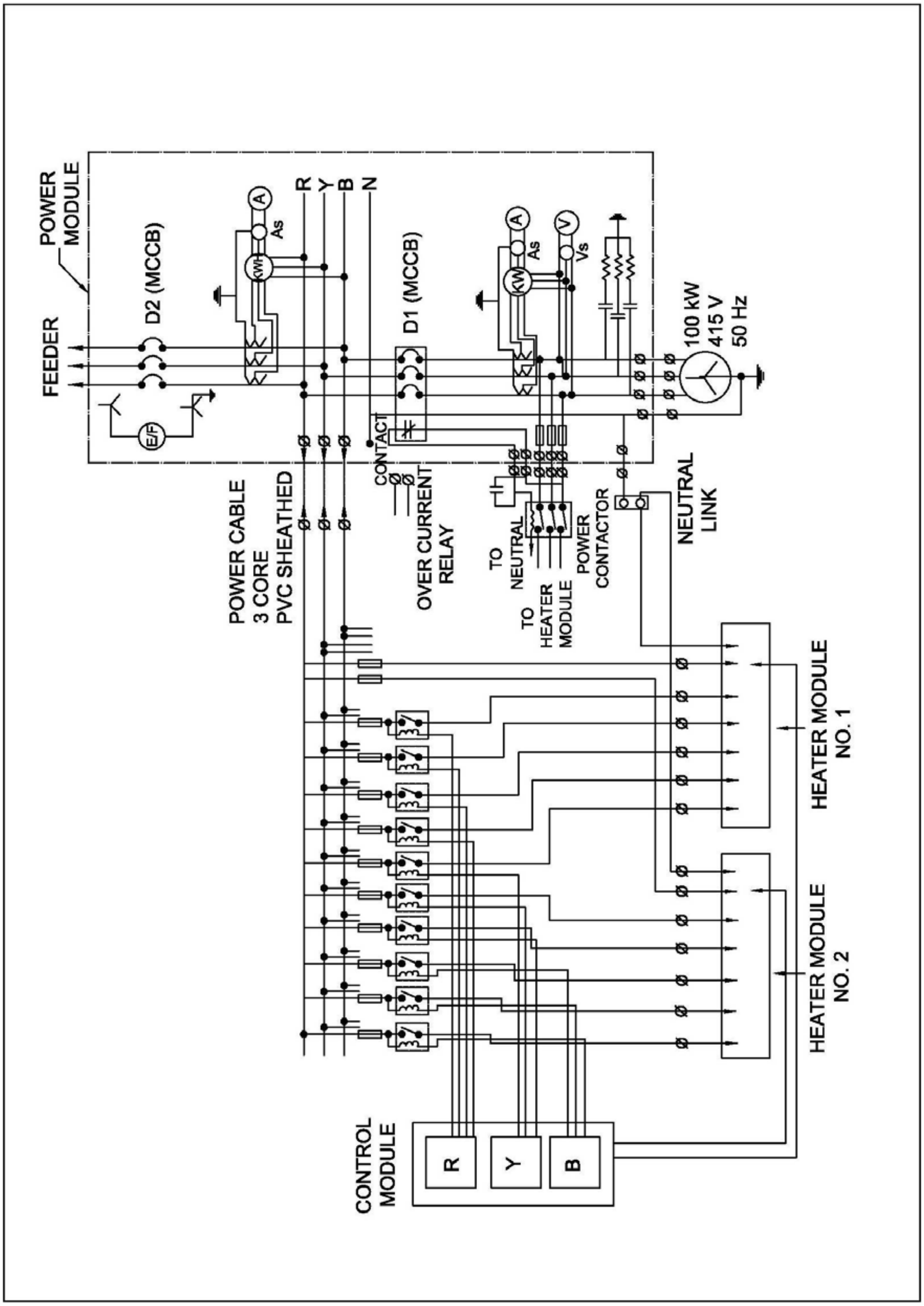


Fig. 27 Electronic Digital Level Controller with induction generators

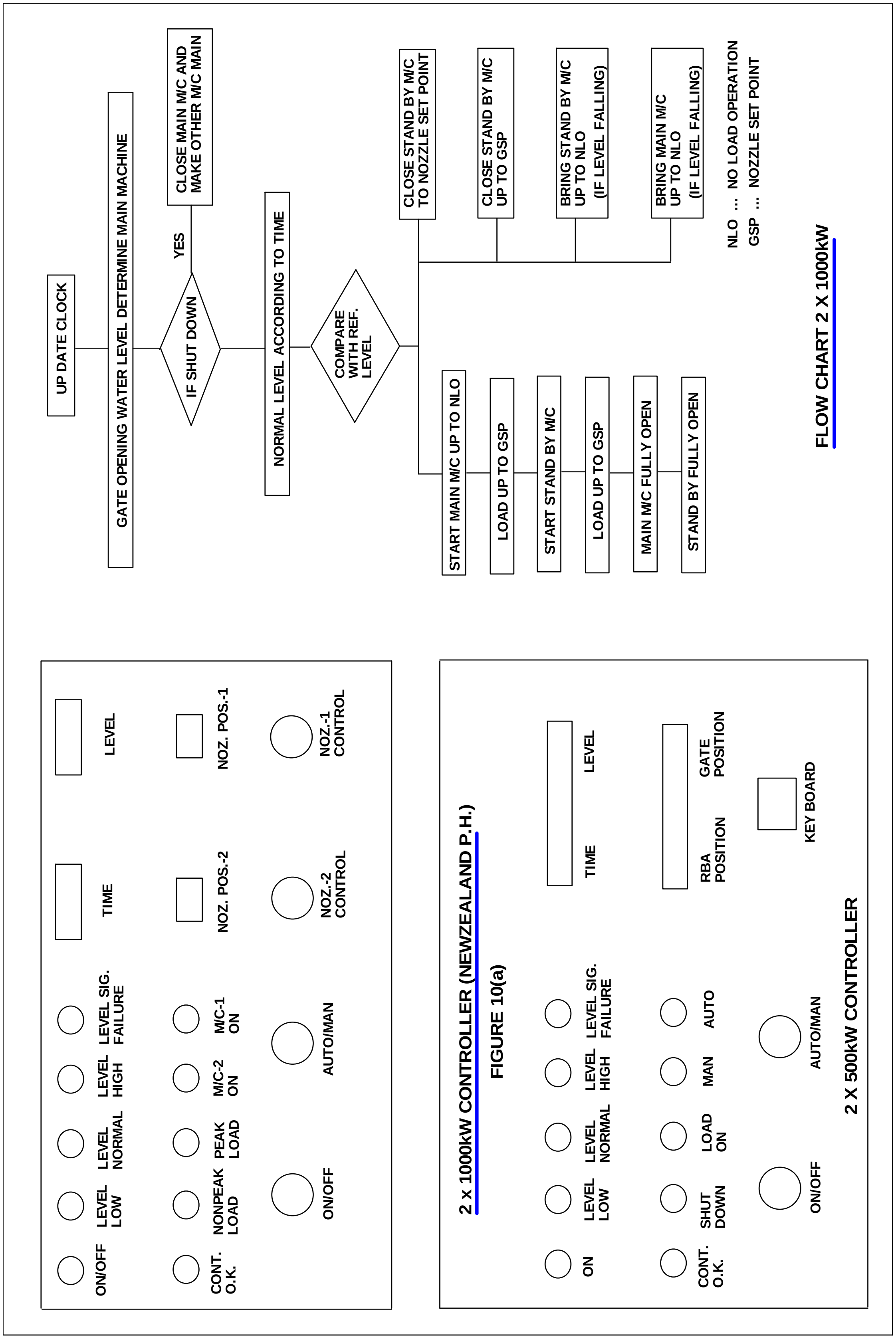


Fig. 28- Electronic Digital Level Controller with synchronous generator

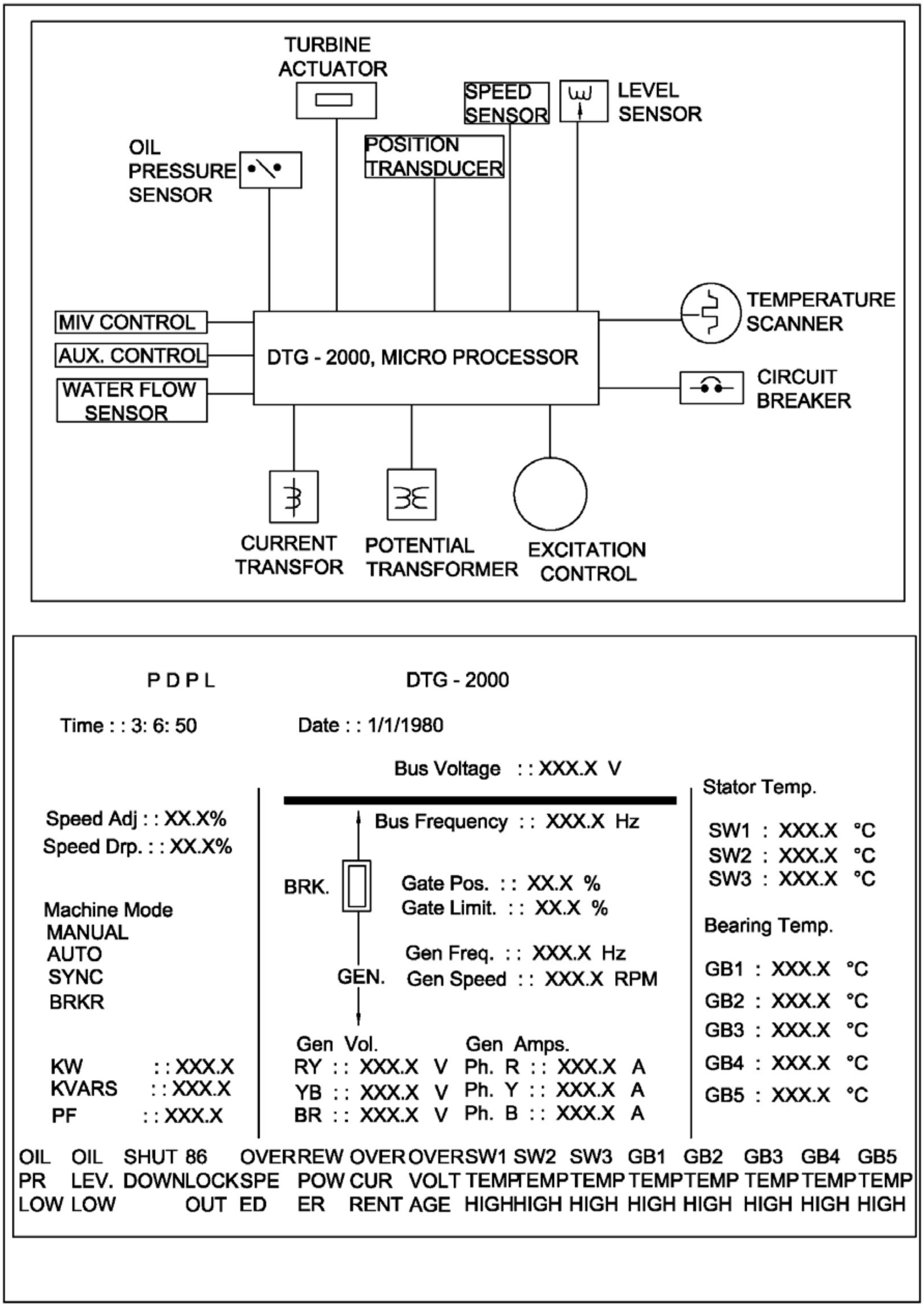


Fig. 29(a) : PC based digital PID controller of a typical power plant

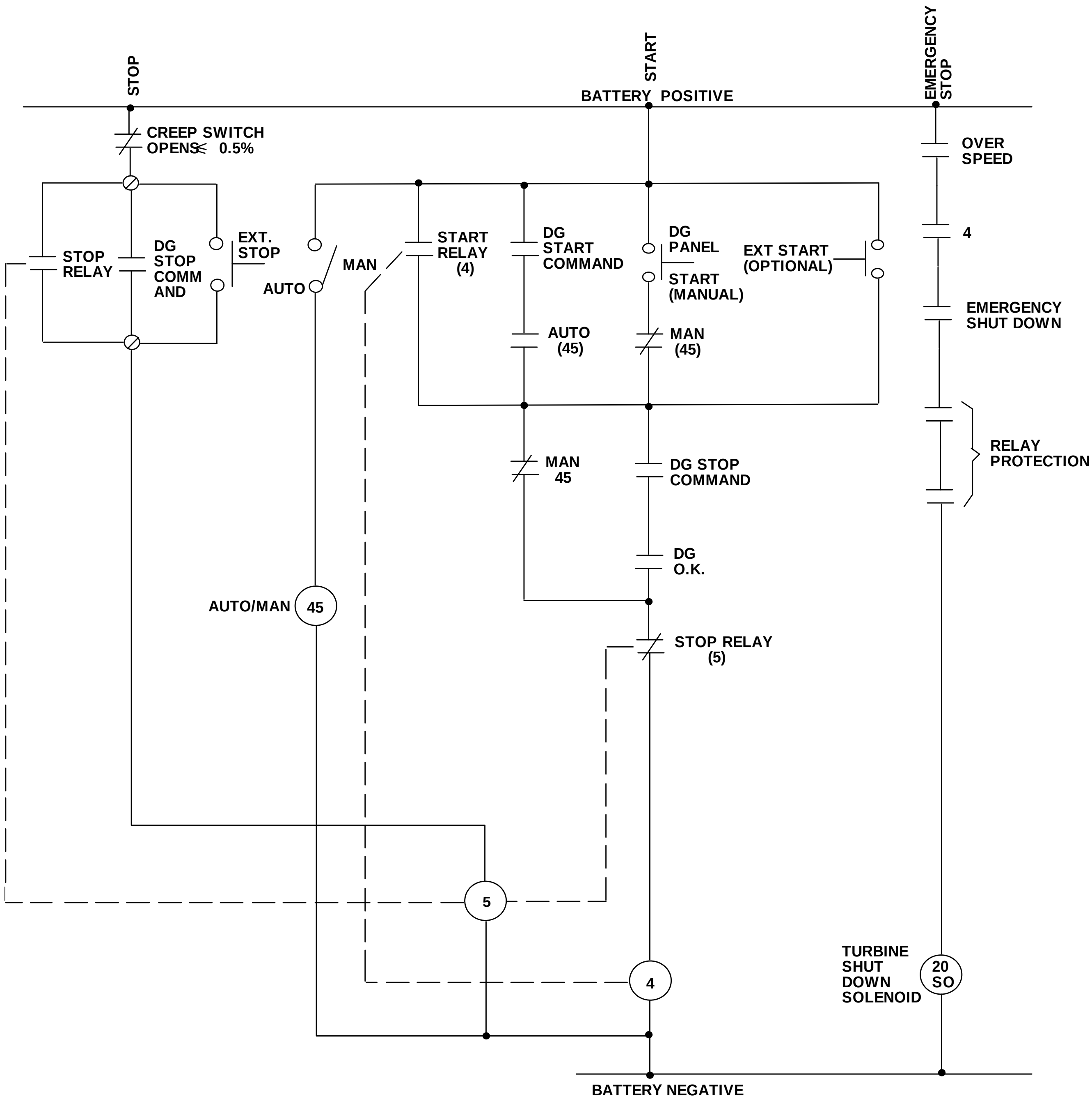


Fig. 29(b) : PC based digital PID controller of a typical power plant

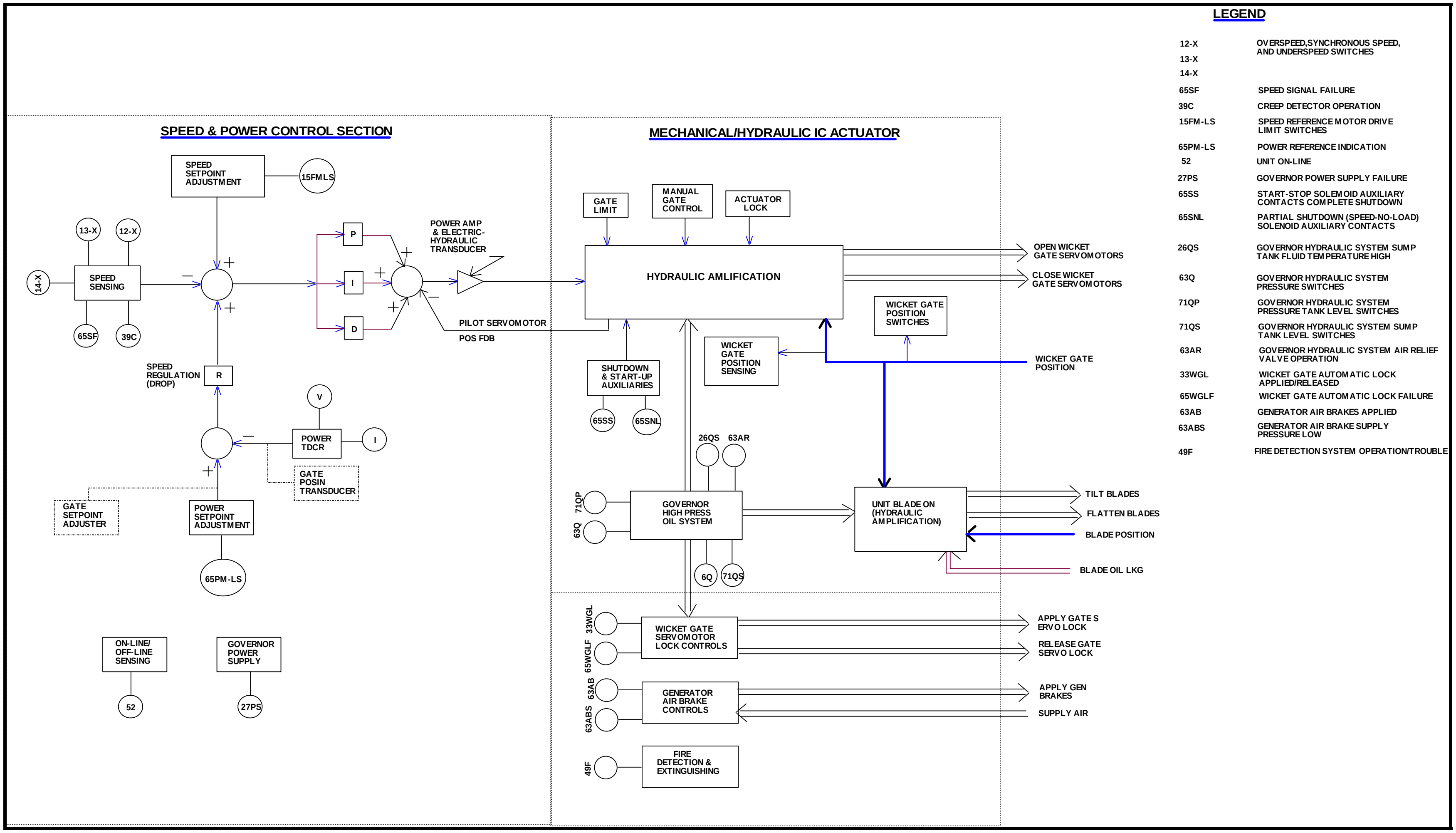


Fig. 30 Electric Hydraulic Turbine Governor Control & Monitoring System Of 2 x 9 MW Bulb Turbine)

Annexure-1

Power Generation Equipment Special Requirement

	Description	Category (Installed Capacity in kW)		
		Category A (Upto 10 kW)	**Category B (Above10kW and upto 50 kW)**	**Category C (Above 50 kW and upto 100 kW)**
Turbine	Types	• Cross Flow • Pump as turbine • Pelton • Turgo • Axial Flow Turbine • Any other turbine meeting the technical requirement	• Cross Flow • Pelton • Turgo Impulse • Axial Flow Turbine • Francis • Pump as Turbine • Any other turbine meeting the technical requirement	• Cross Flow • Pelton • Turgo Impulse • Axial Flow Turbine • Francis • Any other turbine meeting the technical requirement
	Rated Output at rated head (at Generator output)	Up to 10 kW	(Above10kw and up to 50 kW) as specified	(Above 50 kW and up to 100 kW) as specified
	Bid evaluation – equalization for shortfall in overall weighted average efficiency	NIL	Each 3% for every 1 percent difference by which rated average efficiency (computed) is lower than the highest weighted average efficiency	Each 3% for every 1% difference by which rated average efficiency (computed) is lower than the highest weighted average efficiency
Generator	Types	Synchronous/ Induction - Single Phase/3 phase	Synchronous/ Induction 3 Phase	Synchronous 3 Phase
	Terminal Voltage, frequency	240 V, 1 –phase, 50 Hz	415 V 3 phase, 50 Hz	415 V, 3 phase, 50 Hz
	Make and Runaway withstand	Standard / Special generators designed to withstand against continuous runaway condition.		
	Insulation and Temperature Rise	Class F/H insulation and Class B Temperature rise		
Overall Efficiency	Minimum required Weighted Average Efficiency of the turbine Generator set (ηT Av) $0.50 \times \eta T_{100} + 0.50\ \eta T_{50}$	45%	50%	60%