# CHAPTER -4

# TURBINE REGULATORY CHARACTERISTICS AND HYDRAULIC TRANSIENTS

## 4.1 TURBINE REGULATING CHARACTERISTICS

Turbine performance characteristics required to be provided for hydraulic transients during start up from standstill to synchronizing, load changes and stopping the unit considerably impact design and cost of hydro stations. These characteristics depend upon design of associated water passage from forebay 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 hydro electric stations by optimizing pressure water system design and generator inertia ($GD^2/WR^2$).

Simplified method based on Allevis elastic (non rigid) water column theory or using Parmakian's simplified methods have been mostly used as illustrated in this chapter. It is recommended that for mega projects. Proven and applicable computer programmes for calculating pressure changes associated with hydraulic transients for the steady state condition for synchronizing, for partial load changes and those caused by full load changes caused by transmission line disruption. Hydraulic transients from human errors, malfunctioning of equipment, accidents to water conductor systems and earthquakes are taken care of in designing power plant. Indian grid standards (Annexure-1of Chapter 9) require that the frequency shall not be allowed to go beyond the range 49.0 to 50.5 Hz, except during the transient period accompanying tripping or connection of load.

Hydro power plants are being utilized for feeding large grid where precise frequency and voltage control are required to be provided. Complex interrelated effects between the penstock system including surge tank, turbine, governor, generator and power system requires mathematical simulation of the entire system be performed for transient and dynamic stability, following a transient period accompanying tripping or connection of load.

Capability of hydro units for speed or frequency regulation of the interconnected power system cause hydraulic pressure transients in penstocks which may affect strength (wall thickness), diameter and material. Penstock/pressure water system constitutes significant cost in hydro stations.

Means for controlling pressure and frequency control capability are as follows:

a) Provide additional flywheel effect
b) Regulate the opening and closing rate of wicket gates
c) Provide pressure regulatory valves or synchronous bye pass
d) Provide surge tank

Provision of calibrated rupture membrane in penstock which burst at pre- determined pressure and other measures of protection and selection of a Pelton turbine instead of a Francis turbine may also be considered.

## 4.2 Penstock 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. The wicket gate closing time is always kept much greater than critical closure time ($T_c$) i.e. the time of reflection of the pressure wave, this time, $T_c = \frac{2l}{a}$ where l is the length of the pressure water system from tailrace to forebay/ surge tank and a is the velocity of the sound in water (wave velocity).

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

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

Where $T_w$ = 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 penstock 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 (9.81 m/sec$^2$)

During preliminary stage of planning simple and short methods of calculating the pressure regulation are speed rise as given in following references are adopted.

- Brown, J. Guthrie, Hydro-electric Engineering Practice, Volume 2.
- Engineering Monograph No. 20, Selecting Hydraulic Reaction Turbines, United States Department of the Interior, Bureau of Reclamation USA

Allievies formula for pressure variation in metric units is given by

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

Where $n = \frac{\sum LV}{gHT} = \frac{T_w}{T}$

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.
g = gravitation constant (9.81 m/sec$^2$)

This formula is sufficiently accurate only of 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 following empirical relationship.

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

Where T, L & H are same as above;
D – Diameter of penstock in meter
HP – Rated metric Horsepower

Governor is the main controller and discussed in chapter 6.

## 4.3 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 depends 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 ($T_m$). This is the time in seconds for torque to accelerate the rotating masses from 0 to rotational speed

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

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

## 4.4 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 made 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 normally designed to withstand runaway speed, but at excessive speed severe vibrations sometimes develop which may 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.

Pressure Rise and Speed rise Considerations as per IS: 12837.
This criteria is more important in high head machines as higher pressure rise affects the cost of penstock substantially. Necessity of limiting pressure rise is accomplished by use of pressure relief valve in case of Kaplan and Francis turbine with relatively, long water conductor system resulting in increased cost of equipment and power house. Pelton turbine as a rule does not require this device on account of availability of design feature of deflector. Pressure rise and speed rise can therefore be limited to very economical level in case of Pelton turbine, without increase in cost of turbine. Permissible pressure rise and speed rise for various turbines are given below.

| Type of turbine | Pressure rise (%) | Speed rise (%) |
|---|---|---|
| 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 |

## 4.5 Considerations for Permissible Speed Rise on Full Load Rejection

### 4.5.1 Generator flywheel effect and Stability of Turbine Governor System

Large modern hydro generators have smaller inertia constant and may face problems concerning stability of turbine governing system. This is due to the behaviour of the turbine water, which because of its inertia gives rise to water hammer in pressure pipes when control devices are operated. This is in general characterized by the hydraulic acceleration time constants. In isolated operation, when frequency of the whole system is determined by turbine governor the water hammer affects the speed governing and instability appears as hunting or frequency swinging. For interconnected operation with a large system the frequency is essentially held constant by the later. The water hammer then effects the power fed to the system and stability problem only arises when the power is controlled in a closed loop, i.e., in case of those hydro generators which take part in frequency regulation.

The stability of turbine governor gear is greatly affected by the ratio of the mechanical acceleration time constant due to the hydraulic acceleration time constant of the water masses and by the gain of the governor. A reduction of the above ratio has a destabilizing effect and necessitates a reduction of the governor gain, which adversely affects frequency stabilization. Accordingly a minimum flywheel effect for rotating parts of a hydro unit is necessary which can normally only be provided in the generator. Alternatively mechanical acceleration time constant could be reduced by the provision of a pressure relief valve or a surge tank, etc., but it is generally very costly. An empirical criterion for the speed regulating ability of a hydro generating unit could be based on the speed rise of the unit which may take place on the rejection of the entire rated load of the unit operating independently. For the power units operating in large interconnected systems and which are required to regulate system frequency, the percentage speed rise index as computed above should not exceed 45 percent. For smaller systems smaller speed rise be provided.

### 4.5.2 Large Units (grid connected)

(a) Frequency controlling hydro station
(b) Non frequency controlling station

Design requirements of frequency controlling station are availability of water to meet fluctuating requirements e.g. dam, balancing storage and speed regulating capability. Speed rise for full load rejection of these units may vary from 35 to 45% depending size of the grid with respect to the unit. Speed rise on full load rejection provided for some of the frequency controlling stations are given below.

| Sl No. | | Unit Size | Grid | Speed rise on full load rejection |
|---|---|---|---|---|
| 1. | Ganguwal/Kotla units of Bhakra Nangal (1950) | 24,000 kW | Northern Grid (small) | 33.5% |
| 2. | Bhakra Power Plant (1958) | 100,000 kW | - do - | 35% |
| 3. | Dehar Power Plant (Beas Satluj Link Project) 1975 | 165,000 kW | Northern Grid (large) | 41% |
| 4. | Pacha SHP | 1,500 kW | Isolated/weak grid | 35% |

Frequency control generating unit governor characteristics will depend on grid characteristics as follows:

(a) Sensitivity i.e. speed change to which governor will respond may be 0.01% or less for large grids with thermal nuclear stations forming part of grid. This may be evaluated for the particular grid.
(b) Permanent speed droop setting should be 0-5%.

(c) Temporary speed droop, servomotor feed back time etc. should be suitable for grid. National grid requirement are given in Annexure 1 of Chapter 9).

(d) It is recommended that stability studies be carried to fix these settings parameters for frequency controlling stations.

(e) It is further important that efficiency operations of the units be ensured for this purpose frequency control stations governors should be properly equipped to analyse efficiency loading of the units and load on the units is made by changing speed level (speed at no load) for moment to moment load changes by automatic means. This will need digital governors as in manual control power stations load change on the units takes place by permanent speed droop settings and speed level is adjusted manually.

### 4.6 Non Frequency Control Station

Non frequency control grid connected stations having storage of water are equipped for efficiency operation for moment to moment grid load changes by digital slow governors by transferring load from frequency controlling stations which will take instant to instant load changes and transfer them to non frequency control station where water is available. The station is equipped for automatic load frequency control arrangement for optimum efficiency operation. It may be noted that in these stations the load change will occur not for frequency control but for efficiency operation. In Pong Power Plants surge tank had to be eliminated; very slow governor (large governor opening/closing time) and water saving type pressure regulators were employed to reduce penstock stresses for on load rejection and for synchronizing unit. The unit was non frequency controlling as critical regulation occurred during load on conditions.

### 4.7 Small Hydro (grid connected)

Small hydro if grid connected (with no isolated and or islanding provision) cannot take part in frequency control. Accordingly these may be designed for up to 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 are used and loading on the units is controlled by upstream canal water level by controlling gate limiters. These are called non speed control governors.

### 4.8 Small Hydro (isolated grid operation)

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

### 4.9 Micro Hydro

Micro hydro up to 50 kW unit size are controlled by electronic load controllers instead of a traditional governor. This avoids the need to change water flow through the turbine as the electrical load changes. Water heater with variable resistance (dump load) is connected to the generator. As the electrical system load required from the generating unit changes electronic controller changes the dump load. Generator output and corresponding turbine flow remain constant. Micro hydro fitted with conventional water flow governors are designed for 35% speed rise on full load rejection.

### 4.10 Performance Characteristics - Pressure Rise and Speed Rise Calculation

The penstock pressure rise and unit speed rise are calculated from the references given in Para 4.2 entitled 'penstock pressure regulation'. Preliminary economic studies are 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. Method of calculating based on USBR design Monograph No. 20 for a typical power plant is given below. Penstocks for the power plant were embedded for a maximum pressure rise of 28%. The entire power was to be fed into the grid allowing a speed rise on full load rejection up to about 60%.

**Method for Computing Penstock Pressure Rise and Speed Rise on full load rejection with assumed data**

**Data**

| | | | |
|---|---|---|---|
| $T_f$ | = | Servomotor minimum closing time, sec. | – 5 sec. |
| $P_r$ | = | Turbine full gate capacity of hr, kW | – 92.6 MW (Gen. terminals) |
| $h_r$ | = | Rated head, meter | – 58.5 m |
| n | = | Rotational speed: design, r/min. | – 166.6 rpm |
| $GD^2$ | = | Flywheel effect of revolving parts; $kgm^2$ | – $7.068 \times 10^6$ $kgm^2$ |
| L | = | Equivalent length of water conduit, m | – 130.7 m |
| A | = | Penstock diameter | – 5600 mm |
| Q | = | Full gate turbine discharge at rated head | – 183.1 $m^3$/sec. |
| V | = | velocity of water (Q/A) | – 7.4 m/sec. |
| $N_s$ | = | Specific speed | – 320 metric horse power unit |
| $T_m$ | = | Mechanical startup time | |
| $T_w$ | = | Water startup time | |

**Pressure rise on full load rejection for closing Time (Allievies Formula)**

$$\frac{\Delta H}{H} = \frac{n}{2}\left(n + \sqrt{n^2 + 4}\right)$$

Where n = $\frac{LV}{gHT}$

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

130.7 +16.9 = 146.6 m

H – Head in m

T – Governor closing time in seconds

V – Velocity in m/sec.

g = 9.81 m/$sec^2$

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

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

Minimum Governor closing time to be determined (4 to 8 sec)

$$n = \frac{LV}{gHT} = \frac{146.6 \times 7.4}{9.81 \times 58.5 \times T} = \frac{1.89}{T}$$

For governor closing time of 5 sec.; n = 0.378

Pressure rise in penstocks $\frac{\Delta H}{H}$ is as follows:

$$\frac{\Delta H}{H} = \frac{0.378}{2}\left(0.378 + \sqrt{(0.378)^2 + 4}\right) = 0.456 = 45.6\%$$

**Speed rise on full load rejection for 5 sec. closing Time**
(Based on USBR monograph no. 20)

$T_W$ = water start up time = $\frac{LV}{GH}$ = 1.89 sec

Normal $GD^2$ of generator and turbine (x) = 7068000 $kgm^2$

$WR^2$ in ft. pounds ≈ 6 x $GD^2$
(in ft lbs) ≈ 6 x 7.068 x $10^6$ kg. $m^2$ = 4.24 x $10^7$ lb. $ft^2$

$$T_m = \text{Mechanical start up time} = \frac{WR^2 \times n^2}{1.6\times10^6 \times P_r(turbine\ full\ gate\ load)}$$

$$= \frac{4.24\times10^7 \times (166.7)^2}{1.6\times10^6 \times 124084} = 5.9 \text{ seconds}$$

$T_K$ = full closing time of servomotor assumed 0.25 sec. as dead time
= 5 sec. + 0.25 sec. = 5.25 sec.

$$\frac{T_k}{T_m} = \frac{5.25}{5.9} = 0.89$$

Determine $S_R$ from fig. 4.1 using $n_s$ & $\frac{T_K}{T_m}$

Where,

$S_R$ is speed rise in percent of rotational speed, $n_r$ for full gate load rejection to zero, excluding effect of water hammer.

$S_R$ ≈ 34%

$T_W$ = 1.89 sec., $T_f$ = 5 sec.

$$k = \frac{T_W}{T_f} = \frac{1.89}{5} = 0.378$$

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

$$S_R' = \frac{T_K}{T_M}\times(1+k) = 34 \times (1 + 0.378) = 46.7\%$$

Speed rise on full load rejection for a governor closing of 5 sec.

Calculate similarly for governor closing time of up to 8 sec.

Pressure rise and speed rise on full load rejection for different governor closing times was as follows:

| **Sl. No.** | **Gov. closing time** | **Pressure rise** | Speed rise |
|---|---|---|---|
| 1. | 4 | 59% | 41.6% |
| 2. | 5 | 45.6% | 46.7% |
| 3. | 6 | 36.8% | 48.3% |
| 4. | 7.5 | 28.5% | 55.4% |

Minimum Governor closing time of 8 seconds was recommended to keep pressure rise in embedded penstocks below 28.5%. The units are interconnected with grid and entire power was to be injected in the grid. 60 – 65% speed rise in such cases is allowed.

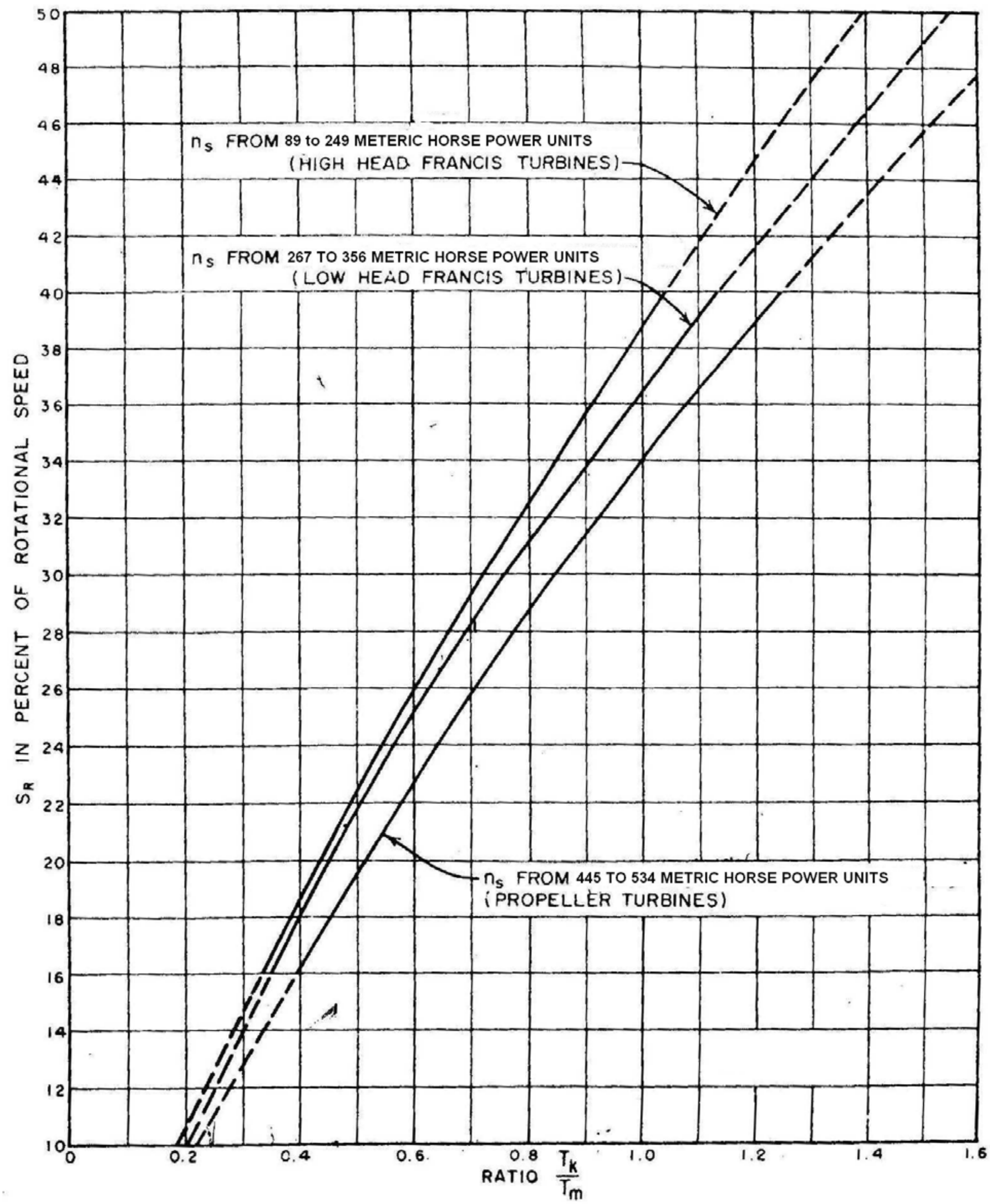


**Fig. 4.1 – Turbine Performance**
**(Based on USBR Design Monograph no. 20)**

**4.11 Mega and Large Units - Turbine Governing, Speed and Pressure Regulation, Relief Valves, Frequency Control Economic Considerations**

Regulating characteristics, speed rise (penstock pressure rise) of hydroelectric plants are discussed in 4.10. Basis for determination when surge tanks (or pressure relief valves) will be required on turbine penstock installations are discussed with special reference to Bhakra Beas Complex (Para 5.1-Overview).

**4.11.1 Bhkra Left Bank – Frequency Controlling Station**

Variable head Bhakra Left Bank Power Plant commissioned in 1959-60 comprises 5 units of 90 MW each and was the first mega power project of the country. Each unit was fed by 4.572 m dia. (15 ft.) penstock.

**Relevant Data**

5 sets of 150,000 BHP (Gen. 90,000 kW+ 15% overload)

Rated head – 400 ft. (121.9 m)

Rated flow – 3610 cusecs for full gate opening at rated head

Speed - 166.7 rpm

$WR^2$ (flywheel effect) - normal for each unit 63 x $10^6$ lbs $ft^2$

Length of penstock (individual) - 750 ft.

Penstock diameter - 15 ft.

Specific speed of runner - 36 (fps units)

The maximum demand of the power system to which the plant was interconnected at that time had maximum demand of about 1000 MW and minimum demand of about 500 MW. Speed rise on full load rejection as an index of regulating ability of the unit was fixed as 35% on full rejection. These units being fed from the storage dam ideally suited for regulating system frequency or peak load operation. Governor closing time of the mechanical governor was fixed from following considerations.

i) Speed rise on full load rejection not to exceed 35% for satisfactory operation as the frequency control station of the system.

ii) The generating units are rated to give a normally continuous output of 125,000 HP by the turbine and overload rating of generators required 150,000 HP turbine output. Maximum pressure in penstock and speed rise on full load rejection to be determined for overload rating.

iii) Retardation of governor closing time above rated head was not considered desirable.

A minimum governor closing time of four seconds was found to be suitable for this purpose. Speed rise and pressure rise for rated head and above is given below.

| i) | Head on turbine (h) | | 121.9 m (400 FT.) | 146 m (480 FT.) | 156 m (512 FT.) | REMARKS |
|---|---|---|---|---|---|---|
| ii) | Gate opening for an output 150,000 HP | Approx. figure as per Hitachi (turbine supplier) | 100% | 72% | 65% | 150,000 HP is over load rating |
| iii) | Actual governor closing time (equivalent closing time of guide vanes)<br><br>Overall closing time 4 seconds including 0.3 sec. as dead time | $\frac{3.7 \times \%\ \text{gate opening}}{100}$ | 3.7 sec. | 2.66 sec. | 2.4 sec. | Assuming time of closure from any part gate opening as directly proportional to the time of closure from full gate opening |

| | | | | | | |
|---|---|---|---|---|---|---|
| iv) | Pressure rise in penstock $(\Delta H)$ | | 38% | 36% | 34% | |
| v) | Max^m head on the turbine including water hammer | | 168.25 m (552 ft). | 198.1 m (650 ft.) | 208.8 m (685 ft.) | SAFE |
| vi) | Speed rise $S_R$ | | 35% | 27% | 25% | |

Penstock designed for 35% penstock pressure rise on full load rejection at maximum head. 4 second governor time for load on or off was provided.

**4.11.2 Large hydro Bhakra Right Bank Power Plant with frequency controlling, capability, increase in unit size on already embedded penstock by providing extra flywheel effect**

Bhakra Right Bank Power Plant was also planned for installation of 5 units of 90 MW each (same as Bhakra Left Bank Power Plant). Five No. of penstock were laid accordingly. Before construction of the plant, a new scheme Bhakra Beas Satluj Link project was envisaged. This project was intended to divert river Beas water into River Satluj upstream of Bhakra Dam. Increased supply of water and need for additional peaking capacity at Bhakra necessitated increase in capacity and size of the generating units to 120 MW at Bhakra Right Bank (Bhakra Left Bank was already constructed). Penstock pipes were already embedded for 90 MW unit size. The power plant was to be interconnected with Northern Regional grid and would be largest unit size in the then grid. It was decided that the power house will be designed as a frequency controlling station. For this purpose, the criteria of keeping speed rise on full load rejection of 35% as the index was decided to be maintained. It was further decided that the maximum stresses in the penstock will not increase 34% at maximum head under governor control. This was achieved by increasing the governor closing time of the power plant units of 120 MW to 6 seconds and increasing generator flywheel effect above normal. Salient data of the water conductor system was the same as for Bhakra Left Bank

**Data**

Rated capacity of the unit was increased from 90 MW to 120 MW and Governor closing time was fixed six seconds so that stresses in the already embedded penstock do not increase original design value (4.11.1). The turbine designer fixed the rated speed at 187.5 rpm.

To keep speed rise on sudden throwing off of load at 35% at rated head and maximum stresses in penstock not to exceed 34% on maximum head was calculated as 6 seconds.

Required minimum flywheel effect of rotating parts of unit was calculated as follows:

**$GD^2$ = 16.1 x $10^6$ kg $m^2$** ($WR^2$ = 95 x $10^6$ lb. ft.$^2$) for satisfactory speed regulation (for a speed rise of 35%).

The normal flywheel effect of a hydro-electric unit was computed from the following empirical formulae (USBR Engineering monograph no. 20-1954):

(i) Generators

$$WR^2 = 379{,}000x\left(\frac{kVA}{(r.p.m)^{3/2}}\right)^{5/4} lb.ft^2 \qquad \ldots(1)$$

where kVA = Generator rating in kVA.
Normal flywheel effect of modern generator is less and may be taken as

$$356{,}000x\left(\frac{kVA}{(r.p.m)^{3/2}}\right)^{5/3} lb.ft^2$$

(ii) Turbine

$$WR^2 = 23800\ x \left( \frac{h.p.}{(r.p.m)^{5/4}} \right) lb.ft^2 \qquad \ldots(2)$$

Where h.p. = Turbine rating at rated head (full gate)
= 170,000 h.p.

Normal $GD^2$ OF GENERATOR AND TURBINE
= Eq. (1) + Eq. (2)
$WR^2 = 63 \times 10^6$ lb. ft$^2$ ($GD^2 = 10.67 \times 10^6$ kg. m$^2$)

It is obvious that about 45 – 50% additional flywheel effect will have to provide in the unit for satisfactory regulating characteristics of the unit for the same speed of the unit.

**Effect of Extra Flywheel**

Extra loading besides affecting the cost, size, weight and efficiency of the unit, may also have a bearing on the stability of the unit as unstable unit, then either unit size may have to be modified or else the need of pressure relief valve studied.

**Power Swing**

Power swing is a periodic transfer of load between machines but not affecting the system as a whole. These swings are in step with the draft tube surges and have a frequency equal to one-third of the revolution per minute of the unit. They may build up to an amplitude that will cause the main breaker to trip and take the unit off the line.

Experience has shown that power swings be expected if the maximum regulating constant (kd) increases the limit (USBR Designed Standards).

$$\text{Maximum kd} = 5{,}400{,}000 \left( \frac{\text{kVA}}{(\text{r.p.m.})^{3/2}} \right)^{1/4}$$

Where kd, the regulating constant, is

$$\text{kd} = \frac{\text{Total}\ \ WR^2 x(\text{r.p.m.})^2}{\text{Design}\ \ \text{h.p.}} \qquad \ldots(4)$$

Where total $WR^2$ = turbine $WR^2$ (normal) + generator $WR^2$ (normal) + loading (additional generator $WR^2$ above normal

Evidently from (4) above kd is increased if $WR^2$ increases when actual $WR^2$ installed is in excess of the power swing limit, the severity may be sharply reduced through the use of a small amount of air admitted to the draft tube and fins or guides in the draft tube just below the runner to reduce whirl and surges. For the example referred to above:

$$\text{Maximum kd} = 5{,}40{,}000 \text{ x} \left( \frac{134{,}000}{(187.5)^{3/2}} \right)^{1/4}$$

$$= 14.5 \times 10^6$$

$$\text{Actual kd} = \frac{95x10^6\ x\ (187.5)^2}{170{,}000}$$

$$= 12.1 \times 10^6$$

Thus it is expected that with a flywheel effect of $GD^2$-16.1 x $10^6$ ($WR^2$-95x$10^6$ lb ft$^2$), stable operation would be there and there would be no undesirable power swings.

It may be conclude as follows:

(i) Speed rise of not more than 35 percent on sudden load rejection is required for controlling stations in weak grids/small grids.

(ii) Governor time (overall) from full gate to no load at normal speed when increased so as to restrict stresses in penstocks may result in increasing the flywheel effect of the revolving parts of the machine (generator) for frequency controlling stations.

(iii) The extra loading thus provided so as to increase the flywheel effect may affect the stability of the unit which should be studied.

**4.11.3 Pong Power Plant (6 x 60 MW) on Beas Dam – Elimination of surge tank**

Rated head 64 m (210 ft); maximum head 95.5 m (310 ft); minimum head 46 m (156 ft); rated discharge 157.64 $m^3/s$ (5600 cusecs); velocity at rated head 4.7 m/sec. (15.6 ft/sec); penstock – diversion tunnels were converted into pressure tunnel and bifurcated to feed two units with following characteristics.

| **Portion of tunnel/penstock** | **1 Concrete** | **2 Steel** | **3 Steel (Branch)** |
|---|---|---|---|
| | Common header for 2 units | | |
| Length m (ft) | 288.7 (947 ft.) | 335.8 (1103 ft.) | 51.8 (170 ft.) |
| Diameter m (ft) | 9.1 (30 ft.) | 7.3 (24 ft.) | 5.18 (17 ft.) |
| Thickness m (ft) | 60 (2.5 ft.) | 40 (0.133 ft.) | 33 (0.108 ft.) |

Mean velocity at rated head 4.7 m/sec. (15.6ft/sec) Length of the penstock L and rated head ratio is $\left(\frac{676}{64}\right) \frac{2220}{210}$ = 10.5. This is more than 5 A power units for stable speed regulation will normally require a surge tank or pressure relieve valve for stable system frequency control. It was considered during planning stage that provision of surge shaft is not feasible due to economic and other considerations. Further pressure relieve valve of water wasting type can not be employed. Accordingly it was decided to make it a non frequency control station with provision of water saving type pressure regulator for synchronizing and for containing stresses in the penstock under normal condition. Studies carried out manually and are summarized in table 4.2 & table 4.1. Water hammer studies for pressure rise in penstock for governor closing times of 6 to 10 seconds for full load throw off for various conditions i.e. normal, emergency and abnormal as defined in table 4.2 without pressure relief valves and with pressure relief valves of 50% and 100% are given in table 4.2. Speed rise on full load rejection studies are summarized in table 4.1. Studies for governor closing time less than 6 seconds were not carried out.

After more detailed analysis and considerations for safety of water conductor system by supplier of equipment (BHEL), it was decided to install 100% pressure relief valves with following main characteristics.

Type : cylindrical balanced type
Discharge capacity at rated head : full discharge

Method of operation: oil operated servomotors coupled to governor servomotor
Time of opening : same as guide vane opening
Maximum pressure rise : 23%

**Governor opening time:** It may be noted that water saving type pressure regulator were installed. Governor opening time was fixed 12 seconds. Critical regulation occurs during load on conditions and accordingly operation of the powerhouse was restricted as per Para 4.6. Generator flywheel effect $GD^2$ = 8.45 x $10^6$ kg $m^2$ ($WR^2$ – 50 x $10^5$ lbs $ft^{2+}$) was provided. Maximum gross head on turbine is123.8 m.

## TABLE -4.1: PONG POWER PLANT

**Speed Rise on 100% Load Rejection At rated Head of 210 ft.**

| Sl. No. | Operating Conditions | Speed rise permissible % | Speed Rise % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Without Regulator | | | 50% capacity Regulator | | | 100% capacity Regulator | | |
| | | | 6 sec | 8 sec | 10 sec | 6 sec | 8 sec | 10 sec | 6 sec | 8 sec | 10 sec |
| 1. | Normal Operation | | | | | | | | | | |
| | (i) One unit on a common penstock working | 45[1] | 47 | 56 | 63 | 38 | 47 | 56 | 32 | 41 | 50 |
| | (ii) Both units on a common penstock working | 60[2] | 60 | 68 | 75 | 47 | 56 | 63 | - | - | - |
| 2. | Emergency operation (One Pressure Regulator fail) (i) Both Units working | 60[2] | | | | 50 | 59 | 67 | 47 | 56 | 63 |
| 3. | Abnormal operation (Both Pressure Regulator fail) (i) Both Units working | Runaway | | | | 60 | 68 | 75 | 60 | 68 | 75 |

Notes:

1. Speed rise are with maximum $GD^2$ of 8.45 x $10^6$ kg. $m^2$ ($WR^2$ of 50 x $10^6$ lbs $ft^2$)
2. [(1)] Used as an index of speed regulating capability of the units
3. [(2)] Used from mechanical safety considerations

## TABLE -4. 2: PONG POWER PLANT

**Water Hammer (Pressure rise) Maximum operating head = 94.5 m (310 ft.)**

| Sl. No. | Operating Conditions | Max. Head attained including Water Hammer Heads | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 6 sec. | | | 8 sec. | | | 10 sec. | | |
| | | W/o R* | 50% R | 100% R | W/o R* | 50% R | 100% R | W/o R* | 50% R | 100% R |
| 1. | 2. | 3. | 4. | 5. | 6. | 7. | 8. | 9. | 10. | 11. |
| 1. | Normal | 186.5 m (612′) | 126.5 m (415′) | 116.13 m (381′) | 153.6 m (502′) | 115.2 m (378′) | 116.1 m (381′) | 135.3 m 444′) | 140.34 m (362′) | 116.1 m (381′) |
| 2. | Emergency | 222.5 m (730) | 198.1 m (650) | 182.9 m (600) | 185.9 m (610 | 170.7 m (560) | 160.3 m (526) | 164.8 m (541) | 153.9 m (505) | 146.3 (480) |
| 3. | Abnormal | 271.2 m (890) | 271.2 m (890) | 271.2m (890) | 225.8 m (741) | 225.5 (740) | 225.8 m (741) | 198.1 m (650) | 198.1 m (650) | 198.1 m (650) |
| 4. | Extreme | 509.0 m (1670) | 509.0 m (1670) | 509.0 m (1670) | 509.0 m (1670) | 509.0 m (1670) | 509.0 m (1670) | 509.0 m (1670) | 509.0 m (1670) | 509.0 m (1670) |

* R means pressure regulation

**Notes:**

1. Water Hammer was calculated for full load rejection on both units simultaneously.
2. Operating condition were assumed as below:

(i) Normal operation: when all equipment works in the manner for which it is designed & adjusted.

(ii) Emergency operation: following maladjustment & malfunctioning of equipment occurs on one of the units.

a. Governor time remains un retarded
b. Cushioning stroke fails i.e. gate closure from 2L/a position.
c. Pressure relief valve if provided is in-operative
d. Gate traversing is taken in min. time for which the governor is designed.

(iii) Abnormal Operation: Malfunctioning of equipment as described under emergency and occurs on both the units on a common penstock.

(iv) Extreme Operation: there is a rapid closure of the gates and full velocity in the penstock comes to zero within the critical interval. Calculation made at rated head of (64.1 m) 210 ft

| | | |
|---|---|---|
| a) | Gate opening time | 10 second (max. 12 seconds) |
| b) | Minimum speed change to which governor will respond | Governor will respond to normal speed changes; however response will be inhibited by adjustable band |
| c) | Gate closing time in conjunction with pressure relief valves | 3.2 seconds –rate of closure excluding damping |

Electro Hydraulic Governor was provided.

### 4.11.4 Dehar Power Plant With Frequency Controlling Capability, Provision of Surge Shaft Tank And Balancing Reservoir

174 MVA, 300 rpm 0.95 p.f. semi umbrella type vertical water wheel generators coupled to Francis turbines were selected for installation in the 1000 MW dehar hydropower plant of the Beas Sutlaj link Project. A longitudinal section of the project is shown in figure 4.2.

Dehar power plant was the largest hydro project at the time of installation and constituted a significant plant capacity in the integrated system to which the power house was to be interconnected. Salient data of the project is given below.

| | |
|---|---|
| Unit size and No. | : Six units each 165 MW at 0.95 pf |
| Design head | : 320 m |
| No. of penstock | : 3 |
| Diameter of penstock header | : 4.88 m |
| Diameter of penstock branch | : 3.35 m |

**Surge Shaft – Differential Type**

| | |
|---|---|
| Diameter of main shaft | : 22.86 m |
| Diameter of riser shaft | : 7.62 m |
| Height | : 125.3 m |

It was decided to make a frequency control power station by providing balancing storage and a differential type surge tank. A maximum speed rise and full load rejection as an index of frequency control capability in the grid was fixed not to exceed 45% (as the grid had become fairly large). The penstock pressure rise for economic considerations was fixed 35% on the basis of both the units tripping on a common penstock header. Load on and load off in about eight seconds was considered satisfactory from system regulation consideration.

Hydraulic pressure water system connecting the balancing storage with the power unit consisting of water intake, pressure tunnel, differential surge tank and penstock is shown in Figure 4.2.

Limiting the maximum pressure rise in the penstocks to 35 percent the estimated maximum speed rise of the unit upon rejection of full load worked out to about 45 percent with a governor closing time of 9.1 seconds at rated head of 282 m (925 ft) with the normal flywheel effect of the rotating parts of the generator (i.e., fixed on temperature rise considerations only). In the first stage of operation (4 units) the speed rise was found to be not more than 43 percent. It was accordingly considered that normal flywheel effect is adequate for regulating frequency of the system.

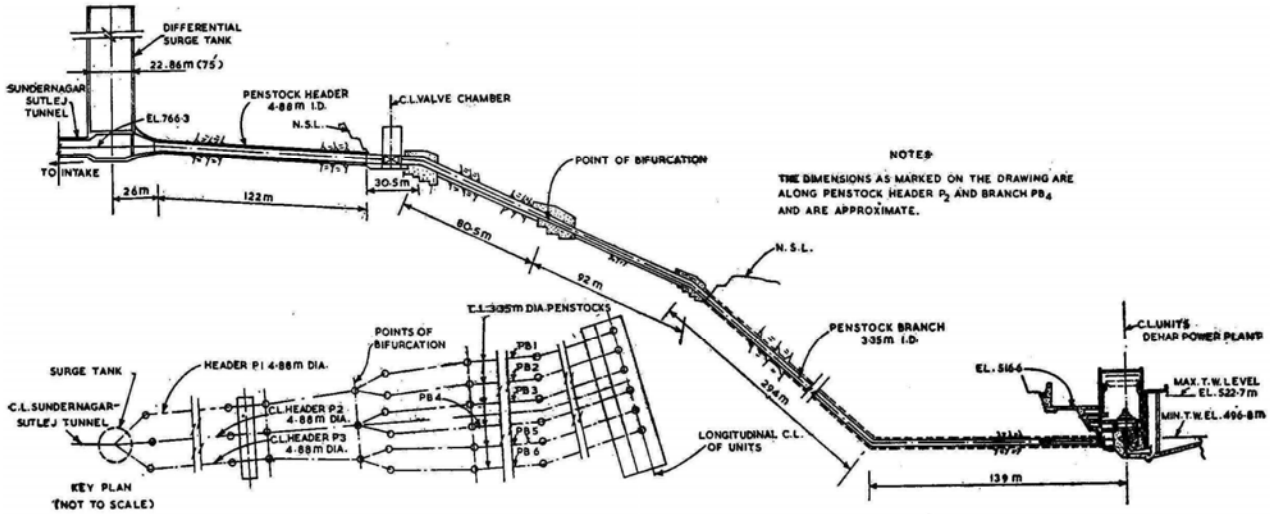


**Fig. 4.2: Longitudinal Section from intake to Dehar Plant (Design Data)**

## 4.12 Small Hydro Projects

Small hydro projects are designed for 35% speed rise in case isolated operation is envisaged. Cost is the major consideration in designing the powerhouses. Canal fall schemes are generally designed for injecting the entire power into the grid and accordingly designed for 60% speed rise on full rejection and cannot provide frequency control of the interconnected power system. Micro hydrohydro is generally designed for isolated operation. In small hydro projects extra flywheel required is not built into the generator but provided as a separate flywheel. Some typical examples are given.

### 4.12.1 1750 kW power unit to be designed for isolated operation (35% speed rise)

**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) (1750 x 1.34 = 2345 HP units)

Rated Head (h) (Full gate) = 46.634 m

Maximum pressure rise in penstock from economic consideration = 30%

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

Assuming governor closing time of 4 seconds

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

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

= 4.78 cusecs

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

$$= \frac{4.78}{\pi/4\times(1.289)^2} = \frac{4.78}{0.7854\times1.661521}$$

= 3.662 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) $= \frac{LV}{gH}$

$$= \frac{153.5\times3.66}{9.81\times46.63}$$

= 1.228 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 $= \frac{GD^2\times n^2}{3.6\times10^5\times P_r} = \frac{7\times10^3\times750^2}{3.6\times10^5\times1750}$ = 6.25 seconds

Closing time of servo motor $T_f$ = 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 4.1)

$T_w = 1.23$

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

$S'_R$ = (26.6) (1 + 0.3075)
= 34.779 = 34.78%

**4.12.2 Rajwakti Small Hydro-Electric Project – Provision of Spilling Type Surge Tank for Economic Pressure Water System**

A run of the river project in cascade with downstream projects. Entire power is to be fed in the grid at 66 kV. Isolated operation was not envisaged. Entire tail race water was proposed to be provided for downstream projects in cascade. Frequency regulating capability was not required. Due to site limitations of locating forebay the penstock length was unusually long i.e. 980 m for head of about 47 m which was affecting the viability of the project. Further it was not possible to provide escape of water from the forebay on full load rejection for downstream project. The problem was solved by providing spilling type surge tank near the powerhouse. It is shown in figure 4.3(a) and figure 4.3(b). The spilling type surge tank and the penstock system are shown in figure 4.4. Relevant data of the powerhouse and spilling type surge tank is given below. A water level sensing system was installed in forebay to control the spilling level in the surge tank.

| | | |
|---|---|---|
| Design head | = | 46.65 m |
| Penstock (L) | = | 980 m |
| Penstock dia. (D) | = | 2.2 m common penstock header bifurcated near power house for each unit |
| Turbines | = | Horizontal axis, Francis |
| Specific speed | = | 218 |
| Rated output | = | 1975 kW |
| Rotating speed | = | 600 rpm |
| Generator | = | 2250 kVA, 3.3kV, 0.9 pf, 600 rpm (Synchronous) |
| Surge Line | | |
| Diameter | = | 2.2 m |
| Length | = | 100 m |
| Input height | = | 933.9 + 2.2 m |
| Output height | = | 983.115 m |
| Design flow | = | 10 $m^3$/sec. |
| Surge tank | | |
| Bottom level | = | 983.115 m |
| Top level | = | 979.45 m |
| Width | = | 6.5 m |
| Length | = | 11.5 m |
| Spilling Pipes | | |
| No. of spilling pipes | = | 2 |
| Bottom level | = | 975.45 m |
| Top level | = | 6.5 m |
| Design flow | = | 0.70 $m^3$/sec |

The pipe line from forebay to the surge tank was designed for static head.

**Solution**

i) Spilling type surge shaft was provided
ii) Penstock header designed as pipe
iii) Spilling level was controlled by level control in forebay
iv) Spilling water from surge tank near the powerhouse was channelised into tailrace for downstream powerhouse in cascade

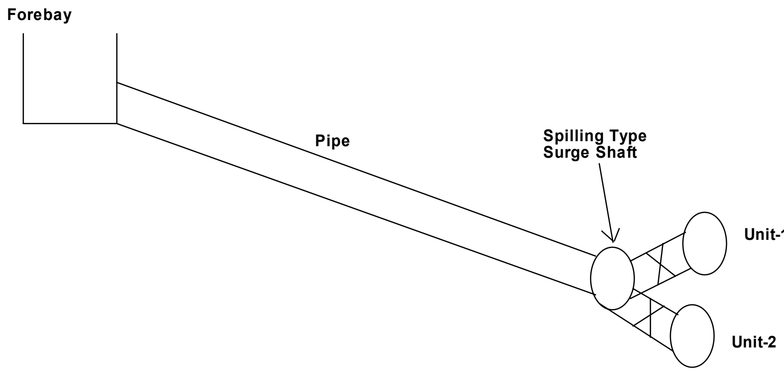


**Figure 4.3 (a) : Proposed Arrangement**

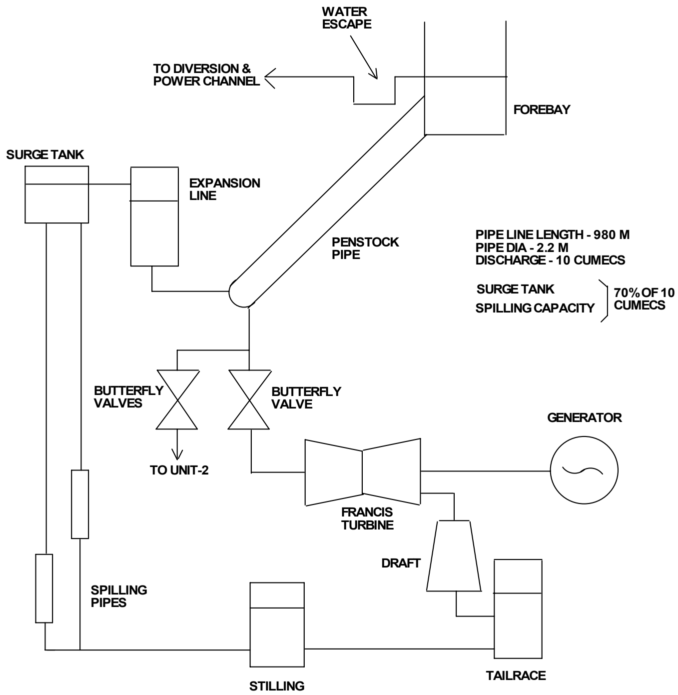


**Figure 4.3(b): Rajwakti SHP – Spilling Type Surge Tank (Source: Alternate Hydro Energy Centre))**

**Fig.: 4.4: Spilling type surge tank and penstock system (Source: Alternate Hydro Energy Centre)**

### 4.12.2 Pacha Small Hydropower Project Designed for Isolated Operation

Layout of the project is shown in figure 4.5.

#### 4.12.2.1 Data

| | |
|---|---|
| Type of Turbine | : Horizontal Francis |
| Guaranteed rated output at rated head | : 1571 kW |
| Rated head | : |
| Rated speed | : 750 rpm |
| Specific speed | : 243.7 m-kW |
| Length of penstock | : 138.9 m |
| Individual penstock for each unit | |
| Penstock diameter | : |
| Max. Pressure rise for economic penstock | : 30% |
| Momentary rise in speed on full load rejection | : 35% |

Pressure rise and speed rise studies were made for 600 rpm and 750 rpm generators (table 4.3 & table 4.4). 750 rpm generators were selected from economic considerations.

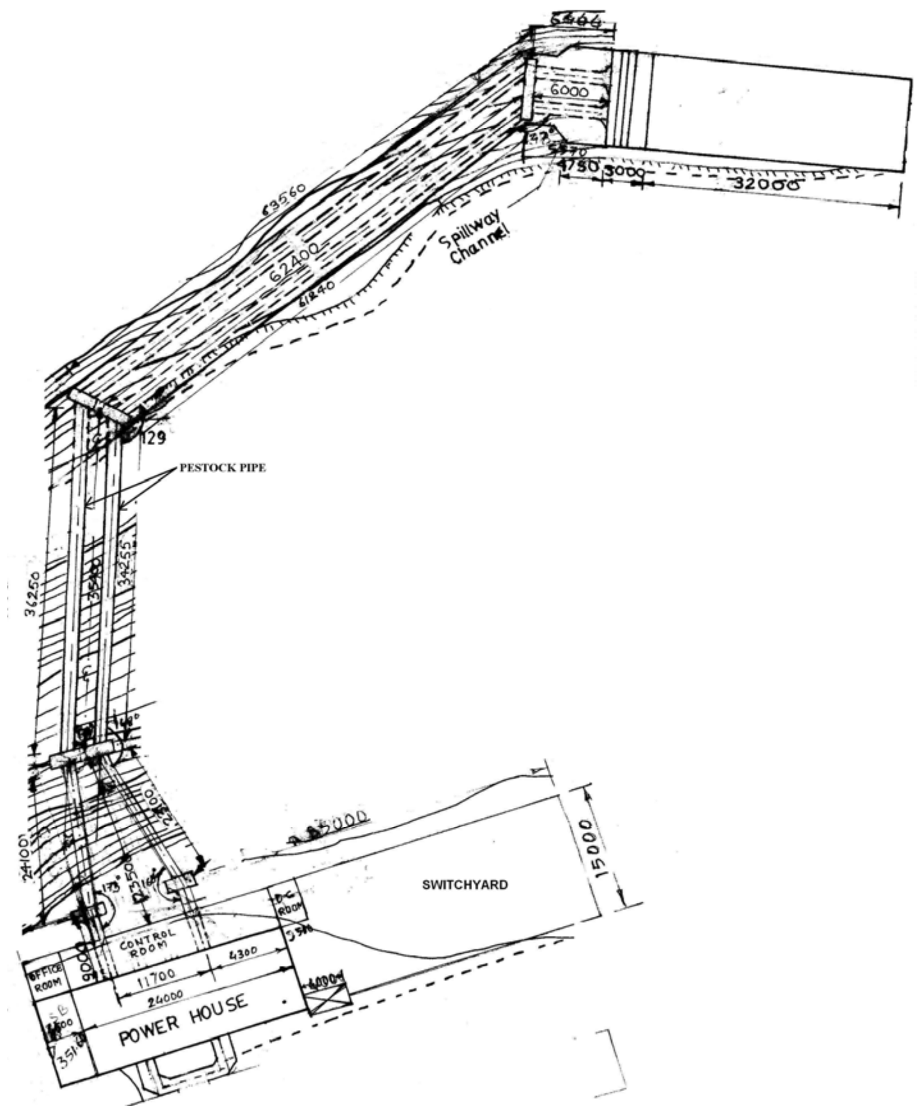


**Fig. 4.5: Layout of Pacha Small Hydro Project**
**(Source: Alternate Hydro Energy Centre)**

**Table 4.3**

**Speed 750 rpm**

| S. No. | Speed rise | Pressure rise | Guide vane closing time | Required $GD^2$ |
|---|---|---|---|---|
| 1. | 35% | 30% | 7.2 sec. | 11.05 T-$m^2$ |
| 2. | 35% | 50% | 4.7 sec. | 8.4 T-$m^2$ |
| 3. | 40% | 45% | 5.1 sec. | 7.35 T-$m^2$ |

**Table 4.4**

**Speed 600 rpm**

| S. No. | Speed rise | Pressure rise | Guide vane closing time | Required $GD^2$ |
|---|---|---|---|---|
| 1. | 35% | 30% | 7.2 sec. | 17.30 T-$m^2$ |
| 2. | 35% | 50% | 4.7 sec. | 13.15 T-$m^2$ |
| 3. | 40% | 45% | 5.1 sec. | 11.50 T-$m^2$ |

4.13 List of Computer Programmes on Hydraulic transients.

## References


1. Hydro Electric Engineering practice by J. Guthrie brown (Book)
2. Engineering Monograph No. 20 – 1976 -Selecting Hydraulic Reaction Turbine – United State Department of Interior; Bureau of Reclamation; USA
3. ASME -1949, Rober Lowy – Speed Regulation Characteristics for Hydraulic Turbine
4. John Parmakian – 1957 – Paper No. 1216 Journal of Power division of ASME vol. 83.
5. O. D. Thapar & S. M. Kumar – A problem of speed regulation in hydro electric units – Power engineer 1962 Vol. 12 pp. 31-34.
6. Thapar O. D.; V. K. Verma; R. C. chauahan – 1980 “Bhakra Left Bank Power House Governor - Study of Behavior – Engineering report No. WRD – Electrical -07- WRDTC IIT Roorkee
7. Thapar O. D. – 1975 “Characteristics of Large Hydro Generator of Dehar Power Plant” – Proceeding Second World Congress International Water Resources Association, New Delhi – December 1975 Volume 1.
8. Alternate Hydro Energy centre – “Guidelines for Selection of Turbine and Governing System for Small Hydro – Electric Project – 2012.