CHAPTER-6

HYDRO-TURBINE GOVERNING SYSTEM
(Reviewed by Dr. R. Thapar)

6.1 Introduction

Governing system or governor is the main controller of the hydraulic turbine. The governor varies the water flow through the turbine to control its speed or power output. Generating units speed and system frequency may be adjusted by the governor.

Governing system as per IEEE std. -75 includes following.

a) Speed sensing elements
b) Governor control actuators
c) Hydraulic pressure supply system
d) Turbine control servomotors-these are normally supplied as part of turbine

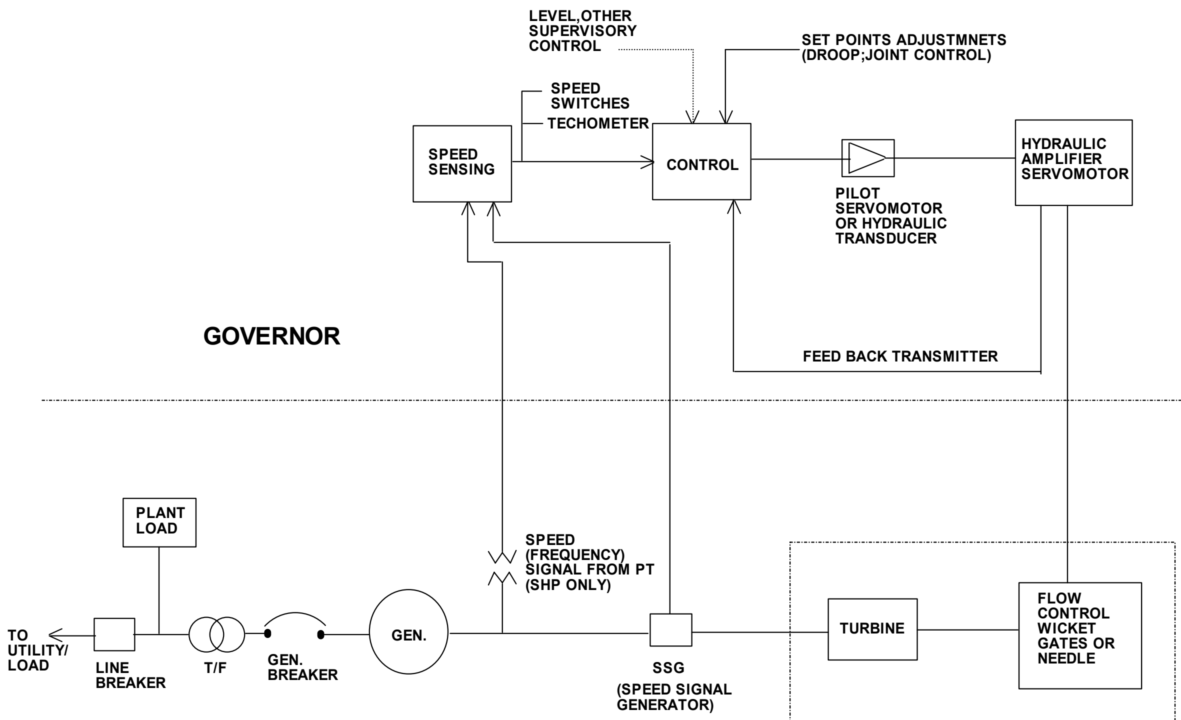

Figure 6.1.: Governing System – Block Diagram (Typical)

The primary functions of the hydraulic turbine governor are as follows:

i) To start, maintain and adjust unit speed for synchronizing with the running units/grid.
ii) To maintain system frequency after synchronization by adjusting turbine output to load changes.
iii) To share load changes with the other units in a planned manner in response to system frequency error.
iv) To adjust output of the unit in response to operator or other supervisory commands.
v) To perform normal shut down or emergency over speed shut down for protection.

In isolated systems the governor controls frequency. In large system it may be needed for load operation control for the system. A block diagram is shown in figure 6.1. Digital electronic load governor are now employed. Mechanical analogue electronic governors used in earlier plants are also briefly discussed.
In small hydro units digital governors are employed for plant control and protection also which is discussed in detail in Vol. II - Control and Protection.

6.1.1 Basic Control System

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 forebay 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 controls the speed and power output of the hydroelectric turbine. Water level controlled power output controllers can be used for grid connected units. Governing system comprises of following sections (figure 6.2).

a) Control section
b) Mechanical hydraulic Actuation section

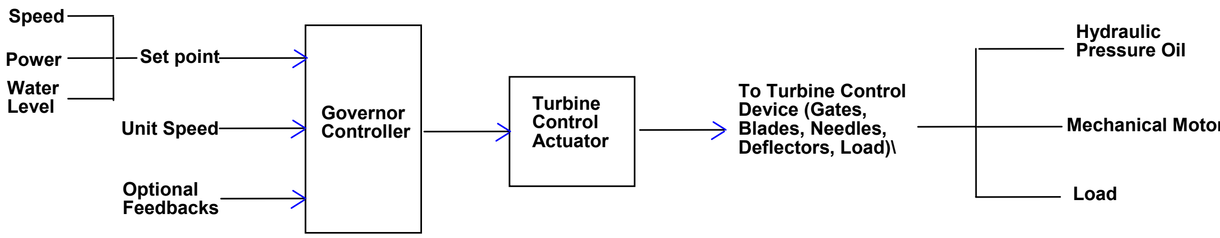

Figure 6.2 – Basic Governor Control System (Typical)

The control section may be mechanical; analogue electronic or digital electronic. Actuator can be hydraulic controlled, mechanical (motor) or load actuator. Load actuator are used in micro hydro range; mechanical (motor operated) actuators may be used say up to about 1000 kW unit size. Hydraulic actuators are mostly used.

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

6.2 Governor Capacity (oil servomotor)

Governor capacity rating in meter-kilogram is the capacity of the wicket gates/nozzles and blade servo motors (Kaplan units) as required for operation of the turbine at minimum rated oil pressure. USBR Engineering monograph no. 20 criteria is mostly followed.

The size, type, and cost of governors vary with their capacity to perform work which is measured in (meter-kilograms). Governor having a capacity of more than 8500 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 following empirical relations:

1. Wicket gates servomotor capacity.

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

Where,

FY_M = Servomotor capacity (m. kg.)
M = wicket gate height
h_{wh} = maximum head, including water hammer, and
D_g = wicket gate circle diameter

2. Blade servomotor capacity (adjustable blade Kaplan 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

FY_b = Servomotor capacity (m. kg.)
H_{max} = maximum head,
n_s = design specific speed, in metric HP units
P_{max} = turbine full-gate capacity at $H_{max.}$

6.2.1 Governor Capacity electronic Load Controller (shunt load governors)

These controllers recommended for hydro generating units in micro hydro range should have dump load capacity equal to the generator rating.

6.3 Type of Governor Controller

6.3.1 Mechanical Controller

Early mechanical governors were directly driven by prime movers through belt 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.

Bhakra Left Bank commissioned in 1960-61 have mechanical cabinet governors supplied by M/s Hitachi Ltd. Cabinet type governors have remotely mounted servomotor and are referred as cabinet actuators. Following operating control are on the cabinet face.

i) Gate –limit control
ii) Speed level control
iii) Speed droop control
iv) Manual gate control
v) Speed level indicator
vi) Speed droop indicator
vii) Speed indicators
viii) Low speed switch
ix) Oil pressure switch

6.3.2 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 determines the position of the turbine control actuators. This is a PID controller.

Examples of Analogue electronic type hydraulic governor are as follow and a typical block diagram is shown in figure 6.3.

i) Bhakra Right Bank (5 x 120 MW)
ii) Pong Power Plant (6 x 165 MW)
iii) Dehar Power Plant (6 x 165 MW)
iv) Chibro Power Plant

All these were with cabinet type actuators.

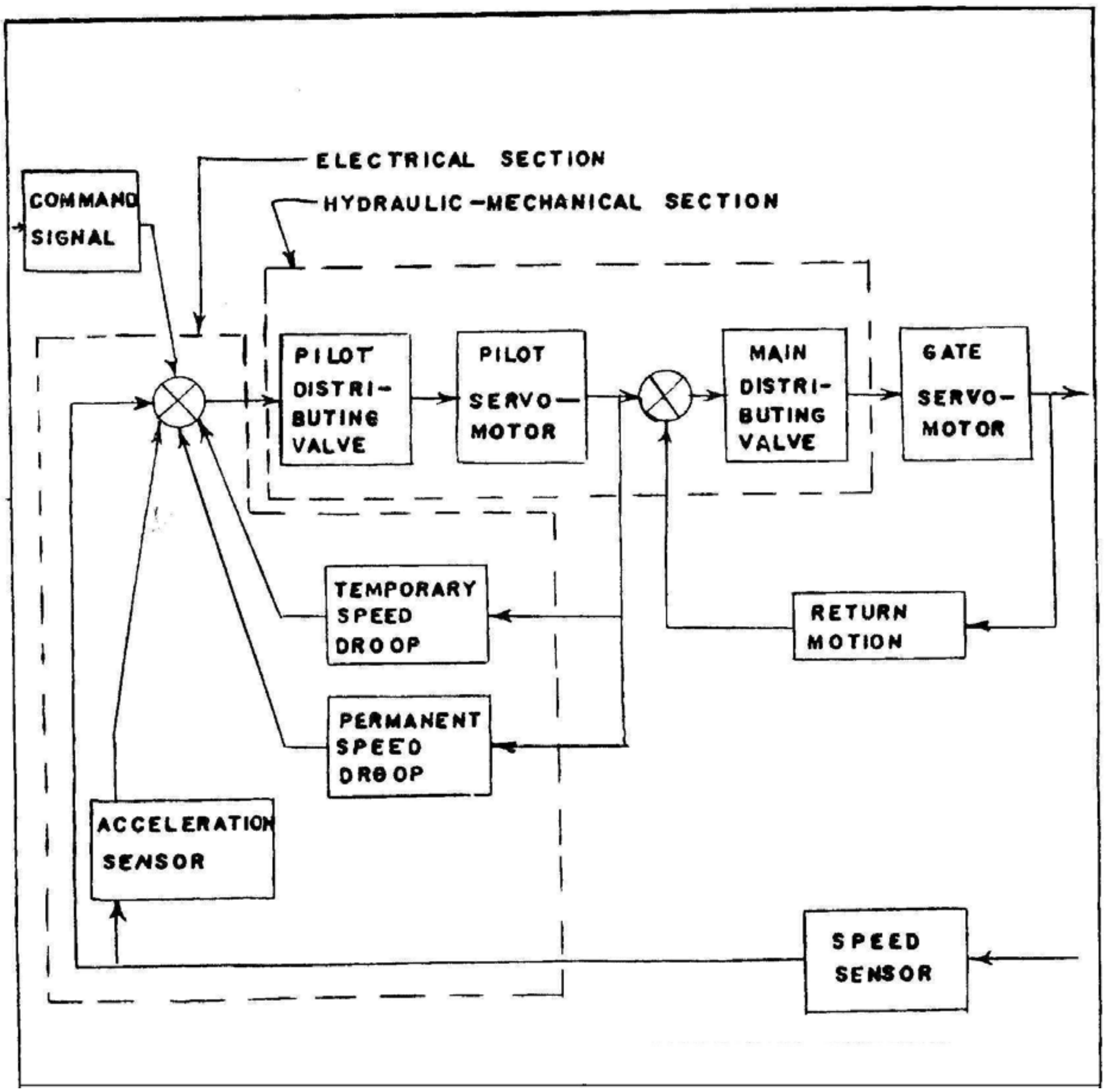

Fig: 6.3: Electro-Hydraulic Governor System (Analogue electronic)

Chibro – Station
(Source: Inauguration Brochure of UPSEB)

6.3.3 Electro Hydraulic Governor – Digital Governors

In digital governor, digital controller is used in turbine governing system. This is also generally PID controller. Digital control hardware running an application programme accomplishes the required control function with this system. Digital controllers 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 practice 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 fiber 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)
- Turbine creep detection
- Control sequencing
- Load optimization
- Dual regulated turbine optimization

In a digital governor, software typically performs functions done in mechanical and analogue governors by devices such as control motors, solenoids, and position switches. Digital controls can be designed in any configuration because software changes or additions can be made easily without requiring additional hardware.

A typical digital governor specified for a Kaplan turbine with control of wicket gates and blades is shown in figure 6.4(a).

Figure 6.4 (b) shows a diagram of a digital governor control system design for four jet Pelton turbine with joint control of the three turbines in the plant.

6.4 Speed Sensing

Speed Response: Elements: The speed of the speed responsive element should vary directly with the speed of the main shaft of the turbine for all rates of acceleration and deceleration. The governor drive should not be affected by variations in the voltage or current of the main generator or exciter or of the power system to which the main generator is connected. Following speed sensing methods are used.

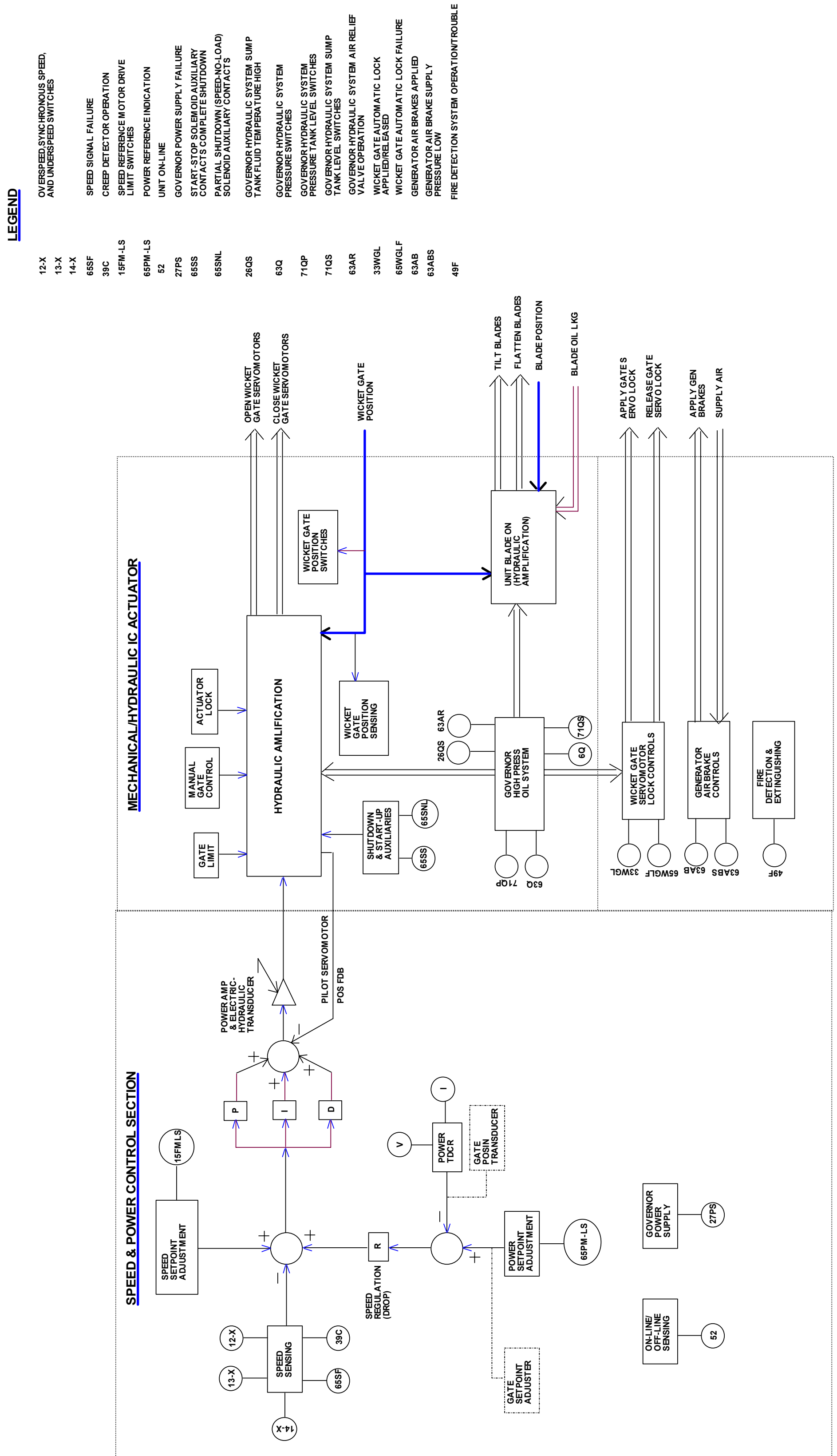

Figure 6.4 (a) Electric Hydraulic Turbine Governor Control & Monitoring System (Mukerian Stage-II canal fall project 2 x 9 MW Bulb turbine)

(Source: Alternate Hydro Energy Centre)

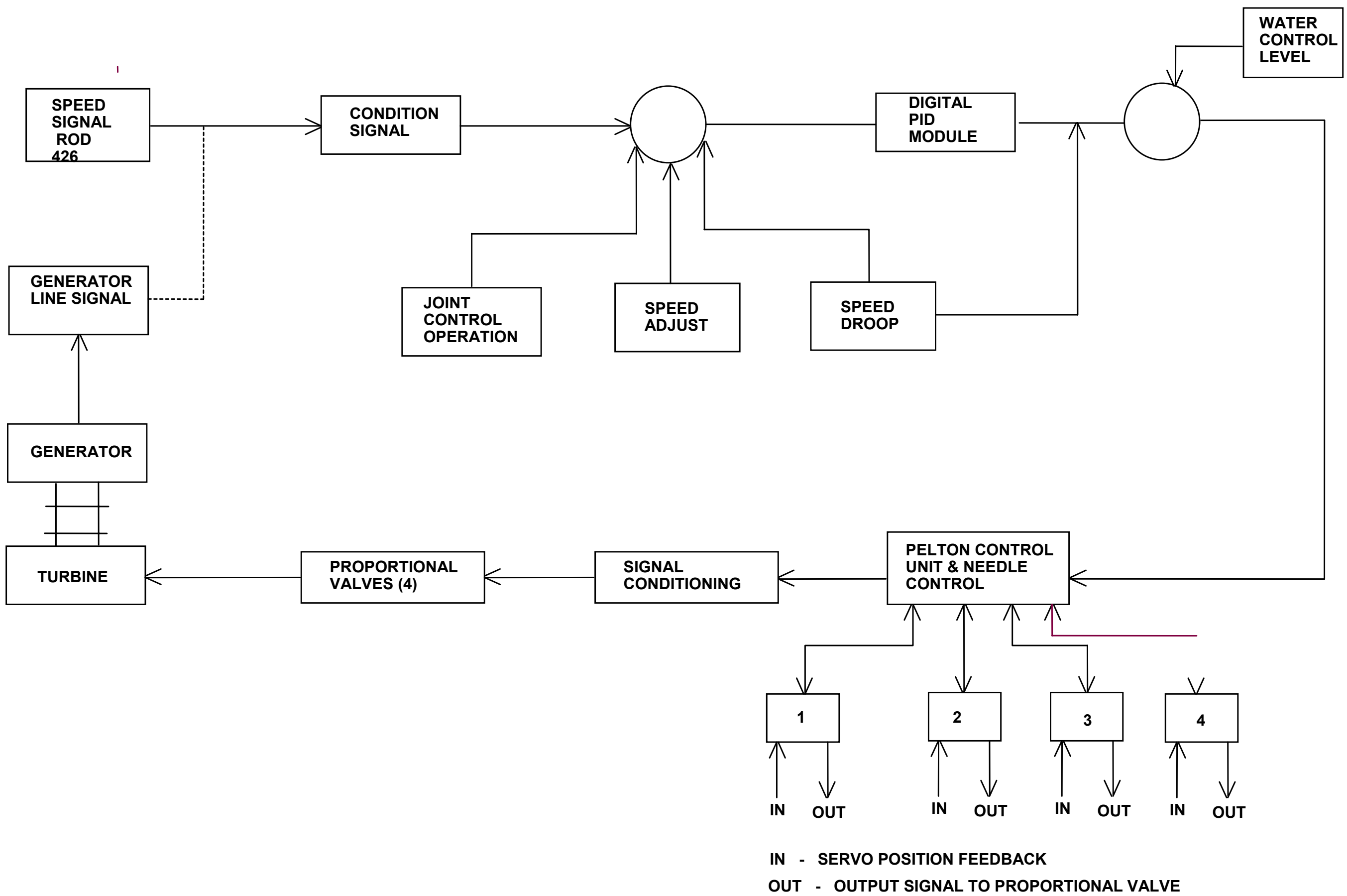

Figure 6.4 (b): Overall Functional Block Diagram (Four Jet Pelton)
PDPL PID Governor (Small Hydro) (Typical)

6.4.1 Permanent Magnet Generator (PMG) For Speed Sensing

Permanent magnet generators (PMG) are coupled to the generator shaft. PMG output frequency and voltage are proportional to unit speed.

In mechanical governor a permanent magnet generator (PMG) mounted on the rotor shaft drives a synchronous pendulum motor as explained the Para 6.3. The ball head mechanics of mechanical governors is the oldest speed sensing devices.

In electro-hydraulic analogue governors the speed sensing was by permanent magnet generator (PMG) mounted on the rotor shaft delivers frequency signals to the governor circuits. Also, it is a source of an output to operate speed relays for various sequence controls and of power to drive the transistor amplifiers.

6.4.2 Speed Signal Generator (SSG)

Sensitivity i.e. speed change to which governor will respond for large units is generally 0.005%. This requires that the speed be sensed at about every 10 mili second or better. Further pulse sensing is preferred for direct use in digital governing.

Modern speed sensing (speed signal generator) is achieved generally by magnetic or fiber-optic sensors operated in conjunction with toothed wheels or other devices directly connected to the generator shaft (speed signal generator-SSG). A typical common device in which speed is sensed electrically by speed signal generator (SSG) is shown in figure 6.5. A centrifugal over speed trip and a means for detecting creep is provided. Speed signal is obtained by a magnetic pick up – frequency of pulses is proportional to speed of turbine shaft rotation and number of gear teeth. The signal from magnetic pick up is fed to the pulse generator card which is used for speed switches and speed as well for tachometer. The creep is sensed by detecting with a photo cell, the interruption of a beam of light passing through the tooth of the speed signal gear. Creep equivalent to 1 tooth is generally required to activate a relay for alarms etc.

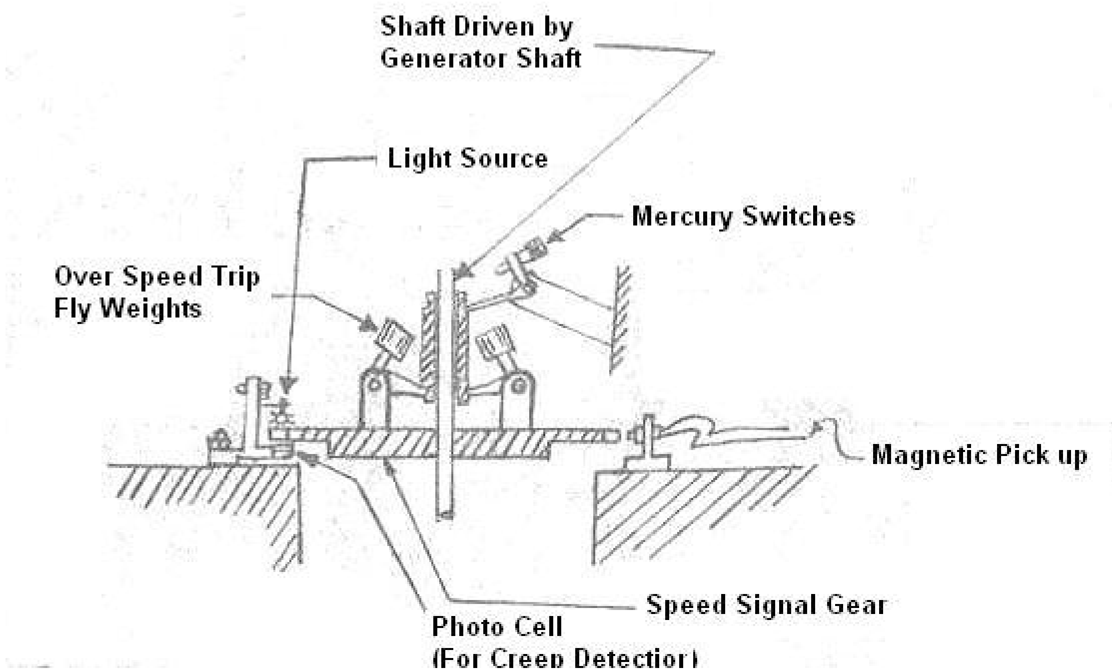

Figure 6.5: Speed Signal Generator for Electro-hydraulic governor (Typical)

Electrical to mechanical transducer accepts the electrical signal from the amplifier and converts it to a force on a spool valve plunger 'which controls a pilot servo motor'.

Modern practice for speed sensing mostly used for large units is toothed wheel with a magnetic pick up. The toothed wheel generally encircles the turbine shaft. The output frequency of the pickup is measured by speed sensor to determine shaft speed.

6.4.3 Voltage Transformers

Voltage transformers Connected to generator output leads are also used to measure speed. The transformer must be capable of operating at very low residual voltages in absence of field excitation.

Speed is measured from PT (voltage transformer) by measuring frequency.

$$\text{Speed in rpm} = \frac{Frequency\ (50\,Hz\,in\,India)\times 60}{Pair\,of\ Poles}.$$

The sensitivity with this method is lower (about 0.01%) and not generally available below 80% speed. This method is used in small units. Speed for control is measured from output voltage (potential transformer secondary) by measuring time period of the output wave.

6.4.4 Mechanical Over speed Switch

In all cases a mechanical device generally a centrifugal switch which closes in cases of over speed to initiate emergency closing of unit in case of turbine runaway condition is provided.

6.4.5 Speed Switches

Speed switches may be actuated mechanically by means of a positive coupling to the rotating elements of the turbine generator unit or may be actuated electrically by comparing the speed signal to a reference signal.

6.4.6 Wicket Gate/Position Indication

These are typically derived from potentiometer or synchro coupled to restoring connection from wicket gate servomotor.

6.5 Pressure oil System

6.5.1 Hydraulic pressure oil system required for operation of servomotors consists of following.

- High pressure oil pumps
- Pressure oil tanks
- Air compressor
- Sump tanks
- Piping

A typical oil pump system includes oil relief valves, gauges, valves, monitoring devices etc. for normal operation.

6.5.2 Oil Pump

Hydraulic pressure oil for operation of servomotors is provided by motor driven oil pumps of the rotary type. Old governor were designed to operate at about 15-25 kg/cm^2 (150 to350 pounds/inch^2). At Bahkra power plants (1955-65) combined capacity of the pump per minute was three times the total oil volume of the servomotor of the turbines. Normal operating oil pressure was specified 17.5 to 21.2 kg/cm^2 (250-300 psi). For Beas project power house (1965-75) oil pressure was specified in the same range.

Present day practice is to specify higher oil pressure. Higher pressures allow using smaller valves, smaller pressure tanks, piping and servomotors for the same effort and may be less expensive. However hazards of leakage increases. Governor for a recent Kaplan unit were specified as 40 kg/cm^2.

Typically two pumps are used one as lead and the other as back up (lag). Lead and back up pumps are frequently interchanged for uniform wear and tear.

6.5.3 Pressure tanks

Each governor is provided with welded pressure tanks tested as per relevant code for pressure vessels. At Bhakra the capacity of the tank was specified not less than 20 times the volume of the servomotor cylinders of the turbine.

6.5.4 Air Compressors

These are provided to supply air and maintaining automatically the required pneumatic cushion in the governor pressure oil tank.

6.5.5 Sump tank

The oil sump tank is designed for a capacity of 110% of total quantity of oil in the entire governor system of the turbine. It may require heating or cooling system to maintain usable oil temperature range for normal governor operation. Level switches high/low are provided.

6.5.6 Governor Piping

Maximum allowable oil velocity commonly determines governor piping size. Normal value for maximum velocity is 5 meter per second. In Bhakra power plant it was about 4.2 meters per second (14 ft./sec.).

A typical hydraulic schematic diagram of 3 MW Sobla Francis turbine with digital governor and servomotor is shown in figure 6.6.

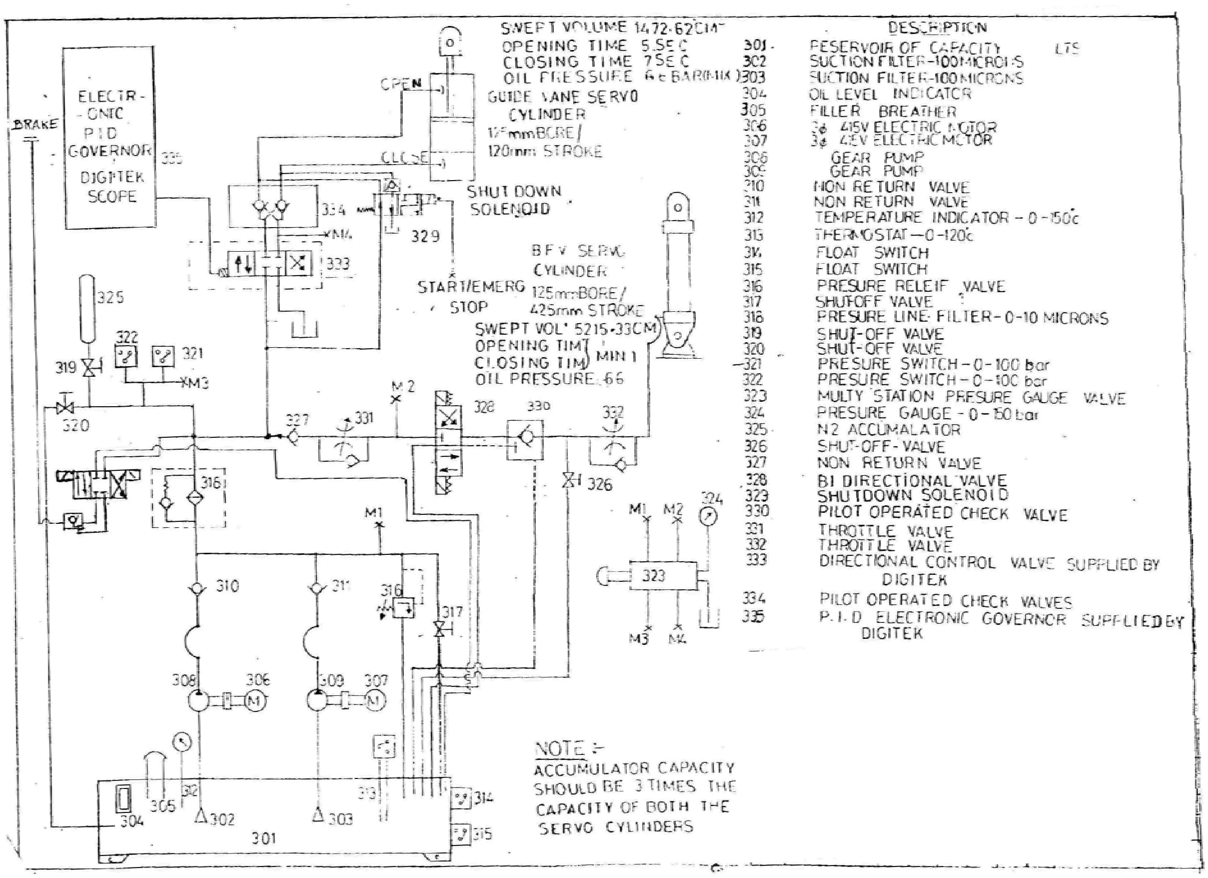

Figure 6.6: Sobla SHP (2 x 3 MW) – Pressure oil System Schematic Diagram (Digital Governor) (Source: Sobla Project Completion Report)

6.6 Control (Electronic Governor)

6.6.1 Control Function

The control function of a governor is to act upon external signal e.g. speed; wicket gate position (nozzles and nozzle position), blade angle, power, pond level to produce commands for governor power amplification elements. Overall strategy to control turbine speed in modern electronic governors is given below. The discussions are with speed reference to digital governors/Analogue electronic governors which are PID governors.

Digital PID algorithm is applied to the speed input from which a signal is developed to adjust with the gate/Pelton nozzle opening. This signal is based on the results of PID algorithm, given speed droop curve and governing dead-band.

Based upon the signal generated, as described above, a signal is generated for (wicket/nozzle) opening or closing as the case may be. This signal interfaces with the proportional valve electronics.

The blade angle in Kaplan units and wicket gate opening/head is coordinated in accordance with curve. Similarly number of nozzles operating in Pelton turbine and nozzle needle opening and closing is in accordance with the given curves between speed and nozzle opening. Some of the end points are hard coded in the ROM memory and other points are extrapolated in software.

User settable parameters include PID parameters KP, KI, KD speed droop, percentage limit on wicket gate/nozzle opening and setting up of speed switches.

6.6.2 PID Algorithm (Electronic Governors)

The analog control algorithm used in modern practice today in electronic governors is the so-called three terms or three-mode controller. This controller has a term that is proportional to the error, and a term that is proportional to the integral of the error, and a term that is proportional to the rate of change (derivative) of the error. The algorithm is called a proportional – integral derivative controller or more concisely a PID controller. The general form of this controller is shown in equation 1.

$$m(t) = K_p E(t) + K_I \int_0^t E(t')dt' + K_d \frac{dE}{dt} \qquad (1)$$

Where,

K_P	=	Proportional constant
K_I	=	Integral constant
K_d	=	Derivative constant
E(t)	=	Error as function of time
M(t)	=	Controller output deviation

The first term in equation (1) provides proportional action. The second term in the controller provides a component of the output that is equal to the integral of the error. In other words, as long as the error differs from zero, the controller output will continue to change. However, it should be noted that there are physical limits beyond which the controller output cannot change even though this algorithm potentially could require it. Without integral action, the process output never reaches the set point following the changes unless the proportional constant is made unrealistically large. The last term in the controller provides a component of the output when the rate of change of error is non-zero. The derivative mode thus "anticipates" the error giving a faster response time but at the same time makes it prone to erroneous control actions when the process measurements are corrupted by noise.
The digital or discrete equivalent of equation (1) is given below:

$$m_i = K_P \left\{ E_i + TK_i \sum_{j=i}^{i} E_i + \frac{K_D}{T}(E_i - E_{i-1} \right\} \qquad (2)$$

Where

T	=	Sampling interval
E_i	=	Error at i^{th} sampling interval
E_{i-1}	=	Error at previous sampling interval

The similarities are equations (1) and (2) should be noted. The proportional term is the same. However, the integral symbol is replaced by a summation symbol and derivative operation is replaced by a first order difference approximation.

More accurate expressions can be used, particularly for the latter term, since numerical differentiation of process data can cause serious problems when there is appreciable process noise. This form of PID controller is called a "position algorithm" since the computer calculates the specific value of the output at the i^{th} sample time. In this form the computer must save the previous error and the sum of all the previous errors defined by:

$$S_{i-1} = \sum_{j=1}^{i-1} E_j \qquad (3)$$

S_1 respresents the sum of all errors.

When E_1 is obtained, the sum S_i is updated and a new output m_i is calculated from equation 4:

$$m_i = K_P\left(1+\frac{K_D}{T}\right)E_i - \left\{\frac{K_P K_D}{T}\right\}E_{i-1} + \{TK_P K_i\}S_i \qquad (4)$$

An alternative form of the PID control algorithm is the "Velocity" algorithm. In this form, the changes in controller output at some time, i, is calculated as opposed to the actual value of the output. One of the primary reasons for using the velocity algorithm is that rather than transmitting the value of the controller position through a DAC channel, it is frequently desirable to transmit the change in output position. With this algorithm, pulses or single-bit outputs can be used to drive a stepper motor or an integrating amplifier. The advantage of this technique is that if the computer system fails, integrating amplifier or a stepper motor automatically holds the control value at the last calculated position.

The form of the velocity algorithm is given below:

$$\Delta m_i = m_i - m_{i-1} = K_P\left(1+TK_i+\frac{K_D}{T}\right)E_i - K_P\left(1+\frac{2K_p}{T}\right)E_{i-1} + \frac{K_P K_D}{T}E_{i-2} \qquad (5)$$

Velocity algorithm is primarily used because the proportional value interfacing requires the actual output and not just the change in controller output and moreover if the system fails then a shutdown is required which is possible with position algorithm while the system will continue operating as per last instruction from the computer in the other algorithm.

6.7 Performance Requirements

6.7.1 General

The main purpose of a speed governor is to maintain the water turbine generator speed regulated in spite of variation of load. The governor is also called upon to respond in various ways to other control signals in addition to speed, and to regulate the energy input to the turbine accordingly. Therefore, it must have stability and high sensitivity. Ease in handling is also desirable.

In large power systems, now-a-days hydro plants are being utilized for the purpose of peaking as well as base load, pumped storage and spinning reserve power operation etc. Specially in a system consisting of large industries, where frequency and voltage fluctuations are required to be kept minimum, their stability determines the quality of power. For efficient use of plant, complex control techniques are employed in the station automation and these involve the turbine governor in control features for which a flexible governor design is essential. Consequently, various functions become requisite for turbine governors and exciter along with improvement in performance.

Stability: Following provisions were made in specifications for large turbine with mechanical governors.

The governing system should be capable of controlling with stability (without hunting) the speed of the turbine when operated at rated speed and no load or when operated at rated speed with isolated load at all power outputs to and including maximum output of the turbine. The governor system should also be capable of controlling with stability the power output of the turbine at all power outputs between zero and maximum power output inclusive when the generator is operating in parallel with other generators in a plant or in a transmission system. The governor system is generally deemed stable, if the hydraulic system of turbine and water conduit is inherently stable (see chapter-4).

a) The magnitude of the sustained speed oscillation caused by the governor does not exceed 0.3% of rated speed with the generator operating at rated speed and no load or operating at rated speed and isolated sustained load with the governor speed droop set at from two to 5% inclusive.
b) The magnitude of the sustained power output oscillation caused by the governor does not exceed 3% of the rated capacity of the turbine with the generator operating under sustained load demand in parallel with other generators which are themselves capable of operating in parallel with other generators and with the governor speed droop set from 2 to 5% inclusive.

These provisions are in general agreement with the stability criteria indicated in IEEE std. 125.

Stability provisions provided with PID electronic governors specified recently for a large turbine governor are as follows:

The governor operation shall be deemed stable:

If peak to peak magnitude of the sustained load oscillation caused by the governor, with 4% or more speed droop setting, does not exceed ± 0.15% of the rated capacity - the generator being connected to the grid with sustained load demand.

The governor shall control, with stability, the turbine at any speed between 85 and 105% of rated speed when operating isolated from the system and while connected to the system at any load between zero and the load corresponding to maximum opening of the guide vanes.

With the turbine running at its rated speed, the total amplitude of speed variations not resulting in any measurable difference in the guide apparatus servomotor position shall not exceed 0.02% of the rated speed at any gate opening.

Dead Band - The dead band adjustment range shall be 0 to ± 3Hz. The governor dead time shall not exceed 0.2 seconds with a sudden load change of 10% or more of the capacity of the turbine.

The adjustment of permanent speed droop shall have a range from 0 to 10%.

Recommendations for Mega/Large Units

IEEE std. 125-2007 specifies more stringent stability criteria for stability for large/mega units designed for frequency control so as to account for persistent oscillatory mechanical power surging which may occur as natural result of water passage or turbine design. The steady state governing speed band (also called speed stability index) under either speed no load or loaded conditions should be no more than 0.1 % with generator off-line and operating at 5% speed droop (position, power, or flow). Power stability index is specified as 0.4 %.

It is considered that large/mega units should conform to IEEE std. 125-2007.

Dynamic Stability Studies

It is recommended that dynamic stability studies be carried out for mega units and frequency controlling large units to meet grid requirement in accordance with IEEE std. 125. These studies should be carried out by supplier by using appropriate method with interaction of surge tank, penstock, turbine generator, load and governors for transient/sustained response of the interconnected system. The study should include isolated and parallel operation and the study should indicate the setting range of governor parameters.

IEEE Committee report 1992 recommends detailed modeling simulation studies of following types.

Hydraulic turbine dynamic model as recommended in the report be used.

6.8 Governor Adjustment

6.8.1 Electronic Governor

The adjustable parameters for electronic governors are as follows:

Proportional gain	k_p
Derivative gain	k_d
Integral gain	k_i

IEEE std. provides that provisions for continuous adjustment of these values be made as follows in electronic governors.

Proportional gain	0 to 20%
Derivative gain	0 to 5%
Integral gain	0 to 10%

6.8.2 Mechanical Governor

In mechanical governor still in use in old existing plants, the adjustable parameters to secure stability of operation are as follows:

i) Permanent speed droop
ii) Temporary speed droop
iii) Dashpot recovery time

6.9 Load Characteristics

The load characteristics of the system that is being supplied power are important in determining overall results of system stability. Normally nothing can be done to the load and should be taken into account in the control design. Two examples are given below.

6.9.1 Bhakra Left Bank Power House & Nangal Fertiliser Load System

Bhakra Left Bank power House had five units, each 100 MVA, generating power at 11 kV. The generated power of three machines was stepped up to 66 kV for supply of power to Nangal Fertilizer load of about 150 MW through three 66 kV transmission lines, 6 km long. The generated power of the other two machines was stepped up to 220 kV and fed to the main grid through two 220 kV transmission lines termed as Ganguwal feeder 1 and 2. There was an interlinking transformer 66/220 kV (3 single –phase transformers of 50 MVA each, total 150 MVA) interlinking the two buses at 66 kV and 220 kV single line in shown in figure 6.7(a). The Bhakra left bank powerhouse units had been experiencing instability of operation in isolated mode which resulted in complete shutdown of the powerhouse on a few occasions. Isolated operation of the powerhouse for supply to fertilizer factory also results in hunting.

The generating units have short penstock and speed rise on full rejection is below 35% (Para 4.11.1) indicating good regulating capability of turbines.

The turbine is equipped with mechanical governors supplied by M/s Hitachi limited. A block diagram of the mechanical governors is shown at Figure 6.7(b). (Units have since been modernized).

6.9.1.1 Fertilizer Factory Load Characteristics and Field Observations

Maximum load 180 MW at 0.9 p.f.

Load mainly consists of rectifier plant (90% of total load) for electrolysis of water to produce hydrogen as the main feed stock for fertilizer production and 10% synchronous and induction motors.

An earth fault on the Bhkra-Nangal 220 kV feeder resulted in the back up relays at Bhakra Powerhouse to be energized and the fault was cleared by tripping of circuit breakers A_6 and A_7. This resulted in all the four units (Then working) supplying power to Nangal fertilizers. The units then started hunting and consequently tripped on account of low governor oil pressure. Further tripping of the bus C. B. A_4 resulted in isolated operation of two machines supplying power to Nangal fertilizers. This caused severe hunting of machines resulting in the similar failure as mentioned above. The settings of the governor parameters were as follows:

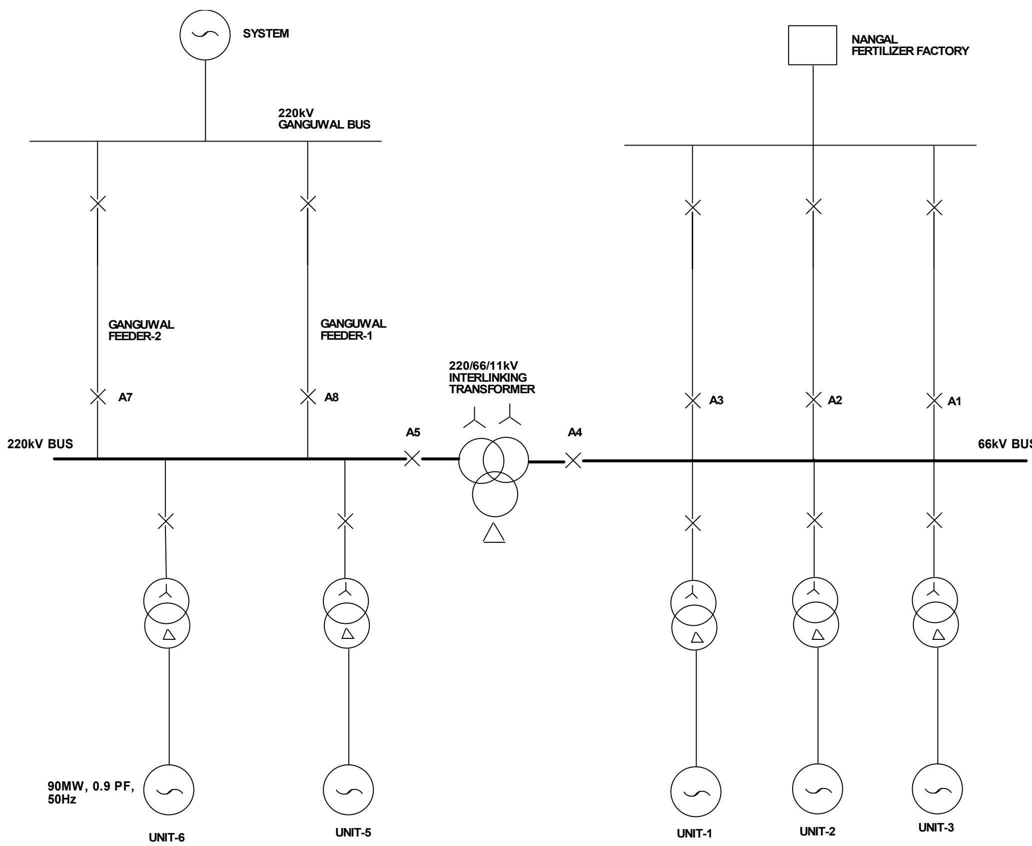

FIG: 6.7 (a): Details of units and buses at Bhakra Left Bank powerhouse

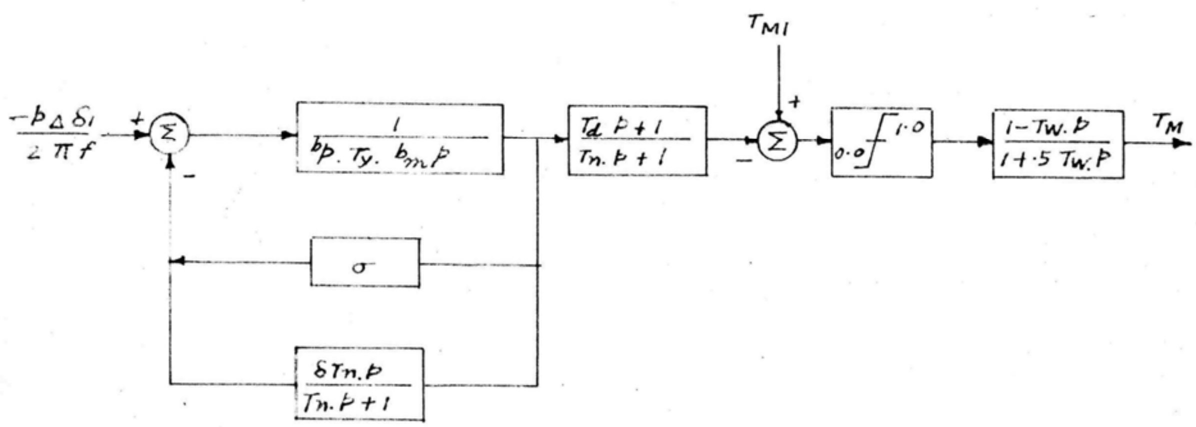

FIG: 6.7 (b): Mechanical Governor Block Diagram

i) Percentage permanent speed droop σ 3 percent
ii) Percentage temporary speed droop ∂ 30 percent
iii) Dashpot time T_n 110 seconds

6.9.1.2 Optimum Governor Adjustment

The powerhouse being inherently stable a detailed study for adjustment of the mechanical governor and possible improvement by replacing the mechanical governor by electronic governors was made.

Note: Studies described were carried out in 1980 in Roorkee University (now IIT) with programmes available at that time with IIT (reference 10 & 12)

A) Mechanical Governor Adjustment Empirical Relations

Mechanical governor adjustments (empirical) and measurement of parameters based on studies carried out by researchers are detailed in reference. These setting for Bhakra governors based on these empirical relations were worked out in table 1.

Governor adjustment (Empirical Relation)

Governor adjustment	N. G. Dennis & M. Paynther	L. M. Hovey	F. R. Scheleif & A. B. Wilbor
Temporary speed droop (δ)	0.25	0.2	0.2
Temporary speed droop (T_n)	4.72 sec.	3.2 sec.	4.0 sec.

Dennis and Paynter

a) **Temporary speed droop** $\delta = 2.5 \frac{T_W}{T_M}$

Where,

T_W is water starting time (0.8sec. for Bhakra L. B. Generators)

T_M is mechanical starting time or accelerating time of rotating masses (0.08 sec. for Bhakra L. B. generators)

b) **Dash Pot recovery time Tn = 5.9 T_w**

L. M. Hovey (Manitoba Hydro)

$\delta = 2\ T_w/T_m$

$T_n = 4\ T_w$

T.R. Schlief and A. B. Wilber (USBR)

$\delta = 2\ T_w/T_m$

$T_n = 5\ T_w$

B) Mathematical Modeling of Mechanical Governing System

Two units of the Bhakra Left Bank Power house were assumed to supply power to Nangal fertilizer load of 100 MW through three circuit transmission lines. The mathematical simulation of the various components of the system was done as follows:

Synchronous Machine

The sending end generators, being identical in every respect, were represented by an equivalent machine. Its mathematical model takes into account the field flux decrement and transient saliency. The equivalent synchronous motor at the receiving end was represented by a constant voltage E_d and the power output was assumed constant during dynamic stability studies.

The excitation system

The excitation system for the Bhakra units is given in figure 6.8. For dynamic stability studies the saturation effect was neglected. The receiving end machine is unregulated.

The governors at Bhakra Left bank power house were Hitachi cabinet type speed governors. The block diagram after some simplification is given in figure 6.7(a).

The electrical governing system explored as an alternate to the existing mechanical governor, is a three-term controller. Its block diagram representation is shown in figure 6.9.

Transmission network including power transformers and rectifier load at Nangal End:

The electromagnetic transients in the transmission network are ignored. The transmission lines and power transformers are simulated by constant lumped parameters. The rectifier load is nearly 90% of the total load at 0.9 pf lagging. It is also represented as a constant impedance load.

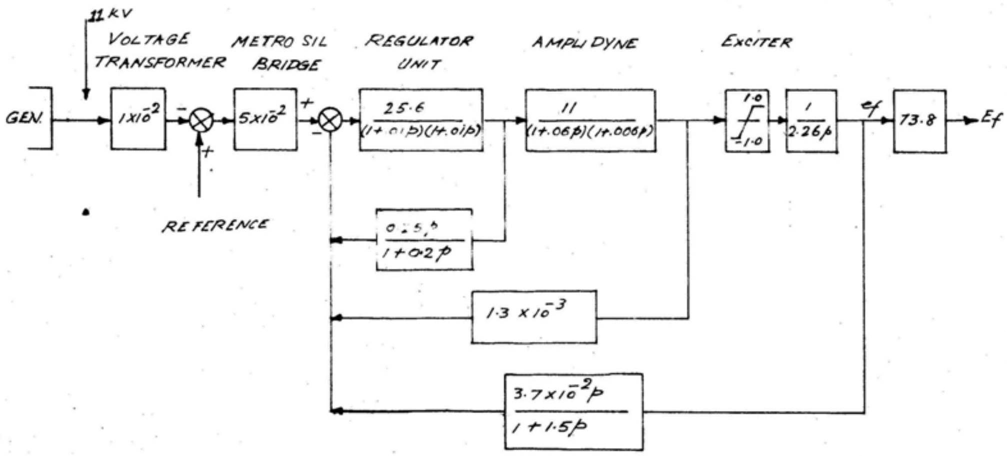

Fig 6.8: Block Diagram of Bhakra PH (Left Bank) Excitation System

The speed governing system

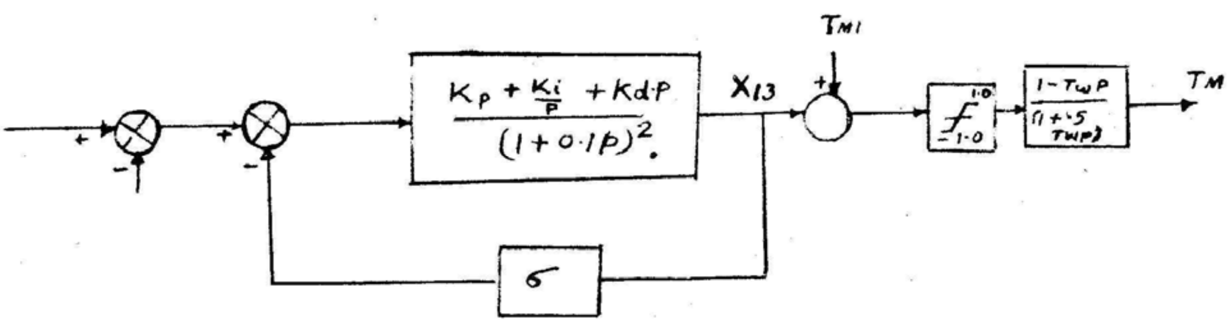

Figure 6.9: Electrical Governor Block Diagram

Stability boundaries in parameter plane

Study with Mechanical Governor

Results in the form of boundaries in the plane of permanent speed droop. σ and δ, the temporary speed droop with varying values of dashpot time constant T_n, are given in Figure 6.10 (A) and figure 6.10 (B).

Figure 6.10 (A) shows contours for $T_n = 6$ s with $\rho = 0.0$, 0.1 and 0.2 s^{-1}. The absolute stability contour ($\rho = 0.0$) shows a wide range of stable zone which considerably reduces for increasing values of degree of stability ρ. The Bhakra governor units, for steady state load sharing reasons, are set for permanent speed droop $\sigma = 0.03$. The $\sigma = 0.03$ and temporary speed droop $\delta = 0.25$ point lies well with within the contour for $\rho = 0.01$.

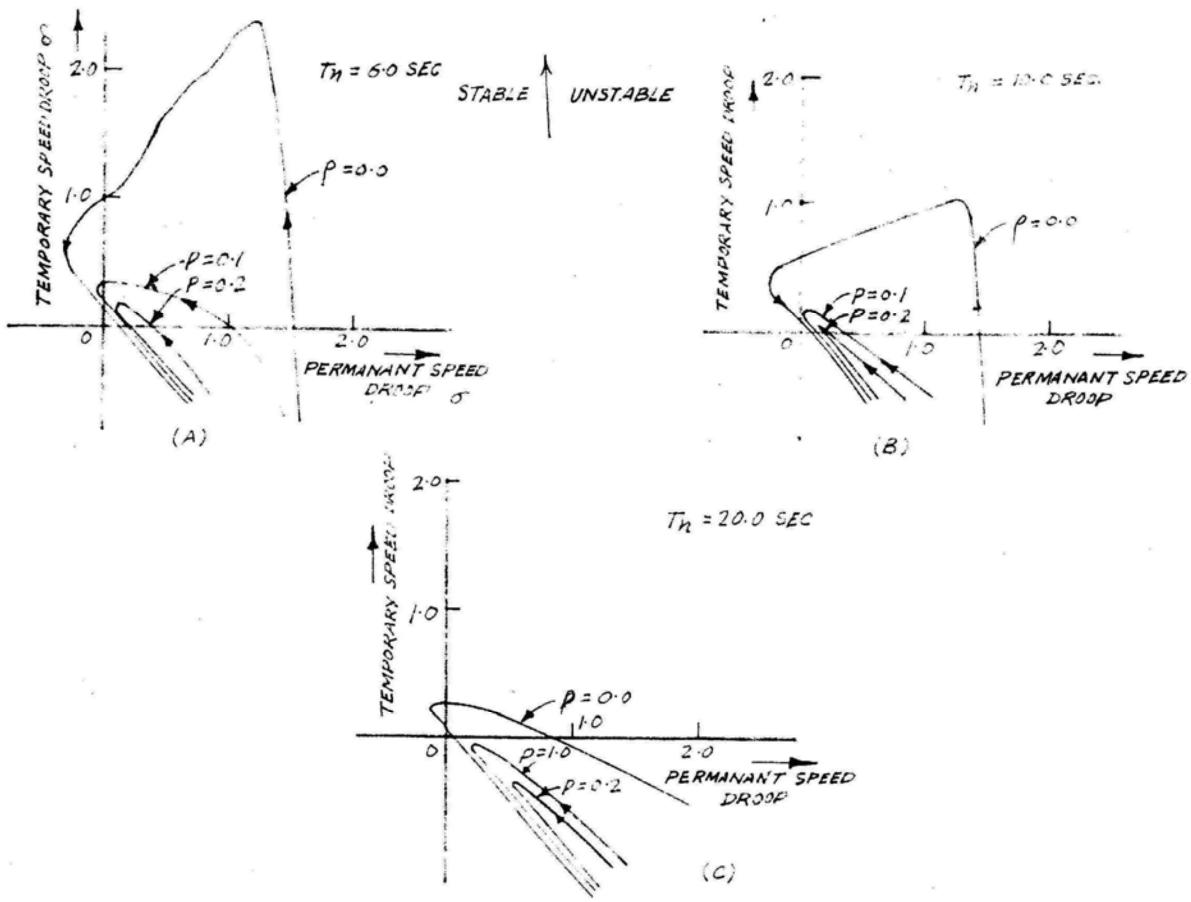

Fig: 6.10: Boundary of D-Partition (with relative Degree of Stability Bhakra PH Governor

Figure 6.10 (B) and Figure 6.10 (C) show the stability zones for T_n = 10 s and 20 s respectively. It will be noted that the stability regions (especially in the first quadrant) shrink rapidly. The σ = 0.03 and δ = 0.25 point lies between ρ = 0.0 and ρ = 0.1 contours when T_n = 10s while for T_n = 20s there is no setting which confirms degree of stability 0.1 or better. This shows the trend of the results with increase in the dash pot time. For dash pot time 50 s and higher, no stable region was found in the first quadrant of σ – δ plane; thus, system is unstable at high dash pot times with all possible settings of σ and δ.

The optimum settings recommended were:

T_n 6 s, σ = 0.03 and δ = 0.25

Study with Electrical Governor

The stability boundaries contour for three values of the integral gain, Ki = 0.5, 1.0 and 2.5 are obtained in the plane of K_P and K_d, the proportional and derivative gain parameters of the electrical governor with varying degree of stability, however, a higher ρ. These contours are shown in figure 6.11.
In all these three cases with varying K_I a degree of stability better than 0.4 is possible. The stability region with larger K_I is smaller for the same degree of stability, however, a higher ρ is possible with larger K_i .

In the above three cases σ was kept constant at 0.03 pu. The optimum settings of the electrical governor was taken as K_I = 1.0, K_P = 5.5.

K_d = 1.5.

Field adjustment

Actual field adjustment for temporary speed droop and dash pot time were carried out as detailed in the report and summarized below:

a) Dash pot time constant (T_n)

With the machine shut down and all floating levers free and governor on auxiliary valve, depress the small piston by hand until it by-passes oil through the milled flats on the piston. Now release the piston and it moves upwards under action of the spring, click a stop watch just as the top edge of the floating lever comes opposite the lower graduation on the measuring rod and time the travel to the point where this edge just comes opposite to the next graduation. Assuming that dashpot has an exponential characteristics, this time interval in seconds is the time constant T_n corresponding to the particular needle valve setting. If correct value is not obtained at the needle valve setting, change needle valve position and repeat the measurement till correct value is obtained.

b) Temporary speed droop (δ)

A load of about 5 MW (three to four percent of rating) was rejected from the machine by separating it from the system with the dashpot orifice remains closed during the test. Frequency and gate position of the machine were recorded before and after load rejection.

The sensitive readings of frequency were taken by connecting a digital frequency meter to generator terminals.

Temporary speed droop (δ) = $\dfrac{\Delta\eta}{\Delta g}$

$\Delta\eta$ = Per unit speed change

Δg = Per unit gate change

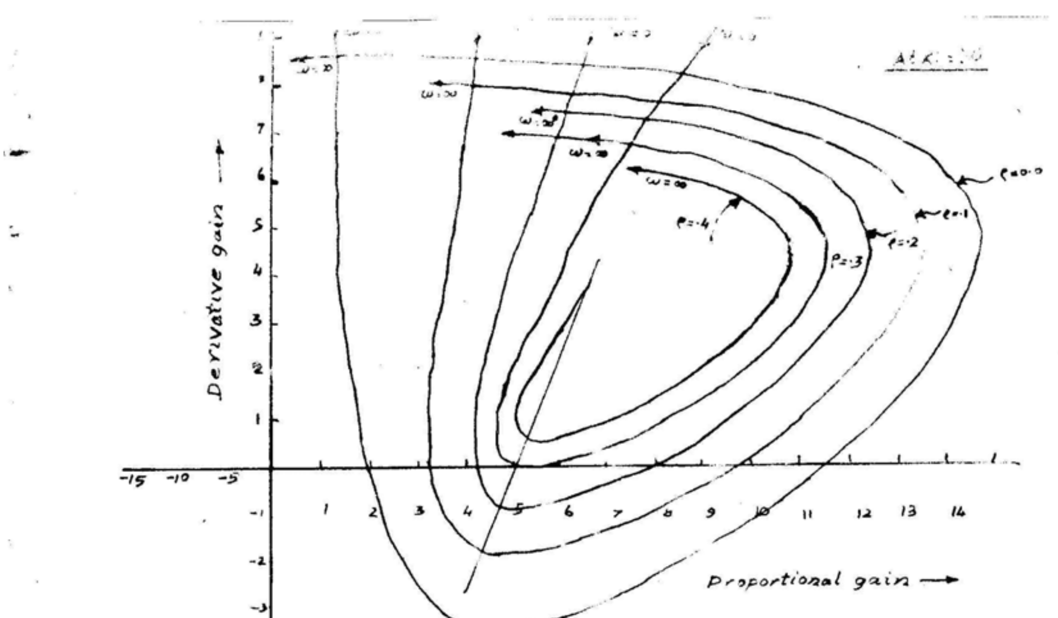

FIG (6.53)

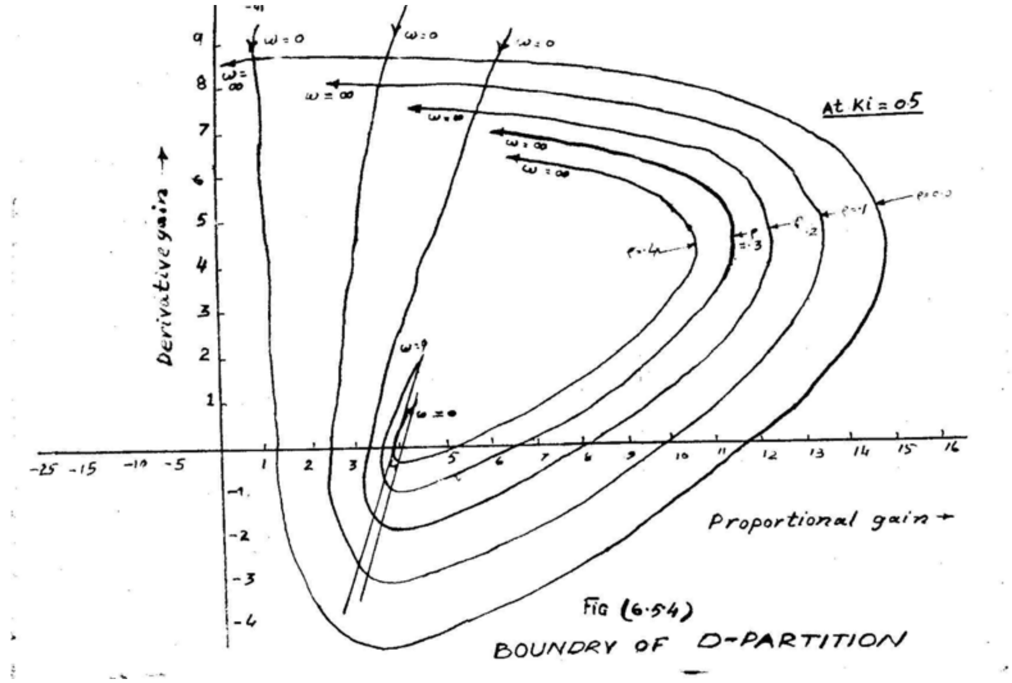

Figure 6.11: Boundary of D-Partition

Conclusions

After adjusting the parameters of the governor as determined by the study i.e.

T_n 6 s, $\sigma = 0.03$ and $\delta = 0.25$

The field testing indicated instability for isolated operation for the fertilizer factory load. Further study indicated that the rectifier plant was frequency sensitive and tripped on small mal-fluctuation and was the cause of the instability.

Subsequently all the five units of left bank were connected to 220 kV grid. The rectifier plant was dispensed and the fertilizer production method was modified being obsolete. This resulted in stable operation.

6.10 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 analog flow governors, unit control and protection systems are high. These systems require attended operation and are mostly based on large capacity hydro units. This makes 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 hydros are usually low affecting economic viability.

(f) Flow Control Turbine Governors are expensive and not recommended for small hydro units in micro hydro range. Electronic load control governing system with water cooled hot water tanks as ballast loads for unit size up to 100 kW are cost effective. This makes a saving of about 40% on capital cost. If the thyristor control (ELC) is used then the alternator needs to be oversized up to 2% on kVA to cope with the higher circulating current induced. Accordingly, in case of small units up to 100 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 even generation scheduling and have been successfully in operation for over ten years.

(j) Programmable logic control (PLC) based systems with automation by personal computers are reliable and have also 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 is required.

6.10.1 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 6.1 with following aspects.

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

6.10.2 Electronic Digital Controller of SHP

Electronic digital governor are now used in both large and small modern hydro-electric unit. Electro-hydraulic servo valves – an electrical to hydraulic transducer is utilized. This is also called proportional control. These valves provide adequate hydraulic power to move hydraulic turbine water control devices.

Small hydro power units 2 × 3 MW at Sobla (Francis unit) with digital governor had proportional servo valves and guide servo cylinders of 765 kg m to give adequate amplification for moving wicket gates. The oil pressure was 66 kg/cm^2.

Hydraulic energy is stored in suitable oil pressure accumulator (tanks) for energy required at least for one closing; opening and closing cycle. Oil pressure systems at high rated pressure with nitrogen cylinder are also used.

6.11 Load Controller for Micro Hydros

An alternative to the conventional flow control governor is shunt load governor (SLG) called electronic load controller (ELC). The shunt load governor use same principle of matching input to turbine with the output at generator terminal. In a SLG based system the input to turbine is kept constant, which means that generator output also remains constant. Therefore, an additional dump load is connected at generator terminal, which is controlled by an analog, electronic or microprocessor based electronic circuit. It switches on and off and adjusts the dump load according to the instantaneous consumer load in such a manner that total load on generator terminal (dump load plus consumer load) remains constant keeping the speed (hence frequency) variation with in the specified limits.

Resistor bank is used as a dump load. The most evident drawback of a SLG is that it actually wastes the surplus energy put into dump load. Due to this fact, SLG has a fairly limited range of application. The domain in the power range is up to 100 kW, usually classified as the range of micro hydro plants.

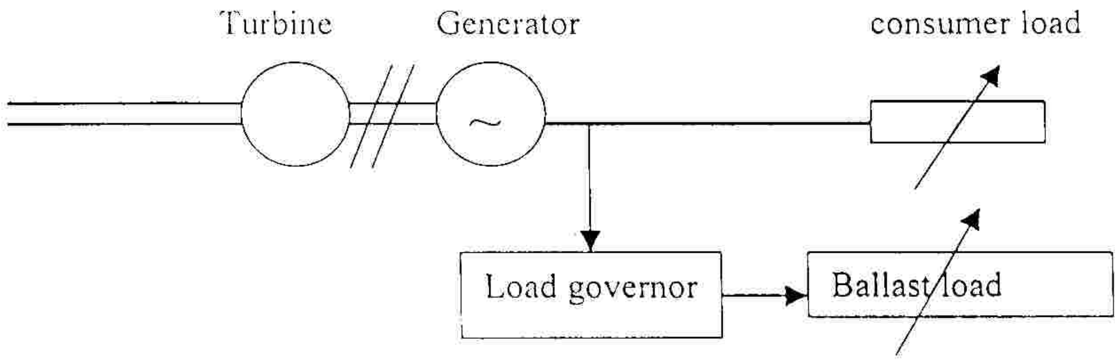

Figure 6.12: Load Governing Principle

Techniques for Dump Load Control: Different techniques employed for controlling the ballast load are as follows:

i) Phase delay action where the firing duration of one of the ballast is varied while rest are directly switched on or off fully. This method gives fine load balancing but results in production of harmonics in output voltage waveform.

ii) Binary load action where ballast load is made up from switched combination of a binary arrangement of resistive load. The load proportion carried by each step is in the ratio 1:2:4 and these are switched in sequence.

iii) Indirect methods have also been used. Either frequency or voltage may be used to indicate the level of load on generator. Voltage being kept constant by AVR the frequency gives fairly good idea of load on governor. This is limited to very small (up to 10 kW) units and mostly induction generator.

Table 6.1: GOVERNORS, CONTROLS AND MONITORING SYSTEMS, TECHNOLOGY

Rating (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, up to 500 kW. Could save more than 20% due to spin effects.	Not considered	Most useful on unit size up to 200 kW on both grid & non grid connected.
Analogue integrated governor and plant control.	3	2	2	2.3	Low cost solution for up to 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.

Advantages: In view of above discussions, the first and the foremost advantage of shunt load governor (ELC) is that cost of the hydroelectric plant can be decreased by 30 – 40% in comparison to conventional plants with hydraulic governors.

It eliminates the need for precision-engineered mechanical governors. It also allows the design of the turbine to be simplified, because there is no need of the guide vanes or rotor blades to be adjustable since the turbine is always running at full load.

Other advantages are as follows:

i) The generator always generates the maximum power possible. The generation not immediately required, is diverted to secondary loads. The secondary loads can be consumed for useful purposes and overall efficiency can be significantly high.

ii) Since the control is by digital means with frequency as reference, the response can be faster and more accurate as compared to the mechanical governors.

iii) As the governing action is not affected by site dependant characteristics such as length and size of the penstock, little or no custom engineering is required.

Load control governors used for micro hydros instead of flow control governors produced stable speed regulation by adjusting a thyristor controlled dump load but was observed to have severe distortion of the generated wave form. The isolated operated power plant consumers complained of difficulty in operating television and other electrical appliances. Oversized generators had been used. Best solution was found to limit phase controlled load to about 20% of total dump load so that over all distortion of wave remains within acceptable limit.

6.12 Governing System used in India for Small Hydro

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 up to 50 mm are used in stainless steel with 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 will load actuator is used.
Small Hydros - 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 up to 1000 kW unit size with microprocessor based level control PI Controller

Small Hydro Above 3 MW - Flow control PID governor with hydraulic actuator

Large hydro - PLC based flow control PID governor with hydraulic actuator

Governing system including controller and actuator used for some different capacity powerhouses designed by AHEC and consultants is given in Table 6.2.

Table – 6.2

Sl. No.	Project Name	Controller	Actuator	Remarks
Arunachal Pradesh Energy Development Agency				
1.	Pein Small Hydro Power Project (Phase I) (2 x 1500 kW), District Lower Subansiri	Digital governor PLC based alongwith plant control capability with PC (SCADA)	Oil pressure servomotor	
2.	Pareng Small Hydro Power Project (2 x 3000 kW), District Papumpare	Digital governor PLC based alongwith plant control capability with PC (SCADA)	Oil pressure servomotor	
3.	Sie Small Hydro Power Project (2 x 2800 kW), District West Siang	Digital governor PLC based alongwith plant control capability with PC (SCADA)	Oil pressure servomotor	

Sl. No.	Project Name	Controller	Actuator	Remarks
Uttarakhand Renewable Energy Development Agency				
1.	Nagling Micro Hydro Power Project (2 x 25 kW), District Pithoragarh	Digital controller (Electronic Load Controller)	Load Actuator	
2.	Dugtu Micro Hydro Power Project (1 x 25 kW), District Pithoragarh	Digital controller (Electronic Load Controller)	Load Actuator	
3.	Kuti Micro Hydro Power Project (1 x 50 kW Phase I), District Pithoragarh	Digital controller (Electronic Load Controller)	Load Actuator	
4.	Rong Kong Micro Hydro Power Project (1 x 50 kW Phase I), District Pithoragarh	Digital controller (Electronic Load Controller)	Load Actuator	
5.	Sela Micro Hydro Power Project (2 x 25 kW), District Pithoragarh	Digital controller (Electronic Load Controller)	Load Actuator	
6.	Borbadala Micro Hydro Power Project (1 x 25 kW), District Bageshwar	Digital controller (Electronic Load Controller)	Load Actuator	

7.	Chillud Gad Micro Hydro Power Project (2 x 50 kW), Uttarkashi	Digital controller (Electronic Load Controller)	Load Actuator	
8.	Nepalchyo Mini Hydro Power Project (2 x 100 kW), District Pithoragarh	Digital controller (Electronic Load Controller)	Load Actuator	
Bihar State Hydro Electric Power Corporation Ltd.				
1.	Rajapur Small Hydro Power Project (2 x 350 kW), District Supaul	PLC based digital electronic governor with integrated plant control	Oil pressure servomotor	Commissioned/ under commissioning
2.	Natwar SHP Project (2 x 250 kW), District Rohtas	Digital Controller with integrated plant control	Oil pressure servomotor	Do -
3.	Jainagara SHP Project (2 x 500 kW), District Rohtas	Digital Controller with integrated plant control	Oil pressure servomotor	Do -
4.	Belsar SHP Project (2 x 500 kW), District Jehanabad	Digital Controller with integrated plant control	Oil pressure servomotor	Do -

Sl. No.	Project Name	Controller	Actuator	Remarks
5.	Rajapur Small Hydro Power Project (1 x 700 kW), District Supaul	Digital Controller with integrated plant control	Oil pressure servomotor	Do -
6.	Shirkhinda SHP Project (2 x 550 kW)	Digital Controller with integrated plant control	Oil pressure servomotor	Do -
7.	Walidad SHP Project (1 x 700 kW), District Jehanabad	Digital Controller with integrated plant control	Oil pressure servomotor	Do -
8.	Arwal SHP Project (1 x 500 kW), District Jehanabad	Digital Controller with integrated plant control	Oil pressure servomotor	Do -
NTPC Ltd., Singrauli (U.P.)				
	Singrauli SHP Project (2 x 4000 kW), District Sonebhadra	Digital Governor with integrated plant control with PC (SCADA)	Oil pressure servomotor	

6.13 Other Examples of Typical Governing Systems

i) 2 x 30 kW Microhydro with Synchronizing, Assam Project (isolated operation)

Digital controller and load actuator (Electronic Load Controller)

ii) 2 x 500 kW – Satpura SHP project

Electronic Digital Level Controller with induction generator – grid connected

iii) 2 x 1000 kW –SHP project Newzeland

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 – Sobla SHP project

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 – Mukerain Stage –II canal fall SHP project

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

References

1. N. G. Dennis, water turbine governors, proc inst- of Mech. Engineering (London), Volume IB, SER. B., pp. 379-400, Sept., 1959.
2. M. Paynter, The analog in Governor design I, a restricted problem, Palimpsest on the electronic analog art, printed by G./A. Philbrick Researches, Inc., Boston, 1960.
3. L. M. Hovey, Optimum adjustment of hydro Governor on Monitoba Hydro System, Trans. AIEE, PAS, Vol. 81, pp 581-585, Dec., 1962.
4. F. R. Schleif and A. B. Wilber, The coordination of Hydraulic turbine Governors for power system operation, IEEE Trans. on power apparatus and systems, vol. PAS – 85, pp. 750-758, July 1966.
5. M. Leum, The development and field experiences of a transistor electric governor, Trans IEEE, Vol. PAS-85, pp 393-402, April 1966.
6. Ferber R. Schleif and Raymond R. Angell, Governor tests by simulated Isolation of Hydraulic Turbine Units, trans IEEE, Vol. PAS-87, No. 5, May, 1968.
7. IEEE committee report, "Hydraulic Turbine and Turbine Control Models for System Dynamic Studies – 1992.
8. IEEE committee report, computer presentation of excitation systems, IEEE Trans. Vol. PAS-87, No. 6, June 1968, pp. 1460-1470.
9. D. G. Ramey and J. W. Skooglund hydro governor representation for system stability study IEEE Trans. Vol. PAS-89, pp. 106-112, 1970.
10. C. C. Young, Equipment and system modeling for large scale stability studies, IEEE trans. Vol. PAS-91, pp. 99-109, 1972.
11. IEEE committee report, dynamic models for steam and hydro turbines in power system studies, IEEE Trans. Vol. PAS-92, pp. 1904-1916, 1973. b
12. The Guide to hydro power mechanical design ASME hydro power committee HCI Publication 1997.
13. O. D. Thapar, V. K. Verma, R. C. Chauhan and K. K. Batta – Optimum Adjustment of Bhakra Governor.
14. Bhakra Left Bank Power House Governor Study Of Behaviors – Engineering Report no. WR-ELEC/7; WRDTC University of Roorkee (Now IIT)- Aug. 1980
15. IEEE std. 125-1988 & 2007 recommended practice for preparation of equipment specification for speed – governing of hydraulic turbines intended to drive electric generator.
16. Brown, J. Guthrie, Hydro-electric Engineering Practice, Volume 2.
17. Engineering Monograph No. 20, Selecting Hydraulic Reaction Turbines, United States Department of the Interior, Bureau of Reclamation USA.
18. Development and supply of five electronic/digital governor PID design and implementation – Pradeep Digital Private Ltd. – 1990.
19. Y. S. Jaduan electro-Hydraulic Governors Regulate Chibro Turbine – Source by OPSEB 'Chibro underground power house'.