MODELING AND STABILITY ANALYSIS OF ELECTRO HYDRAULIC GOVERNOR IN HYDRO POWER PLANTS

A DISSERTATION

Submitted in partial fulfillment of the

Requirement of award of degree

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in

ALTERNATE HYDRO ENERGY SYSTEMS

By

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CANDIDATE’S DECLARATION

I hereby declare that work which is being presented in the dissertation entitled **“MODELING AND STABILITY ANALYSIS OF ELECTRO HYDRAULIC GOVERNOR IN HYDRO POWER PLANTS”** in partial fulfillment of the requirements for the award of the degree of **Master of Technology** in Alternate Hydro Energy Systems, submitted in **Department of Hydro and Renewable Energy, Indian Institute of Technology Roorkee, Uttarakhand, India**, is an authentic record of my own work carried out under the supervision of **Dr. R. P. Saini**, Professor, Department of Hydro and Renewable Energy, Indian Institute of Technology Roorkee.

I have not submitted the matter embodied in this report for the award of any other degree or diploma.

Place: Roorkee

Date: June, 2019 **(RAN BIR CHHETRI)**

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Global renewable energy generation has been on the rise over the last few decades and continues its strong progress in energy sector. Of all renewable energy sources, hydro power is renewable, environment friendly and has high energy pay back ratio. It not only offers clean energy but also provides additional facilities such as water services, energy security, regional cooperation and balanced socio-economic development. The flexible generation technology asset as well as energy storage in reservoirs has led to crucial driving agent for global development. Therefore, hydro power is important and cost-effective renewable energy source of electricity generation worldwide. The power sector is one of the key economic drivers of world's economy. With the construction of new hydropower plant and development of inter-area transmission network, the power system stability becomes a challenge.

The constant speed requirement of hydro turbine-generator set is met by critical device called speed governor. Therefore, speed governor of hydraulic turbine controls its speed or power for specific purpose. Diverse disturbances emerge in the power system and stability becomes a great concern as the process is not linear. In order to study the stability of speed governor of hydraulic turbine unit in the power plant, the modeling is identified as fundamental platform.

Under the present dissertation work, modeling and analysis on stability of electro-hydraulic governors on hydropower plants is carried out. An extensive literature review is carried out on modeling and stability problems on hydropower plant and electro-hydraulic governor. The model of the hydropower plant using MATLAB, Simulink is developed. The characteristics of plant under different operating conditions are presented. The investigations on stability of electro-hydraulic governor when subjected to external disturbances such as transients due to load change as well as three-phase fault in power system are illustrated. For the interconnected hydropower plant, comparative investigation on PID and PI governors on different operating conditions are also presented. Based on simulation results of model of hydropower plant, it has been found that change of derivative gain to higher value led to instability of governor. The electro hydraulic PI governor resulted better output for grid connected plant under to transient fault conditions.

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NOMENCLATURE

Symbol	Description	Units
P	Power	kW
η	Efficiency of plant	-
g	Acceleration due to gravity	m/s^2
Q	Discharge	m^3/s
H	Head	m
ω_1	Maximum speed	rad/s
ω_2	Minimum speed	rad/s
T_w	Water starting time	s
l	Length of given portion water column	m
A	Cross-sectional area of water column	m^2
T_m	Mechanical starting time	s
I	Combined inertia of turbine, generator, shaft etc	$kg\text{-}m^2$
Hi	Inertia constant	-
ξ	Damping ratio	-
ω_d	Damped natural frequency	rad/s
ω_n	Undamped natural frequency	rad/s
bp	Permanent droop	-
bt	Temporary droop	-
Td	Damping time	s
Kp	Proportional gain	-
Ki	Integral gain	-
Kd	Derivative gain	-
Q_{in}	Inflow to reservoir	m^3/s
Q_{out}	Discharge	m^3/s
$S_r(t)$	Water stored on reservoir	m^3
Δt	Incremental time duration	s
Δh	Incremental head of tunnel	m
Q_{hrt}	Discharge through headrace tunnel	m^3/s
β	Resistance factor of the pipe or tunnel	-
n	Manning roughness coeffiecient	-
R_h	Hydraulic radius of water conduit	m
U_{tu}	Velocity of water in tunnel/HRT	m/s
H_0	Initial steady state	m
Us	Velocity of water in surge tank	m/s
Hs	Water level in surge tank	m
Cs	Storage constant of surge tank	-
Q_0	Rated discharge through surge tank	m^3/s
Te	Wave Travel time	s
Pm	Mechanical Power	kW

G	Ideal gate opening	m
U	Velocity of water	m/s
P_{hyd}	Hydraulic power	kW
Unl	No load velocity of water	m/s
ΔG	Incremental gate opening	m
s	Laplace operator	-
L	Inductance	H
R	Resistance	Ω
Vq	Quadrature axis voltage	V
Vd	Direct axis voltage	V
ω_R	Rated angular frequency	rad/s
V'_{fd}	Field voltage	V
i_d	Direct axis current	A
i_q	Quadrature axis current	A
L_d	Direct axis inductance	H
L_q	Quadrature axis inductance	H
Rs	Stator winding resistance	Ω
Φ_d	Flux linkage direct axis	Weber-turn
Φ_q	Flux linkage quadrature axis	Weber-turn
V_{fd}	Exciter voltage	V
e_f	Regulator out put	V
Ke	Exciter feedback gain	-
Te	Exciter time constant	s
V_{max}	Maximum amplifier output	V
V_{min}	Minium amplifier output	V
Vs	Sending end voltage	V
V_R	Receiving end voltage	V
Is	Sending end current	A
I_R	Receiving end current	A
Z	Impedance of transmission line	Ω

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Energy is one of the crucial inputs in universal activities. Numerous functions that are essential for the existence tends to halt when energy supply stops. It is one of the vital driving forces for socio economic activities. The indispensable role that the energy has played for the existing civilization cannot be under estimated. With increased in industrial and agricultural production, modern transport and communication facilities and reduction of working hours has been realized as a result of the availability of energy. Subsequently, there is very close connection between the energy consumed and living standard, which indicates that higher the per capita energy consumption, higher is the living standard. The energy access is also vital for the accomplishment of many sustainable development goals, in addition to those involved with gender equality, progress in health sector and poverty alleviation. It is estimated 15% of total population, i.e. 200 million people in developed economies, suffer from energy shortage [1].

The transition from agricultural economy towards industrial development and knowledge-based economy has attributed to economic growth. Consequent structural changes in economy led to deviations and level of energy consumption. The conventional sources of energy are not enough to provide energy as the utilization of energy has doubled with increased population, energy intensive industries, expansion of economy and modernization. In fact, the production and usage of energy have adversely affected the environment across the globe. Excessive emission of greenhouse gas in the atmosphere has caused to climate change. It has been projected that globally energy related GHGs emission would increase by 13% [2]. Due to the fast depletion of the fossil fuels and their associated environmental impacts, it is compelling to explore different renewable energy sources in order to support the sustainable development of a country. Therefore, renewable energy plays vital role to mitigate climate change, in sustainable manner.

The energy resources are categorized as fossil fuels, nuclear resources and renewable resources. The renewable energy resources are naturally replenished despite being used and considered as clean source of energy. Fig.1.1 shows the current global energy system dominated by fossil fuels, which is about 28.4% of coal, 22.1% of gas and 34.6% of oil whereas Nuclear and Renewable Energy contributed 2% and 12.9% respectively [3].

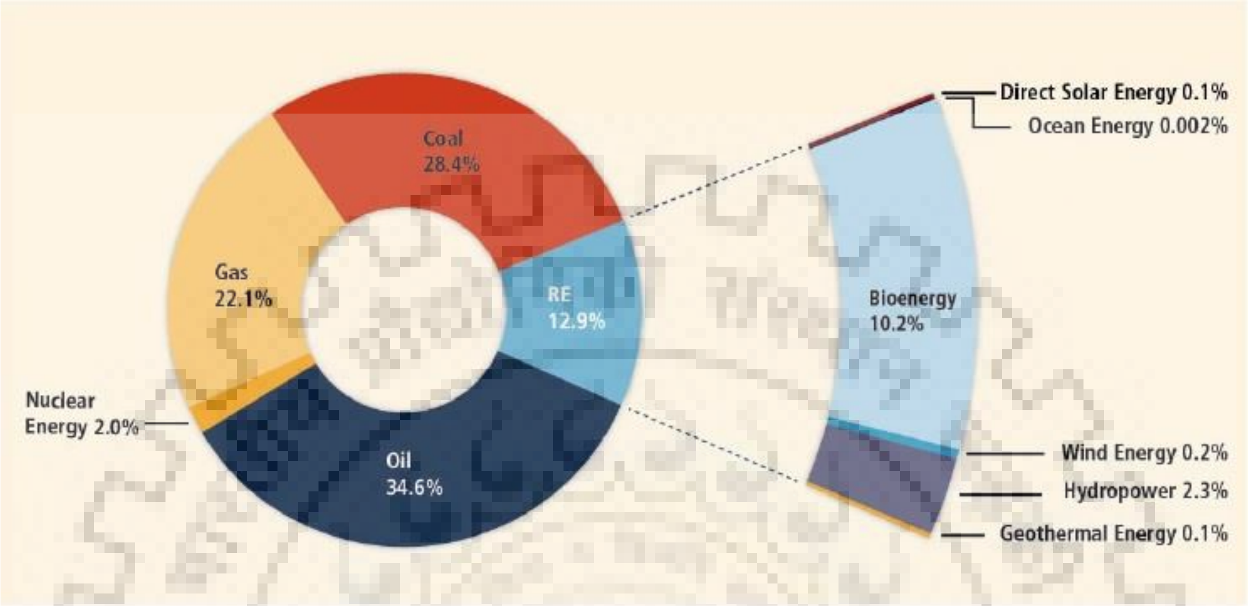

Fig. 1.1: Shares of Energy Sources in Total Global Primary Energy Supply [3]

The ultimate source of all kinds of energy on earth is the sun, either directly or indirectly. Biomass is the product of photosynthesis of plants, where plants converts energy from sun. The fossil fuels such as coal, oil and gas are converted substance of flora and fauna that once lived on earth, existed by capturing sun’s energy. Likewise, solar energy has become significant source of renewable energy, wind energy, tidal energy, wave power all depends on solar energy. Similarly, hydroelectric energy relies upon the hydrological cycle that is dependent on sun.

Hydropower is one of the principal renewable sources for generation of electricity worldwide, providing 71% of all renewable electricity. It has reached 1267 GW of installed capacity in 2017, it provides over 16% of global electricity production [4]. The hydropower resources are widely distributed as compared to nuclear and fossil fuels [5].

Large Hydro Power & SHP potential in India is 148701 MW and 20000 MW respectively and so far, only 30% and 22% has been tapped. All India total Installed capacity of Large Hydro and SHP are 44963.42 MW and 4418.15 MW [6].

1.2 HYDROPOWER AS SUSTAINABLE ENERGY TECHNOLOGY

Hydroelectric power is one of the oldest technologies of generating electricity, which is most important and widely-used renewable source of energy. The electricity is generated by conversion of energy from moving water in hydropower technology. The generation electricity from hydropower is the clean and green source of renewable energy with a low carbon footprint therefore has economical, technical and environmental gains. The charge of hydroelectricity is comparatively low compared to others sources. Thus, it is one of the primary resources of generating electricity worldwide due to commitment of all nations for minimizing carbon emission. As matter of fact, most countries give priority to hydropower development to meet the increasing demand of electricity.

Hydropower is a proven, mature, foreseeable, viable and highest efficient convertible renewable energy source which also has highest energy payback ratio. The typical new hydropower has conversion efficiency from hydraulic to electrical in the range of 90 % to 95% and thereby indicating the most efficient renewable energy sources.

In addition to low-cost electricity supply, hydropower offers energy storage and other supplementary services that contribute to the more dynamic management of the electricity supply system. Therefore, it plays an important role in balancing of the grid and ensures energy security in a world that is going towards rising amounts of intermittent renewable energy sources, such as solar and wind followed by growth of smart grid. The alternate sources of energy provided by hydropower, helps to conserve the fossil fuels, consequently reducing the environmental impacts. As hydropower has good interactions with all generation technologies, its role is likely to increase in importance with electricity systems of the future. Greater consideration of water resource management benefits offered by hydropower facilities are flood control, water conservation during droughts or dry seasons, solving irrigation problems, making the river navigable and construction of recreation amenities. These multiple services and benefits have revived curiosity in hydropower and have changed perceptions of its importance. The sustainable development practices in the hydropower sector plays vital role towards fighting climate change in the world [7].

Basically, hydropower has been developed to base load at low cost. The continuous water flow through the turbine attributes consistent generation for the energy mix. As the hydro plant can be started or stopped quickly, also provide peaking power since it has ability to release water in short duration thereby responding to immediate requirement of power on the grid. The role of hydropower is continuously increased with the installations of wind power and solar PV. Hydropower plant with storage of water in dam provide energy storage mechanism which gives more flexibility. The pump storage plants can provide energy storage, stability and energy balancing. As the share of renewable energy increasing day by day, the pump storage plants play vital role in energy the power system stability [5].

The existing commercially available technologies for electricity generation is through the conversion of hydraulic energy into mechanical energy with the help a turbine coupled to a generator. The following equation represents the power generated from hydropower;

$$P = \eta g H Q \tag{1.1}$$

Where,

P is power generated in kW
η is overall efficiency of the plant
g is acceleration due to gravity in m/s^2
Q is discharge in m^3/s
H is head in meter

Synchronous generators are mostly used in hydropower plants, due to better power factor, high efficiency, constant speed and other constructional features. However, asynchronous generators or inductions are also used in hydropower plants. The typical hydroelectric plant system is shown in Fig.1.2. Hydropower plant is essentially categorized as base load plant and peak load plant. The base load plant normally operates continuously at the same time generates constant power all over the year. The power plant of run-of river without pondage and storage type are the base load plant. The peak load plant is the hydro power that is capable to supply electricity during peak hours. Classic examples of peak load hydropower plant are pump storage and run-of river with pondage. Similarly, hydropower plant are of isolated and grid-connected type based on the site condition and availability of resources [8].

In the hydropower plant, the speed of turbine must be kept constant despite change of load demand. The constant speed requirement of hydro turbine-generator set supplying an AC grid by synchronous generator needs speed regulation, sometimes in connection with distribution and load regulation [9].

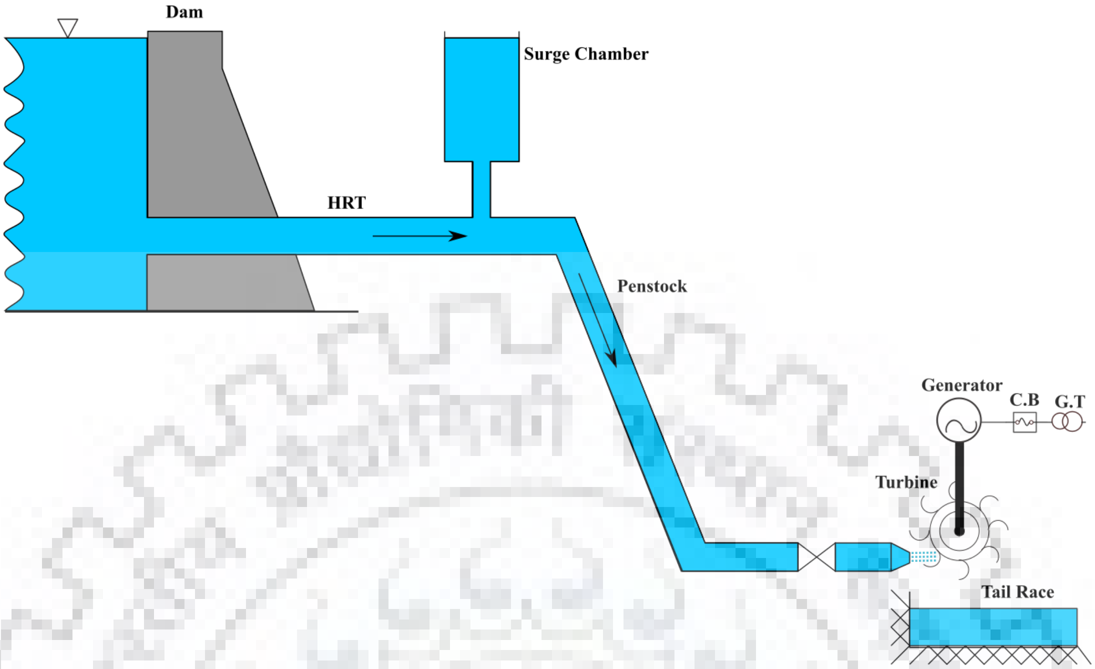

Fig. 1.2: Typical Hydroelectric Plant

1.3 MERITS OF HYDROPOWER

With increase in energy price from other sources and climate change mitigation measures, hydropower can be most preferred solution to electrify urban and rural area. The main advantage of hydropower technology is its robustness and last for 50 years with less operation and maintenance cost. The following are merits of hydro power.

i. It is renewable, clean and non-polluting free source of energy.
ii. Operational and economic superiority.
iii. The technology offers reliable and flexible operation.
iv. Hydro Power plants have long span of life.
v. Quick start and stop and also respond very quickly in few seconds to meet the load changes as a result enhance the power system stability.
vi. It has low generation cost.
vii. It can be used as multi propose project and contributes to socio-economic benefits.

1.4 DEMERITS OF HYDROPOWER

The drawbacks of hydropower projects as listed below.

i. High capital intensive and long gestation period.

ii. Primarily depend on snow melt and rainfall.
iii. Hydropower based on run of river scheme cannot be used for peaking of load.
iv. Large hydropower project may have environmental consequences such as submergence of land by reservoir and migration of aquatic animals in river is hampered by creation of barrier by dam.

1.5 HYDROPOWER SCHEMES

Basically, hydropower plants are site-specific, they can be classified into following categories as per the operation and type of flow.

1.5.1 Storage Schemes

Large quantity of river water is impounded by construction of dam that acts as electricity storage system. The storage takes care of variation of water supply at the time of such as draught, flood and load fluctuations. The electrical energy is produced by discharging water from reservoir with the help of gates and valves the in turn rotates turbine -generator sets. The storage hydropower plant can be operated as peak load as well as base load as per the system requirement [10]. The schematic of storage scheme is shown in Fig.1.3.

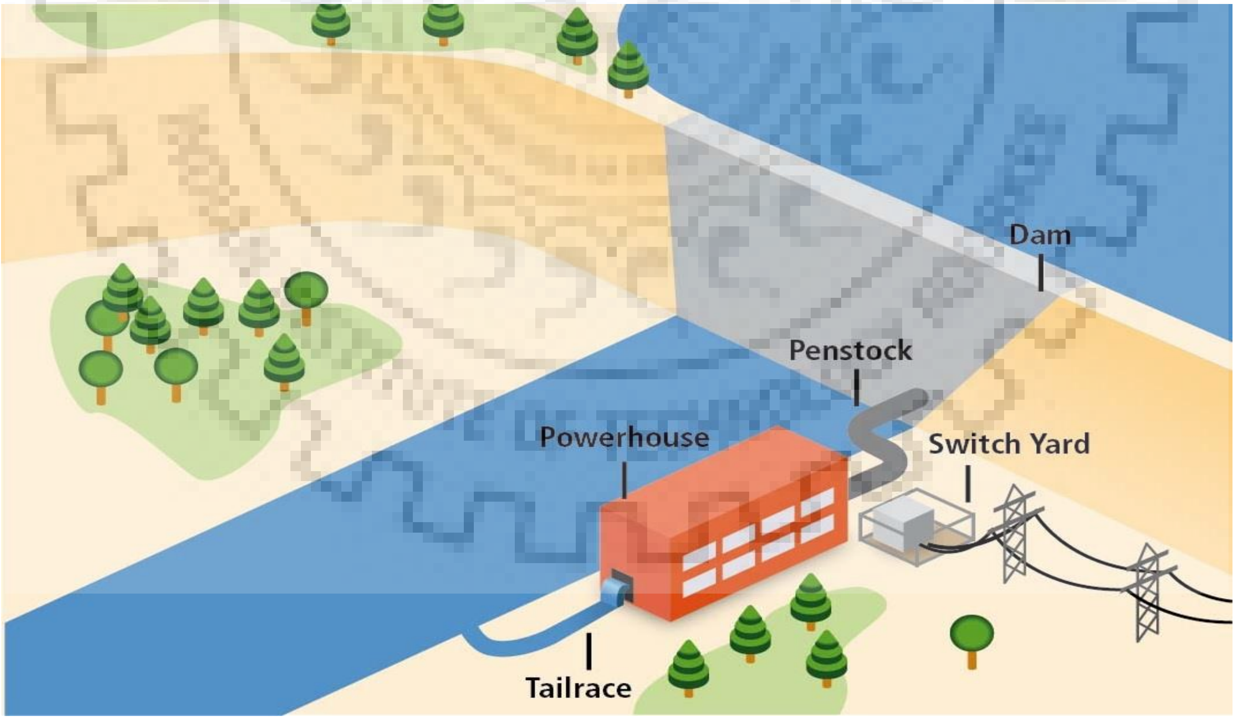

Fig. 1.3: Storage Type of Hydropower Scheme [11]

1.5.2 Pump Storage Schemes

Some portion of water is pumped back to reservoir from lower tail race during off peak period as shown in Fig.1.4. The turbine-generator set is utilized for pumping of water, however in some case separate pump is coupled with the shaft. Water is released back to lower reservoir when electricity demand is high. Most advantage of pump-storage scheme is their interaction with other renewable energy supply system which are variable in nature such as solar and wind.

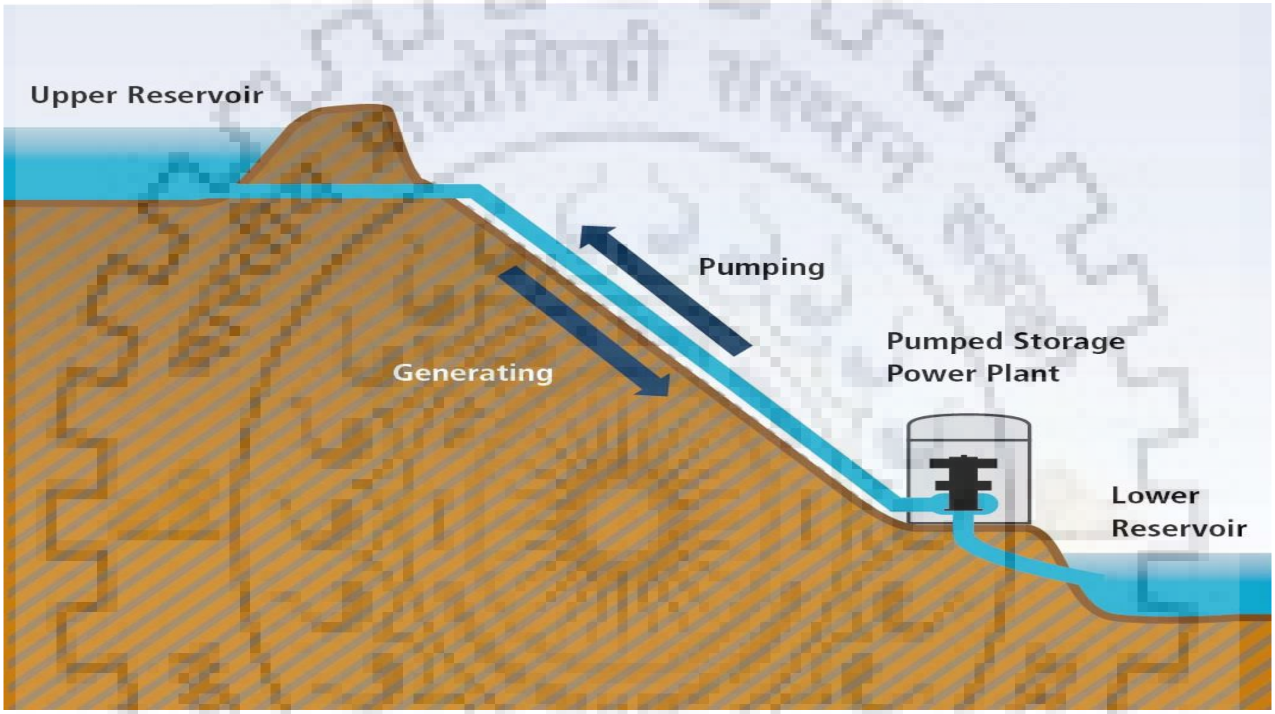

Fig. 1.4: Pump Storage Hydropower Scheme [11]

1.5.3 Offshore Schemes

Growing group of hydro power technologies that uses tidal currents or wave power of harness the electrical energy from sea water. Some of the technologies are tidal, ocean thermal, osmotic and hydro kinetic [7].

1.5.4 Run-of-River Schemes

Essentially the run-of-river scheme, can be with or without water pondage, storage only for short term and utilizes as it flows such as canal based or with penstock as shown in Fig.1.5. As a result, the water is not stored at the time of flood. The hydropower plant of run-of- scheme deliver continuous electricity supply that principally base load to grid system. The output of the plant is subject to the weather condition and seasonal variations.

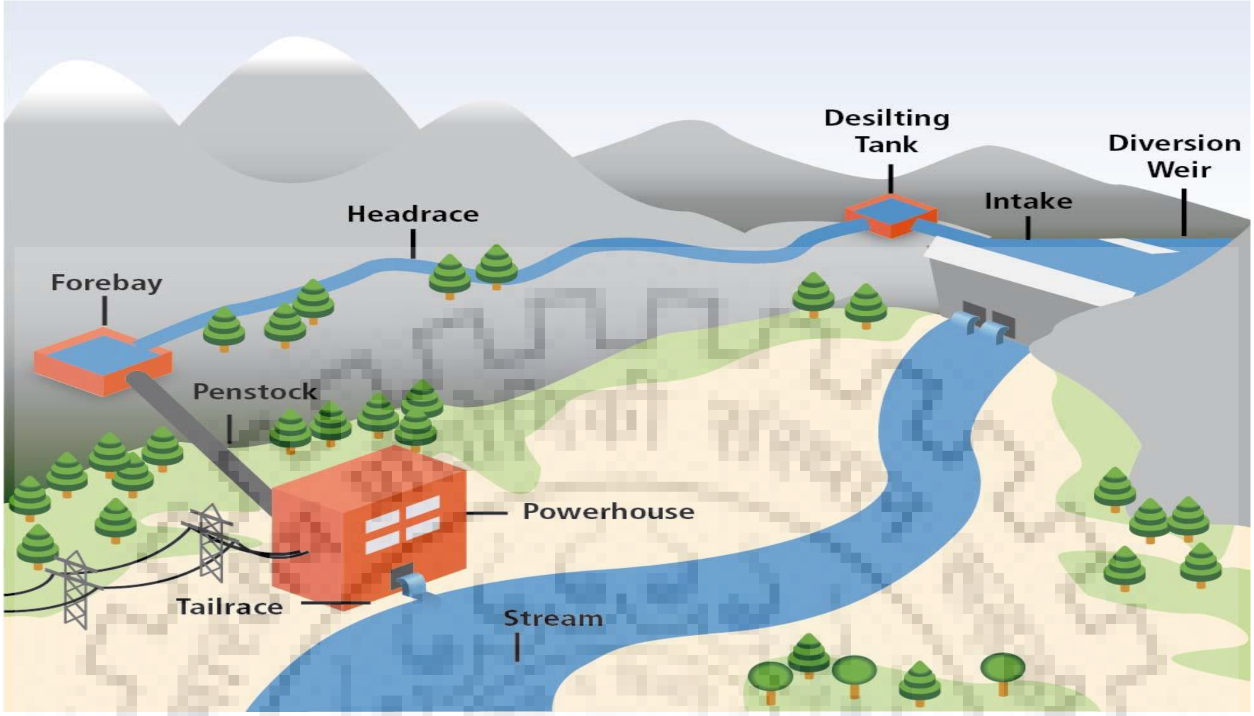

Fig. 1.5: Run-of-River Hydropower Scheme [11]

1.6 HYDRAULIC TURBINES

The power generated from water is most important contribution to total power production in the world. With the development of hydraulic turbine, it made possible, in which energy of flowing water is transferred to the shaft of generator that produces electricity. The blades or buckets are fitted to rotating disc or shaft of hydraulic turbines. When flowing water pass through the hydraulic turbine it strikes the buckets or blades of turbine thereby producing torque to rotate.

Most of modern hydraulic turbines are directly coupled to synchronous generator which must run at constant designed speed. However, for low speed turbine with horizontal shaft are equipped with gear box system as speed increaser to match the speed of generator. The generator speed is fixed by number of poles pair and the required frequency of the power system. Due to several reasons frequency cannot be allowed to vary. Classification of modern hydraulic turbines can be based on following ways [10].

1.6.1 Based on Head and Discharge

i. High head low discharge turbine such as Pelton, Turgo Impulse, Cross flow.
ii. Medium head and medium discharge, Francis turbine.
iii. Low head, high discharge turbine such as propeller, Semi Kaplan, Kaplan.

1.6.2 Based on Action of Water Over Runner

i. Impulse turbine which requires high head and low discharge.
ii. Reaction turbine which requires low head high discharge.

1.6.3 Based on Direction of Flow Over the Runner

i. Tangential flow turbine.
ii. Radial flow turbine.
iii. Mixed flow turbine.
iv. Axial flow turbine.

1.6.4 Based on Shaft Disposition

i. Vertical shaft.
ii. Horizontal shaft.

1.6.5 Based on Specific Speed

i. Low specific speed.
ii. Medium Specific speed.
iii. High specific speed.

1.7 HYDRO POWER TURBINE GOVERNORS

The critical component of a hydro power unit is a turbine governor that help in efficient conversion of hydraulic energy to mechanical energy and further electrical energy. One of the important of parts of hydropower plant unit is the turbine governing system, which plays vital role in maintaining safety, stability, economical and efficient operation of plant.

The speed of hydro turbine-generator needs to be controlled in order to keep the speed within the specified limit, so as to meet the requirements of grid frequency value. Therefore, with regard to speed and load control, hydro turbine governor is one of the important equipment in a hydroelectric turbine-generator set.

1.7.1 Purpose of Governing System

In standalone hydropower plant, frequency is maintained by balancing the generation and demand. The electricity supply frequency is determined by speed and number of poles of synchronous generator. The power system stability is main concern as the load at consumer side varies continuously. Similarly, in grid- connected hydropower station, the variation load in normal condition in grid has very less effect, therefore impact to governing system is less. The governor plays a role when there is change in inputs to the hydraulic turbine such as head, discharge and part load of generator. Moreover, turbine governor must act to satisfy all the conflicting situations.

1.7.2 Approach of Governing System

There are non-conventional and conventional approach of governing system used to control the speed of hydraulic turbine. Basically, non-conventional approach is used only in power plant in micro and pico range in order to minimize the cost. In such technique, proper adjustment of either turbine input or load is required. Whereas the conventional approach is utilized in the power plant of all sizes may be complex and expensive with high standard [9].

1.7.2.1 Non-Conventional Governing System

Fundamentally the output is not superior quality due to large variation of parameters like voltage, frequency and speed. However, it can serve the purpose rural communities where high quality of supply is not required. The non-conventional type of governing system where the load is managed by the Electronic Load Controller (ELC) and inputs to the turbine are fixed. It is used in low capacity plants such as Pico and micro hydel.

1.7.2.2 Conventional Governing System

In the conventional governing method of turbine, the inlet of water into turbine is regulated, with the variation of load which in turn controls speed. A governor senses the speed (or load) of a turbine and controls the inlet water to the prime mover to maintain its speed (or load) at a preferred level.

Due to increase in development of hydropower projects in Bhutan, the power system network is becoming more complex. As the complexity of grid increases, hydropower plant should be operated more efficient and optimize the operation auxiliary equipment of unit such as governing system, excitation system etc. The load fluctuations and outages of unit as a result of governing system instability are experienced in hydropower plants. The governing system of the unit must be balanced to obtain desired output of turbine control system; however, the balancing of governor gets altered after due course of operation. Likewise, to investigate the governor settings in line with guidelines of power system operator both national and international without compromising the stability of governor of hydropower generating units is area of study.

1.8 ORGANIZATION OF DISSERTATION

The dissertation has been organized and presented in sequence as follows:

Chapter 1 presents the overview of different energy scenarios, hydropower as sustainable technology for energy generation, different types of hydropower plants, types hydraulic turbines and purpose of hydro turbine governor.

Chapter 2 presents the extensive literature review of modeling and simulation of hydropower plant to investigate the stability of electro hydraulic governor. The researches on advancement of electro hydraulic governor used in unit of hydropower plants and the optimization of tuning of governors are also reviewed in depth. Based on the literature review, research gaps are identified, objectives of the study have been framed thereafter and discusses the methodology adopted.

Chapter 3 covers overview of hydraulic turbine governor development, operating mechanism, different parts of governor, types of governor used in hydraulic turbine control, characteristics of governor, parameters of governor, stability of governor and justification for selecting electro hydraulic governor for stability study through modeling.

Chapter 4 discuss the modeling of hydropower plant, modeling process, mathematical modeling of different components of hydropower plant, the sub-system like reservoir, head race tunnel, surge chamber, penstock, turbine, governor for hydraulic turbine, synchronous generator, excitation and transmission line.

Chapter 5 presents on simulation of model of hydropower plant prepared in MATLAB Simulink, validation of model performance, results and discussion of simulation results under different operating conditions and analysis of PID and PI governors.

Chapter 6 includes conclusions and future scope of work

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Extensive literature review has been carried out on hydraulic turbine speed governor and more emphasize is given on electro-hydraulic governor in order to model and carry out the stability analysis. An attempt has been made to find gaps and scopes for the future work in the area of hydraulic turbine governing system. In this chapter several studies and researches available in literature has been discussed to understand the fundamental principle of governing system of hydraulic turbines.

2.2 MODELS AND SIMULATIONS OF HYDROPOWER PLANT

Kishor et al. [12] studied on hydropower plant models and control in line with requirements of advance modeling and control methods for effective and efficient control of power plants. It presented that the new approach in turbine control systems with artificial intelligence in recent development. The usage of artificial intelligence in turbine governing is the substitute of PID electro-hydraulic governor with neural network, fuzzy logic or hybrid controller of neural network. It is noted that as far as turbine modeling is concerned, linear modeling was carried out in earlier in the tuning the governor by classical technique. Due to the drawback of linear model, investigation was done in non-linear model which provided better solution for optimum performance of governing system.

Murat et al. [13] constructed the hydropower plant model considering a long penstock, an upstream surge tank for vertical Francis turbine and investigation was carried out for the model. The model was tested on MATLAB/SIMULINK. The hydropower plant model was constructed considering characteristics of Kadincik II HEPP and validated through comparison between field test measurements and simulation results.

Junjun [14] developed the mathematical model and conducted simulation on the digital electro-hydraulic servo system of speed governor system of turbine. The critical component of governing system which was analyzed. The servo system showed good stability, fast response and good robustness in simulation and external load has no implication on servosystem’s dynamic quality. The results of simulation on the mathematical models demonstrate that the system has good dynamic properties.

Hannett and Fardanesh [15] highlighted and presented the field test procedure to obtain the accurate model of governor for hydro turbine. The steps to identify various parameters of the model for better output is also discussed. With the case studies, the result from the simulation program indicated that required refining in order to match with recorded measurements.

Mello et al. [16] studied the modeling of linear and non-linear for turbine, surge tank and penstock. The modeling of different governors is also depicted. Application of model that describe the actual operating device is given due importance. In this work, fundamental of hydraulic turbine and its controls for model is discussed in depth.

Jaeger et al. [17] carried out modeling of nonlinear system for hydro turbine and system dynamics was investigated. Both single turbine and multiple turbines with water conduit system of power plant model was carried out and compare with simulated and experimental results. The transient condition due to load rejection was studied and showed the correctness of the model.

Hannett et al. [18] derived the modelling of hydropower plant with multi units of different capacity and investigated model through simulations under operating conditions such as islanding and black start and discussed the parameter settings as well. The tuning criteria for whole plant rather than individual unit for stability under islanding also highlighted and hydraulic coupling effect were also discussed.

Robert and Michaud [19] presented the simplified model of reduces order for multiple units, one model for slow and other for fast dynamics considering penstock and surge tank elasticity. The simulation of model was performed in MATLAB Simulink for validity. Power system equivalent model proposed shows the suitability in power frequency studies.

Weber and Prillwitz [20] investigated the hydropower plants in Macedonia and Yugoslavia through modeling. The mathematical models of hydropower plants components were presented and measurement of various parameter of the plants was conducted at the site to validate the model. The modeling of hydro power plants demonstrated the practical and convenient mathematical model for such complex system that can be utilized for analysis.

Babunski et al. [21] presented both non-linear and linear model of hydropower plant components and studied dynamic features of the model. Comparative analysis of linear as well as non-linear models were carried out. From the simulation results the author concludes that though there is problem in designing the best non-linear model, but the non-linear model response characteristics showed better result when subjected to large signal disturbances.

Kawkabani et al. [22] addressed the modeling and simulation for dynamic analysis of hydropower plant which included electrical and hydraulic system. The author presented simulation for short circuit which indicated the positive impact of PSS. Similarly, the load rejection simulation showed the effectiveness of turbine governor. The simulation result revealed that precise modeling of various hydropower plant components would ensure better stability results.

Barbieri et al. [23] developed a hydro power plant model for Futaleufu to investigate and subsequently improve the plant performance. With model of various parts of hydro power plant, grid fault simulation was studied. The power plant model developed ensures the detailed studies of PSS and proper tuning of governor under different operating conditions.

Oguz et al. [24] carried out the modeling of Adiguzel HPP in MATLAB Simulink program. The speed governor (PID) performance was studied under different load conditions. The dynamic characteristics of the system was through various parameter such as load, frequency, generator terminal voltage and active power. With the proper tuning of PID controller, various parameters like speed, voltage and frequency was stabilized.

Weber and Holst [25] presented the procedure to model and parameters identification of the model regarding the hydro power project. The case study of Djerdap-I hydropower plant in Serbia was carried out. Model was prepared in MATLAB Simulink and simulated with designed parameters. The simulated result was compared with the measurement from the site which indicated the model that can be used for analysis of the power plant.

Izena et al. [26] carried out the modeling of practical Francis turbine and pump storage turbines. Through the modeling the investigation on the implication of hydraulic turbine governor system parameter on the power system was studied. The author concludes through the simulation output that the frequency stability of the power system can be achieved by proper adjustment of the parameters of the turbine governor.

Prillwitz et al. [27] prepared the model of Shkopeti hydro power plant in MATLAB Simulink as per the mathematical models of various critical parts of hydropower plant. Initially the measurements were conducted at plant site for only one hydro turbine generator set. Dynamic model was designed based on the documents and measurements at site. With the simulation results of model, it was concluded close resemblance of the actual plant for interconnected scheme.

Arnautovic et al. [28] presented the mathematical modeling hydro turbine governor for Kaplan unit in state space control system with multi variables. Provided the methodology for structure amendment of the governor to achieve the optimized parameter settings. It is therefore concluded that suboptimal design of the governor model evaluates the superiority as compared to earlier version.

Li et al. [29] developed the modeling of three types for hydro turbine and speed governor as per the prerequisite hydropower generation system in Nordic grid. Off-line and real time simulation of models were carried out for the validation of the performance. The model simulation was conducted in MATLAB software, basically offline simulation in Sim Power System (SPS) and real time simulation in RT-LAB. It is highlighted the significance of transfer of model from offline to real time simulation platform.

Nassar and Weber [30] presented the modeling and simulation of Ataturk hydro power plant in Turkey. Testing for the unit-1 of power plant was carried out especially for the measurement of the governing system parameters. The model was prepared based on the available documents of plant in MATLAB Simulink software. The islanding mode test was simulated and comparative for the measured signal and the simulated signal output was carried out. From the test result depicted the closeness of plant model with real plant for the performance test of speed governor that implemented later as per the power system requirement of Turkey.

Dorji [31] carried out modelling and software simulation on hydro power plant. The different parts of power plants are modeled in MATLAB Simulink software and simulated the overall plant scheme. The investigations were carried out under different operating conditions of the plant. The simulation results were compared with RT-LAB environment to validate.

Holst et al. [32] presented modelling and analysis of hydropower plant, Tala in Bhutan. The model of the plant was developed through MATLAB Simulink environment in details for all the components of the hydro power plant. Overall idea developed to investigate the stability of the power plant in island mode in considering only grid of Bhutan. The simulation result showed that extensive investigation still required for stability in power system network within Bhutan. The hydropower plant performance to be studied properly only with parameter optimization in the detail model of the plant.

2.3 LINEAR & NONLINEAR MODELS OF GOVERNING SYSTEM

Naghizadeh et al. [33] investigated the modeling of components and related controllers which are very significant in analysis of dynamic performance of power system. The comparison of different model is carried out for the simulation of real hydropower plant. The methodology for modeling, simulation and governor tuning of hydro power plants are reviewed. Suitable methods for tuning different types of hydro governors are studied and classical technique is used for PID governors tuning.

Naik et al. [34] studied speed governing system for hydropower plant consisting of novel controller considering the water hammer effect. The controller is PID based on low pass filter which offered efficient in controlling the overshoot, stability and the dynamics of speed governing in hydroelectric plant that supplies isolated and grid connected load. The author carried out the comparison based on open loop frequency response shows that proposed controller offered better improvement in stability of system compared as with conventional PID controller. It concludes that robust PID-low pass filter controller enhanced the stability of hydraulic unit for isolated load under water hammer effect. The author considered such system can be used to study the performance of governor in grid connected hydro power plants under the effect of water hammer. It is established that the PID low pass filter controller gave better stability for hydropower unit that supplies isolated load.

Nanaware et al. [35] carried out dynamic studies of hydropower power plant through modeling hydraulic turbine and governor. The non-linear model was preferred for the study on large deviation of power output and frequency. The simulation of model was performed with MATLAB Simulink and dynamic response of turbine governing system under different disturbances like variation of load was investigated. The study concludes that accurate non-linear modeling revealed the better results under different operating conditions over entire operating range.

Altey et al. [36] presented a technique to design and enhance the performance of hydraulic turbine governor for aged power plants. Developed the mathematical model for the governor by using plant parameters and subsequently the aging and backlash effect was added to the model to match the simulation output with site measurement. Investigated for the mitigation of backlash impact feed forward and Zeigler-Nichols (ZN). The author studied for both the methodology and output was satisfactory however, feed forward method proved to be appropriate as it provides better result in interconnected as well as island mode.

The optimization technique for hydraulic turbine governing system was carried out by Lei [37] through fuzzy self-adaptive PID control method based on the characteristics of hydraulic turbine governing system. The mathematical model of hydraulic turbine governing system was developed and simulation was performed in different operating under the disturbance of frequency to verify the performance and effectiveness of the proposed system. The investigation showed that, in comparison with traditional PID parameter control algorithms, fuzzy self-adaptive PID control is stronger robust with better control performance.

Qian et al. [38] carried out the study on modeling and associated control problems of governing system of hydraulic turbine-generator unit basically of Francis turbine with surge tank. The investigation carried with introduction of additional state variable, a reduced order sliding mode controller. The proposed reduced order sliding mode controller model is simulated to check the performance. It concludes that the proposed technique is feasible and robust.

Bajya and Taparia [39] presented analysis on modeling of hydro station considering the nonlinearity of the system with different kinds of PID controllers. The models were simulated under external disturbances to study the dynamics of the system. Through the simulated result, it was found the impact of nonlinear characteristics during the load disturbances and load changes which can be improved through PID optimization techniques.

Murphy et al. [40] developed and tested the model of microprocessor based electro hydraulic governor the step to substitute the electronic analog governor. The hardware and software components of the digital governor was designed for the testing. The model was tested on simulator for the performance. The authors highlighted that the development and testing of the digital governor would substitute the analog governor. The overall performance indicated that advantages of digital governor as compared to the analog type.

Yongling et al. [41] investigated controller of type Active Disturbance Rejection Controller (ADRC) for hydraulic turbine generator system, which does not depend on an accurate model of the controlled object which could replace the PID control technology. ADRC evolved from PID controller that uses the core concept of error feedback control. As per the simulation results, the performance compared with PID controller revealed reduction of overshoot, decreased in compensation and quality of system gets improved. The research pointed that adjustment time increased slightly. Concludes that ADRC can solve the signal processing defect of PID which makes better control system performance.

Strah et al. [42] presented the procedure of architecture of active power and speed controller of hydro turbine sets in line with the mathematical model of system. Non-linear model was considered for turbine, however, for speed and power controller design the linear was used. Hydro turbine parameters were derived from analytical formulae for wide operating range. The simulated result indicated the good performance and has conformity with experimental results.

2.4 STABILITY STUDIES ON GOVERNOR

Yu et al. [43] investigated stability on hydro turbine governing system through state space method graph theory. For the study the coefficient matrix of state space has been considered for complexity of plant lay out. The regular features of state equations were examined based on stability analysis for governor of hydraulic turbine. The order of state variable specification and use of matrix transformation the coefficients of matrix was determined. The planned method exhibited the small deviation of hydraulic turbine governing system parameters and was in line with theoretical analysis on system stability. Therefore, it establishes from the analysis that the methodology would give basis for analysis of system stability and tuning the governor.

Vereide et al. [44] studied the consequence of throttling of surge tank on governor stability, power control, and hydraulic transients in hydropower plants. Stability study on governor is applicable for hydropower plants applied for automatic control of the frequency in the power system. Author points out that surge tank introduces problem of mass oscillation. Minimum size of surge tank ensures the damping of mass oscillations over the time. However, insufficient size leads to instability of governor system. Surge tank with throttle in greater size will reduce mass oscillation amplitude. Study on throttling effect has been highlighted and numerical modelling showed positive impact on governor stability and power control.

Zhang et al. [45] investigated the transient and dynamic stability analysis of governing system of hydro turbine through modeling by surface cluster approach. The turbine governor characteristics in the start-up process while opening the guide vane was demonstrated by numerical simulation. In this work, it shows that surface-cluster method improved characteristics equations of turbine governing system, where by transient torque and flow can be accurately computed.

Yao et al. [46] presented the analysis on influence of turbine governor on damping characteristic in inter-area fluctuations of the power system and ultra-low frequency production by governing system. With the help of modeling and simulation, it concludes that governing system provides negative damping torque to fluctuation in inter-area and inject ultra-low frequency mode to grid.

Guo & Yang [47] investigated the model of hydro turbine governing system considering the surge tank for dynamic response of frequency control. The study was carried out by assuming sine wave for oscillations of water in surge tank for dynamic response of out power under primary frequency regulation. It concludes that surge tank and penstock parameter can be optimized in design point of view and for operational aspect, the parameters can be tuned based on the analyzed result of sine wave oscillation theory of surge tank.

Chen et al. [48] developed the nonlinear modeling of governing system for hydropower plant with surge tank. State space control system approach adopted for controlling of Francis turbine. Extensive study on dynamic performance of the system with different parameters was made. The numerical simulation depicts that differential adjustment coefficient resulted the better output results for small signal disturbance.

Li et al. [49] presented the investigation on dynamic analysis of transient on turbine governor during sudden loading of turbine-generator. Developed nonlinear model considering the elastic water hammer of penstock model and investigated dynamic behavior of governor by bifurcation diagram and time wave forms. Numerical experiments on governor during sudden load increase with examination on PID controller parameters was analyzed for certain range only for stable operation.

Zhang et al. [50] addressed the load transient phenomena in hydro turbine governor through mathematical modeling. Nonlinear modeling approach is considered for dynamic model. The PID parameters remained unchanged during the transient due to load rejection. Runge-Kutta method is used for numerical simulation. Presented the nonlinear dynamic response by bifurcation diagram, time waveform and steady state range of time $0.22<t<2.63$ was determined for load rejection scenario.

Wang et al. [51] studied the stability of hydro power plant particularly the turbine governing system. The nonlinear mathematical model for governing system of Francis turbine, in view of fractional order derivative in penstock and time delay of hydraulic servo system was considered. The model was numerically solved by the help of modified Admas-Bashforth-Moulton algorithm. The stability of governor was investigated under the influence of fractional order factor and time delay. Based on the simulated results, it shows that increase in time delay of hydraulic servo has bad effect stability of turbine governor irrespective values of fractional order values.

Guo et al. [52] addressed the stability of hydraulic turbine governor for primary frequency regulation considering the surge tank in the power plant system. With the nonlinear model of head loss in penstock, the stability of governor for frequency regulation was investigated. For the opening mode, stability is same for linear as well as nonlinear model. Whereas, for the power control mode the stability is conditional. Author concludes that, stability is better under negative disturbance and worse under positive disturbance for the nonlinear system as proposed.

Nawaz et al. [53] highlighted the modeling hydropower plant including all the critical components to study the dynamic performance of the micro hydro power plant. MATLAB software was used for mathematical model to simulate. The results indicated the non-linearity of hydro turbines that consisted the time varying parameters. Researcher emphasized the significance of modeling and simulation outcome for the stability studies in transient and steady state conditions.

Du et al. [54] studied the power system stability through the modeling of hydroelectric unit governor. The traditional mechanical hydraulic governor model and characteristics of dead zone electro-hydraulic governor model was focused for investigation. PSD-BPA software was used for system stability studies. The output of the simulation for power imbalance as result of fault in power system was studied. The author concludes that the modern digital electro hydraulic governor model has better speed control performance.

Murthy and Hariharan [55] investigated the effect of water column elasticity on stability limit of hydro-turbine unit having long penstock which operated in isolated mode. The study on impact of water column in the system which directed to adjust the parameters of the governor. Its finding showed that the stability margins and the dynamic performance can be improved by incorporation of changed version of water column compensator.

Leonov et al. [56] carried out study on the oscillations in hydropower unit that comprised of hydro turbine generator set and turbine governor system. Various mathematical models for different components of hydro power plant was examined to see the steady state and dynamic stability of the system. The investigator concludes that the modeling exhibited sufficient reliable result for different operating conditions including transient after load changes.

Phi et al. [57] addressed the stability boundaries of hydro turbine generator set based on PID function. Modeling was carried out for different components of the hydropower plant system. The generating unit’s stability was investigated by considering the steady state speed regulation considering loading, system damping, interconnection and PID gains. Outlined synchronous and mechanical oscillations. Application of analysis was successful in actual power system where the system falls under large disturbance.

Xu et al. [58] carried out the sensitivity study based on turbine torque as new technique on hydro power plant with Pelton runner. The investigation covers the mechanical, hydraulic and electrical parameters focused on turbine torque. Mathematical models of various components of hydro power plant carried out and simulated for examinations of mechanical parameters such as misalignment of UGB, LGB and TGB rigidity. Also, excitation current and hydraulic parameters studied for operating stability of turbine generator unit. The researchers conclude that with the result, it ascertains the success of non-linear dynamics for study of stability hydro power plant. Due to the distortion of shaft alignment and bearings in gradual process under operating condition as a result of vibrations of electrical, mechanical and hydraulic factors which ultimately impacted on governor stability.

Kamwa et al. [59] studied the analysis of small signal for hydraulic turbine governor in large interconnected hydro stations. The linearized model of hydro power plant was used in MATLAB software. The state space method was adopted for mathematical modeling. Transient stability of the three different governors was investigated. With the simulated result, it depicts the negative impact of derivative factor of the governor controller for the power plant connected to the grid.

Hagihara et al. [60] investigated stability of hydro turbine generating set comprised of PID governor. The impact of derivative gain and other parameters of the governor on boundaries of stability of the unit of standalone was studied. Root locus method was adopted for research for the implication of governor parameters in dynamics of hydro power station. The author highlights the exceptional adjustment of the turbine governor.

Choo et al. [61] designed hydro turbine modeling for performance analysis and dynamic studies. The modeling considered the long penstock, effects of water hammer and frictional losses in the water conduit system. With the help of the model, the stability of governor under transient condition, especially for load rejection was investigated. The comparative study for model with detail representation of hydro power components and the classical model was carried out. Under the dynamic responses of the turbine governor system, the model with long penstock considering friction and water hammer showed the better performance as per the simulated results.

Choo et al. [62] investigated the hydro turbine governor stability in case of isolated operation situation. The conventional approach where the modeling of turbine generator set connected to isolated system having single load. Through the modeling the PID governor response was examined especially for transient response with least speed deviation and faster restoration after the disturbance. Relative stability was studied through frequency response techniques, like Bode plot, Nicholas chart and Nyquist diagram. The governor settings at optimum to achieve desired response is emphasized.

Chen et al. [63] studied the nonlinear model of hydraulic turbine governor system considering the non-linearity in small signal disturbances. The stability of governor for the hydro turbine was carried out by Hopf bifurcation technique. The mathematical model of the hydropower plant considering the major components that affect the stability was presented in Hopf bifurcation. In order to study the dynamic behavior of the system, parameters such as Tw, Tab etc. were considered. The simulated results with unpredicted limit cycles fluctuations in turbine governing system indicated that need to meet the prerequisite of PID parameters. Simulated result shows that validation of theoretical study.

Schleif et al. [64] addressed the issue of hydro turbine governors and power system operation coordination. The various methods to adjust governor for operation power plant, interconnected as well as isolated were highlighted. Author pointed out the speed governor adjustment in line with power system requirement provided better coordination platform for power system operation. Similarly, delay in servo system and servomotor gain accounts for better achievement of governor response under immediate action.

Finvik [65] studied the effect of hydraulics and the influence on overall hydro power plant performance. The hydro power plant model was prepared on software called LVTrans and simultaneously compared with real plant to simulate. The stability of Riksheim Hydro power plant was investigated and difficulty to maintain the stability as per the power system operator specifications. The negative effect of water hammer on dynamic performance and governor parameter selections for optimum settings was highlighted for isolated condition. From the simulation results, it reveals that proper selection of governor parameters and coordination with power system operator would achieve better stability under different operating conditions.

Choo et al. [66] presented the modelling of hydro turbine governor for control stability study. MATLAB Simulink software was used for modelling. The dynamics of isolated hydraulic system was studied by stability margin evaluation, eigenvalues, root locus and frequency change of in time response of the power plant system. From the simulated result of PI and PID governor, the detailed modelling gives better dynamic behavior of the system.

2.5 TUNING OF GOVERNORS

Vournas and Daskalakis [67] investigated the ideal settings of hydro turbine governor and the regulating capacity chart for hydropower unit. The author addressed the problems of governor tuning in classical approaches. The study shows that results by classical Paynter is very closed to optimal tuning for the stability. The regulating capacity chart also presented that is often required at the planning stage of hydro power project.

Schleif and Angell [68] highlighted the test and settings of hydro turbine governor for optimization of the performance under diverse operating circumstances. Simulated result depicted the effect of internal non-linear characteristics and delay in the improvement and optimization. The researchers conclude that such simulation isolation test gives any gate positions and synchronization under adverse gate position, thereby achieving better response at entire operating range.

Xi et al. [69] presented the backlash setting of governor that effects the power system frequency and electro-mechanical oscillations was also studied. Addressed the proper tuning of the of the governor settings to overcome the stability problem of frequency response in the power system by injecting the disturbance in the model. The simulation results showed the validation of the actual power system during the sinusoidal perturbations. With the alterations of parameters with in the limit showed the damping of the electromechanical oscillations. The backlash incorporation in the modeling of governor shows the achievement of better results in the simulation.

Singh et al. [70] studied optimum tuning of governor parameters for hydraulic turbine system through genetic algorithm. The hydropower was modeled and tuning of temporary droop in governor controller was done with genetic algorithm by minimizing the performance indices like criteria like ISE, IAE, ITAE and ITSE. It presented that temporary droop controller parameters with GA gave the optimal response of the frequency when step load change was taken into consideration. From the simulation results, the frequency response indicates the good damping, less settling time and overshoot for Integral Time multiplied by Absolute Error (ITAE).

Sarasua et al. [71] investigated the dynamic response of the hydropower plant with long penstock. The power plant is of pump-storage type with doubly fed induction generator supplying the load to island power system. The two methods of governor tuning such as root locus and Pareto approach are presented. The performance was compared through the simulations of non-linear model. Pareto-based governor tuning offered better response in terms of damping and overshoot of variables of mechanical and hydraulics components.

Olivera et al. [72] carried extensively studied the optimal method for tuning of PID controller of hydraulic turbine governor with transient droop compensator. The proposed system was studied on the Desired Time Response Specification (DTRS) in input guide vane servomotor with typical rate limiters and gain saturation in power plants. The problem of adjustment of parameter of controller and compensator was overcome by linear programming to the values of PID & TDC by use of state space representation in MATLAB, linprog toolbox. The investigation shows that proposed method offered advantage in the tuning of PID controller and transient droop compensator in load frequency control of hydro turbine problems in coordinated fashion in less computational time. In comparison with performance of other method of tuning such as maximum peak resonance specifications, the proposed method indicates very effective under different operating conditions.

Culberg et al. [73] reviewed the new technology in hydro turbine governing system, which where the improved technology in this field ultimately increases the performance of the system. The analysis carried out current standard control algorithm for turbine governors, the PID controller. It illustrated the processes involved and the limitations of conventional manual tuning of PID controller. It pointed out the tuning of governor for hydro turbine by intelligent system such as Artificial Neural Network and Fuzzy Logic which provides ability for automatic tuning of PID controllers.

2.6 SUMMERY OF LITERATURE REVIEW

The summery of different modelling techniques on hydraulic turbine governors by various researchers is presented in Table 2.1.

Table 2.1: Summary of Modeling of Hydraulic Turbine Governors by Different Researchers.

Sr. No	Author	Parameters	Modeling	Findings/Remarks
1	Naghizadeh et al. [33]	P_m, T_w, G, Z_p, T_{ep},	Turbine and Penstock; $\frac{\Delta \mathrm{Pm}}{\Delta \mathrm{G}} = \frac{(a23 + a11a23 - a13a21).Tws}{1 + a11Tws}$ Hydraulic Surge Impedance; $Zp = \frac{Tw}{Tep}$	The equation for determination of model parameter have been presented by researcher. Review and comparison of different model would benefit to choose best model for specific purpose.
2	Naik et al. [34]	P_m, G, Z_p, T_{ep},	$\frac{\Delta \mathrm{Pm}}{\Delta \mathrm{G}} = \frac{(1 - Zp.tanh.Teps)}{(1 + 0.5Zp.tanh.Teps)}$	Studied speed governing system for hydropower plant consisting of novel controller considering the water hammer effect. It concludes that robust PID-low pass filter controller enhanced the stability of hydraulic unit for isolated load under water hammer effect.
3	Nanaware et al. [35]	q, hs, h_1, T_w, G, h, A_t, q_{nl}, β, ω	Penstock; $\frac{dq}{dt} = \frac{(hs - h - hl)}{Tw}$ Turbine; $q = G.\sqrt{h}$ $Pm = At.h(q - qnl)$ $Pm = At.h(q - qnl)) - \beta G \Delta \omega$	Carried out dynamic studies of hydropower power plant through modeling hydraulic turbine and governor. The results of nonlinear model showed the suitability for dynamic studies of hydropower plant.

4	Murat et al. [13]	H, Hs, Hl$_2$, T$_w$, U$_{tu}$, Cs, U$_s$, H$_{tr}$, H$_l$, H$_Q$, Z$_p$, U$_{tr}$, G	Tunnel dynamics; $\frac{dUtu}{dt} = \frac{(H - Hs - Hl2)}{Tws}$ Surge Tank dynamics; $Hs = \int Us.dt$ Penstock dynamics; $Htr = Hs - Hl - HQ$ $HQ = Zp.\tanh(Tep.s)\,.Utr$ $Utr = G\sqrt{Htr}$	The model is validated through comparison between field test measurement and simulation results.
5	Altey et al. [36]	P$_m$, U, U$_{NL}$, H, D, ω, G	Hydraulic Turbine; $Pm = (U - UNL)H$ Turbine penstock; $Pm = (U - UNL)\mathrm{H} - \mathrm{D}.\Delta\Omega.\mathrm{G}$	The response time has improved after the implementation of compensator, using mathematical model simulations.

6	Qian et al. [38]	h, q, T_w, T_r, H_f, T_y	Penstock; $\frac{\mathcal{L}h(t)}{\mathcal{L}q(t)} = -2\frac{Tws}{Tr}.\tanh(\frac{Trs}{2}+\frac{Tr.Hf}{2Tw})$ Wicket gate and Servo mechanism; $\frac{\mathcal{L}y(t)}{\mathcal{L}u(t)} = \frac{1}{(Ty+1)}$ Reduced order model for control design; $\frac{\mathcal{L}hre(t)}{\mathcal{L}qre(t)} = -Tw2.s - Hf2 - Hf1$	The controller with reduced order sliding mode is simulated to investigate the performance. It concludes that the technique contributes to the stability of governor.
7	Hannett and Fardanesh [15]	q, hs, A, L, g, h, h_l	Single penstock; $\frac{dq}{dt} = (hs - h - hl).g\frac{A}{L}$ $\bar{q} = \bar{G}.\sqrt{\bar{h}}$	Presented the field test procedure to obtain the accurate model of governor for hydro turbine. The steps to identify various parameters of the model for better output is also discussed. With the case studies, the result from the simulation program indicated that required refining in order to match with recorded measurements.

8	Mello et al. [16]	q, hs, A, L, g, h, h_l, T_w, G, Cs, As	Conduit dynamics; $\frac{dq}{dt} = (hs - h - hl).\,g\,\frac{A}{L}$ Non-elastic water column $\frac{dq}{dt} = \frac{(1 - h - hl)}{Tw}$ Water starting time; $Tw = \frac{L}{A}\,.\,\frac{qbase}{hbase.\,g}$ $q = G\sqrt{h}$ Surge tank constant $Cs = \frac{As.\,hbase}{qbase}$	Studied the modeling of linear and non-linear for turbine, surge tank and penstock. The modeling of different governors is also depicted. Application of model that describe the actual operating device is given due importance. In this work, fundamental of hydraulic turbine and its controls for model is discussed in depth.
9	Jaeger et al. [17]	q, po, p, pf Tw, G, Twi, Twc	Water column; $\frac{dq}{dt} = \frac{(po - p - pf)}{Tw}$ Turbine; $q = G\sqrt{p}$ $Tw = Twi + Twc$	Carried out modeling of nonlinear system for hydro turbine and system dynamics was investigated. Both single turbine and multiple turbines with water conduit system of power plant model was carried out and compare with simulated and experimental result. The transient condition due to load rejection was studied and showed the correctness of the model.

10	Hannett et al. [18]	P, v, m, G, Tw	Tunnel dynamics; $\Delta P(Ac) = m\frac{dv}{dt}$ Linearized model; $\frac{\Delta P(s)}{\Delta G(s)} = \frac{1 - sTw}{1 + 0.5Tw}$	Derived the modelling of hydropower plant with multi units of different capacity and investigated model through simulations under operating conditions such as islanding and black start and discussed the parameter settings as well. The tuning criteria for whole plant rather than individual unit for stability under islanding also highlighted and hydraulic coupling effect were also discussed.
11	Robert and Michaud [19]	pm, u, H, ϖ, pe	Non-linear model; $G1(s) = \frac{\Delta pm(s)}{\Delta u(s)}$ $= \frac{a1s3 + b1s2 + c1s + d1}{a2s3 + b2s2 + c2s + d2}$ Rotating mass; $2H\frac{d\varpi}{dt} = pm - pe$	Presented the simplified model of reduces order for multiple units, one model for slow and other for fast dynamics considering penstock and surge tank elasticity. The simulation of model was performed in MATLAB Simulink for validity. Power system equivalent model proposed shows the suitability in power frequency studies.

12	Babunski et al. [21]	q, h, hl, L A, g, Pm, c, D, Tw, ϖ	Hydraulic turbine; $\frac{dq}{dt} = (1 - hl - h)\frac{1}{Tw}$ $Tw = \frac{L.qbase}{A.g.hbase}$ $Pm = At.h(q - qnl) - Dc\Delta\varpi$	Presented both non-linear and linear model of hydro power plant components and studied dynamic features of the model. Comparative analysis of linear as well as non-linear models were carried out. From the simulation results the author concludes that though there is problem in designing the best non-linear model, but the non-linear model response characteristics showed better results when under large signal disturbances.
13	Kawkabani et al. [22]	Q11, N11, T11, H, Dref, N, Dref, Q, Tw, l, g, A	Hydraulic system; $N11 = N.\frac{Dref}{\sqrt{H}}$ $Q11 = \frac{Q}{\sqrt{H}.Dref^2}$ $T11 = \frac{T}{\sqrt{H}.Dref^3}$ Water starting time; $Tw = \frac{Qn}{Hn}\,\Sigma\frac{l}{g.A}$	Addressed the modeling and simulation for dynamic analysis of hydro power plant which included electrical and hydraulic system. The author presented simulation for short circuit which indicated the positive impact of PSS. Similarly, the load rejection simulation showed the effectiveness of turbine governor. The simulation results revealed that precise modeling of various hydropower plant components would ensure better stability.

14	Oguz et al. [24]	U, Ku, G, H, Pm, Kp, l	Turbine and penstock; $U = KuG\sqrt{H}$ $Pm = KpHU$ $\frac{dU}{dt} = -\frac{ag}{L}\Delta H$	Carried out the modeling of Adiguzel HPP in MATLAB Simulink program. The speed governor (PID) performance was studied under different load conditions. The dynamic characteristics of the system was studied, by author through various parameter such as load, frequency, generator terminal voltage and active power. With the proper tuning of PID controller, various parameters like speed, voltage and frequency was stabilized.
15	Weber and Holst [25]	a, H, r, q, g	Penstock; $\Delta h = h_B - h_N = r_{DR}q^2$ $a = \frac{q}{\sqrt{(2.g.h_N)}}$	Presented the procedure to model and parameters identification of the model regarding the hydro power project. The case study of Djerdap-I hydropower plant in Serbia was carried out. Model was prepared in MATLAB Simulink and simulated with designed parameters. The simulated results was compared with the measurement from the site which indicates the model that can be used for analysis of the power plant.

16	Izena et al. [26]	L, Q, A, g, H, Tw, Tm, G, D, Mn	Hydraulic system; $\Delta H = -\frac{L}{gA}\frac{dQ}{dt}$ Water starting time; $Tw = \frac{Qn}{g.Hn}\,\frac{L}{A}$ Mechanical starting time; $Tm = \frac{\pi G D^2 N^2}{120 g M n}$	Carried out the modeling of practical Francis turbine and pump storage turbines. Through the modeling the investigation on the implication of hydraulic turbine governor system parameter on the power system was studied. The author concludes through the simulation output that the frequency stability of the power system can be achieved by proper adjustment of the parameters of the turbine governor.
17	Arnautovic et al. [28]	q, h, a, ω, Φ, Tw, Ta, m, D	Turbine flow; $q = q(h, a, \omega, \Phi)$ Turbine torque; $m = m(h, a, \omega, \Phi)$ Water hammer; $\xi = -Tw\,\frac{dq}{dt}$ Electro-mechanical; $Ta\frac{d\omega}{dt} = m - ml - D\omega$	Presented the mathematical modeling hydro turbine governor for Kaplan unit in state space control system with multi variables. Provided the methodology for structure amendment of the governor to achieve the optimized parameter settings. It is therefore concludes that suboptimal design of the governor model evaluates the superiority as compared to earlier version.

18	Nassar and Weber [30]		Unit control; $Speed\ droop = \frac{\Delta f/f_n}{\Delta P/P_n} X100$ Hydraulic system $Tw = \frac{Q}{g.H}\frac{L}{A}$ Penstock; $\Delta h = h_B - h_N = R_{fr} q^2$	Presented the modeling and simulation of Ataturk hydro power plant in Turkey. The model was prepared based on the available in plant documents in MATLAB Simulink software. From the test results depicts the closeness of plant model with real plant for the performance test of speed governor that implemented later as per the power system requirement of Turkey.
19	Zhang et al. [45]	h, Tw, q, Tab, e_n m_t, m_{g0}	Turbine governor; $h = -T_w \frac{dq}{dt}$ Rotational torque; $T_{ab}\frac{dx}{dt} + e_n x = m_t - m_{g0}$	Investigated the transient and dynamic stability analysis of governing system of hydro-turbine through modeling by surface cluster approach. The results indicates that surface-cluster method improved characteristics equations of turbine governing system, where by transient torque and flow can be accurately computed.

20	Guo & Yang [47]	Z, h_y, q_y, T_{wy}, T_F, b_p, K_i, K_p, e_p	Head race tunnel; $z - \frac{2h_{y0}}{H_0} q_y = T_{wy0} \frac{dq_y}{dt}$ Surge tank; $q_y = q_t - T_F \frac{dz}{dt}$ Penstock; $T_{wt0} \frac{dq_t}{dt} = -h - z - \frac{h_{t0}}{H_0} (2q_t + q^{2}{}_{t})$ Governor; Opening control $\frac{dy}{dt} + b_p K_i y = -K_p \frac{dx}{dt} - K_i x$ Power control $\frac{dy}{dt} + e_p p_t = -K_p \frac{dx}{dt} - K_i x$	Studied the model of hydro turbine governing system considering the surge tank for dynamic response of frequency control. The study was carried out by assuming sine wave for oscillations of water in surge tank for dynamic response of out power under primary frequency regulation. It concludes that surge tank and penstock parameter can be optimized in design point of view and for operational aspect the parameters can be tuned based on the analyzed results of sine wave oscillation theory of surge tank.
21	Phi et al. [57]	m, q, z, h, b	Turbine torque & discharge; $m = \frac{\partial m}{\partial z} z + \frac{\partial m}{\partial h} h + \frac{\partial m}{\partial b} b + \frac{\partial m}{\partial n} n$ $q = \frac{\partial q}{\partial z} z + \frac{\partial q}{\partial h} h + \frac{\partial q}{\partial b} b + \frac{\partial q}{\partial n} n$	Modeling was carried out for different components of the hydro power plant system. Stability was investigated by considering the steady state speed regulation considering loading, system damping, interconnection and PID gains.

2.7 GAPS IDENTIFIED

Based on the extensive literature review on hydropower plant modelling and stability, following gaps are identified:

i. There are number of approaches to model the hydropower plants such as experimental and classical approach. Linear model and non-linear models of plant and controller discussed by different researchers. Representation of linear model is not adequate for stability study especially for large variation of output power and frequency. Though researchers carried out modelling for the hydro power plant with reaction turbines consisting of long penstock. There are still additional techniques to model the hydro power plant in non-linear, particularly Pelton turbine with long penstock.

ii. The hydraulic coupling effects of pressurized water path on stability of turbine governing system have not been addressed properly. Therefore, there is a need to study the hydraulic coupling effect on governor stability.

iii. Impact of water hammer on hydraulic turbine governor stability considering the grid connected hydro power station is one of the areas to be investigated further.

iv. Many investigations were carried out earlier on PID governor for both mechanical and electro-hydraulic governor. The settings of governor changes with due course of operation. Such causes of change have not been addressed in depth.

v. The turbine governor’s parameters are tuned to achieve stability and develop robust control strategy. The optimum tuning to obtain desired stability of governor considering the restricted orifice surge tank effect in hydro station with Pelton runner is area of further investigations.

2.8 OBJECTIVES

The main objectives of this study are to analyze the performance of electro-hydraulic governor in hydro power plant through modelling and simulations for better study. Based on literature review and gap identified, the following objectives are outlined.

i. To study the speed governors used for hydro turbines.
ii. To identify the performance parameters of hydraulic turbine.
iii. To develop the model for hydro power plant through software.
iv. To perform stability investigations on electro-hydraulic governor.
v. To analyze the performance of governor under different operating conditions with the help of software simulation results.

2.9 METHODOLOGY ADOPTED

In this section, the research methodology for the modeling and stability analysis of electro-hydraulic governor in hydropower plants is discussed.

The main objectives of the research work are to study the different types of governor used in hydro power plants. Find out the different parameters that associated in the hydraulic turbine governing system. The parameters associated with stability of the turbine governor for the electro hydraulic governor need to considered for the research work. As far as the hydropower project development in world and in Bhutan is concerned, there is much more needed to study stability of power system. In order to carry out the stability investigations, the mathematical modeling of various components in hydropower plants need to be addressed. Similarly, the mathematical models to be developed in MATLAB Simulink software. With the help of simulation results the stability issues to be addressed. The research methodology to be adopted for best strategy in order to minimize the errors in analysis. The methodology adopted for the present study is discussed in the following steps;

i. The whole process of modeling and stability analysis of electro-hydraulic governor in hydropower plants is adopted. The research work on the subject carried out by different authors, published across the globe is reviewed so as to compare and contrast to get optimum results.
ii. Tala Hydropower Plant in Bhutan has been considered to develop the basic model before the developing the complex model.

iii. In the parameter analysis, measured parameters are obtained from the plant and are refined to overcome the errors of the instrument and other necessary processes carried out.

iv. Different parameters that influence the overall performance of the hydro power plant are identified. Some parameters are computed from the basic mathematical model.

v. The plant model is developed on the software and simulated with input parameters. Simulated signal and actual measurement signals are compared. When the measure signal and the simulated signal are identical, the model is then finalized. In case of unsatisfactory results, the whole process starting from the literature reviewed to figure out the errors. Once the model is validated, it was further used for investigation and analysis of the stability of governor in the hydropower plant.

Based on above steps, a flow chart of the methodology for the study has been prepared and illustrated in Fig.2.1

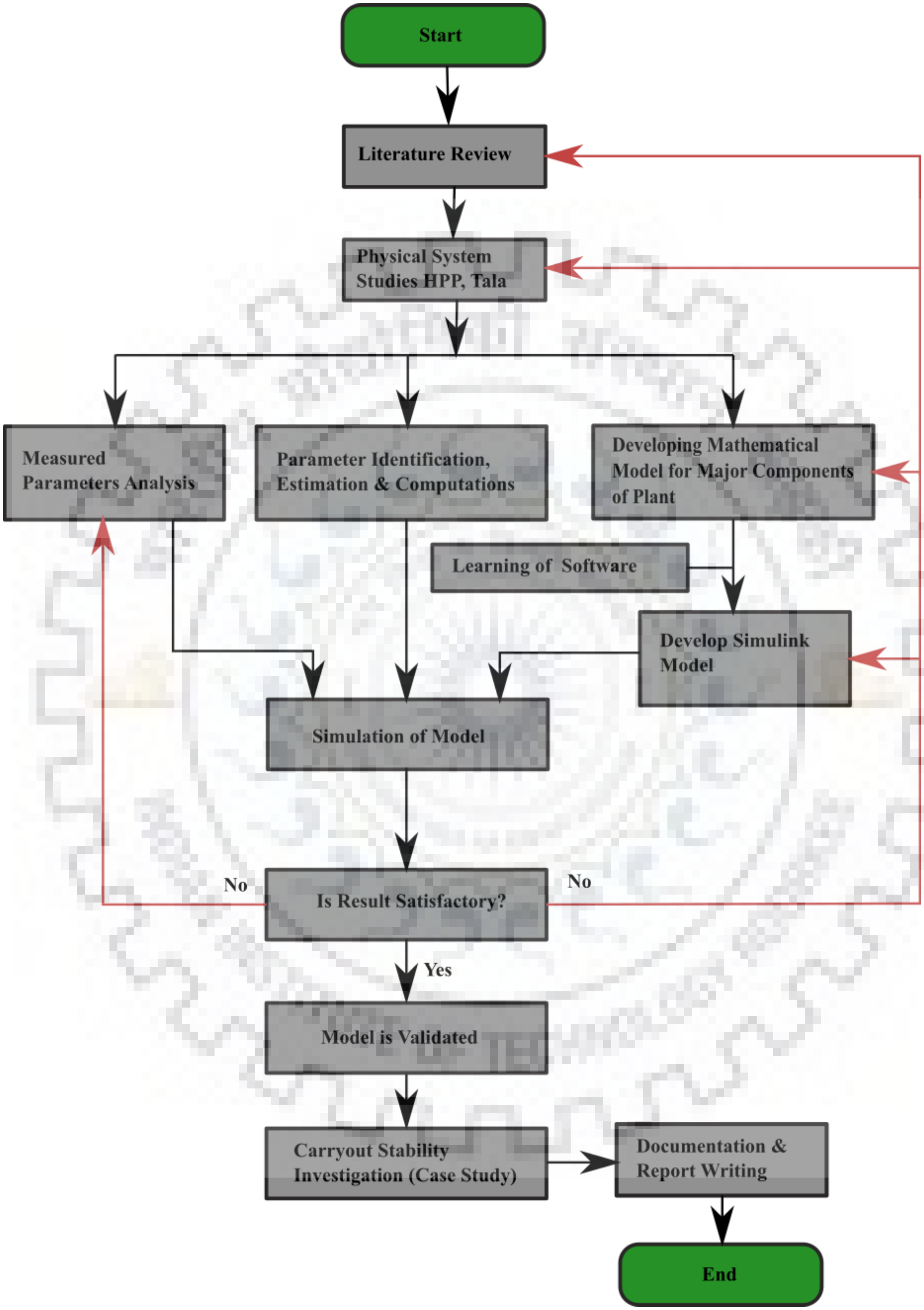

Fig. 2.1: Flow Chart of Methodology

CHAPTER 3

HYDROELECTRIC TURBINE GOVERNOR

3.1 OVERVIEW OF SPEED GOVERNOR DEVELOPMENT

Speed governor of fly ball type integrated with feedback mechanism and servo system was conceived in 1884 and first standardized universal governor was developed in 1906 in Escher Wyss, Zurich. The ‘first -generation’ turbine governor are of mechanical type, that was manufactured after 1930 and recognized as one of the masterpieces of engineering. The mechanical governor was replaced by electric or electronic pilot units integrated with conventional hydraulic servo system, so called ‘second generation’ turbine governor. The automatic speed control system for the hydraulic turbines was developed in the mid of nineteenth century. The introduction of computers gave birth to the digital control philosophy with a backup of analog control system and the modern governor of “third generation” are compact multiprocessor controllers [74].

3.2 HYDRAULIC TURBINE GOVERNOR OPERATING MECHANISM

The speed control system includes the devices such as fly ball and PMG to detect the speed in earlier governor. Whereas in the modern governor, the speed signal generator mounted on the turbine generator shaft for sensing of speed. Other components like servomotors, relays, pressure or power amplifying devices, levers and linkages between speed governor and governor-controlled wicket gate or valve which adjust the flow of water through the turbine consisting of feedback control system. The appropriate valves are opened to admit the more water when the speed gets reduced thereby increasing the power and meet the increase in demand. Likewise, if the power required is less, governor senses increased in speed and allows the valve to decrease the flow of water through the turbine [9]. Therefore, by adjustment of movement of spear valve or guide vane, the flow of water is regulated to maintain the constant speed.

In order to damp the rapid flow changes as result of spear valve or guide vane movement, the oil dashpot is incorporated so as to minimize the pressure surge in water conducting system and subsequently reduced the tendency of fluctuations of governor. Essentially deflector is used in Pelton turbine and pressure-relief valve is fitted for Francis turbine to avoid the excessive pressure development in penstock by diversion of water impinging the runner [75].

3.3 MAJOR PARTS OF GOVERNING SYSTEM

The major parts of speed governors are discussed as follow.

3.3.1 Speed Sensor

In the mechanical speed governor, the permanent magnet generator (PMG) is used as speed sensor. Multi-phase PMG is electrically connected to a matching multi-phase motor (ball head motor) inside the governor cabinet that drives the fly-ball assembly. The speed is sensed by permanent magnet generator (PMG) mounted on the rotor shaft delivers frequency signals to the governor circuits in electro-hydraulic governor. Also, it is a source of an output to operate speed relays for various sequence controls and of power to drive the transistor amplifiers. Toothed wheel mounted on turbine shaft with a magnetic pick up is used for speed sensing. The output frequency of the pickup is measured by speed sensor to determine shaft speed. At present the speed sensing is realized generally by magnetic or fiber-optic sensors incorporated in conjunction with toothed wheels or other devices directly connected to the generator shaft. This type of technique is used in digital electro-hydraulic governor speed sensor [76].

3.3.2 Governor Controller Unit

The governor controller unit was of mechanical at early stage of development and later replace by analog system followed by electronics and digital controller. Proportional Integral (PI) and Proportional-Integral-Derivative (PID) based controller used in control system, however due to the better performance, the governor has been replaced by controller Proportional-Integral-Derivative (PID). Further, microprocessor based digital controller with PID system are being used.

3.3.3 Oil Supply Unit and Hydraulic Oil Supply

The oil pressure unit consists of oil sump, oil pumps, piping system, hydraulic valves and oil filter. During the operating condition, pressurized oil is supplied to main distributing valve by a pumping unit. The pumping unit has rotary (gear or screw type) pump, oil sump tank and pressure tank with appropriate valve and fittings.

3.3.4 Servomotor

It is a linear actuator consist of cylinder in which a piston moves inside when subjected by action of oil pressure. The motion of the piston is transmitted to the guide vanes in reaction turbine and the needle/deflector in Pelton turbine.

3.3.5 Dashpot and Pilot Valve

The dash pot act as damping device during sudden too large opening or closing in of flyball. Thus, damped motion from pendulum is received by pilot valve and subsequently transmitted to relay valve. In order to stabilize and compensate in the governing system, the elements like dash pot and pilot valve are used. The signal of pendulum’s flyball is communicated to relay valve through dash pot and pilot valve [10].

3.3.6 Overspeed Device

The overspeed devices are installed on the turbine shaft. In case of hydraulic overspeed device, it activates an emergency oil supply for servomotor that further actuates emergency solenoid valve during the rise of turbine speed above rated speed, setting may be for instance 110% of rated speed. The unit will be shut down immediately. The other overspeed may be mechanical or electrical, which are integrated for back up protection of unit.

3.3.7 Linear Variable Differential Transformer

The transducer that interlinks, governor controller, HMC, nozzle control cabinet and nozzle spear valve. The feedback signal corresponding to nozzle spear valve position is obtained in the form of current across a linear variable differential transformer (LVDT) in Pelton turbine.

3.3.8 Needle Control Cabinet

The needle control cabinet is basically for Pelton turbine, which is linked with HMC with pipes for flow of oil in directional control valve that is connected to spear valve of nozzle.

3.3.9 Hydro Mechanical Cabinet

The Hydro-Mechanical Cabinet (HMC) is the housing of gate limiter, electro mechanical transducer consisting of electro-hydraulic transducer and hydraulic amplifier, mechanical linkages for the thrust rod which connects to spool of main distribution valve, rotary cam switch, feedback potentiometer, throttling valve, emergency shut down valve, filter and pipe fittings. Along with HMC, the guide vane or deflector servomotor is incorporated.

3.3.10 Main Distributing Valve

The governing system consists of regulating valve which moves the servomotor basically controlled by actuator of valve further controlled by action of pilot valve. The oil pressure unit and these valves connected for power amplification, whereby small displacement by low mechanical signal are amplified to larger values for servomotor movement.

3.3.11 Accumulator (Air/Nitrogen)

Accumulator plays a very vital role in control oil system. It is connected with oil pressure unit and being pressurized by the working oil. The accumulator helps in building up the gap in transient conditions such as spike in oil control system, changeover of pump etc. by releasing stored energy at that particular time. The air accumulator and nitrogen accumulator are used based on the system operating pressure. Usually nitrogen accumulator is used for unit with higher system pressure.

3.3.12 Control System

Depending on the type of governor, control system can be of mechanical, analog or digital. All the components in governing system are inter-connected to form control system to obtain desired out puts based on inputs. The closed loop with feed system, PID control system is common in governing system of hydro turbine.

3.4 FUNCTION OF HYDRAULIC TURBINE GOVERNOR

The hydraulic turbine governor serves following function [76];

i. Controls speed before synchronization: Helps to start, maintain and adjust the speed of unit for synchronization with grid.
ii. Controls active power of unit.
iii. It maintains the system frequency after synchronization by flow adjustment to turbine as per the load variations.
iv. It regulates the output of unit based on the commands.
v. Executes the normal shutdown or emergency shutdown for protection.

3.5 TYPES OF HYDRAULIC TURBINE GOVERNOR

The speed governor for hydraulic turbine are of following types.

3.5.1 Electronic Load Controller

A load “actuator” is incorporated to control the electrical load on the generator so as to maintain the generator rotor at the desired speed despite change of consumer loads. There is no flow changeable device and therefore, flow through the turbine is set at a constant rate [9].

The typical schematic of electronic load controller as load governor is represented in Fig.3.1. This type of governing approach is non-conventional and normally employed in Pico and Micro hydropower stations having load bank equivalent of rating of generator due to the economic considerations.

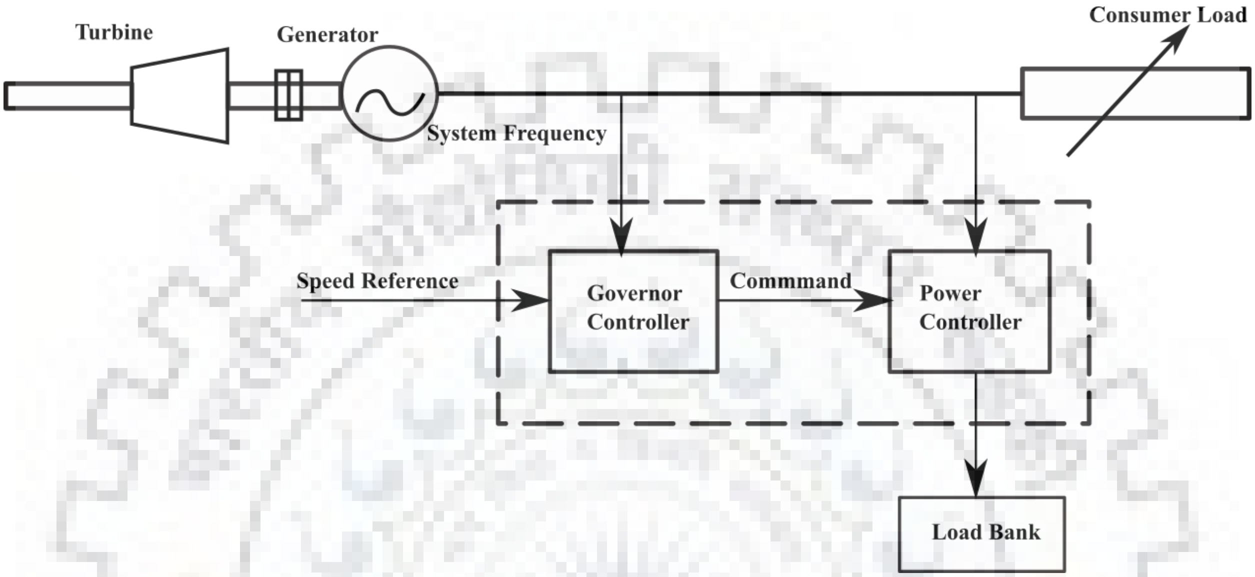

Fig. 3.1: Typical Load Controller

3.5.2 Mechanical-hydraulic Governor

The mechanical hydraulic governor comprises of flyball suspended from the top of vertical shaft. With increase or decrease of speed of the shaft, flyball moves up or down accordingly thereby controlling the flow control gates, either open or close based on the response. The schematic of mechanical-hydraulic governor is shown in Fig.3.2.

During the increased of load on the turbine, the speed of flyball gets reduced and drops to lower position. This triggers the floating lever to raise the sleeve in the pilot valve and opens the upper part. The pressurized oil flows to the upper compartment of servomotor resulting actuation of piston that open the valve of turbine allowing the increased in flow to match the power. The dash pot is incorporated to provide transient droop compensation. It is bypassed to disable if not required in the system [9].

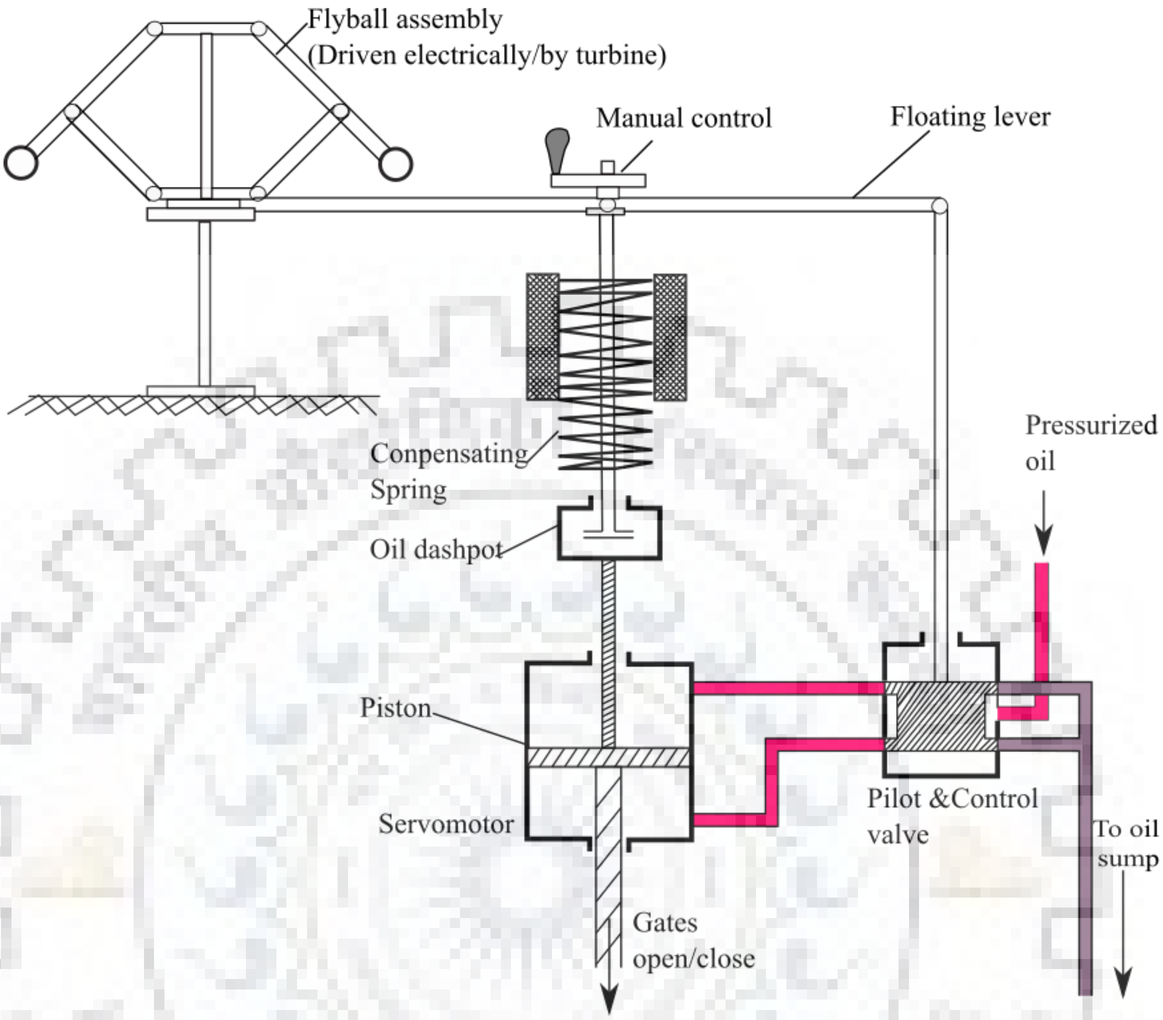

Fig. 3.2: Mechanical -hydraulic Governor [9]

3.5.3 Analog Electro-hydraulic Governor

The operation function is similar to that of mechanical-hydraulic governors. The speed sensing, permanent droop, temporary droop and other measuring and computing functions are realized electrically. The electro-hydraulic governor of analog electronics-based use analog circuit which is used generate set point signal to control the actuators turbine-generator set. An interfacing component is the electrohydraulic transducer that connects the electronic controller and hydro mechanical cabinet. The electronic signal command is transformed to mechanical movement in hydromechanical cabinet and hydraulic oil flow hydraulic oil flow from a hydraulic servo valve system that determines the movement of servomotor [77]. The PID controller is commonly used in governing system.

3.5.4 Digital Electro-hydraulic Governor

It is the advanced type analog electro-hydraulic governor with digital electronics. A turbine governor controller that uses digital electronic circuitry to develop the set point of signal that is used to position the control actuators on the hydroelectric turbine. An electro-hydraulic interface is used to convert the electronic setpoint signal into a hydraulic oil flow from a hydraulic servo-valve system. The schematic of the digital electro hydraulic governor is shown in Fig.3.3. The hydraulic servo-valve system determines the position of the turbine control actuators.

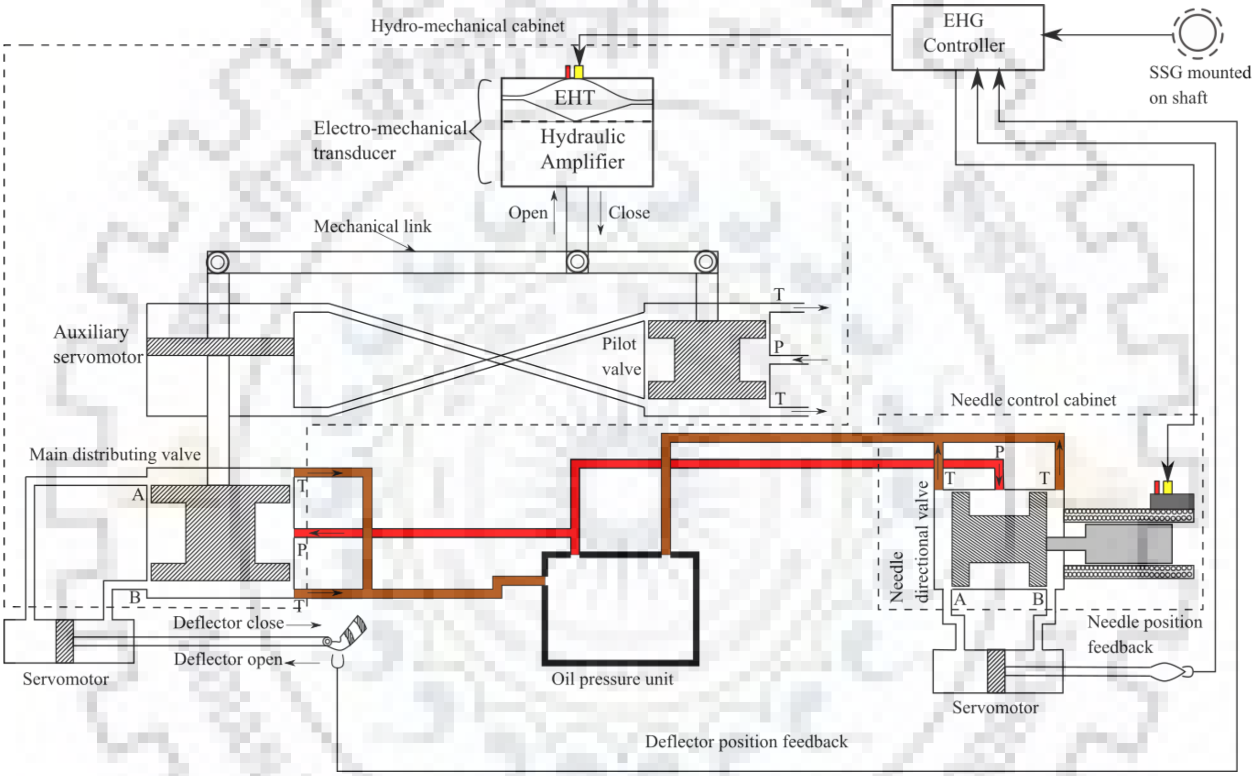

Fig. 3.3: Schematic of Electro-hydraulic Governor

3.6 CHARACTERISTICS OF GOVERNOR

The main performance characteristics of a governor are discussed as follows: -

3.6.1 Sensitive

The ratio of mean speed of action to the difference between the maximum and minimum speeds is the sensitivity of governor.

$$Sensitivity = \frac{\omega_2+\omega_1}{2(\omega_2-\omega_1)} \quad (3.1)$$

Where,

ω_2 is Maximum speed

ω_1 is Minimum speed

In other way, it is the smallest deviation of speed at any turbine gate opening which change the position of governor.

3.6.2 Stable

The governor is said to stable, even if the balls slightly displaced from their equilibrium position the speed remaining constant, they will have tendency to return to normal setting corresponding to speed. Therefore, stable governor supports the hydraulic turbine gate to come in proper position in minimum possible oscillations.

3.6.3 Rapidity of Action

The governor action must be rapid such that during increase or decrease of load the governor should take quick action to open or close the gate. However, during reduction of load the fast closing of gates checks the water flow in penstock that may cause water hammer. If the penstock is long relative to head, increase in pressure will be significant which may be serious and in order to avoid such pressure rise the closing time of governor must be increased. In doing so, turbine speed increases considerably unless fly wheel is fitted.

3.6.4 Hunting or Racing

The governor is said to hunt or race if there is periodic oscillation of speed with steady load. It may be caused due to high sensitivity of governor.

3.6.5 Isochronism

The governor is said to be isochronism, if it remains in equilibrium speed is same for all radii of balls. It is possible when sensitivity of governor is infinite. Necessary and sufficient condition is when $\omega_1=\omega_2$.

3.6.6 Speed Regulation

Sudden increase or decrease of full load or partial load causes the variation of hydraulic turbine speed which needed to be regulated by governor so that turbine regain its normal speed.

3.6.7 Capacity

The capacity of governor which controls the flow of pressurized oil to turbine servomotor. It is computed from the force to move turbine wicket gates. Governor capacity rating in meter-kilogram it is the sum of capacities of the gate servomotor and blade servo motors (Kaplan units) as required for operation of the turbine at minimum rated oil pressure. As per the capacity work which is measured, the type, size as well cost may differ. Governor having a capacity of more than 8500 m kg are of cabinet actuator type. Those having capacity less than 7000 m kg are gate shaft type [76].

3.6.8 Governor's Time

The time in second required by governor to move turbine gates from open to close or vice versa [10].

3.7 PARAMETERS OF GOVERNOR

The governor parameters are discussed as follow;

3.7.1 Permanent Droop (b_p)

Permanent droop or set proportional band is expressed as a percentage of the original speed setting from no load to full load. For base load plant permanent droop setting of units is in the range of 3-5%. For peak load plants plant permanent droop setting of units is in the range of 1- 2% [8].

3.7.2 Temporary Droop (b_t)

In order to achieve stable control action, a large temporary droop with long resetting time is provided in governor control feedback system. It helps to stabilize the transient phenomena due to large inertia of hydraulic system [78].

3.7.3 Time Constant of Damping Device (T_d)

It is also called as dashpot time constant or reset time. The time constant of the damping device determines the rate at which the effect of the temporary droop decays to zero.

3.7.4 Proportional Gain (K_p)

Proportional gain is defined as the magnitude of the proportional element output (in percentage) divided by the magnitude of the governor controller error (in percentage). The proportional gain contributes an immediate response to a governor controller error.

3.7.5 Integral Gain (K_i)

Integral gain is defined as the rate of change (in percentage/second) of the integrator output divided by the governor controller error (in percentage). Integral gain, also known as “reset,” acts to trim the controller error to a value of zero.

3.7.6 Derivative Gain (K_d)

Derivative gain is defined as the magnitude of the derivative element output (in percentage) divided by the rate of change of the governor controller error input (in percentage/second). The derivative gain term acts to limit controller overshoot by reducing the controller action proportional to the rate of error input to the governor controller.

3.7.7 Water Starting Time (T_W)

It represents the time required for a head H to accelerate the water in the penstock from standstill to the velocity U. Tw varies with load and typically Tw at full load lies between 0.5 second and 4.0 second [77]. Water starting time or water inertia time affects the water hammer effect of changing the water flow through the turbine using the primary turbine control device, such as the wicket gates. The dynamic performance of the control system is very much dependent on the penstock water time Tw. Water starting time is generally calculated for the unit at rated generation and at rated head. For simple penstock system, the value of water start time is calculated by following formula.

$$Tw = \frac{Q}{gH}.\Sigma \frac{l}{A} \tag{3.2}$$

Where,

T_w is water start time (s)

Q is rated water flow (m^3/s)

g is gravitational acceleration (m/s^2)

H is rated operating head (m)

l is length of each given portion of water column with constant area (m)

A is cross-sectional area of the corresponding portion of water column (m^2)

3.7.8 Mechanical Starting Time (T_M)

It is also called mechanical inertia time which is used to describe the mechanical inertia of the rotating parts.

$$T_m = \frac{I.\varpi_2}{P} \tag{3.3}$$

Where,

T_m is mechanical inertia time (s)

I is combined rotating inertia of generator, turbine, shaft, flywheel, and generator speed increaser (kg-m^2)

P is rated power output of the unit (W)

$$H_i = T_m/2 \tag{3.4}$$

Where,

Hi is Inertia constant

3.7.9 Governor Speed Dead band

It is the degree of smallest speed change that can be sensed and to which governing system can respond. In the unit of hydropower plant which is operating to an isolated system, governor speed band determines the smallest band within which the unit can maintain the system frequency under steady state loading conditions. Typical setting of governor speed dead band for hydro turbine is 0.02% [78].

3.7.10 Governor Deadtime

It is the measure of amount of time elapsed between a change in speed to the first corrective action by the governing system of hydraulic turbine. The governor deadtime affects the peak overspeed after load rejection resulting to rise of unit speed due to delay in governor response. Typical governor dead band for hydraulic turbine is 0.2 second.

3.7.11 Blade Control Dead band

The blade control dead band is a measure of smallest change in blade position setpoint that can be detected and subsequently the blade servomotor positioning system can respond. The accuracy of gate/blade relation relationship for an adjustable-blade turbine can be determined by blade control dead band. Achievable blade control dead band is 1%.

3.7.12 Damping Ratio

The damping ratio is defined as follow for second order closed loop control system;

$$\xi = \sqrt{}\{1 - \left(\frac{\varpi_d}{\varpi_n}\right)^2\} \tag{3.5}$$

Where,

ξ is damping ratio

ω_d is damped natural frequency of the system response after a step change

ω_n is undamped natural frequency of the system response after a step change

3.7.13 Stability

The stability of governing system for hydraulic turbine can be expressed as a damping ratio and a settling time [78]. By specifying the desired damping ratio and the settling time adequately defines the desired stability and responsiveness of the unit.

3.7.14 Speed Stability Index

The speed stability index or steady-state governing speed band is peak to peak variation in speed to turbine expressed as percentage of rated speed, that is caused by turbine governing system, when unit is disconnected from inter-connected power system and connected to a constant local electrical load. The unit operating 5% permanent droop is provided with speed stability index of 0.3%

3.7.15 Power Stability Index

The power stability index or steady state governing of load band is the peak to peak variation in power generation of unit, expressed as percentage of rated power generation, that is caused by turbine governing system when connected to large interconnected power system with constant turbine governor setpoint.

3.8 TECHNICAL PERFORMANCE

The hydro turbine governing system performance can be specified in different methods. It basically depends on the hydro power plant envisioned to operate.

3.8.1 Stability of Speed Governor

The stability of speed governing system is the capacity to remain in a state of operating equilibrium under ordinary operating condition and to regain satisfactory state of equilibrium after being exposed to excursions.

The disturbance may be of frequency or the load in the power system. When the power system under goes the major disturbances or the tripping of elements of network, the governor control and maintain the frequency within the acceptable range. Therefore, during the islanding mode the governor must function as per the desired condition. The settings should be adjusted such that its stability achieves as desired and also in line with the preview of grid code as required by the power system operator. This is due to the effect of governor setting the power system frequency [78]. The stability studies of governor of the unit for stand-alone plant and grid connected need to be carried out separately as the governor settings of the grid connected unit differs from isolated plant’s unit despite similarity in operation [75].

3.8.2 Stability of Different Model Considering Components in Plant

The hydropower plant models are of different kinds linear model with elastic and non-elastic water column effect as well as non-linear with elastic and non-elastic water column effect [12]. For the control system stability, the linear models used, however non-linear models are considered for better performance analysis for large signal stability for simulation of time-domain [77]. In the non-linear model, frictional loss in the water conducting system, especially in long penstock, water hammering and surge tank effects taken into consideration.

The studies are possible through different powerful software simulations. As the simulations of hydro turbine governing systems is used to forecast performance under operating conditions which are expected. With the help of precise modeling and its simulations, the performance of actual system can be predicted within acceptable range.

3.8.3 Effect Under Load Rejection Condition

The turbine generating units are provided with over speed protection schemes, such as electrical, mechanical and hydraulic over speed devices. After the load rejection, the maximum speed is function of water column, inertia of rotation and time of gate closing. Allowable maximum speed increase is calculated based on turbine-generator’s mechanical characteristics. The speed of unit after load rejection to maximum permissible value is decided by the generator rotor construction. The speed governor must act upon the unit tripping such that the unit retards smoothly without any damages to mechanical sub components of turbine regulator.

Sluggish response of the hydraulic system and turbine governor makes the primary swing stability insignificant. The damping is affected by turbine and governor. Based on the control parameters of governor, the hydro turbine may subtract or add as of the natural damping [16].

The transient stability depends on various parameters of turbine-penstock such as water starting time (Tw), mechanical starting time (Tm), selection of temporary droop and dashpot reset time. It is applicable to mechanical-hydraulic as well as the electro-hydraulic PID governor [62].

3.8.4 Performance Under Islanding Condition

The speed governor stability is good, when subjected to isolation mode if the tuning is properly addressed. The frequency parameter is affected in islanded system when disconnected from grid. In order to cope up with the worst situation in power system, the governors of the units in hydropower plant are connected to grid are tuned as isolated mode. The nature of load also affects the turbine governor system capability to control generator frequency. The nature of power system load varies seasonally, the performance of governor also changes accordingly and thus required the tuning.

3.8.5 Inter-communication of Speed Governor with Excitation

In order to address the proper interaction of governor with generator excitation system, the adjustment of governor parameters and the settings are key issues. Inferior adjustment of governor may adversely affect the oscillation of prime mover integrated with water column at plant level. Similarly, poor adjustment of power system stabilizer (PSS) or automatic voltage regulator (AVR) may impact negatively to generator oscillations.

3.8.6 Droop Adjustment for Stability

There are two types of droops that impacts the overall performance of the governor in hydro turbine units.

3.8.7 Permanent Speed Droop Adjustment

Basically, the permanents speed droop settings must be in line with the power system operation. Normally, permanent speed drop of 5% ensures the reasonable involvement all the generating units in the large grid. However, lower value may be opted for unit connected to smaller grid [78].

3.8.8 Temporary Droop Adjustment

In order to accomplish desired performance of governing system, the damping adjustment must be considered. It is achieved by temporary droop and the adjustment range is from 0-150%. Actual value depends on the site condition.

3.8.9 Proportional, Integral and Derivative (PID) Adjustment

The gains of Proportional, Integral and Derivative adjusted in the governor controller.

3.8.10 Tuning of Speed Governor

Adequate tuning of parameters is essential to optimize the performance in hydraulic system and proper parameter selection to be prioritized. Improper tuning of governor may result instability of system and there by affecting the system performance. The following conditions are considered while executing the adjustment of governor parameters [62].

i. Minimum speed deviation after the change of load
ii. Fast regain to conventional speed
iii. Reasonable stability of turbine governing system

3.9 ELECTRO-HYDRAULIC GOVERNOR FOR HYDROELECTRIC UNIT

Aged hydro power stations are still running with mechanical-hydraulic or analog electrohydraulic governor. However, the earlier turbine set governor may needs to be upgraded with modern speed governor. For standalone power station of low capacity in the range of pico and micro, the use of electronic load controller becomes techno-economically feasible. But with interconnection with grid during the course of time either with micro or mini grid, the upgradation of governing system becomes evident due to the need of power quality for consumers. Additionally, it can be changed to the existing hydropower plant unit. Governor based on digital electronic are now used in small as well as large hydropower unit.

The digital controllers are flexible and versatile which can also be used for functions not directly related to governing system of hydraulic turbine. Basically, the software of electro-hydraulic governor controller executes task carried out in mechanical and analogue governors by devices like position switches, control motors and solenoids. There are several advantages of micro-processor based digital electro-hydraulic governor such as better stability, high reliability, self-diagnostic feature, modular design, flexibility of changing control function via software, stability of set parameters, minimized wiring and easy for remote controlling through fiber optics. The electro-hydraulic governor has improved response characteristics as compared to mechanical-hydraulic type. Due to reduction of cost of digital components and reliability, the digital governing system is used in modern hydroelectric units.

Following are the task performed by digital electro-hydraulic governor in addition to speed control in no load condition, operating in interconnection, operation in isolated grid and islanding operation.

i. Auto start/ Stop through single push button
ii. Control of output power depending on variation in grid frequency
iii. Control of power as per water levels in forebay or tailrace
iv. Remotely control through SCADA system
v. Responses quickly to transient conditions

Practically, there is no difference in governors used in large and small hydro turbine units except the size, capacity, operating pressure and other control structures as per the power plant requirement. Due to the above numerous merits and its applicability in hydraulic turbine unit, electro-hydraulic governor is thus selected for the stability study through modelling.

CHAPTER 4

MODELING OF HYDROPOWER PLANT

4.1 GENERAL

The generation of electrical energy may be low as compared to projected, owing to the losses as result of inadequate performance of turbine generator auxiliary equipment. However, the outages of the units may be minimized, after root cause identification and subsequent remedial measures on time. Therefore, analysis is crucial which can be performed on model developed in relevant software. Similarly, upgradation, rehabilitation and renew of old hydropower plant are needed in due course of time. As a result, it is useful to have dynamic model of the power plant for investigations.

In the present work, the modelling of hydropower plant considering the parameters of Tala Hydropower has been done in MATLAB and Simulink software. This programing tool provide basic devices for building, simulating as well as testing the hydraulic turbine governor through over all simulation of hydropower plant. The contributions from this platform are like ease of execution, optimization and control approaches for the tests. The graphical interface is one of the features of Simulink which may reduce the complexity of system.

4.2 MODELING PROCESS

The following procedures has been followed in order to model the hydro power plant.

4.2.1 Background of Hydropower Plant

Tala Hydro Power Plant is located in Chukha district in western Bhutan as shown in location map in Fig.4.1. It is situated in the downstream of Chukha Hydro Power Plant that utilizes the water of Wangchuk. The plant was fully commissioned in the year 2007 with plant capacity of 1020 MW. The underground power house comprises of six generating units of 170 MW capacity each. The project has head race tunnel of 23 km and net head of 819 m.

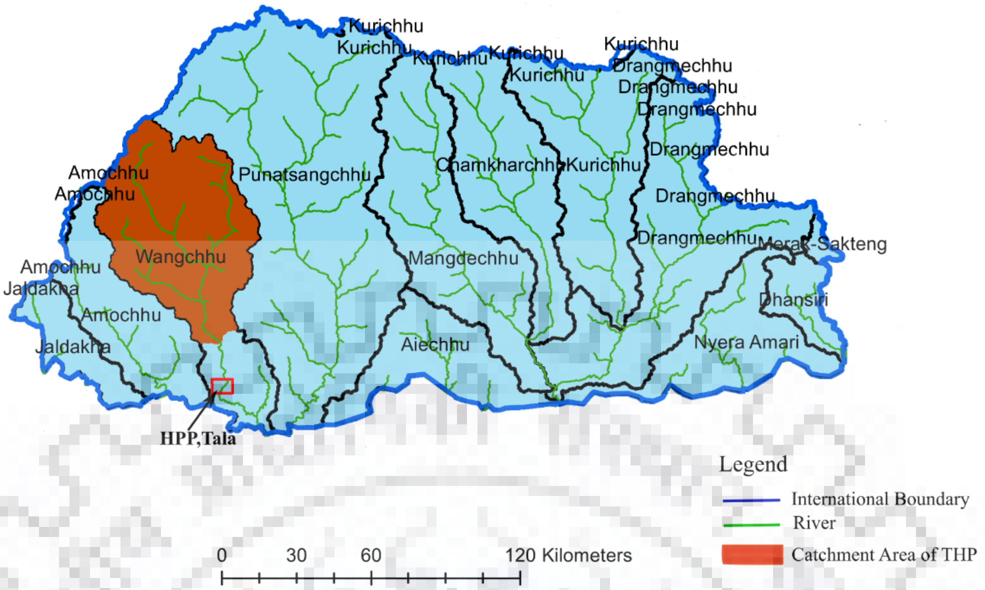

Fig. 4.1: Location HPP Tala, Bhutan

4.2.2 Water Conducting Arrangement for Power Station

Layout of water conducting system for the hydropower station, at Tala is shown in Fig.4.2.

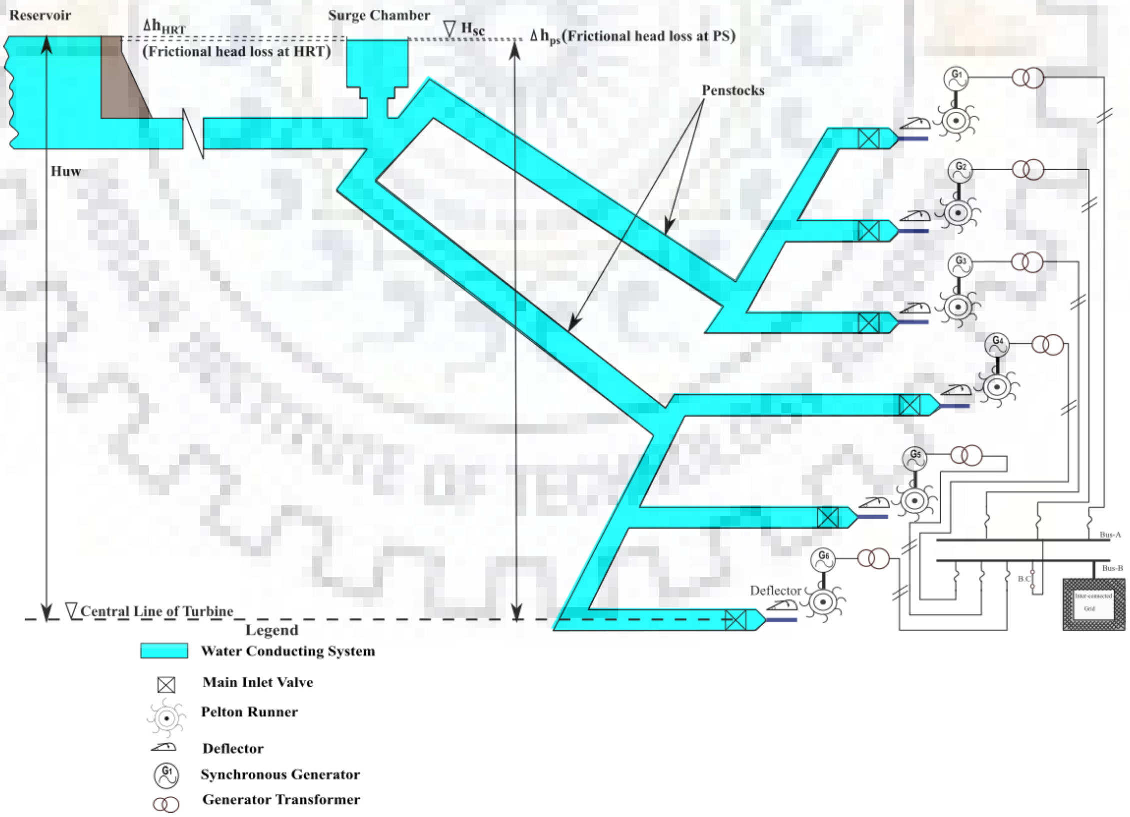

Fig. 4.2: Schematic of Water Conducting System of HPP, Tala

It consists of following components.

i. Reservoir
ii. Head race tunnel
iii. Surge Chamber
iv. Two pressure shafts each trifurcated to feed six turbines

4.2.3 Layout of Turbine-Generator Set

Simplified layout of a unit in single line diagram is represented in Fig.4.3. Essentially, single unit is chosen in order to show the maximum details of unit such as turbine-generator set, regulating and control elements of the hydro unit. Same arrangement is applicable to all the six units in for power evacuation.

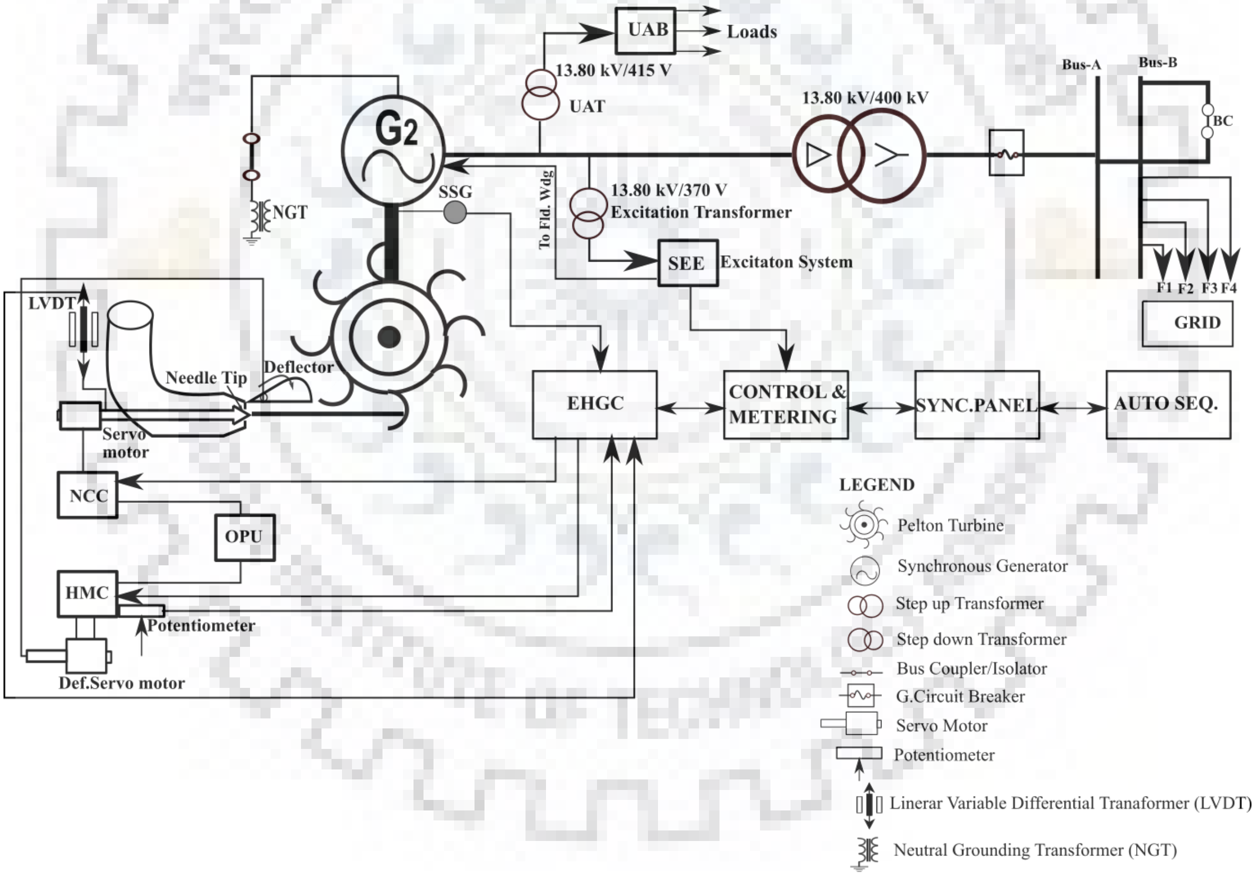

Fig. 4.3 : Schematic Representation of a Unit in HPP Tala

The structure of hydro power plant shown in Fig.4.4, where the important parameters are specified.

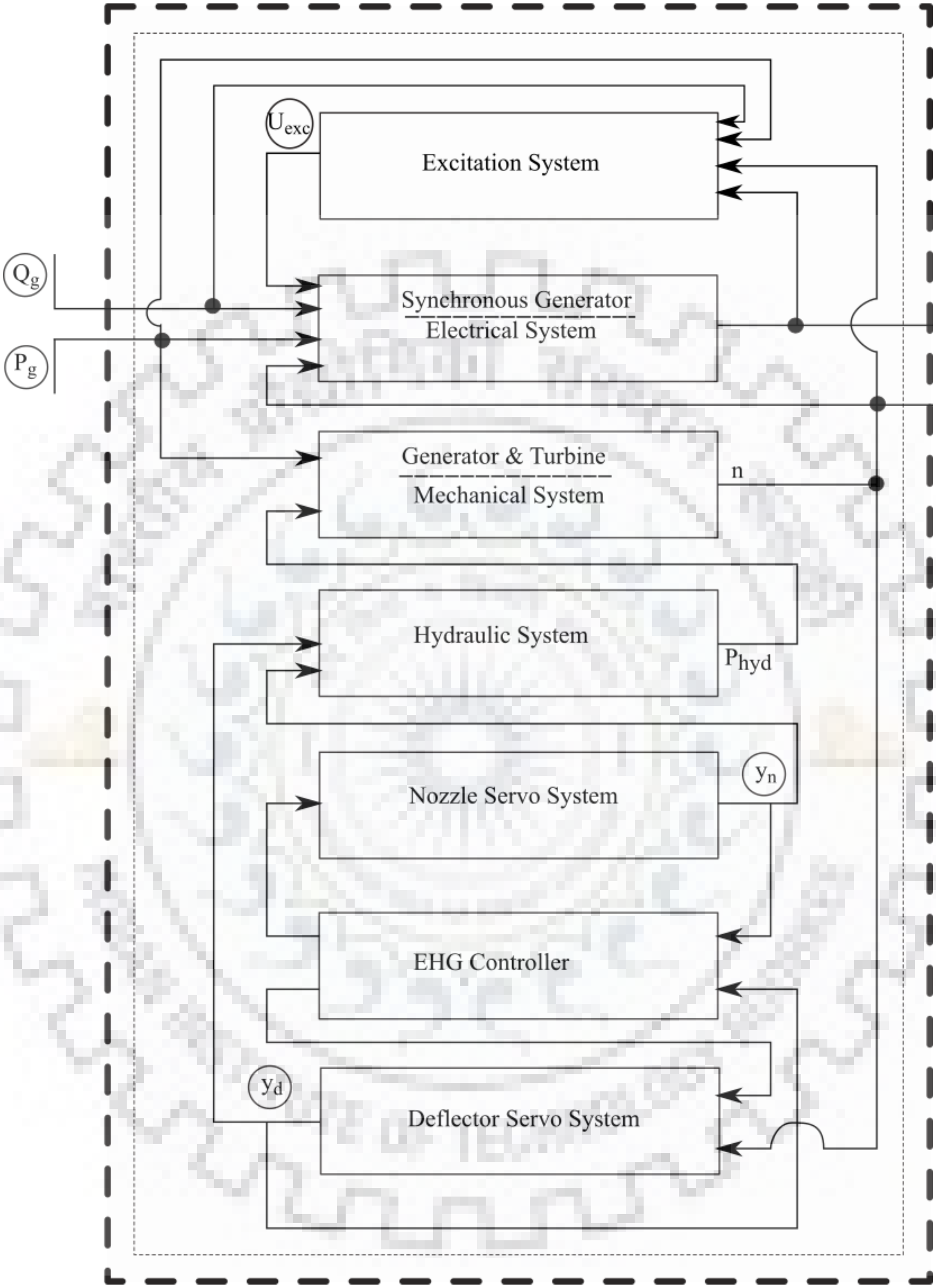

Fig. 4.4: Structural Layout of Various Systems of Unit

4.2.4 Mathematical Model of Different Components

The mathematical modelling of various components of hydropower plant are discussed in sequence as follow. The sub-headings 4.2.4.1 to 4.2.4.4 which explain mathematical modeling of hydraulic system followed by subheadings 4.2.4.5 to 4.2.4.9 basically deal with turbine, governor, excitation and transmission line respectively.

4.2.4.1 Modeling of reservoir

The simplified diagram for reservoir model is represented in Fig.4.5.

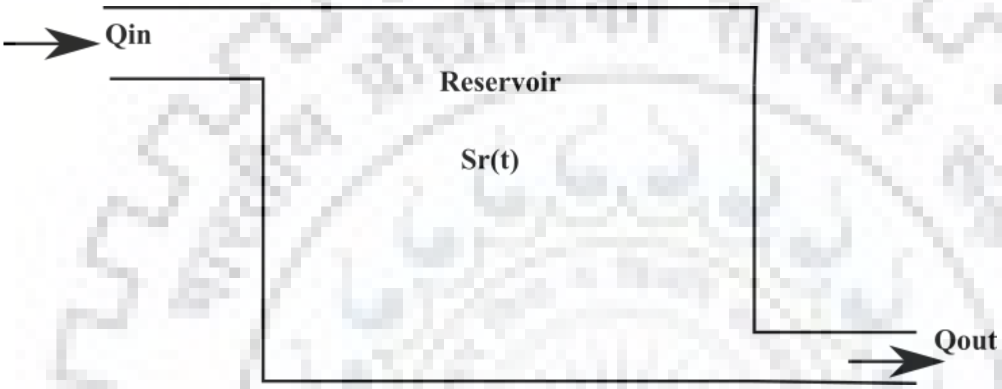

Fig. 4.5: Reservoir Model

The water stored in the reservoir during the time (t+Δt) is;

$$Sr(t + \Delta t) = Sr(t) + Q_{in}\Delta t - Q_{out}\Delta t \tag{4.1}$$

$$\frac{Sr(t+\Delta t)-Sr(t)}{\Delta t} = Q_{in} - Q_{out} \tag{4.2}$$

The equation (4.2) can be simplified and rewritten as

$$\frac{\Delta Sr(t)}{\Delta t} = \frac{dSr}{dt} = Q_{in} - Q_{out} \tag{4.3}$$

Where,

Q_{in} is Inflow in cumecs

Q_{out} is discharge in cumecs

$S_r(t)$ is water stored on reservoir in cubic meter

Δt is incremental time duration in seconds

4.2.4.2 Modeling of headrace tunnel

The equation of tunnel dynamics is given by;

$$\Delta h = Q_{hrt}.\beta \qquad (4.4)$$

Resistance factor of the pipe or tunnel is given by;

$$\beta = \frac{n^2.l}{A^2.Rh^{4/5}} \qquad (4.5)$$

Where,

Q_{hrt} is flow rate in the tunnel

n is Manning roughness coeffiecient

l is length of tunnel in m

A is cross-sectional area of tunnel/pipe in m^2

R_h is hydraulic radius of water conduit

$$\frac{dUtu}{dt} = \frac{H-\Delta h}{Tw} \qquad (4.6)$$

is equation of tunnel dynamics

Where,

U_{tu} is velocity of water in tunnel/HRT in m/s

H is reservior level in m

Tw is water starting time in second

The water staring time for HRT is computed as ;

$$Tw(hrt) = \frac{Utu*l}{g*Ho} \qquad (4.7)$$

Where,

H_0 is initial steady state head in m

g is acceleration due to gravity in m/s^2

4.2.4.3 Modeling of surge chamber

The surge tank dynamics equation is given by;

$$Hs = \frac{1}{Cs}\int Us\ dt \qquad (4.8)$$

Where,

Hs is water level in surge tank in m

Cs is storage constant of surge tank

Us is velocity of surge tank in m/s

Time constant of surge tank Tw(st) is the time required for rated discharge to fill the surge tank from level zero to nominal head level.

$$Tw(st) = \frac{A*Ho}{Qo} \qquad (4.9)$$

Where,

A is cross sectional area of surge tank in m^2

Q_0 is rated discharge through surge tank in m/s

4.2.4.4 Modeling of penstock

The fundamental water starting time constant calculation expression is same as head race tunnel. For a dynamic system considering the compressible water effect and wall of the pipe dynamics, the transfer function equation is given by;

$$\frac{\Delta H(s)}{\Delta Q(s)} = Zp.tanh(sTe + \beta(PS)) \qquad (4.10)$$

Where,

Zp is penstock surge impedance

Te is wave travel time in seconds

β(PS) is penstock friction factor

$$Zp = \frac{Tw(ps)}{Tep} \qquad (4.11)$$

$$Tep = l/c \tag{4.12}$$

Where,

l is length of penstock in m and

c is wave speed in m

4.2.4.5 Modeling of turbine

The relationship of mechanical power with discharge and hydraulic head in non-linear form can be stated in equation 4.13

$$Pm = f(Q, H) \tag{4.13}$$

The discharge through the turbine is the function of head and percentage of gate opening.

$$Q = G\sqrt{H} \tag{4.14}$$

Where,

G is the gate opening and

H is net head at the turbine

Velocity of water is given by;

$$U = Ku.G.\sqrt{H} \tag{4.15}$$

Where,

Ku is proportionality constant

Power in put to the turbine is hydraulic power given by;

$$P_{hyd} = K_{pm}.U.H \tag{4.16}$$

Where,

K_{pm} is proportionality constant

Mechanical power out put from the turbine;

$$Pm = K_{pm}(U - Unl)H \tag{4.17}$$

Where,

U_{nl} is no load velocity of water in m/s

Simplified linear model of turbine-penstock, based on classical approach

$$\frac{\Delta Pm}{\Delta G} = \frac{1-Tws}{1+0.5Tws} \tag{4.18}$$

4.2.4.6 Modeling of hydraulic turbine governor

A speed governor controls the speed and output power of a hydraulic turbine as control system. The general form of governor controller is expressed mathematically as below [76].

$$m(t) = KpE(t) + Ki\int_0^t E(t)dt + Kd\frac{dE}{dt} \tag{5.19}$$

Where,

m(t) is controller out put

Kp is Proportional constant

Ki is integral constant

Kd is derivative constant

E(t) is Error, function of time

The electro-hydraulic governor with proportional, integral and derivative action is modeled that gives higher speed response and increase the transient gain.

4.2.4.7 Modeling of synchronous generator

The synchronous generator model which the mechanical as well as electrical characteristics is considered. The sixth order statespace model represents the electrical part of generator. Input parameters are turbine power Pm and excitation voltage. The different paramaters of the generator were obtained from the documents of the power plant, Tala. All the dynamics of stator, rotor field and damper windings are due considered. The comparable circuit of the model is represented in dq frame which is rotor reference frame. Following equations represents the electrical model syschronous generator [77].

$$V_q = R_s\, i_q + \frac{d}{dt}\Phi_q + \omega_R \Phi_d \tag{4.20}$$

$$V_d = R_s\, i_d + \frac{d}{dt}\Phi_d + \omega_R \Phi_q \tag{4.21}$$

$$V'_{fd} = R'_{fd}\, i'_{fd} + \frac{d}{dt}\Phi'_{fd} \tag{4.22}$$

$$V'_{kd} = R'_{kd}\, i'_{kd} + \frac{d}{dt}\Phi'_{kd} \tag{4.23}$$

$$V'_{kq1} = R'_{kq1}\, i'_{kq1} + \frac{d}{dt}\Phi'_{kq1} \tag{4.24}$$

$$V'_{kq2} = R'_{kq2}\, i'_{kq2} + \frac{d}{dt}\Phi'_{kq2} \tag{4.25}$$

$$\Phi_q = L_q\, i_q + L_{mq} i'_{kq} \tag{4.26}$$

$$\Phi_d = L_d\, i_d + L_{md}(i'_{fd} + i'_{kd}) \tag{4.27}$$

$$\Phi'_{kd} = L'_{kd}\, i'_{kd} + L_{md}(i_d + i'_{fd}) \tag{4.28}$$

$$\Phi'_{fd} = L'_{fd}\, i'_{fd} + L_{md}(i_d + i'_{kd}) \tag{4.29}$$

$$\Phi'_{kq1} = L'_{kq1}\, i'_{kq1} + L_{mq} i_q \tag{4.30}$$

$$\Phi'_{kq2} = L'_{kq2}\, i'_{kq2} + L_{mq} i_q \tag{4.31}$$

4.2.4.8 Modeling of excitation system

An excitation system is employed to excite field winding of synchronous generator by direct current. Control and protection operations are performed by it beside excitation of generator field winding for optimum performance in the power system. PID controllers are used to regulate the excitation voltage in coordination with turbine power which is realized by appropriate feedback system [79]. Mathematically, excitation is represented in transfer function as follows.

$$\frac{V_{fd}}{e_f} = \frac{1}{K_e + sT_e} \tag{4.32}$$

where,

V_{fd} is the exciter voltage in volts

e_f is regulator output in volts

K_e is the feedback gain

T_e is time constant in seconds

4.2.4.9 Modeling of transmission line

The evacuation power from the power plant is through overhead lines and cables. For the simplicity the circuit with lumped parameters are considered for computation [77].

$$V_S = V_R \frac{e^{\gamma l}+e^{-\gamma l}}{2} + Z_c I_R \frac{e^{\gamma l}-e^{-\gamma l}}{2} \quad (4.33)$$

$$V_S = V_R \cosh(\gamma l) + Z_c I_R \sinh(\gamma l) \quad (4.34)$$

$$I_S = I_R \cosh(\gamma l) + \frac{V_R}{Z_C} \sinh(\gamma l) \quad (4.35)$$

The transmission lines in case of Tala feeders falls under the category of medium length, the π model to be considered for analysis. The equation for sending end voltage is given by;

$$V_s = \left(\frac{Z_e Y_e}{2} + 1\right) V_R + Z_e I_R \quad (4.36)$$

$$Z_e = Z_c \sinh(\gamma l) \quad (4.37)$$

Where,

V_s is sending end voltage in volts

V_R is receiving end voltage in volts

γ is propagation constant

C_C is characteristics impedance

l is line length in meter

I_R is current at receiving end in ampere

4.2.5 Modeling of Various Parts of Hydropower Plant in MATLAB Simulink

The different components of hydropower plant modeled in MATLAB Simulink are presented as follows.

4.2.5.1 Model of hydraulic turbine

The linear model is not precise as a result, non-linear system is considered for the better simulation output result and represented in the Fig.4.6.

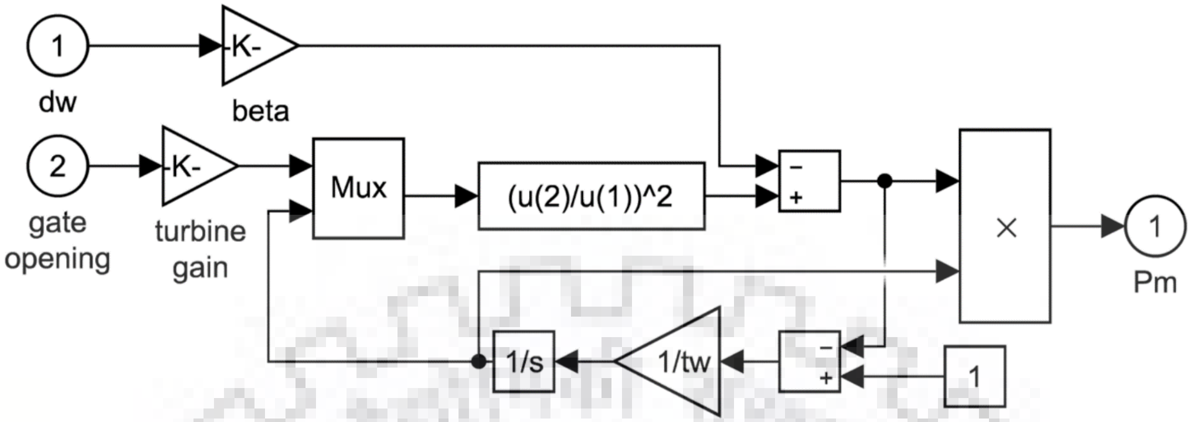

Fig. 4.6: Subsystem of Hydraulic Turbine, Simulink Model

4.2.5.2 Model of electro-hydraulic governor

The MATLAB Simulink model of electro-hydraulic governor used in turbine-generator set is shown in Fig.4.7. It is PID governor which is integrated with speed feedback as speed error for gate position control. Main servomotor is used for controlling the gate valve as per the signal from electro-hydraulic governor controller.

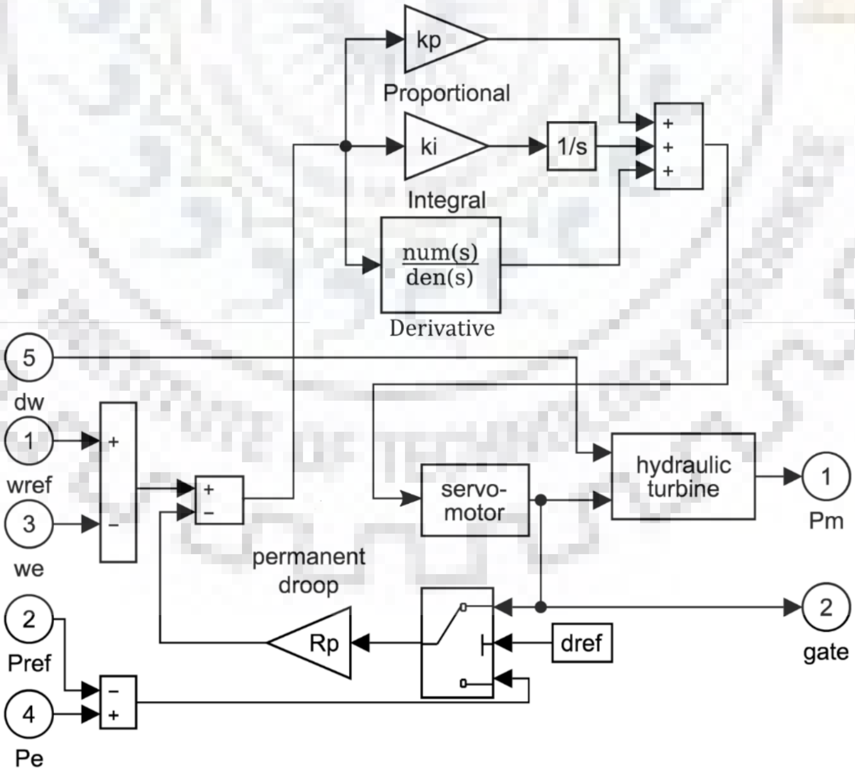

Fig. 4.7: Subsystem of Hydraulic Turbine Governor, Simulink Model

4.2.5.3 Model of generator excitation system

The synchronous generator is supplied DC supply system as exciter. For the simulation purpose the standard model from standard IEEE is used [80]. The model is basically DC excitation in absence of exciter's saturation through DC generator as shown in Fig.4.8.

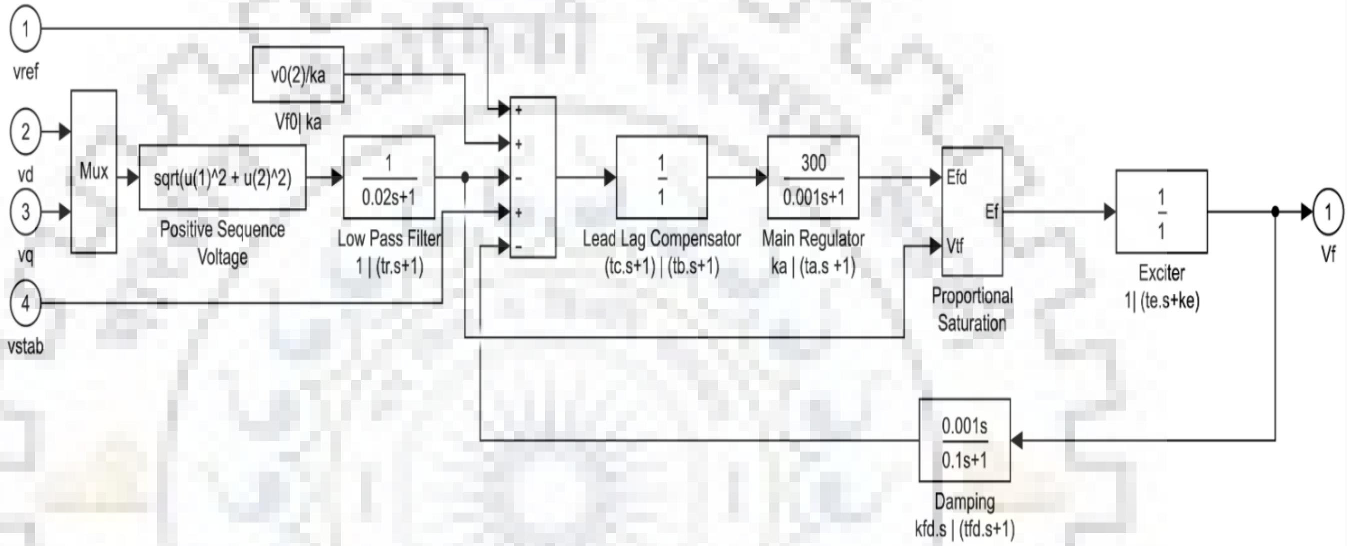

Fig. 4.8: Subsystem of Generator Excitation system, Simulink Model

4.2.5.4 Complete model of single unit

All the major parts of hydropower plant system that are modeled in systematic way are combined to realize the unit of generating station. The complete hydropower plant unit model is represented in Fig.4.9. The model is used for the simulation under various operating states.

In order to simulate the model of hydropower plant under different working conditions, all parameters required to represent existing unit of the plant has been incorporated. For the operation of plant under fault condition, additional logic circuit was integrated with model.

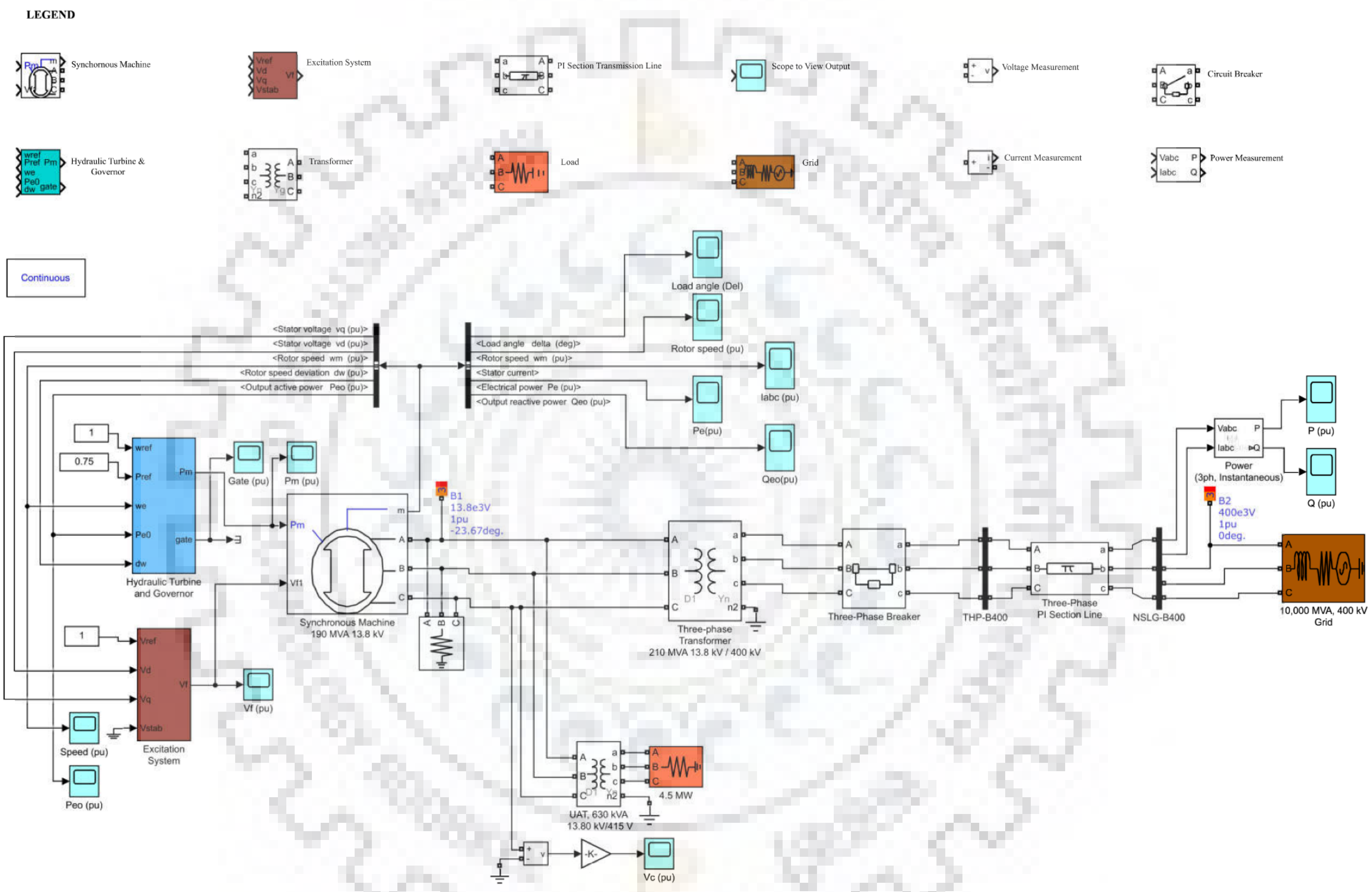

Fig. 4.9: Model of Complete Hydro Power Unit

4.3 DATA USED IN MODEL FOR SIMULATION

Hydro power plant data presented in Table 4.1 are used for the simulation. The specifications and parameters are obtained from the plant document [81]. The parameters of major parts of hydropower plant are given in Table 4.2, Table 4.3 and Table 4.4.

Table 4.1: Data of HPP Tala, Bhutan.

Sl.No.	HPP Components		Data
1	Water Conduit System	Reservoir	Minimum drawdown level:1352 m Full reservoir level: 1363 m
		Head Race Tunnel	Length: 23 km Diameter: 6.8 m Velocity: 3.75 m/s
		Surge Chamber	Restricted orifice type, Height: 184 m Orifice diameter: 1.5 m
		Penstock/Pressure shaft	Diameter: 4 m before trifurcation 2.3 m after trifurcation Length: PSI-1078 m, PSII-1024 m Velocity at design discharge: 5.6 m/s
2	Turbine		Pelton runner, vertical shaft No. of Unit: 6 Capacity: 173.5 MW Net head: 819 m Rated discharge: 23.52 m^3/s Speed: 375 rpm
3	Generator		Synchronous generator Capacity: 190 MVA Generator voltage: 13.80 kV Excitation type: Static excitation
4	Generator Transformer		Three single phase transformers for each unit Capacity: 70 MVA Voltage Transformation: 13.80 kV/400 kV

Table 4.2: Synchronous Generator Parameters

Description of Parameters		Value
Synchronous Reactance	Xd	1.04 pu
	Xq	0.65 pu
Transient Reactance	Xd'	0.27 pu
	Xq'	-
Sub-transient Reactance	Xd"	0.165 pu
	Xq"	0.145 pu
Stator Leakage Reactance	Xl	0.10 pu
Transient Time Constant	Td'	0.27 pu
	Tq0'	-
Sub-transient Time Constant	Td"	0.165 pu
	Tq"	-
Stator Resistance	Rs	2.85e-3 pu
Inertia Coefficient (Turbine+Generator)	H	3.80 s
Friction Factor	F	0
Pole Pair	-	8

Table 4.3: Excitation System Parameters

Description of Parameters		Value
Filter Time Constant	Tr	2.00E-02
Regulator Gain	Kreg.	200
Regulator Time Constant	Treg.	0.001s
Excitor Gain	Ke	1
Excitor Time Constant	Te	0
Transient Gain Reduction	Tb	10
	Tc	1
Damping Filter Gain	Kf	0.001
Damping Filter Time Constant	Tf	0.1s
Regulator Output Limit	Emax	11.5 pu
	Emin	(-)11.5 pu
	Gain (Kp)	0

Table 4.4: Servomotor and Gate Parameters

Description of Parameters		Value
Servo-motor Gain	Ka	3.33
Servo-motor Time Constant	Ta	0.07 s
Gate Opening Limit	gmax	0.975 pu
	gmin	0.01 pu
Gate Opening Limit Speed	Vg max	0.10 pu/s
	Vg min	(-)0.1 pu/s

Table 4.5: Turbine and Governor Controller Parameters

Description of Parameters		Value
Inertia Constant of Turbine	H	0.12 s
Water Starting Time	Tw	0.0462 s
Friction Factor	β	0.743
Permanent Droop	bp	0.06
Temporary Droop	bt	0.48
Proportional Gain	Kp	2.0
Integral Gain	Ki	0.50
Derivative Gain	Kd	0.002
Damping Time Constant	Td	10.0 s

Tala Hydropower Plant was identified for the case study. The back ground and physical system was carefully studied to develop the final model for analysis of plant especially the electro hydraulic governing system. As per the objective, mathematical model of various components was carried out. Subsequently, final model was developed in MATLAB Simulink software in sequence. All the parameters of the plant were incorporated to realize the real plant. In order to examine stability of electro hydraulic governor appropriately, damping time constant (Td) has been kept to 0.01. The proportional gain Kp is kept as 2.0, integral gain as 0.5, derivative gain as 0.002 and permanent droop bp as 0.05

The configured model has been used for simulation under various states of operation, which is discussed in the succeeding Chapter-5.

CHAPTER 5

SIMULATION OF MODEL OF HYDROPOWER PLANT

5.1 GENERAL

In previous Chaper-4, the details of mathematical modeling and MATLAB, Simulink modeling of different parts of hydropower plant including turbine governor has been discussed. The main objective of simulations of hydropower plant model is to examine the stability of electro-hydraulic governor when the hydropower unit is subjected to different operating conditions. The MATLAB Simulink model of HPP is simulated for time period of 30 seconds to check the performance of the governor used. Major operating conditions of hydropower plant considered for the investigation are steady state, sudden load change, three-phase fault both temporary as well as permanent. The disturbance has been introduced to the turbine generator set running in steady state to check the performance of the governor. The conditions like sudden load change, three-phase fault both temporary and permanent fault are the perturbations under which hydropower plant model is simulated.

At the first step, the performance is thus compared in order to validate the results obtained from simulation of model prepared. The model correctness has been checked by real time measurement data of Unit-2 at Tala Hydropower Plant. However, the correlation is being made for selected test conditions to represent the validity of transient scenarios.

5.2 OPERATION UNDER DIFFERENT CONDITIONS

The model is simulated under steady state condition, where no external as well as internal disturbance is present. Fundamental idea is to carry out the simulation without disturbance during the time of unit connected to grid for the study the basic performance of governing system. Likewise, the performance of governing system during the interruption are compared and examined. The model for steady state is given in Fig.5.1.

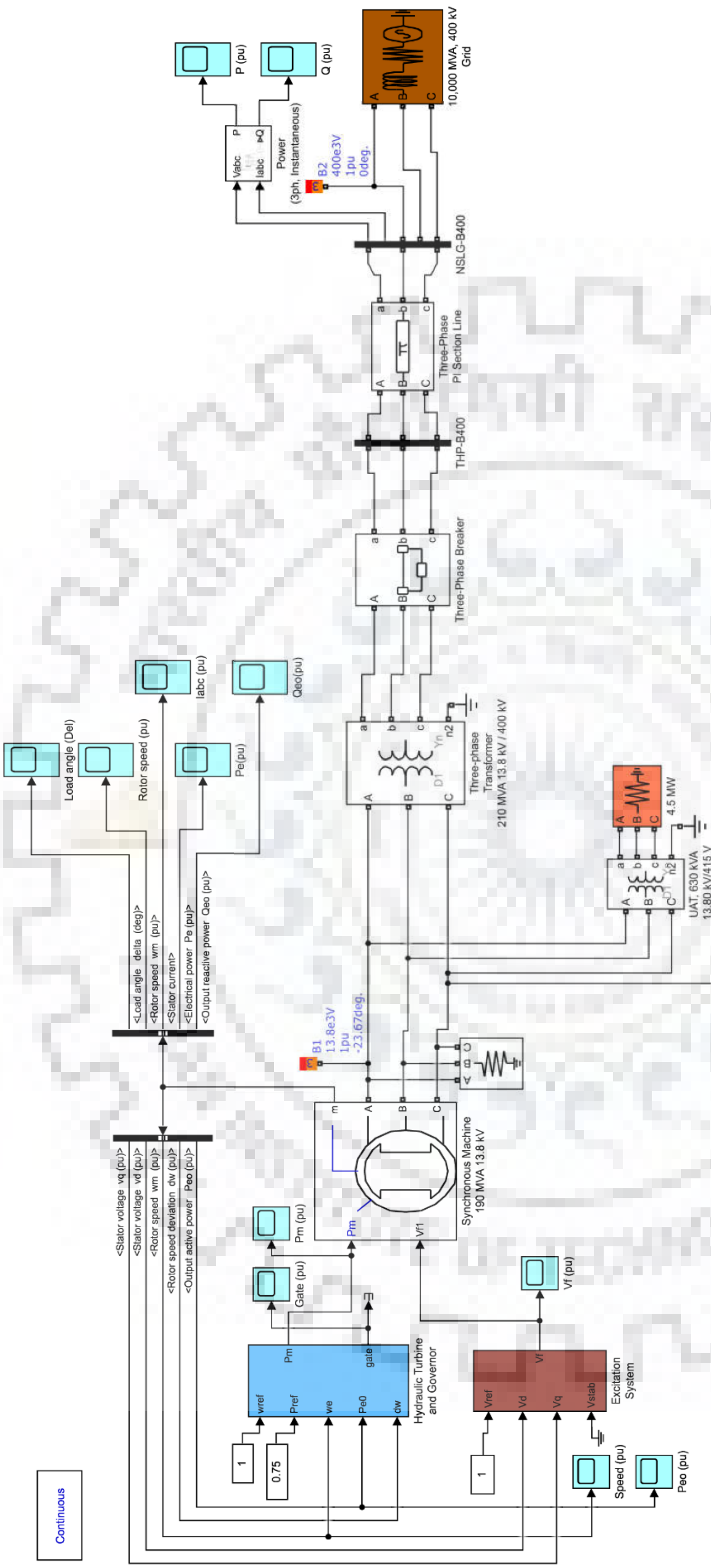

Fig. 5.1: Model for Steady State Condition

Simulink model of hydropower plant for load increase as well as load decrease state is shown in Fig.5.2. The power system active load transient is established by increase of load on generator. The magnitude of load increased was 70 MW on the existing load. Due to the disturbance in system, it is observed some deviation of operating parameters of generator, hydraulic turbine and governing systems. Likewise, disturbance is created by reduction of load where the parameters of generator, turbine and governing system tend to change as shown in simulation results.

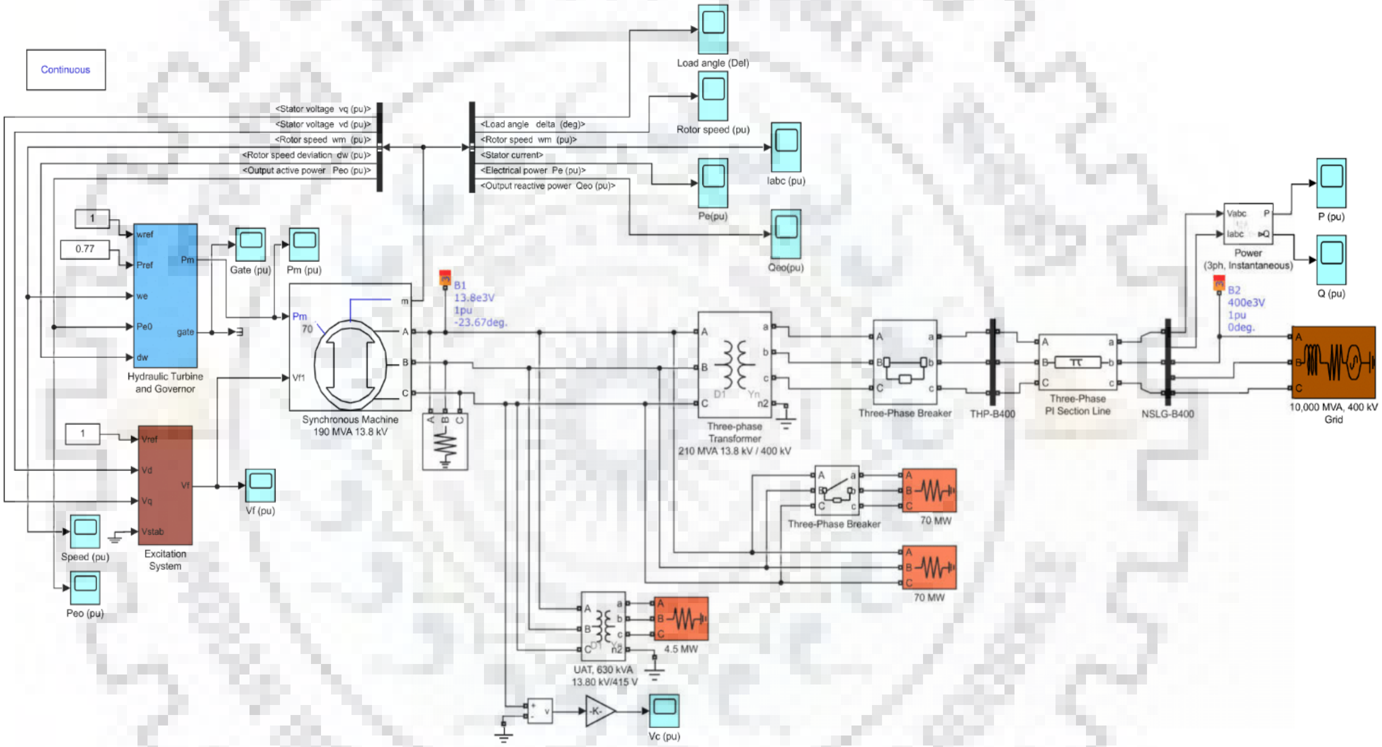

Fig. 5.2: Model for Load Increase/Decrease

A fault is also known as short circuit in the power system. It is basically categorized into two classes such as temporary and permanent faults. For the simulation of model three-phase fault is considered.

Temporary fault causes momentary interruption however the fault is cleared without operation circuit breaker if the auto-reclosure facility is incorporated. Such fault in the power system is temporary. Common type of temporary fault is due to lightning. The temporary disturbance is created during the three-phase to ground fault which in turn affects the parameters of turbine governor and power system as whole as shown in Fig.5.3. The load on the unit was kept 0.75 pu at the time fault.

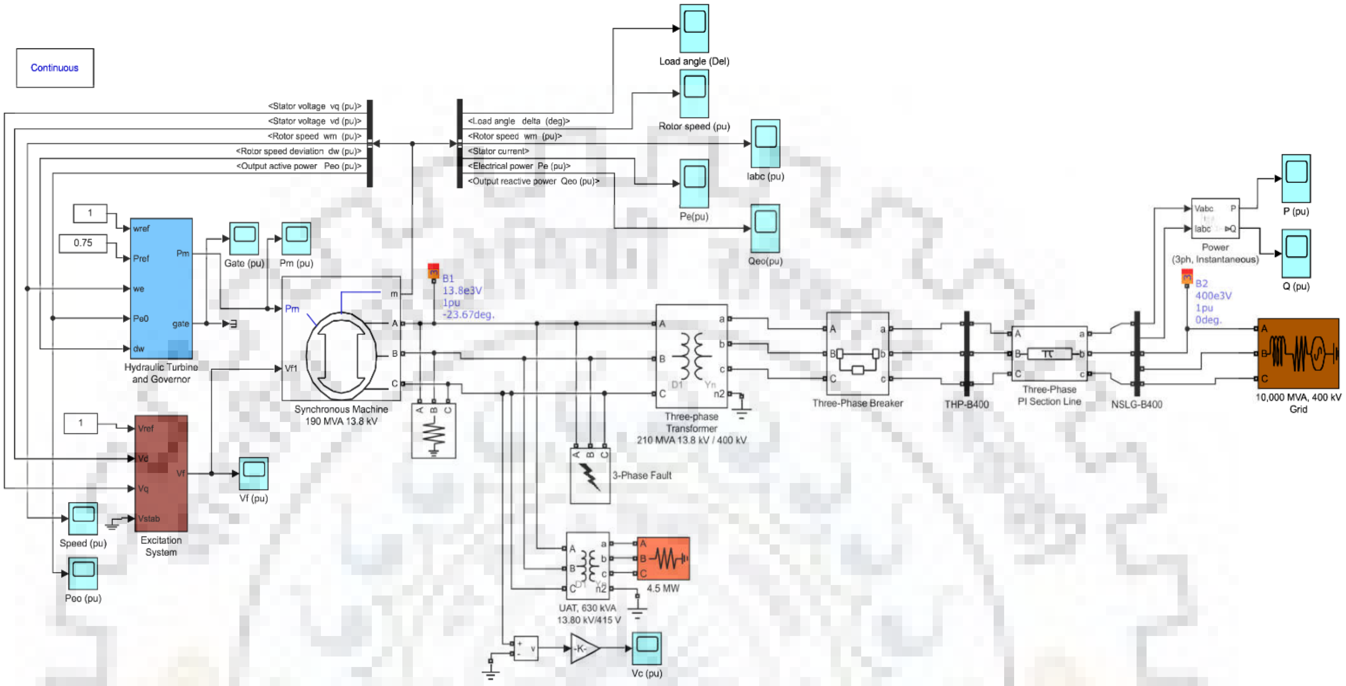

Fig. 5.3: Model with Temporary Fault

Permanent fault trigger sustained disruption for longer time and the fault is not cleared therefore, faulty section is isolated by protection system. Permanent faults are associated situations such as wind, ice loading, thermal heating, falling of trees on transmission lines, any elements short circuiting the phase conductors etc. Three-phase to ground fault is used in model where the circuit breaker operates by signal from relay as soon as it senses the fault current. MATLAB Simulink model for the permanent fault in hydropower plant system is represented in Fig.5.4.

In the basic model, the logic circuit of over current relay has been implemented. As soon as the fault current increased above the set value in relay at the time of fault, the circuit breaker is operated and isolates the faulty section of power system.

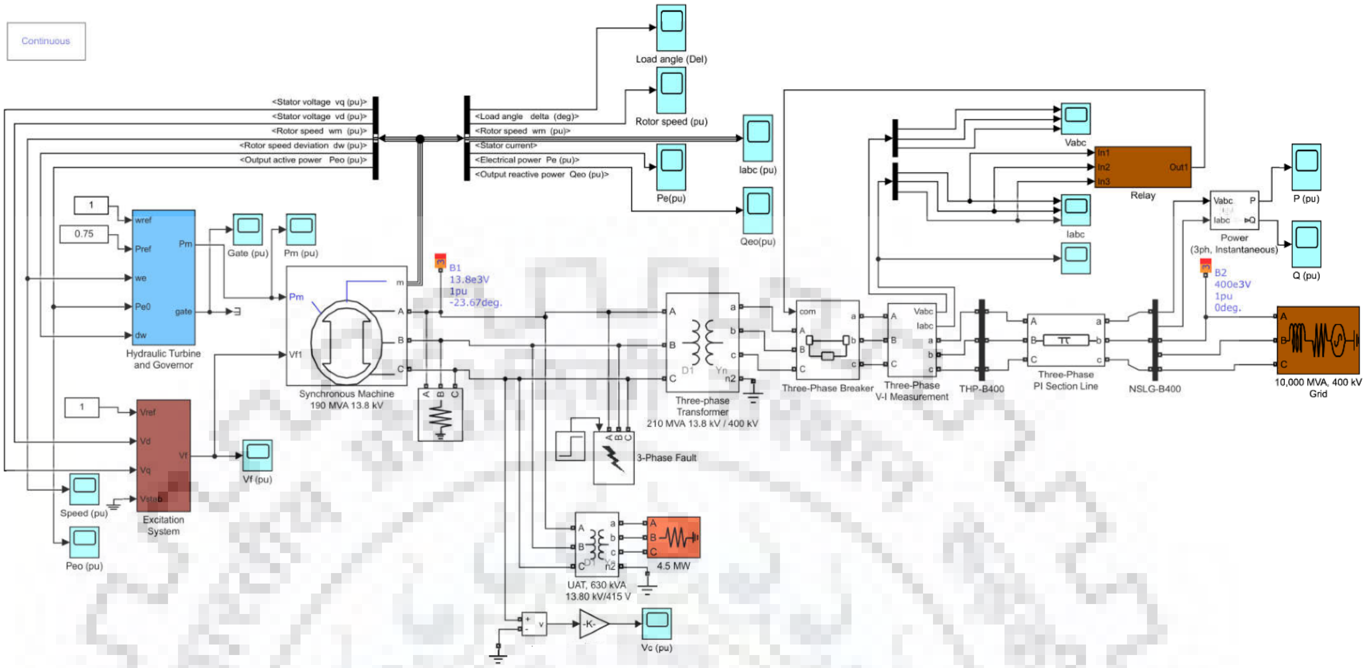

Fig. 5.4: Model with Permanent Fault

5.3 VALIDATION OF MODEL PERFORMANCE

As discussed earlier, simulation of HPP model is to examine the performance of electro-hydraulic governor which can be carried out under steady state and transient state. The validation is carried out to examine the output of model which is close to the real system. The following approach has been used to confirm the performance of the model.

5.3.1 Performance Measurement

Output of MATLAB Simulink model of hydropower plant is compared with real time measurement. The overall performance measurement of hydropower plant comprises steps as given below.

i. Data acquisition/ Real time measurement
ii. Measured data processing, refining and analyzing
iii. Determining the stationary values for measured signals

Unit-2 was identified to conduct the test on March 24-26, 2014 at Tala Hydro Power Plant [81]. The test was performed jointly by professionals from CoECAP of DGPC, College of Science and Technology, University of Rostock and Bhutan Power Corporation.

The test engineers from CoECAP, College of Science and Technology, University of Rostock and Bhutan Power corporation completed the required connection of test signals at the test bench to LabView data acquisition (DAQ). The input channels of DAQ were allocated for each signal and adjusted to fit actual measurement range of different signals. Subsequently, healthiness and availability of signal at DAQ input was inspected. The measurements were done as given below.

i. Performance measurement for load increase/decrease on Unit-2 in interconnected mode by change of power setter.

Unit was loaded to 70 MW at the initial stage, the test DAQ was set to record the measurement signal for given load. The load on unit was gradually increased/ decreased at certain steps of power setter, P_{ref}. Simultaneously, the signal was recorded at each step. All the measured signals were acquired by LabView DAQ.

Table 5.1: Loading/De-loading of Unit-2 [81]

Power Setter Steps P_{ref}	**Unit Loading**	
	MW	**% Loading**
1	70	40
2	90	53
3	140	82
4	187	110
5	170	100
6	120	70
7	75	44
8	40	23
9	30	17
10	15	9
11	10	6
12	40	23
13	100	59
14	170	100

ii. Performance measurement during emergency shutdown.

The load was kept on unit as 70 MW and arranged for the sudden shutdown and kept the kit ready for recording. The unit was given the command of emergency shutdown command from controller panel. All the required signals were recorded by DAQ for the process.

5.3.2 Validation of Results

The output of complete model comprising of sub-system has been validated based on real time signal for the power plant. Properly validated mathematical model closely representing the actual power system would allow the investigation on simulation results. With such HPP model the stability of electro-hydraulic governor can be examined properly based on the operating conditions.

In the following section, it is attempted to compare measured real time performance and simulated. The following two situations are selected for validation such as unit generation under no disturbance and load increase/decrease.

5.3.3 Unit Running Under Constant Load Condition

The simulated results were compared with real time measurement of Unit-2. The parameters selected for the comparison are electrical power, turbine speed and gate/nozzle opening. The generating Unit-2 is loaded to 70 MW initially and measured the parameters during the test. Fig.5.5 shows variation of turbine speed with respect to time, Fig.5.6 shows change of electrical with respect to time and Fig.5.7 shows change of gate/ nozzle opening with respect to time. The figures are presented analytically to validate the measured data.

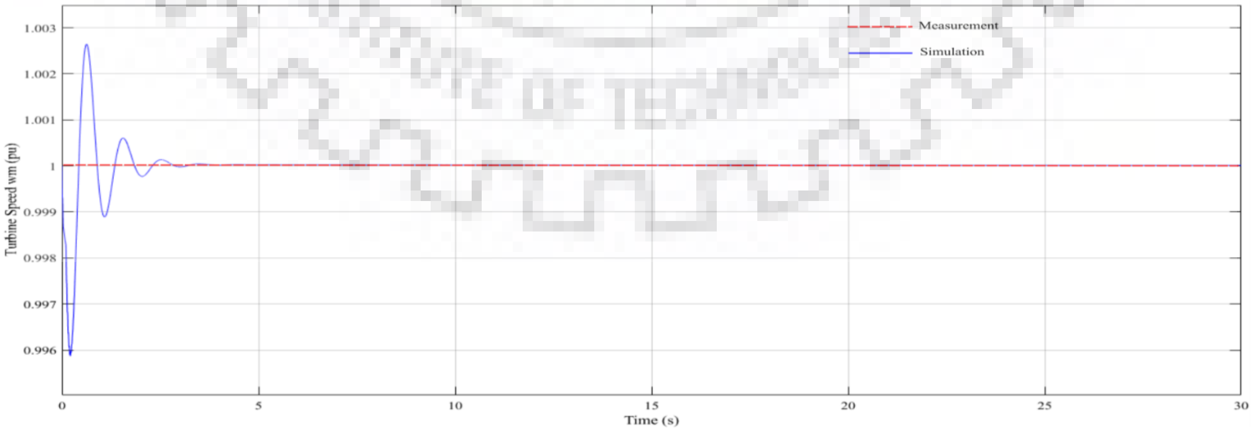

Fig. 5.5: Comparison of Simulation & Measurement of Turbine Speed at Constant Load

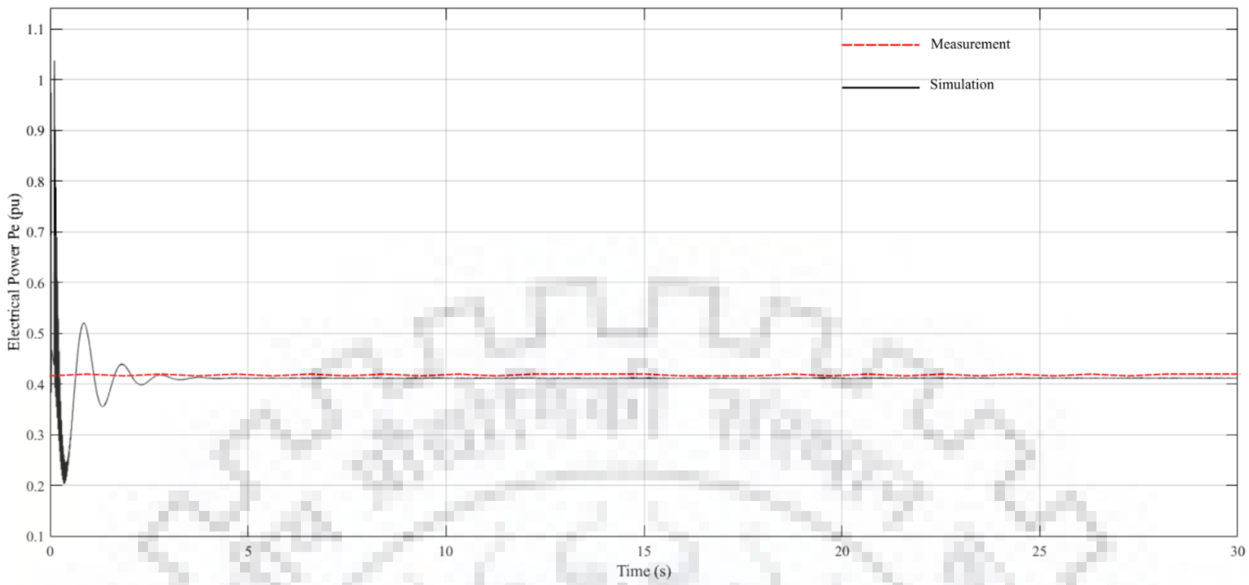

Fig. 5.6: Comparison of Simulation & Measurement of Electrical Power at Constant Load

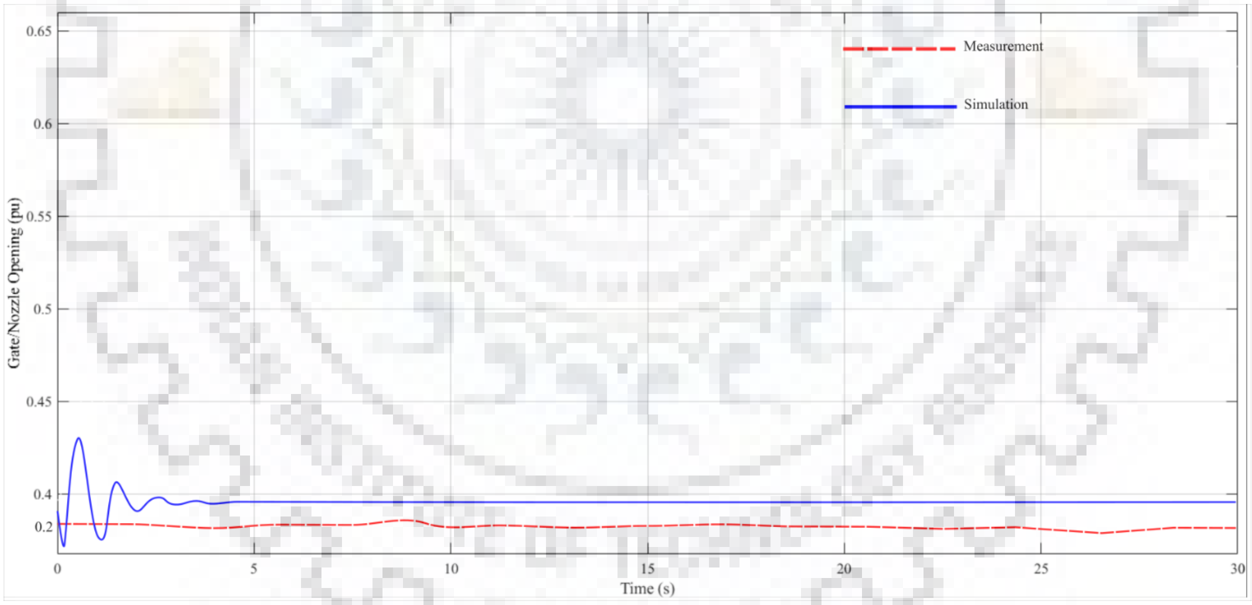

Fig. 5.7: Comparison of Simulation & Measurement of Gate/Nozzle Opening at Constant Load

Turbine speed at 70 MW of load on the unit is shown in Fig.5.5. The measured and simulated speed of model observed close to 1pu. In the simulation result the initial speed is deviated from desired value; the main cause is due to transient behavior in the beginning at the time of circuit breaker closure.

The validation of electrical power is shown in Fig.5.6. The actual load on unit was 70 MW which is 0.40 pu. In the simulated power vs time curve, there is oscillations in the beginning due to transient as explained earlier. The simulated result is closed to measured value after 5 seconds.

Similarly, Fig.5.7 represents the gate/nozzle opening during the constant load of 70 MW on generator. The fluctuations of gate/nozzle opening at starting time is noticed, which stabilized within 4 seconds in simulated result whereas no such deviation noticed in real time measure value. In the measurement at the site, 0.20 pu opened for 70 MW whereas it is noticed that 0.38 pu of nozzle is opened in the simulation result.

5.3.4 Unit Under Load Increase Condition

For the load increase condition, the simulated results were compared with real time measurement of Unit-2. The parameters selected for the comparison are electrical power, turbine speed and gate/nozzle opening. The generating Unit-2 is loaded to 140 MW and parameters were measured during the test. Fig.5.8 displays variation of turbine speed with respect to time, Fig.5.9 shows the electrical power change with respect to time and Fig.5.10 shows the gate/nozzle opening with respect to time.

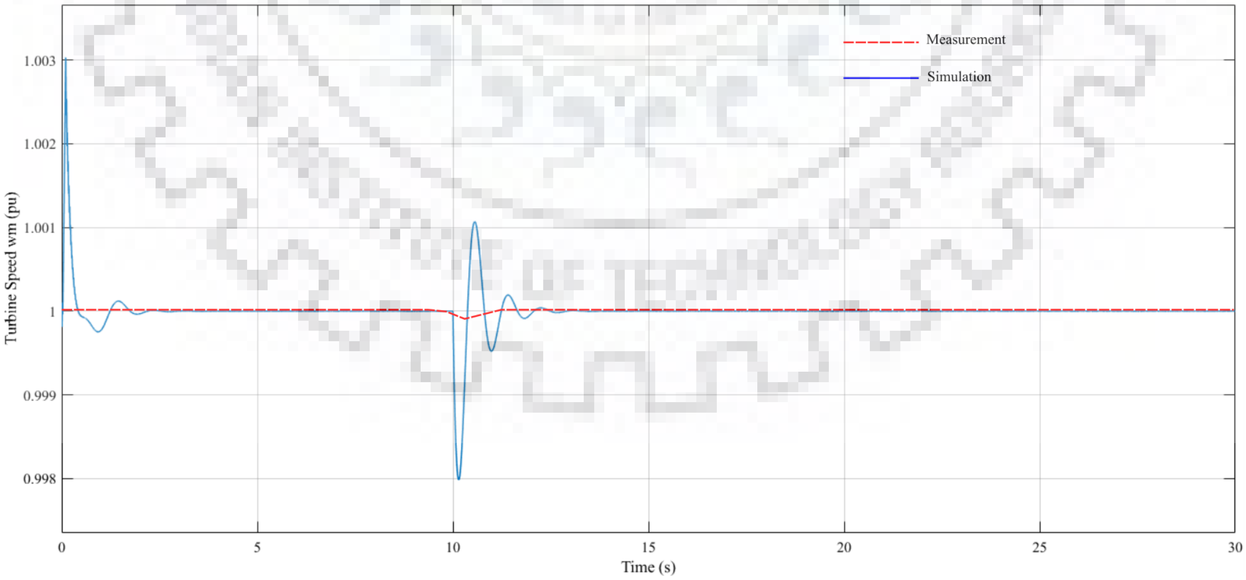

Fig. 5.8: Comparison of Simulation & Measurement of Turbine Speed at Load Increase

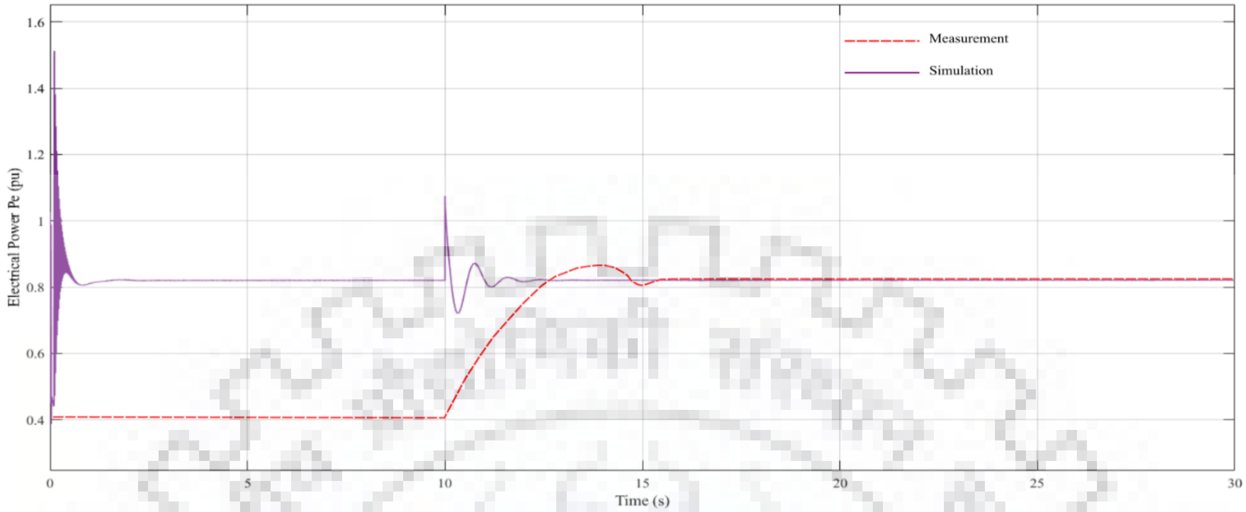

Fig. 5.9: Comparison of Simulation & Measurement of Electrical Power at Load Increase

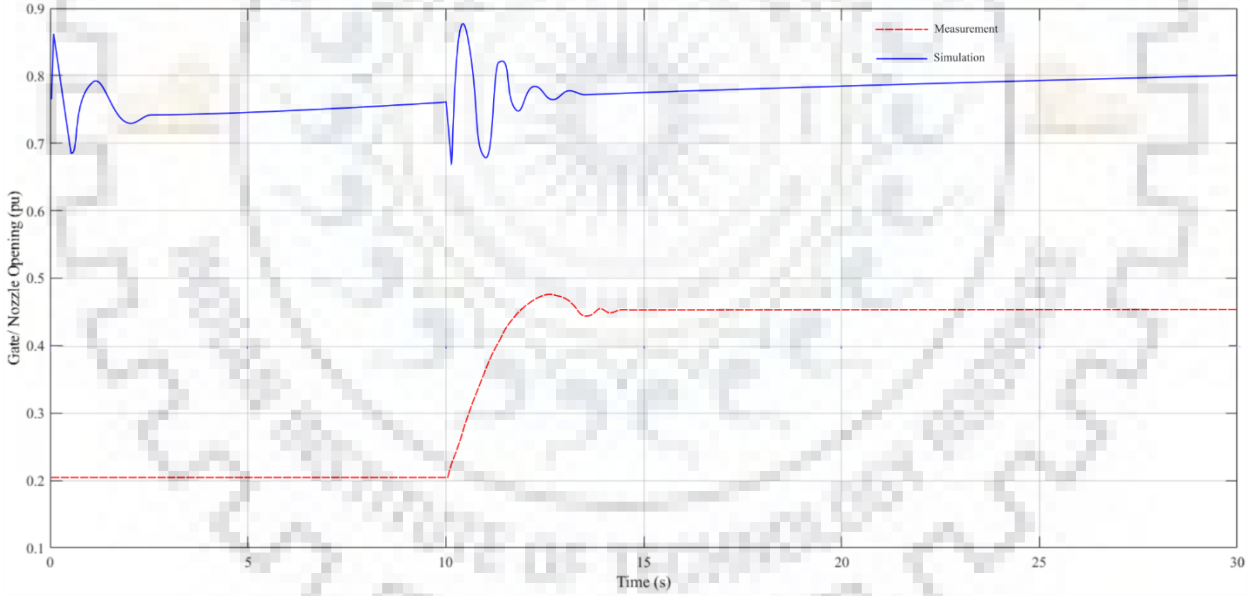

Fig. 5.10: Comparison of Simulation & Measurement of Gate/Nozzle Opening at Load Increase

Fig.5.8 shows the turbine speed when the generator load increased to 140 MW. The measured speed and simulation speed are 1 pu. However, there is disturbance of speed at the starting time in the Simulink model and no such major fluctuation is noticed on the unit. There is fluctuation of speed after load increase in the model, which lasted for few cycles and reached to steady state after 3 seconds. The variation of speed after loading on the unit was very less.

The electrical power is represented in Fig.5.9 for load increase condition. The electrical power for model is 0.41 pu initially and for 140 MW it is 0.82 pu. The electrical power is deviated from 10 second after load increase and reached to steady state after 2.5 seconds. The electrical power recorded of Unit-2 showed increase of electrical power in steps and reached to 0.82 pu as per governing action.

The gate/nozzle opening during the loading of generator to 140 MW is shown in Fig.5.10. The nozzle opening of 0.21 pu was recorded for 70 MW and 0.46 pu for 140 MW. In the simulation it is observed the nozzle 0.79. After the load disturbance, the oscillations of nozzle opening in the output of model is noticed and gets damped within 4 seconds. Whereas, in the data recorded for the unit at the site, it was observed step wise governing action and nozzle opening as per the load on unit. No significant fluctuations of nozzle opening at the time of load regulation was noticed.

5.3.5 Validation of Sensitivity of Governor Parameters

For the validation of sensitivity of governor, the change of inertia constant (H) is presented in Fig.5.11, damping time constant (Td) is shown in Fig.5.12 and permanent droop (bp) is shown in Fig.5.13 for the condition of load addition.

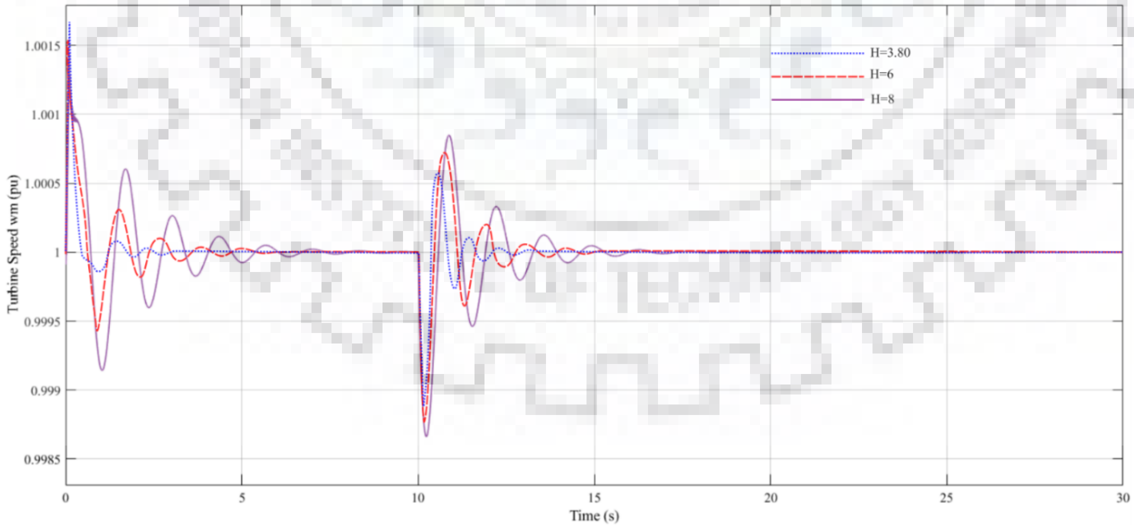

Fig. 5.11: Unit Response with Change of Inertia Constant (H)

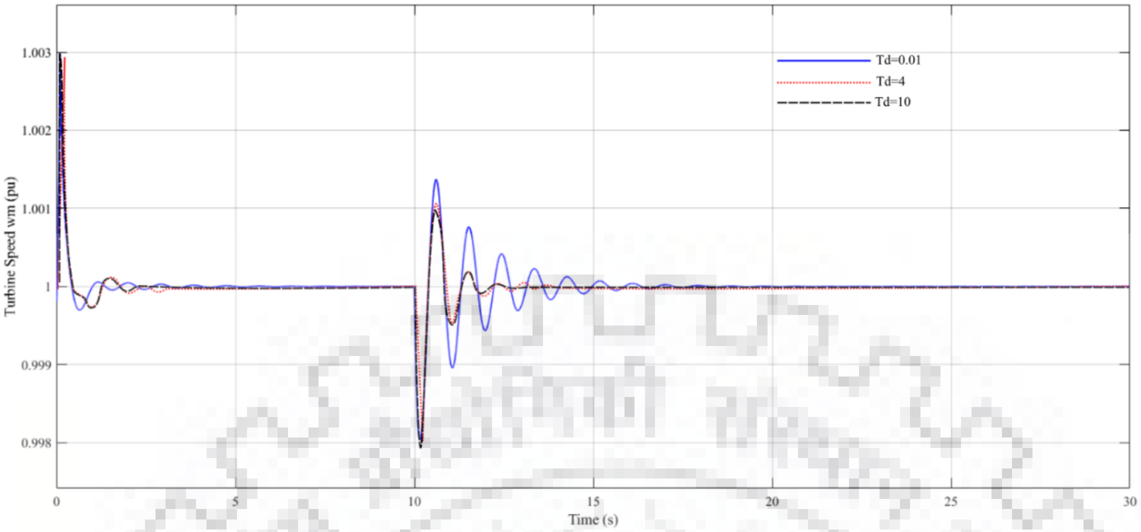

Fig. 5.12: Unit Response with Change of Damping Time Constant (Td)

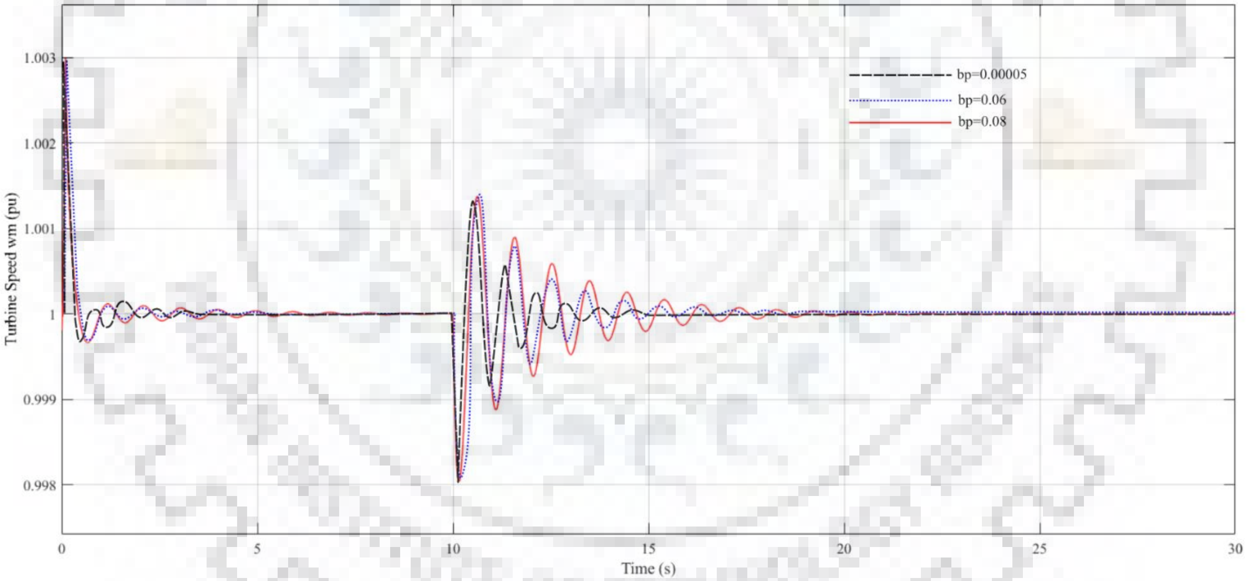

Fig. 5.13: Unit Response with Change of Permanent Droop (bp)

For the grid connected hydropower plant, it is observed that at higher inertia constant, the oscillations are damped lesser as shown in Fig.5.11. The oscillation is observed for longer duration for low value of damping time constant. For better stability, the oscillations are damped for higher damping constant as shown in Fig.5.12. The range of the permanent droop for hydropower unit is from 1-10%. The performance of unit in terms of speed with different permanent droop values is presented in Fig.5.13. With increase in permanent droop speed deviation is noticed for longer duration. However, low permanent droop is only valid for isochronous operation. Therefore, for hydro unit connected to grid, the permanent droop may be set to 5-6% as per the grid code requirement. The simulation results are validated with IEEE standard 1207-2011.

5.4 RESULTS AND DISCUSSION

In order to investigate the stability of electro hydraulic governor of hydraulic turbine, the simulation results of model of hydropower plant under different scenarios are analyzed below.

5.4.1 Operation Under Steady State Condition

The hydropower plant model is simulated under steady state condition for the duration of 30 seconds. The simulation results are shown in the Fig.5.14 for turbine speed, Fig.5.15 for electrical power and Fig.5.16 for gate/nozzle opening.

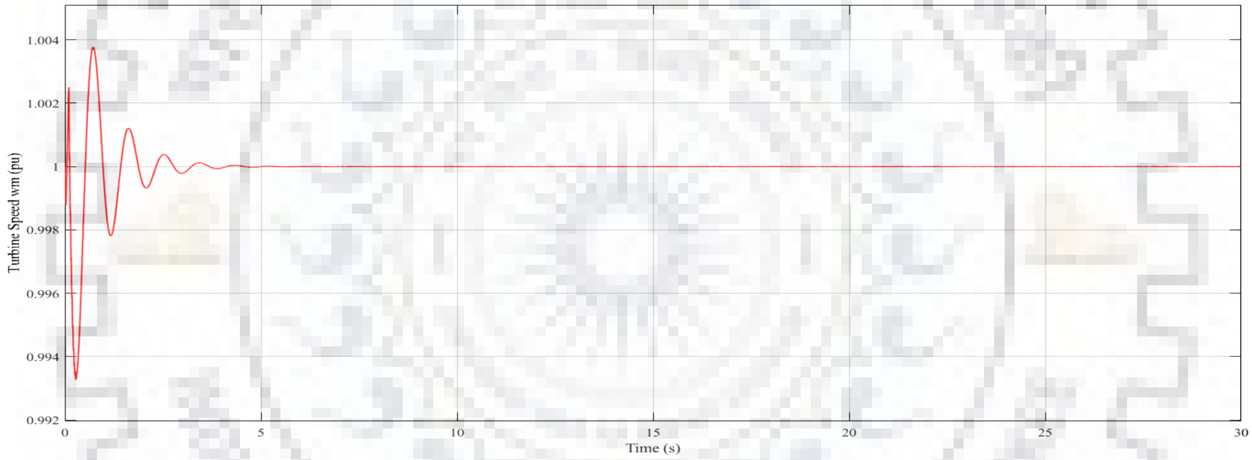

Fig. 5.14: Turbine Speed vs Time

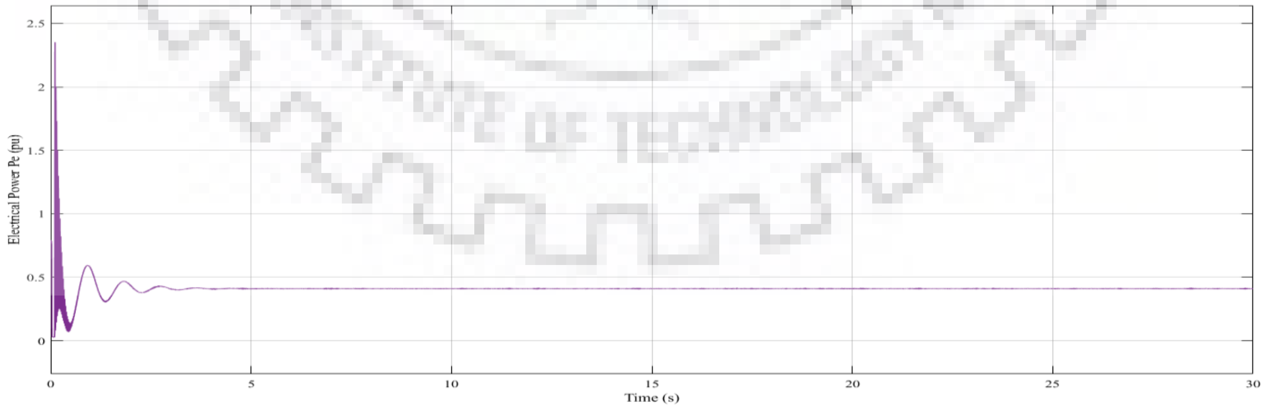

Fig. 5.15: Electrical Power vs Time

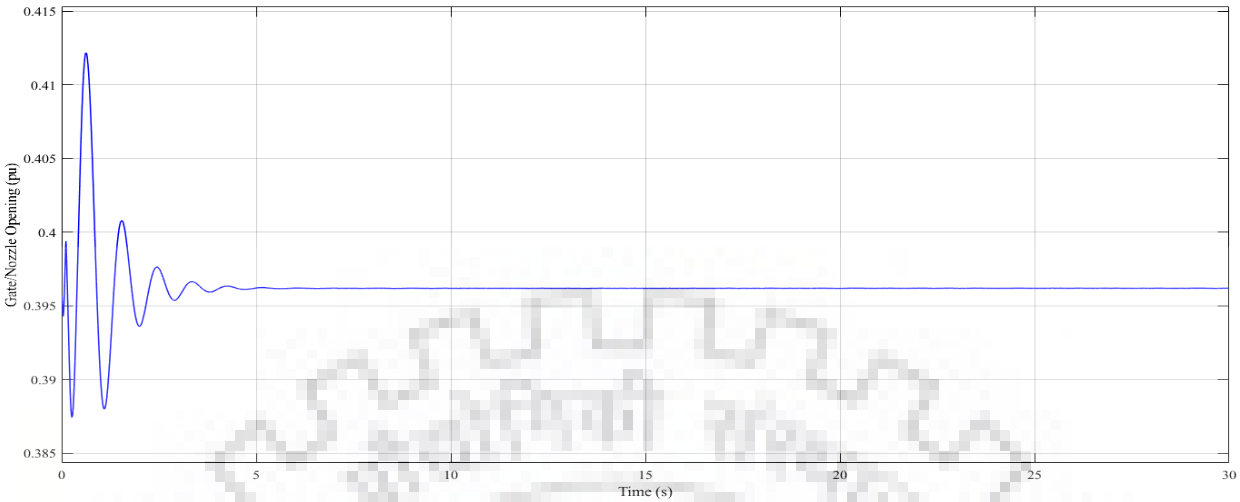

Fig. 5.16: Gate/Nozzle Opening vs Time

In the initial stage, it is observed some deviation of parameters, this is mainly due to closing of circuit breaker. After 4 seconds the oscillations are damped and reached to steady state. All the parameters like turbine speed, electrical power and gate/nozzle opening are found stable.

5.4.2 Operation Under Load Increase Condition

The power system load disturbance was applied at t=10 seconds by increase of load on generator. The simulation results are represented in the Fig.5.17 for turbine speed, Fig.5.18 is shown for electrical power and Fig.5.19 is shown for gate/nozzle opening.

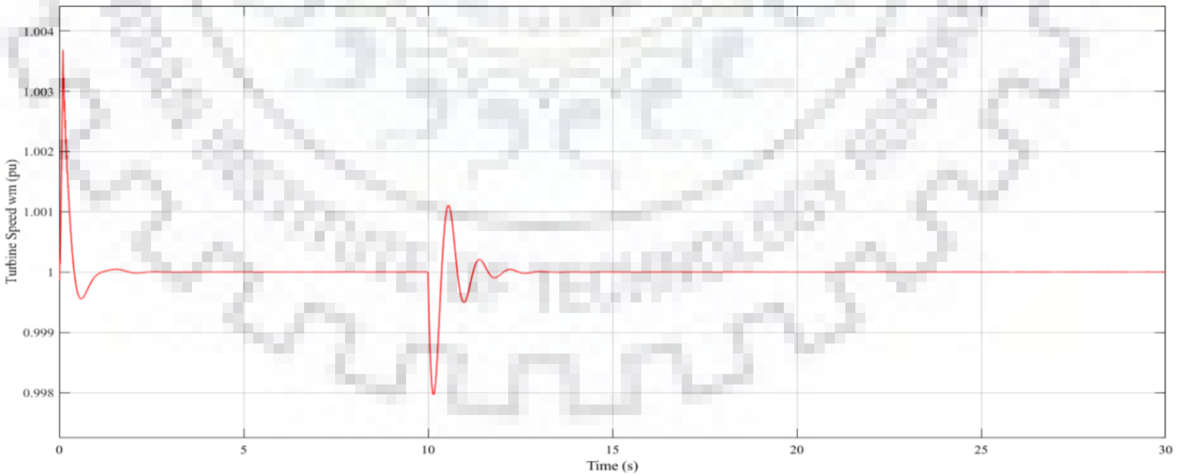

Fig. 5.17: Turbine Speed While Increase in Load

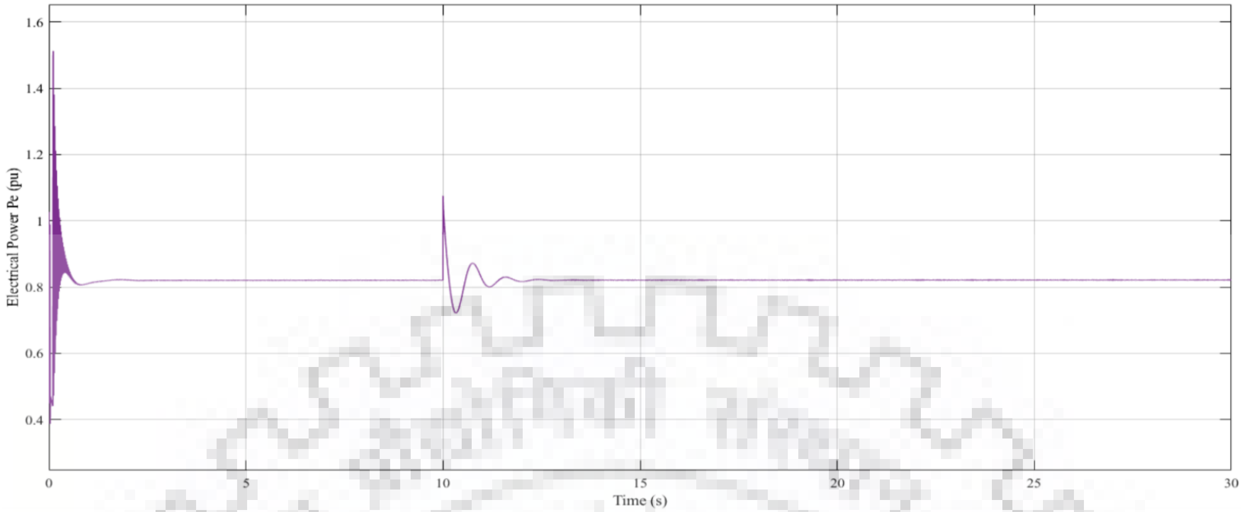

Fig. 5.18: Electrical Power While Increase in Load

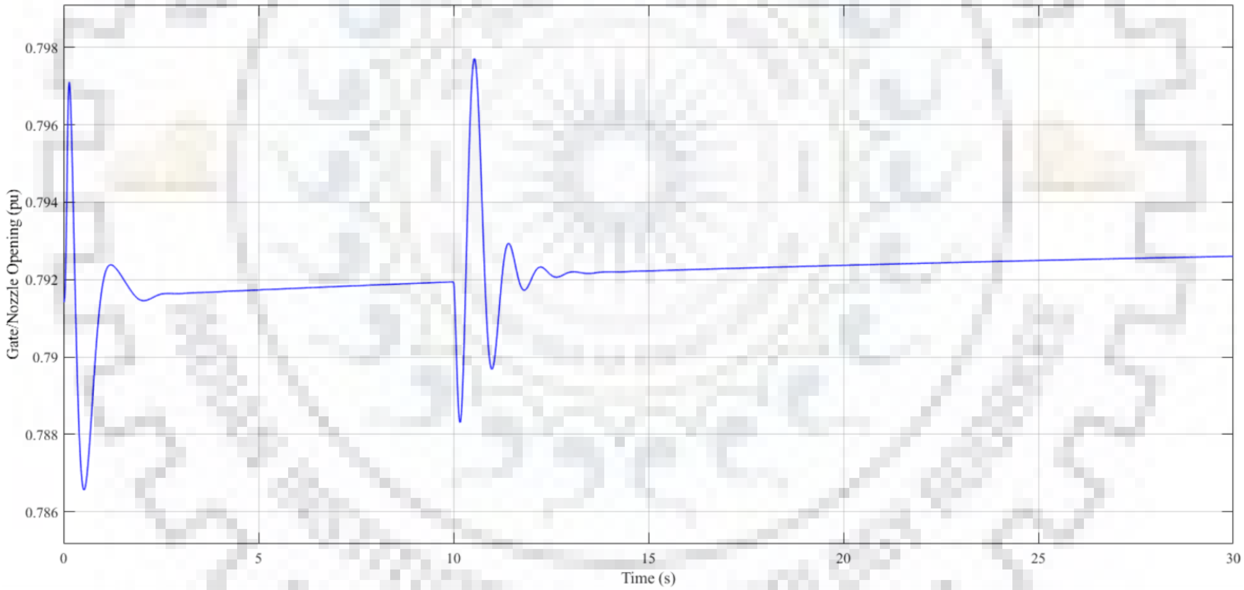

Fig. 5.19: Gate/Nozzle Opening While Increase in Load

From the Fig.5.17, it is observed that the speed of turbine reached to steady state after 1.5 seconds in the beginning. The speed of turbine is decreased at time of the load addition t=10 seconds however, reached to steady state after 13 seconds. It is noticed that electrical power reached to 1.25 pu at the time of load increase and gradually reached to stable position after 13 seconds as shown in Fig.5.18. Like wise, Fig.5.19 is represented for gate/nozzle opeining while load on unit is regulated t=10 second. It is noticed steady state gate/nozzle opening is in between

2.5 to 10 seconds, after 10 seconds there is disturbance in the gate/nozzle opening and reached to steady state after 13 seconds.

5.4.3 Operation Under Load Decrease Condition

The transient condition to the system was introduced at t=10 second by reduction of load on generator. For the load decrease situation, the simulation results are represented in the Fig. 5.20, Fig.5.21 and Fig.5.22 for turbine speed, electrical load and gate/nozzle opening, respectively.

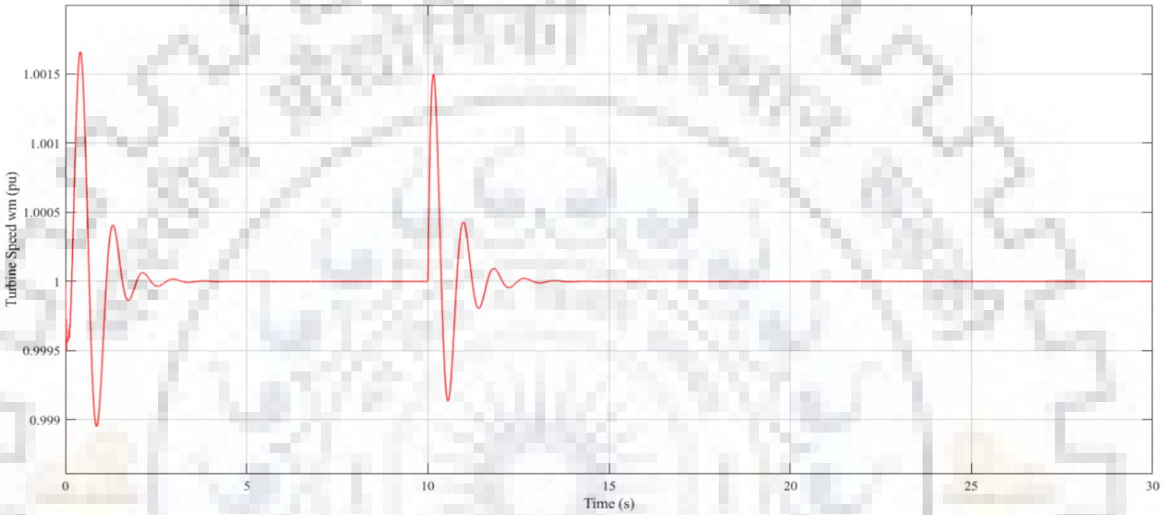

Fig. 5.20: Turbine Speed While Decrease in Load

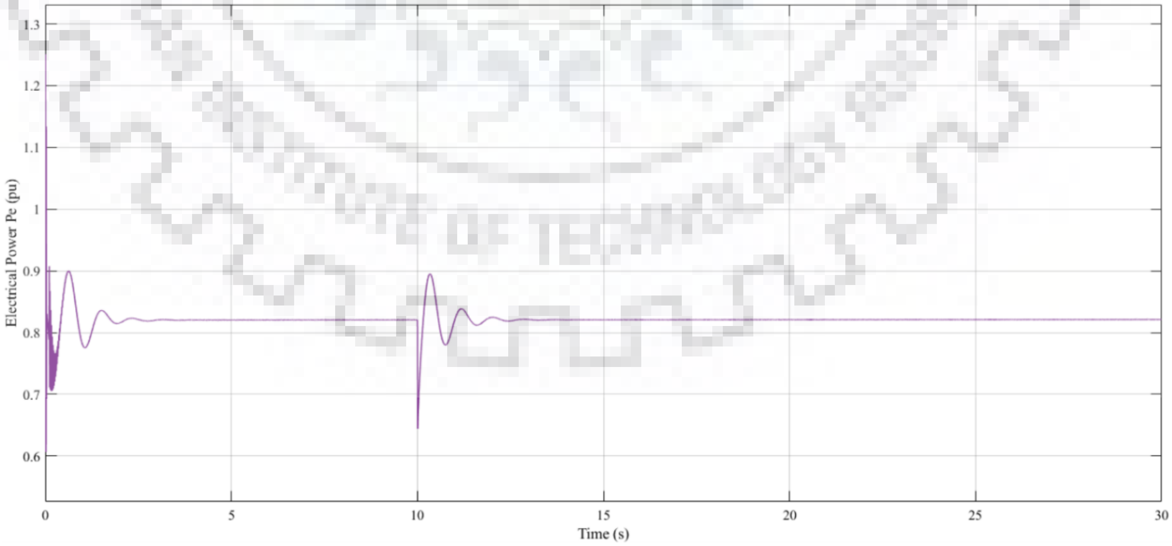

Fig. 5.21: Electrical Power While Decrease in Load

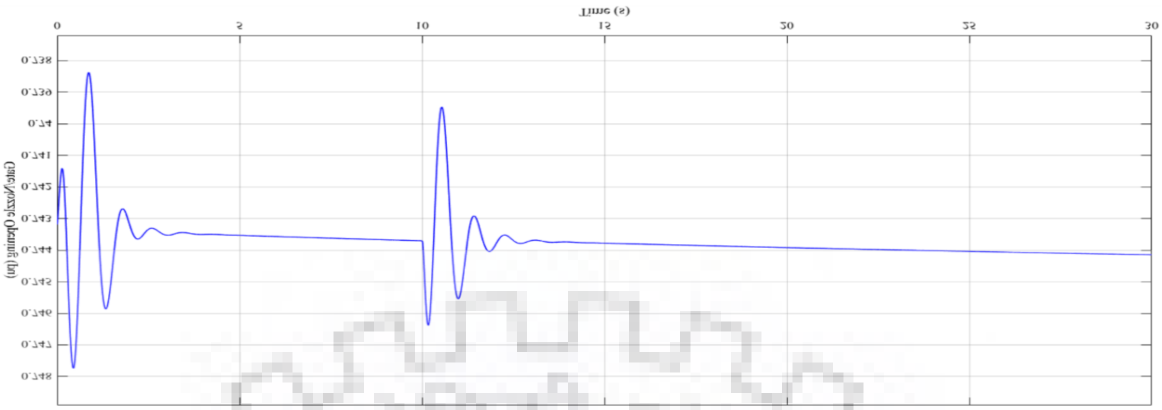

Fig. 5.22: Gate/Nozzle Opening While Decrease in Load

The speed of turbine during reduction of load is shown in Fig 5.20. When the load is reduced by 41% at t= 10 seconds the turbine speed increases to 1.0015 pu. The oscillation speed of turbine is noticed at time of the load addition t=10 seconds however reached to steady state after 13 seconds. The electrical power of the generator is given in Fig.5.21. The sudden reduction of load give rise to power swinging for the period of 3 seconds after the disturbance and reached to steady state after 13 seconds. In the same way, the gate/nozzle opening for load decrease situation is given in Fig.5.22. From the unit response, it is observed that after 10 seconds, the gate/nozzle opening fluctuates for the duration of 4 seconds and reached to stable position.

5.4.4 Operation Under Temporary Fault Condition

The three-phase fault in the system is introduced at time 10.5 to 10.6 second when the load on unit was kept as 0.75 pu. The variation of parameters like turbine speed, electrical power and gate/nozzle opening are illustrated in Fig.5.23, Fig.5.24 and Fig.5.25 respectively.

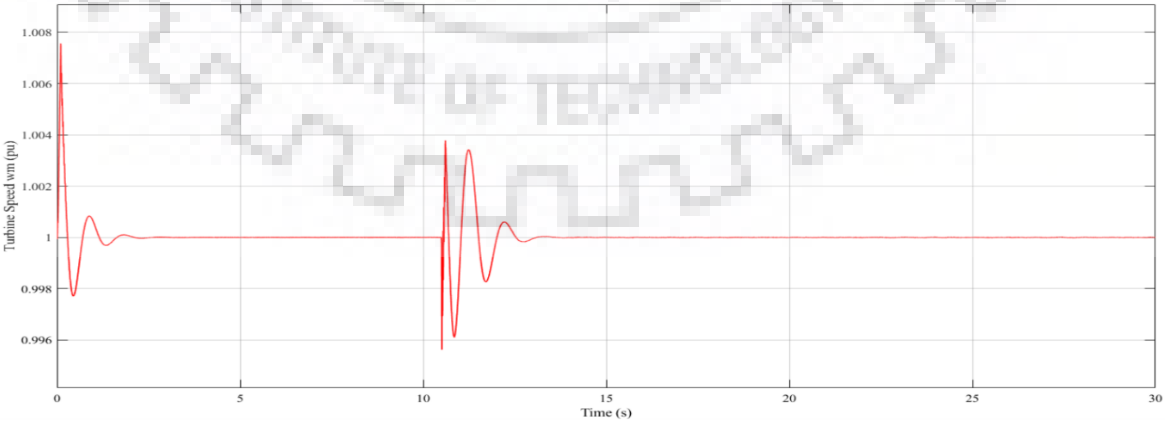

Fig. 5.23: Turbine Speed Variation During Temporary Fault

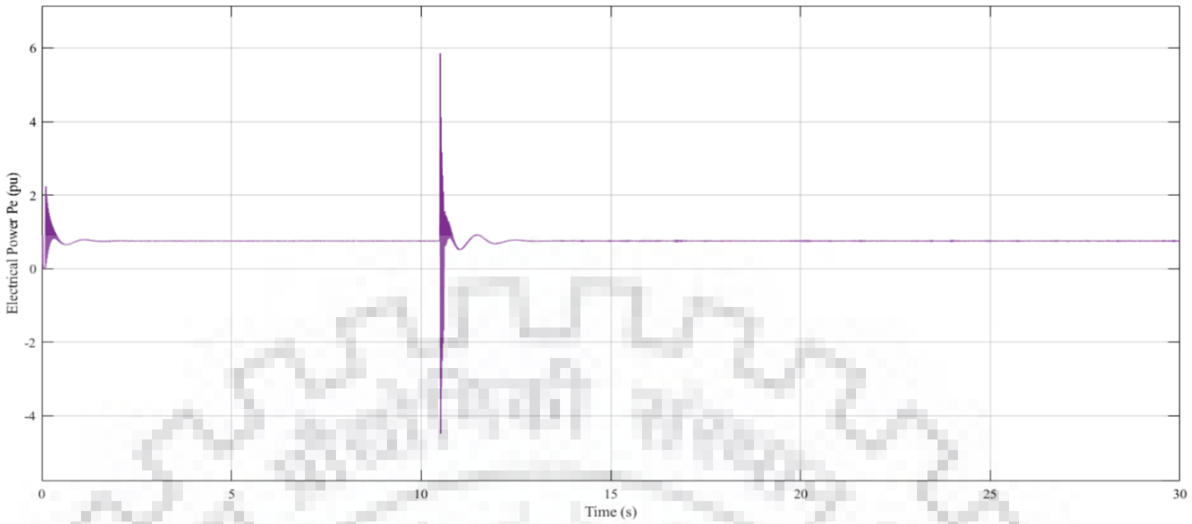

Fig. 5.24:Electrical Power During Temporary Fault

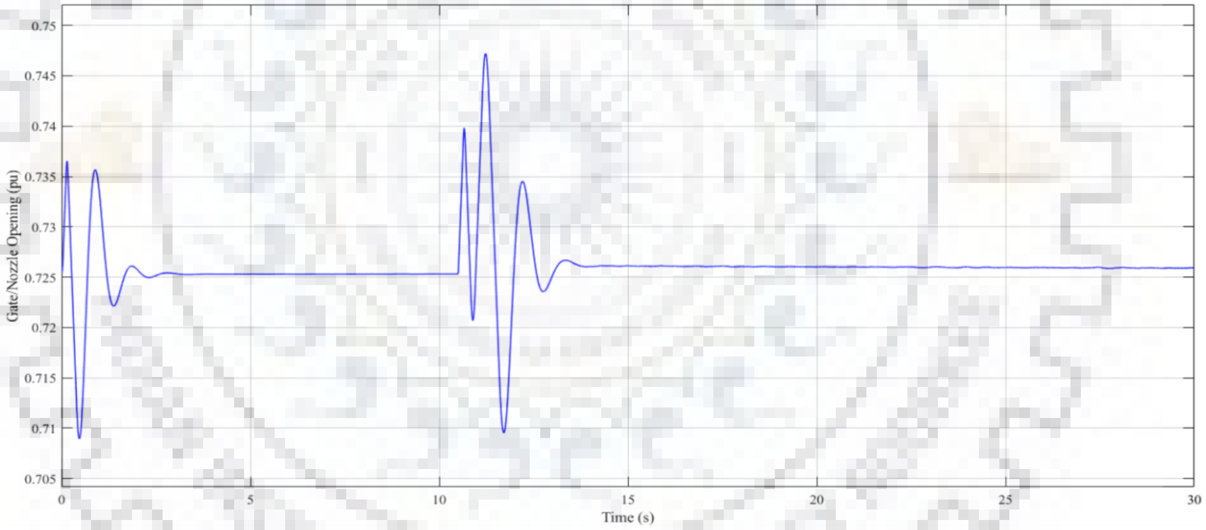

Fig. 5.25: Gate/ Nozzle Opening During Temporary Fault

The turbine speed after unit is under temporary three-phase fault condition is illustrated in Fig.5.23. It is observed that the speed deviated from stable position. However, it returned to nominal value after 3.5 seconds after the fault. The electrical power is shown in Fig.5.24 and during the fault the power fluctuates approximately 5.6 pu and returned to steady state at t=12.5 second after the fault is cleared. The gate/nozzle opening deviation due to the fault at 10.5 seconds is presented in Fig.5.25 and it is noticed that oscillations of gate/nozzle opening lasted for about 3.5 seconds and settled to stable state.

5.4.5 Operation Under Permanent Fault Condition

The permanent fault in the system is activated at 10.5 second keeping the load on unit as 0.75 pu. Due to the high current above the setting of relay, the circuit breaker operates to isolate the faulty section. The parameters like turbine speed, electrical power and gate/nozzle opening that have changed when the fault occurred are shown in Fig.5.26, Fig.5.27 and Fig.5.28.

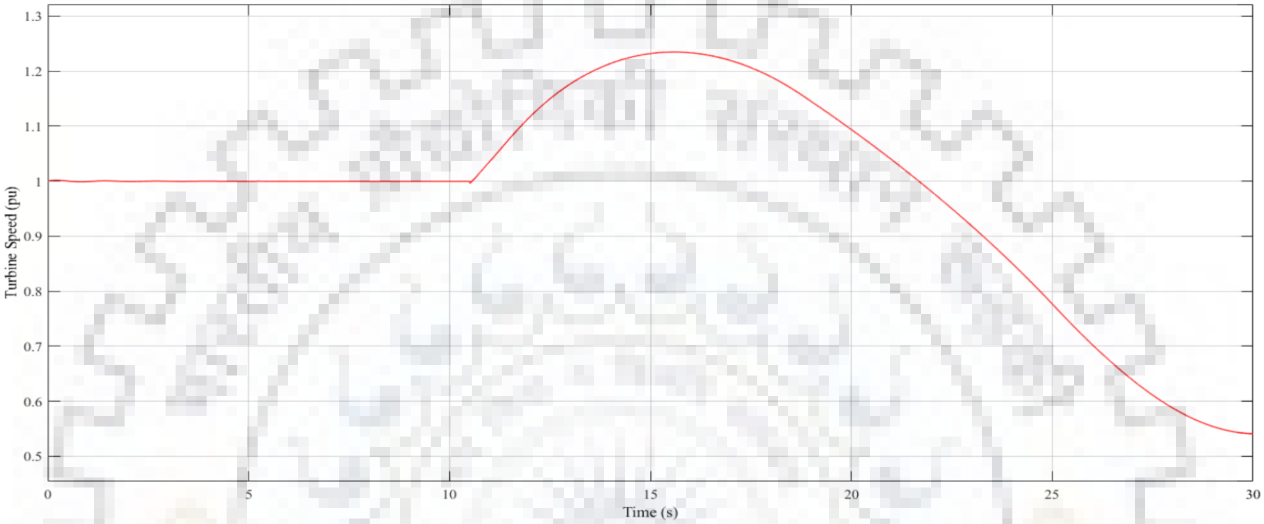

Fig. 5.26: Turbine Speed During Permanent Fault

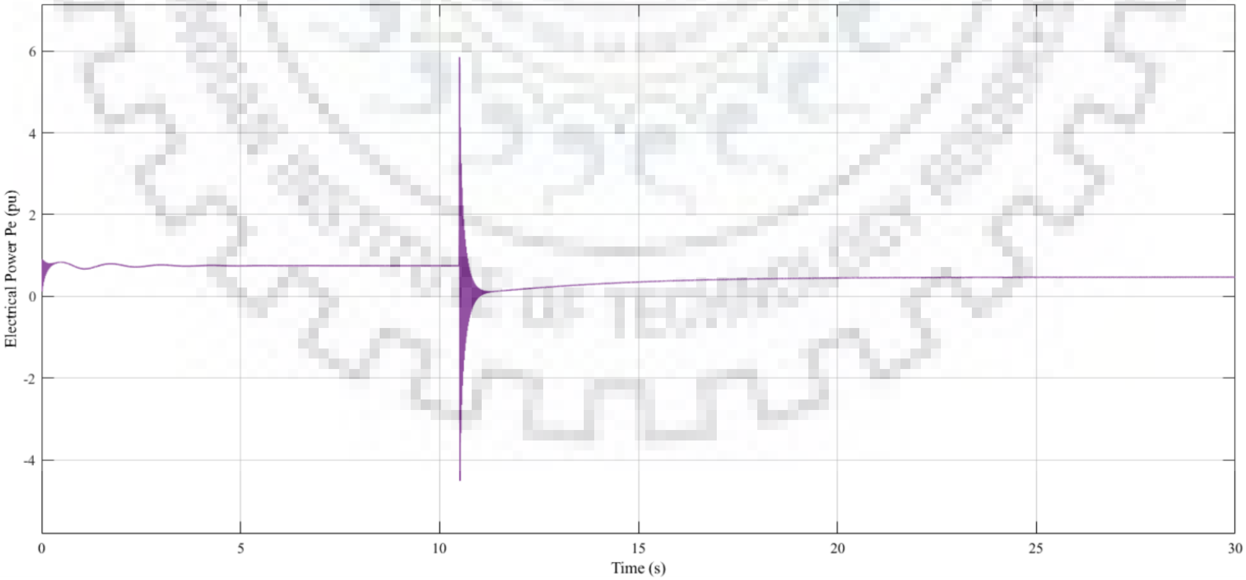

Fig. 5.27: Electrical Power During Permanent Fault

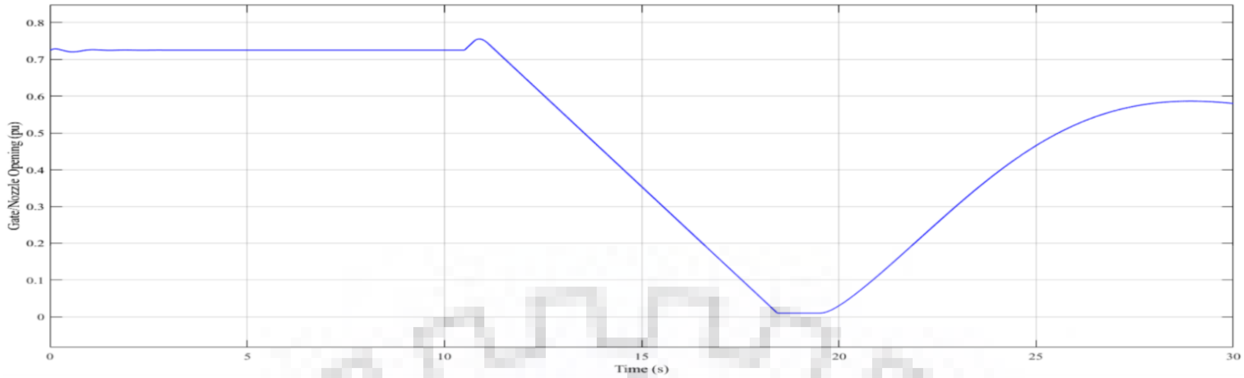

Fig. 5.28: Gate/Nozzle Opening During Permanent Fault

The speed of turbine rises to 1.23 pu as soon as circuit breaker is operated as shown in Fig.5.26. However, with governing action the speed has not reached to abnormal value and finally reached to standstill. The electrical power drops to zero after the operation of circuit breaker due to permanent fault as given in Fig.5.27. It is observed that sharp increase of electrical power at the time of fault which got damped within 1 second. Likewise, Fig.5.28 shows the disturbance of gate/nozzle opening after introduction of permanent fault. The gate/nozzle opening reached to zero at t=18 seconds. After 20 seconds the gate/nozzle opening position moved to its set value. Therefore, it is observed that there is no abnormal increased in turbine speed after the fault in the system.

5.4.6 Performance Under Different Values of Proportional Gain (Kp)

As a closed control loop system of turbine governing system, the proportional, integral and derivative (PID) controller is used for better performance. PID governor controller is tuned by determination of appropriate values of proportional gain (Kp), integral gain (Ki) and derivative gain (Kd). It is attempted to carry out the PID gain analysis of governor when the unit is subjected to transient fault. The hydropower plant model is simulated for different values Kp, Ki and Kd. The values of PID gains are given in Table 5.2. The integral gain (Ki) and derivative gain (Kd) are kept as 0.5 and 0.002 respectively.

Table 5.2: Different Values of Kp at Constant Ki and Kd

Governor	Kp	Ki	Kd
PID	2	0.5	0.002
	4	0.5	0.002
	8	0.5	0.002

The range of Kp of turbine governor controller of the generating unit is 0-10. The model is simulated by changing the proportional gain and outputs are illustrated in Fig.5.29, Fig.5.30 and Fig.5.31.

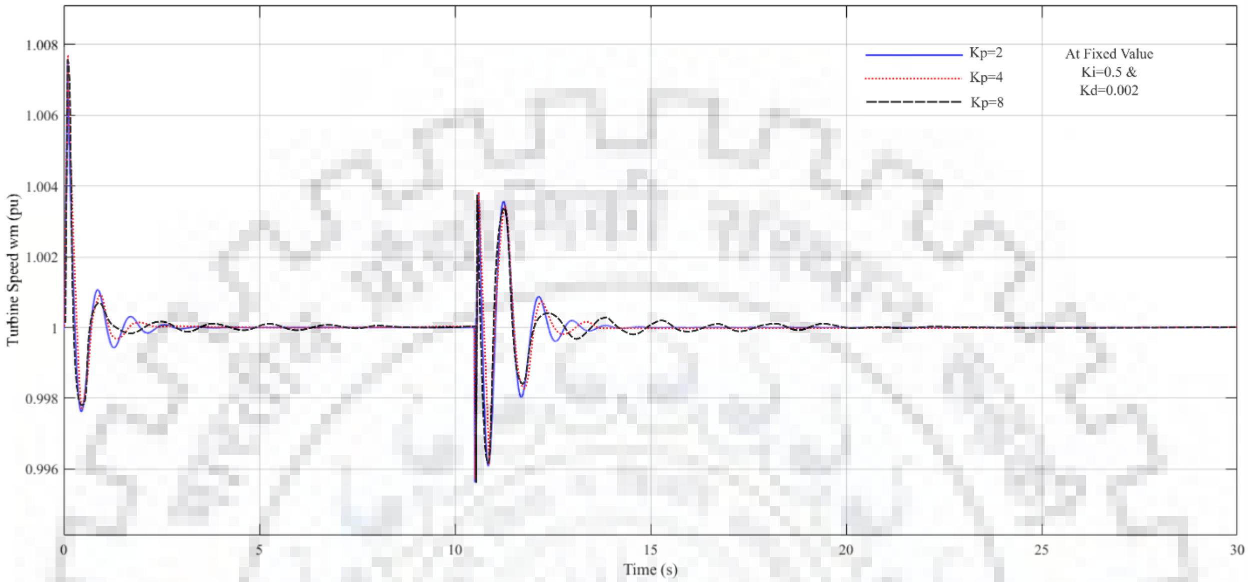

Fig. 5.29: Turbine Speed vs Time Under Varying Kp

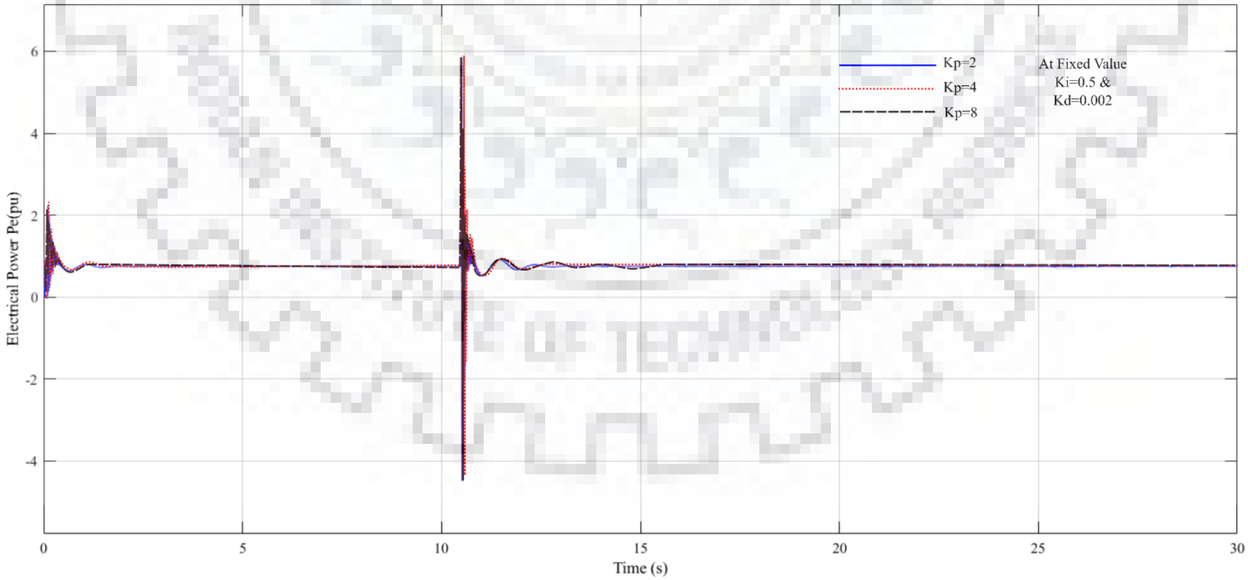

Fig. 5.30: Electrical Power vs Time Under Varying Kp

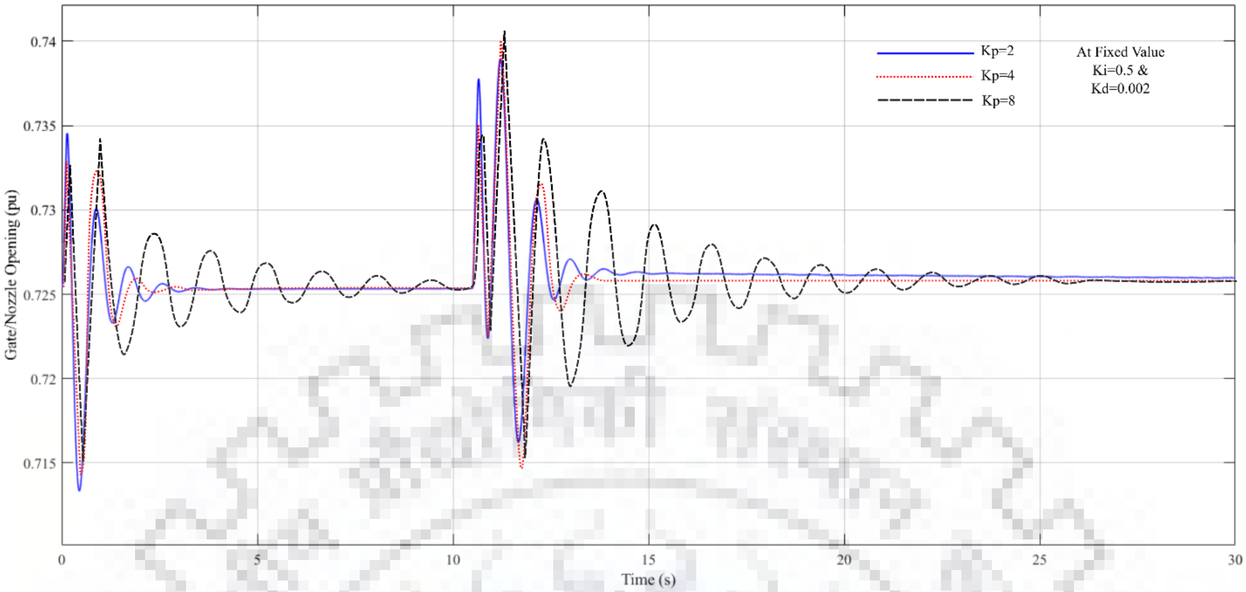

Fig. 5.31: Gate/ Nozzle Opening vs Time Under Varying Kp

As proportional gain (Kp) is increased, the deviation of turbine speed, electrical power and the gate/nozzle opining reduces, however further increase of Kp above 4.0 till 10.0, the oscillations are noticed significantly and affected the governing system and resulting the unstable state of unit. From the simulation by variation of Kp, it is observed that keeping Kp below 2.0 also resulted instability of unit. Therefore, tuning of governor controller has been carried out by keeping value of Kp between 2 and 4.

5.4.7 Performance Under Different Values of Integral Gain (Ki)

The hydro power plant model is simulated under transient fault condition to examine the performance of governor controller. Basically the range of integral gain (Ki) of electro hydraulic governor controller given as 0-1 for generating units. The proportional gain (Kp) and derivative gain (Kd) are kept as 2.0 and 0.002 respectively. The values of PID gains are shown in Table 5.3.

Table 5.3: Different Values of Ki at Constant Kp and Kd

Governor	Kp	Ki	Kd
PID	2	0.1	0.002
	2	0.5	0.002
	2	0.9	0.002

The hydropower plant model has been simulated for different integral gain (Ki). The simulation results for change of integral gain values are given in Fig.5.32, Fig.5.33 and Fig.5.34.

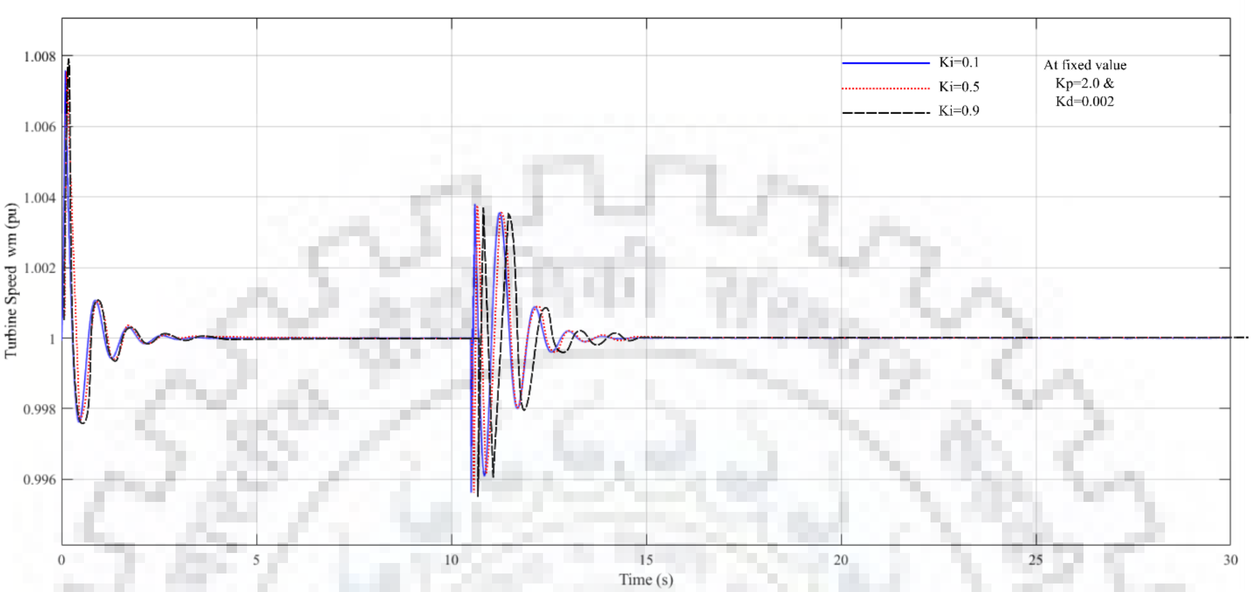

Fig. 5.32: Turbine Speed vs Time Under Varying Ki

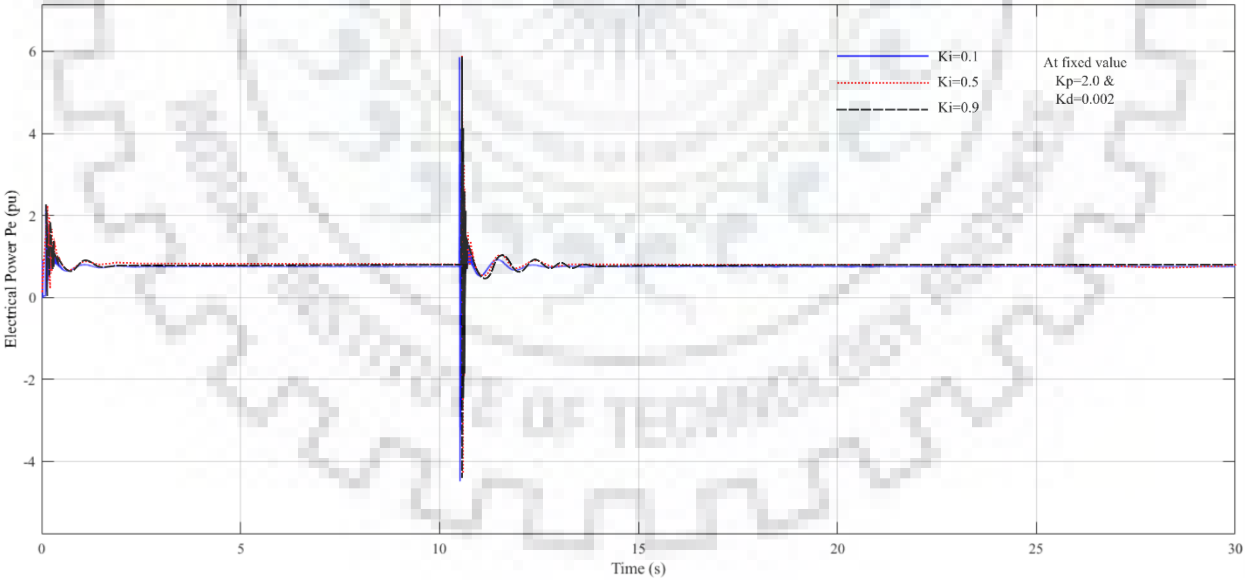

Fig. 5.33: Electrical Power vs Time under Varying Ki

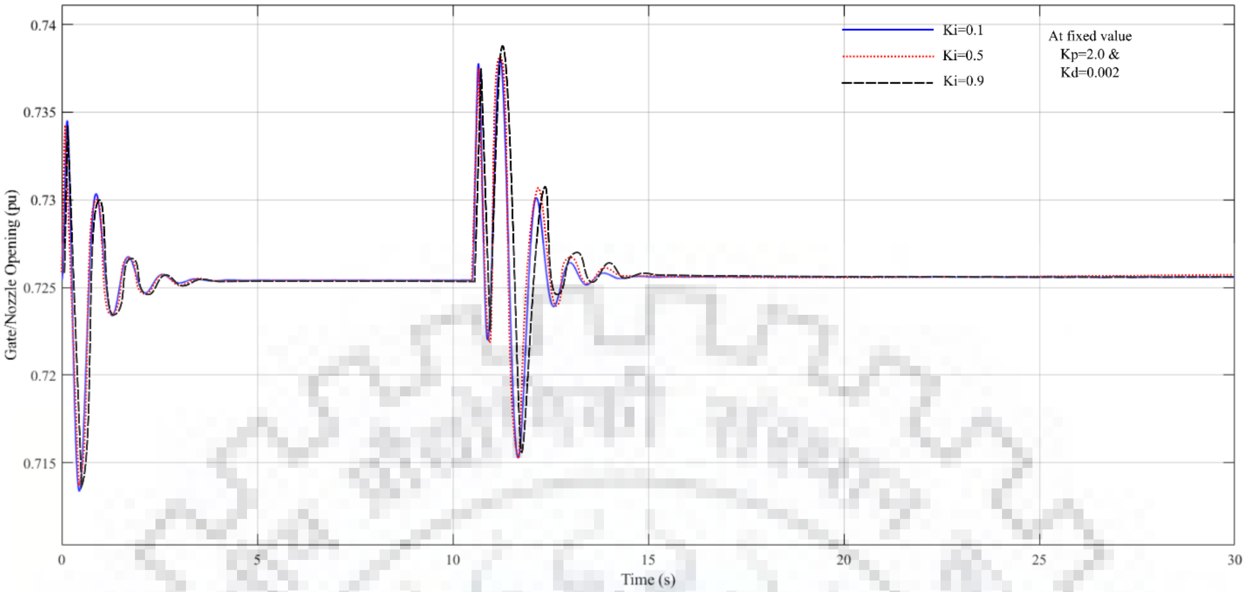

Fig. 5.34: Gate/Nozzle Opening vs Time Under Varying Ki

The integral gain (Ki) is increased and examined various parameter such as turbine speed, electrical power and gate/ nozzle opening. The proportional gain Kp and derivative gain Kd are kept constant as shown in Fig.5.34. For higher value of integral gain (Ki), it is noticed increased in oscillations and settling time has increased. Therefore, turbine speed, electrical power and gate/nozzle opening reached to unstable state because of increased in integral gain.

5.4.8 Performance Under Different Values of Derivative Gain (Kd)

The performance of electro hydraulic governor controller has been studied through simulation of plant model under transient fault condition. The range of Kd is 0-10 as per the specifications of turbine governor controller. The proportional gain (Kp) and integral gain (Ki) are kept as 2.0 and 0.5. The PID gain values are presented in Table 5.4.

Table 5.4: Different values of Kd at Constant Kp and Ki

Governor	Kp	Ki	Kd
PID	2	0.5	0
	2	0.5	1
	2	0.5	2

The model of hydropower plant has been simulated for different values of derivative gain (Kd). The simulation results for change of derivative gain (Kd) presented in Fig.5.35, Fig.5.36 and Fig.5.37.

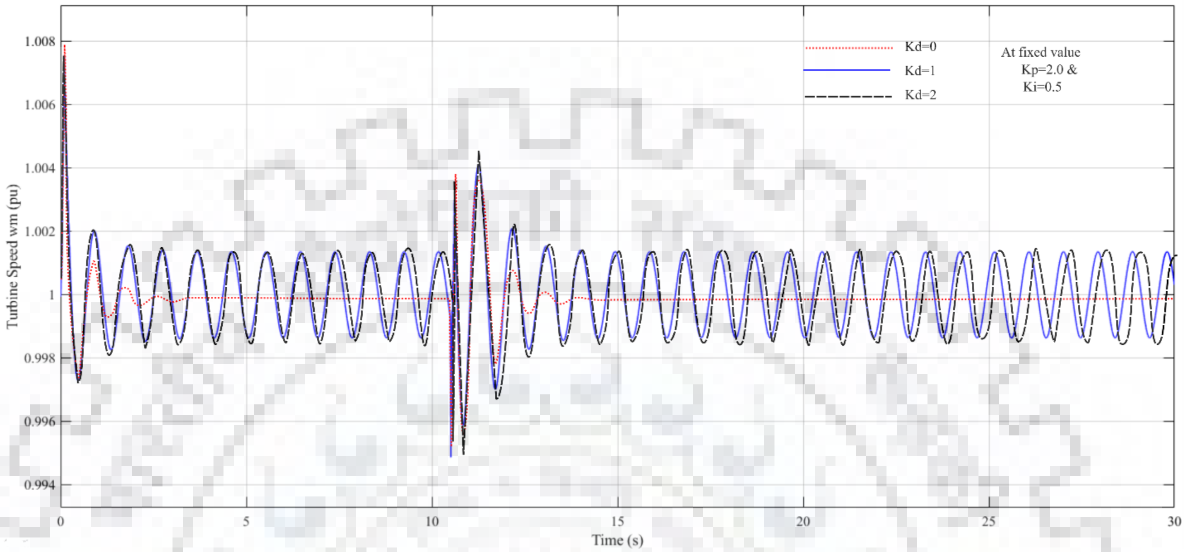

Fig. 5.35: Turbine Speed vs Time Under Varying Kd

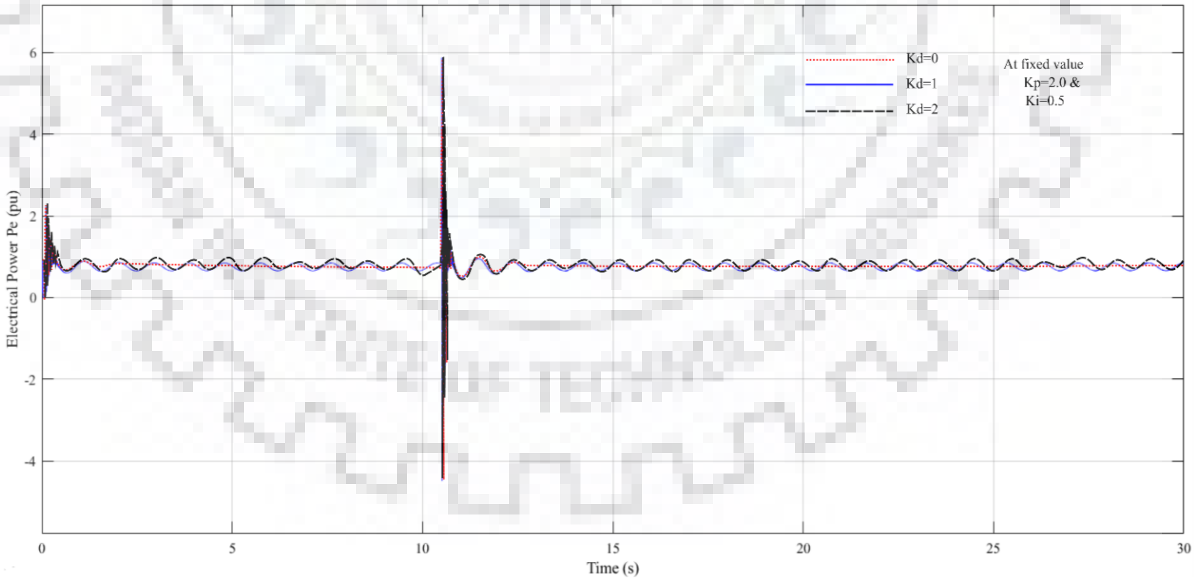

Fig. 5.36: Electrical Power vs Time Under Varying Kd

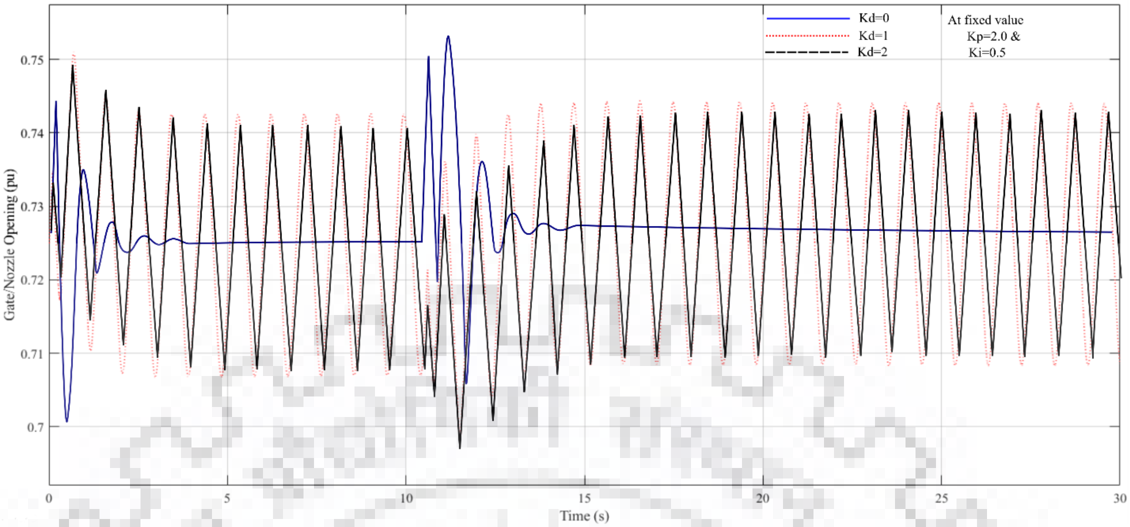

Fig. 5.37: Gate/Nozzle Opening vs Time Under Varying Kd

In this scenario, the deivative gain (Kd) of governor controller has been changed in the model to study its effect during the transient condition. When the derivative gain (Kd) is kept 0, the turbine speed, electrical power and gate/nozzle opening was found stable within 4 seconds after the disturbance. However, with increased in value of derivative gain (Kd), excessive oscillations of turbine speed, electrical power and gate/ nozzle opening has been noticed. As a result, it caused instability of unit. Thus, it is desired to keep low value of derivative gain.

5.4.9 Analysis of PID and PI Governor Under Different Operating Conditions

The comparative study of PID and PI governor has been carried out based on simulation of hydropower plant connected to grid. To evaluate the regulation performance of hydraulic turbine governor, the HPP models are simulated for PID and PI governor controller considering three-phase to earth fault at load of 0.75 pu and load change conditions. In the simulation process the damping time constant has been kept 0.01 in order to investigate the stability during the change of PID gain parameters. The gain values of PID and PI governor is shown in Table 5.5, that are used for simulations.

Table 5.5: Gain Values of PID and PI Governor

Governor Type	Kp	Ki	Kd
PID	2	0.7	0.5
PI	4	0.5	0

5.4.9.1 PID and PI governor under transient fault condition

The simulation out put of PID and PI governors for transient fault is illustrated in Fig.5.38

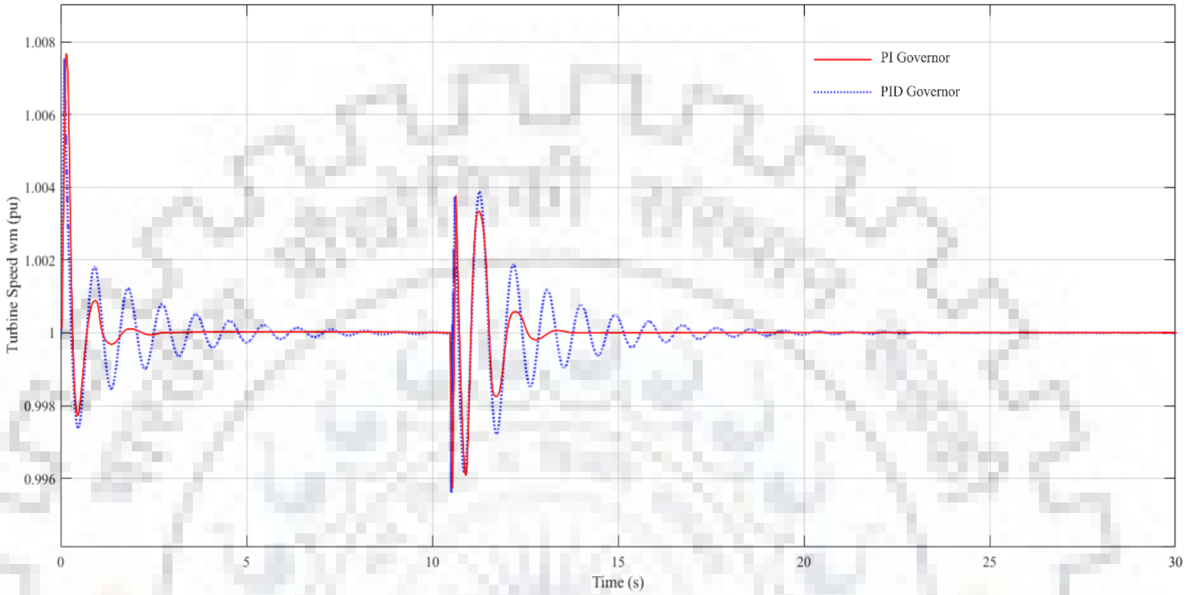

Fig. 5.38: Response of Governor During Transient Fault

From Fig.5.38, it is noticed that for the PID governor the turbine speed oscillates for longer duration after the transient fault. It is observed that, the settling time t=10 seconds. Whereas, in case of PI governor, the speed of turbine reached to steady state at t=2.5 seconds after the transient fault. Therefore, unit with PI governor controller resulted better speed response compared to PID governor controller.

5.4.9.2 PID and PI governor under load increase condition

The parameter settings of governor controller has been altered in the model of hydropower plant to realize PID and PI governor. The disturbance on the unit was created by increase of load.

The plant models with governor controller features of PID and PI are simulated under same operating condition. Turbine speed has been considered for the study impact of load change. The simulation results obtained from model are compared in graphical form as shown in Fig.5.39.

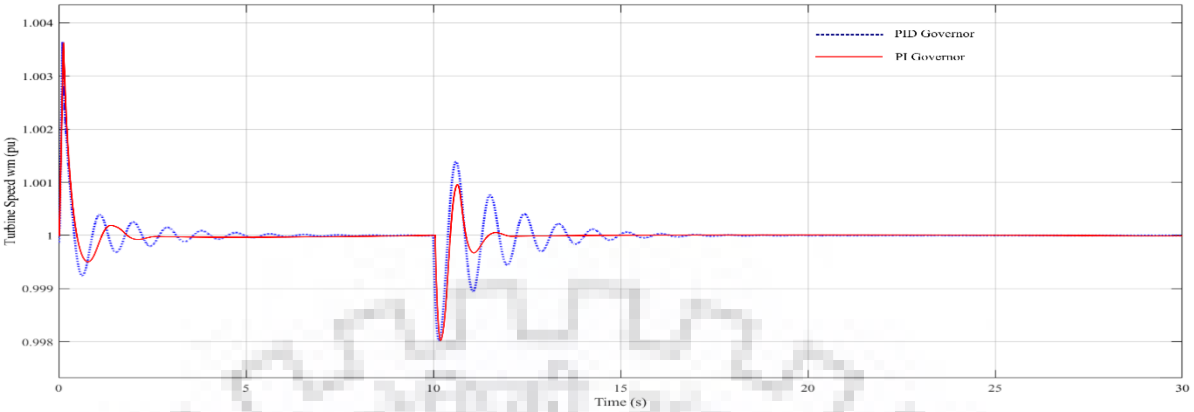

Fig. 5.39: Response of Governor During Load Increase Condition

The load on unit has been increased at t=10 second and due to this load disturbance, the speed of turbine is decreased at that instant for both type of governors. It takes 7.5 seconds to reach steady state after load disturbance in case of PID governor. Whereas, incase of PI governor, the turbine speed reached to steady state in 2.5 seconds after the interruption of load. Based on response of governor of unit, it showed that unit with PI governor reached to stable state faster as compared to PID governor.

5.4.9.3 PID and PI governors under load decrease condition

The models of hydropower plant configured for load increase condition has been used for load reduction as well.The parameter settings of governor controller has been kept as it is. The disturbance on the unit was created by decrease of load. The simulation results of PID and PI governors is presented in Fig.5.40.

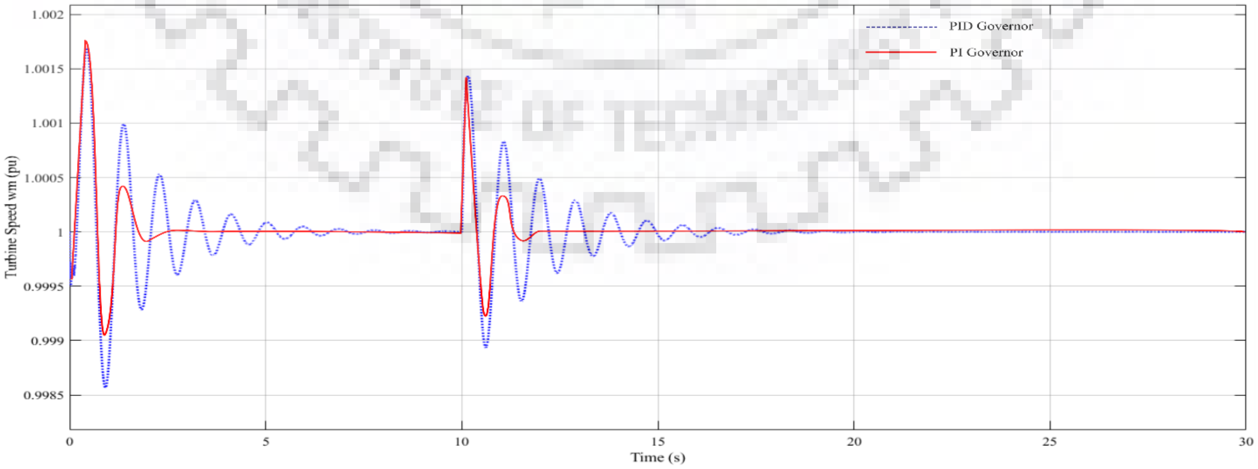

Fig. 5.40: Response of Governors During Load Decrease

The load on unit has been reduced at t=10 second, the speed of turbine increased and continued to oscillate. The settling time of 8 seconds is observed in case of PID governor. The turbine speed of unit with PI governor reached to steady state in 2 seconds after the interruption of load. The response of unit showed that unit with PI governor is more robust as it reached to stable state faster as compared to PID governor.

Based on stability study of governor, the derivative gain (Kd) of electro-hydraulic governor of the hydropower plant unit connected to grid, is kept very low or zero. Similarly, the damping time constant of governor controller is kept as Td=10 seconds for optimum performance.

The model of hydropower plant developed in MATLAB Simulink software was simulated under various operating conditions and validated with measured data of Unit-2 at Tala Hydropower Plant. An attempt has been made to develop the overall model better after initial simulations to study and analyze the stability of electro hydraulic governor.

The stability analysis of electro hydraulic governor used in hydropower plant was carried out with the help of simulation results of model of hydropower plant developed in MATLAB Simulink environment. Different operating conditions like steady state, transient due to load change, temporary fault and permanent fault in the power system that affect the performance of the generating unit has been taken into consideration.

From the overall simulations of model, it is learnt that the stability of electro hydraulic governor gets affected when the unit is subjected to abnormal operating conditions. Therefore, careful settings of governor parameters resulted the better stability. The PID and PI governor tuning has been carried out by changing the gains of the governor controller. The comparative analysis through simulation results of PID and PI governor has also been carried out.

CHAPTER 6

CONCLUSIONS AND FUTURE SCOPE OF WORKS

6.1 GENERAL

Under the present dissertation work, modeling and stability analysis of electro-hydraulic governor in hydropower plant unit has been carried out through the simulation results. The hydropower plant model was simulated under different operating conditions. In the model, the parameters were varied to investigate their implications on the operation. The hydropower plant connected to the grid was adapted to test in simulation model. An effort has been made to validate the simulation results and the measured parameter values obtained from Tala Hydropower plant in Bhutan.

6.2 CONCLUSIONS

i. The mathematical modeling of different components of hydropower plant has been done. The sub-system of hydraulic turbine, governor, excitation, generator, transmission line and grid were prepared in MATLAB, Simulink. The sub-systems were integrated stepwise to develop the unit, where the test was conducted. Subsequently, the stability analysis of electro-hydraulic governor of the unit in hydropower plant has been carried out through simulation results.

ii. The Simulink model of hydropower plant was tested for various operating conditions as; (a) Steady state, (b) Load increase condition, (c) Load decrease condition, (d) Temporary fault and (d) Permanent fault.

iii. Pertaining to the operating conditions, the gains of PID governor controller analyzed to obtain suitable value to get desired output. From the simulation results, it is noticed that change of derivative gain to higher value led to significant instability compared to proportional and integral gains in the unit of grid connected hydropower power plant.

iv. Similarly, the comparative analysis of PID and PI governor has been made through the out put of simulations. According to the results, electro-hydraulic PI governor shows best output for large disturbance of load variation and transient fault for grid connected hydropower plant. Infact, it takes less time to reach steady state after disturbance. The derivative gain of governor may be kept very low or zero to optimize the performance.

However, proportional gain and intgral gains must be judiciously optimized as the value of these parameters govern the time to reach steady state after the disdurbance in the system.

v. From the stability analysis based on simulation results, it is concluded that optimum tuning of governor controller parameters gives better output under different operating conditions. Therefore, the load hunting of the unit during the operation would be eliminated by proper settings of governor parameters inline with grid code of transmission system operator.

6.3 FUTURE SCOPE OF WORK

Based on the present study, it is recommended the more studies are required to in detail on stability of electro hydraulic governor used in hydropower units.

i. More details about components of hydropower unit in modeling of sub-system to develop accurate model close to real plant is needed.
ii. The hydropower plant model can be investigated for islanding mode by developing accurate model.
iii. The impact of water hammer on stability of governor can be explored.
iv. There is a need to study in-depth regarding the change of turbine characteristics due to vibration.

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