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Development and Implementation of Non-Linear Hydro Turbine Model with Elastic Effect of Water Column and Surge Tank

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Abstract: **Hydro Power is one of the most important and vital renewable energy resources; hence exploitation of hydro-power naturally attracts more and more attention worldwide. With the development of large-scale hydropower stations, we cannot neglect complex water conduit, turbine and governor's functions which participate in frequency control. This paper studies accurate dynamic response of the complex water conduit system and non-linear hydro turbine model because of simplicity, accurate modeling cannot be studied in hydro power plant system. The developed model is implemented in Matlab/ Simulink. Simulation studies are investigated for frequency response for 1% step load disturbances by considering different water inertia time of penstock.**

***Keywords*: Power Plant Dynamics, Water Hammer Effects, Hydraulic System, Turbine Governor Modeling.**

I. INTRODUCTION

Today's life is dependent upon electricity and the world is opting for renewable electricity generation/ green power, as renewable energy being environment friendly. Hydro Power is one of the most important and vital renewable energy resources; hence exploitation of hydro-power naturally attracts more and more attention worldwide. With the development of large-scale hydropower stations, the associated security and stability issues are prominent among hydrodynamic, mechanical and electrical systems which are studied by experts of each field. Among those researches, the coupled interaction is usually not considered and the model accuracy always cannot meet the demand of research, which leads to simplification of the impacts among hydrodynamic, mechanical and electrical system has been considered [1]. Hence the hydrodynamic-mechanical-electric coupled system is considered for study as shown in Fig. 1.

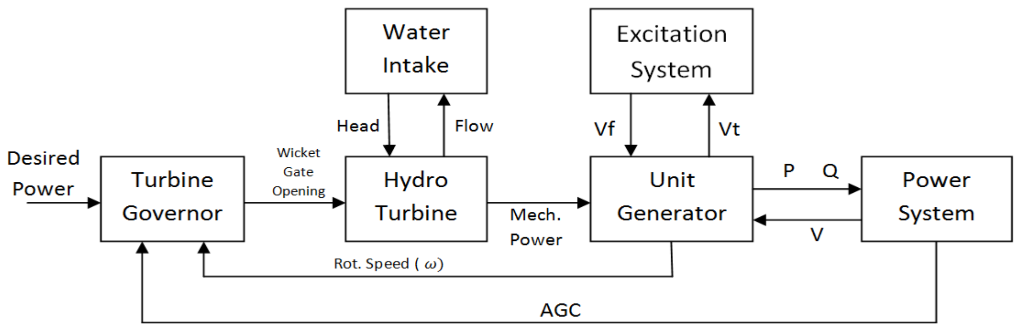

Figure 1: Hydrodynamic-Mechanical-Electric Coupled System

The water inertia time T_w (often called the "water starting 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. This parameter also affects the small signal stability of the frequency control system. The dynamic performance of the control system is very much dependent on the penstock water timeT_w. $T_w$is a simplified approximation of the relative inertia of the water column, and it does not include the effects of wave time on the dynamic influence of the water column. Water starting time T_w is normally calculated for the unit at rated generation and at rated head as under:

$$T_w = \frac{Q_r l}{gAH_r} \tag{1}$$

Normally, dynamic performance degrades with increasing T_w. As T_w is directly proportional to the length of the penstock, control performance degrades with increasing penstock length. The computation of the water start time is meaningful only if the water start time is relatively short. For very long penstocks, the wave travel time of the water column becomes significant, and the reflected pressure waves in the water column cause the preceding treatment of water start time to no longer be valid. When the wave travel time approaches 25% of the T_w, engineers should not rely on only the classic value of T_w, and the performance of the turbine governing system should be evaluated by considering the effects of both the water starting time and the wave travel time [2].By using the concepts of [2] – [3], design and development of modeling of hydrodynamic and turbine system is done in which different parts (HRT, Surge Tank, Penstock etc.) of water column system are used instead of only penstock and turbine.

II. HYDROELECTRIC POWER PLANT

In a hydroelectric power plant, stored water flows from high elevation to the hydro turbine, gravitational potential energy is converted into kinetic energy. Then, the turbine shaft, obtaining mechanical energy from the conversion, drives the machine to generate electricity. In a turbine, the power is controlled by regulating the flow into the turbine using the position of the wicket gates or nozzles. This regulation is achieved by the turbine governor, which is also called the speed governing system or turbine governing system. Fig. 2 illustrates the main components of a typical hydro power plant unit. Generally, hydro turbine governors can be classified in two types: mechanical hydrodynamic or electro hydrodynamic, depending on if there are electronic apparatus participating in sensing and measuring work in the turbine governor.

For dynamic and transient stability studies, accurate mathematical modeling of power system components are significant. Furthermore, tuning of the parameters of the unit controller like governor is one important application and should be properly tuned.

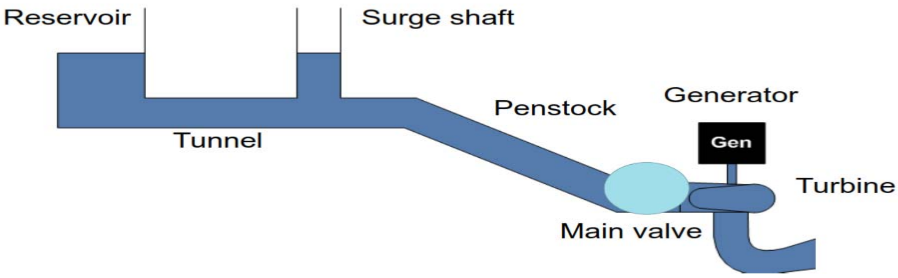

Figure 2: Simplified Schematic of a Hydro Power Plant

III. MATHEMATICAL MODELING

1. Hydrodynamic system modelling:

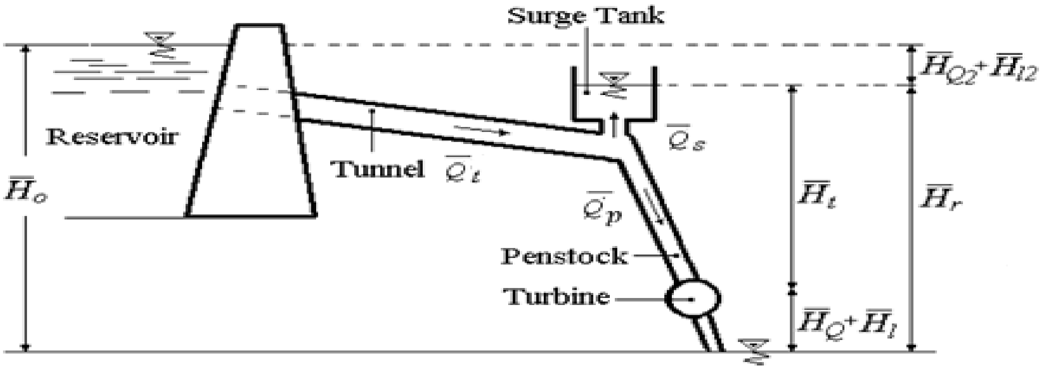

Figure 3: General Layout of a High Head Hydropower Plant with Surge Tank

A typical hydro power plant (Fig. 3) consists of a reservoir with water level H_o (in meters), an upstream water tunnel (HRT) with length L_t (in meters) and cross-section area A_t (in square meters), an upstream surge tank with water level H_r and cross-section area A_s (in square meters). The penstock between hydrodynamic turbine and surge tank has a length L_p (in meters) and cross-section area A_p (in square meters). Finally, water goes from turbine to river or lack through Tail Race Tunnel (TRT). Reservoir water level and tail river water level are considered as constants.

The basic mathematical modelling for each component can be derived by taking the basic idea as an equivalent electrical component like T-shaped equivalent scheme as transmission line.

For the study of transient flow process in hydro power plant, the hydrodynamic (Water column) system is generally calculated as 1-D compressible unsteady flow, Newton's Second Law can be applied which gives a differential equation of motion [3] as under:

$$\frac{\partial H}{\partial x} + \frac{1}{gA} \times \frac{\partial Q}{\partial t} + \frac{fQ}{2gDA^2} \times Q = 0 \tag{2}$$

For a control volume by taking into account of water compressibility and tube elasticity, law of conservation of mass gives the continuity differential equation [3] as under:

$$\frac{\partial Q}{\partial x} + \frac{gA}{a^2} \times \frac{\partial H}{\partial t} = 0 \tag{3}$$

Therefore, the general expression for the incremental head and flow at turbine inlet by transfer function by considering the uniform conduit water supply from large reservoir is given as [7]

$$\frac{h}{q} = -2\left(\frac{T_w}{T_r} + \frac{\bar{H}_l a}{Ls}\right)\tanh\left(\frac{T_r s}{2} + \frac{T_r \bar{H}_l}{2T_w}\right) \tag{4}$$

The above equation can be simplified by consideration of elastic water hammer effect only as under:

$$\frac{\bar{H}}{\bar{Q}} = \frac{h}{q} = -T_w s - \bar{H}_l \tag{5}$$

when travel wave velocity is considered alongwith water hammer effect, above equation can be written as under:

$$\frac{\bar{H}}{\bar{Q}} = \frac{h}{q} = -Z_p \tanh(T_e s) - \bar{H}_l \tag{6}$$

Where $Z_p = \frac{T_w}{T_e}$, $T_e = \frac{l}{a} = \frac{T_r}{2}$;

H_l is proportional to the flow rate square and water column frictional factor i.e. $\bar{H}_l = f_p\, q^2$ and the pressure head is related to the flow rate as $q = G\sqrt{h}$.

Also the relationship between the normalized flow and normalized water velocity in water column i.e. in tunnel or penstock can be taken as under:

$$\frac{Q}{Q_{base}} = \frac{A_{(p,c)} \cdot U}{A_{(p,c)} \cdot U_{base}} \text{ or } \bar{Q} = \bar{U} \tag{7}$$

1.1.Head Race Tunnel (HRT):

It joins the reservoir and upstream surge tank together. Since the inlet of HRT is constant for $\bar{H}$ and $\bar{Q}$ during hydrodynamic transients. Therefore using the equation of continuity

$$\overline{Q_p} = \overline{Q_t} - \overline{Q_s} \tag{8}$$

Dynamics of the Head Race Tunnel (HRT)

$$\frac{d\overline{Q_t}}{dt} = \frac{\overline{H_0} - \overline{H_r} - \overline{H_{l2}}}{T_{wt}} = \frac{\overline{H_{Q2}}}{T_{wt}} \tag{9}$$

$$\overline{H_{l2}} = f_{p2} \,.\, \overline{Q_t} \,.\, |\overline{Q_t}| \tag{10}$$

1.1.1 Surge Tanks:

Dynamics of the surge tank can be expressed including hydraulic losses as under:

$$\overline{H_r} = \frac{1}{T_s} \,.\int \overline{Q_s} dt - f_0 \,.\, \overline{Q_s} \,.\, |\overline{Q_s}| \tag{11}$$

Surge tank filling time (in seconds)

$$T_s = \frac{A_s H_r}{Q_r} \tag{12}$$

1.1.2 Penstock:

When water is supplied from a large reservoir uniformly in Penstock and water inertia in the draft tube is considered within penstock. Then, transfer function for the incremental head $\overline{H}$ and flow $\overline{Q}$ of penstock with surge tank assuming inelastic water column in upstream and elastic water column in penstock can be calculated as

Hydraulic losses in penstock can be expressed as

$$\overline{H_l} = f_{p1} \,.\, \overline{Q_p}^2 \tag{13}$$

Dynamics of the penstock by considering the elastic effect in water column expression as

$$\overline{H_t} = \overline{H_r} - \overline{H_l} - Z_p \tanh(T_e s) \,.\, \overline{Q_p} = \overline{H_r} - \overline{H_l} - \overline{H_Q} \tag{14}$$

$$\overline{Q_P} = \overline{G} \,.\, \sqrt{\overline{H_t}} \tag{15}$$

A functional block diagram for the complete hydraulic system (HS) / water column system can be made according to the above equations for the general nonlinear model is shown in Fig. 4.

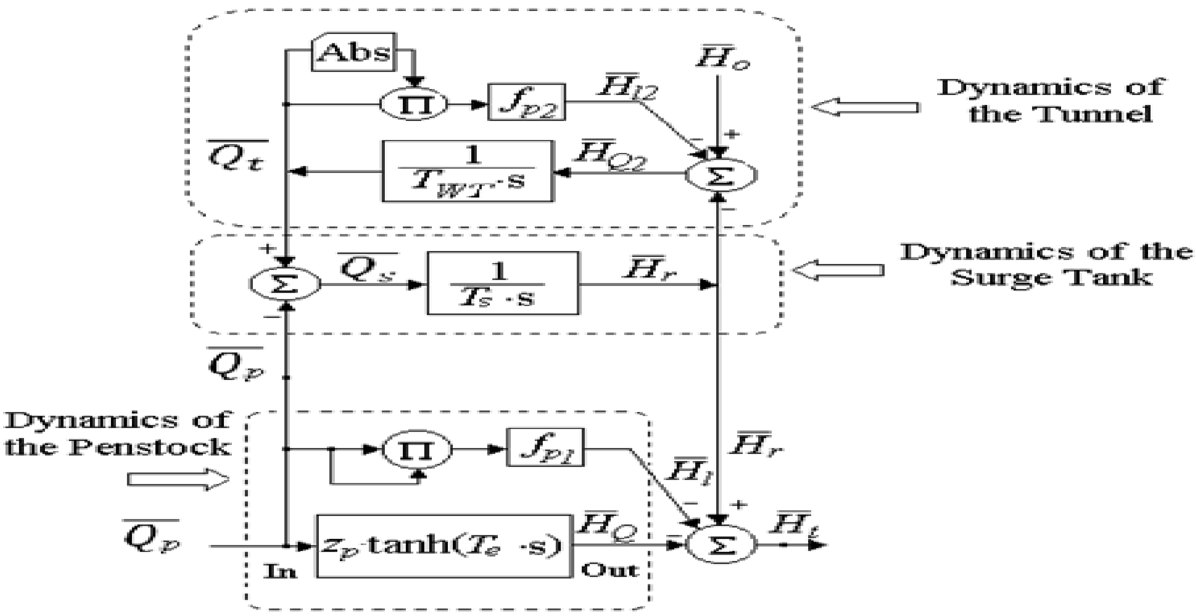

Figure 4: Functional block diagram for Complete Water Column System (HS)

2. Mechanical Power:

Mechanical power developed by the hydro turbine is proportional to the pressure head and flow rate. As there is no-load flow $\overline{Q_{nl}}$, it should be subtracted from the actual flow rate,

$$P_m = A_t . \overline{H} . (\overline{Q} - \overline{Q_{NL}}) \quad (16)$$

Where

$$A_t = \frac{\text{turbine power (MW)}}{\text{generator rating (MVA)}} . \frac{1}{\overline{H_{tr}} . (\overline{Q} - \overline{Q_{NL}})} \quad (17)$$

If damping effects are also considered, then

$$P_m = A_t . \overline{H} . (\overline{Q} - \overline{Q_{NL}}) - D_a G \Delta\omega \quad (18)$$

Linearizing the turbine characteristics around the operating point can help in simplifying the turbine model. In hydro-turbine systems, the mechanical power increment ΔP_m and the water flow increment $\Delta\overline{Q}$ are dependent on the gate opening increment $\Delta\overline{G}$, the rotating speed increment $\Delta\overline{\omega}$, and the head increment $\Delta\overline{H}$.

The mathematical model of hydrodynamic turbine (says in this case Francis) in the neighborhood of a certain operating point can be expressed as

$$\Delta P_m = e_H \Delta\overline{H} + e_\omega \Delta\overline{\omega} + e_G \Delta\overline{G} \quad (19)$$

$$\Delta\overline{Q} = e_{qH} \Delta\overline{H} + e_{q\omega} \Delta\overline{\omega} + e_{qG} \Delta\overline{G} \quad (20)$$

Where

$$e_H = \frac{\partial(M_t/M_{tr})}{\partial(H/H_{tr})}, e_\omega = \frac{\partial(M_t/M_{tr})}{\partial(n/n_r)}, e_G = \frac{\partial(M_t/M_{tr})}{\partial(G/G_{max})}$$
$$e_{qH} = \frac{\partial(Q_t/Q_{tr})}{\partial(H/H_{tr})}, e_{q\omega} = \frac{\partial(Q_t/Q_{tr})}{\partial(n/n_r)}, e_{qG} = \frac{\partial(Q_t/Q_{tr})}{\partial(G/G_{max})} \quad (21)$$

When the rotational speed deviation is small i.e. $\Delta\omega \approx 0$, then the turbine transfer function which relates as under:

$$\frac{P_m}{G} = \frac{\Delta P_m}{\Delta G} = \frac{e_G + (e_{qH}.e_G - e_{qG}.e_H)T_w s}{1 + e_{qH} T_w s} \quad (22)$$

Block diagram for the linear model of hydro-turbine can be made as

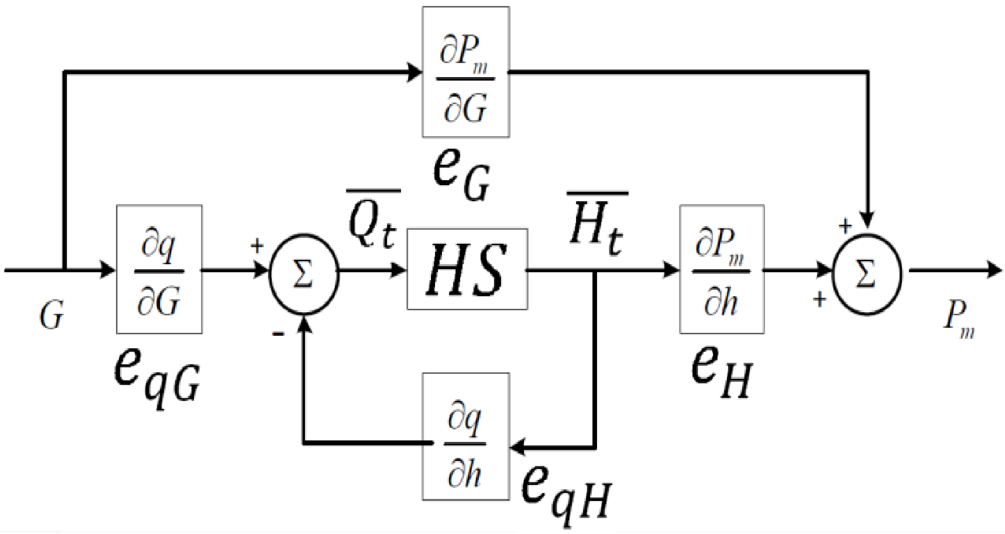

Figure 5: Block diagram for the linear model of hydro-turbine

These six constants/ coefficients represents the main non-linear characteristics of the turbine depend on machine loading. Some proposed values of these constants from turbine characteristic equations can be used (see Table I) [1], [4]–[5]. These constants or coefficients can be calculated from the turbine characteristics chart (Hill charts) at the operating point [6].

Table 1: Proposed Equations for Calculation of Turbine Constants

Coefficients	Classical Values [1]	Reference [4]	Reference [5]
e_H	1.5	$1.5\eta\overline{G}$	$A_t\overline{P}_r\left(\frac{3}{2}\overline{G}\sqrt{\overline{H}} - \overline{U_{NL}}\right)$
e_ω	0	0	$D_a\overline{G}$
e_G	1	η	$A_t\overline{P}_r\sqrt{\overline{H}} - D_a(\overline{\omega} - 1)$
e_{qH}	0.5	$0.5\overline{G}$	$\frac{\overline{G}}{2\sqrt{\overline{H}}}$
$e_{q\omega}$	0	0	0
e_{qG}	1	1.0	$\sqrt{\overline{H}}$

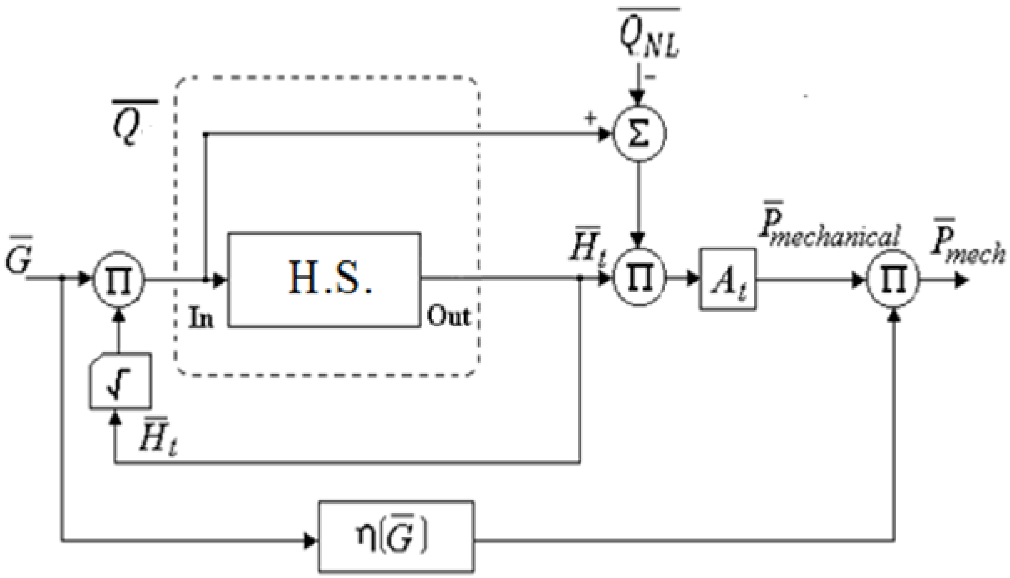

Figure 6: Functional Block Diagram for the Linear Model of Hydro-Turbine

IV. SIMULATION MODELING

A real hydropower plant of NHPC, India named "Uri-I Hydro Power Plant" located at Baramulla, J&K state of India is selected for this work. Its capacity is 4 x 120 MW = 480 MW. We take here a single unit only for simulation purpose. The required data is given in Table-2 for parameter determination.

Plant Data:

Table 2: Plant Data Uri-I Hydropower Plant, NHPC

Component	Parameter	Symbol	Value
Water Column System (HS)			
HRT	Length	L_C	10,650 m
	Area of Cross-section	A_C	59.6 m^2
	Frictional Constant	f_{p2}	0.06
Surge Tank	Height	L_S	90 m
	Diameter	D_S	22.50 m
Penstock	Length of Pressure Shaft	L_P	283 m
	Diameter	D_P	5.00 m
	Frictional Constant	f_C	0.001
Francis Turbine			
Turbine	Rated Output	P_r	122 MW
	Rated Discharge	Q_r	59.21 m^3/s
	Rated Head	H_r	222.2 m
	Rated Speed	N_r	333.3 rpm
	Rated Efficiency	η	0.94
	Gate position at rated condition	$\overline{g_{FL}}$	0.94
	Gate position at No-load condition	$\overline{g_{NL}}$	0.06
Generator			
Generator	Rated Power	P_{gr}	136 MVA
	Frequency	f	50 Hz

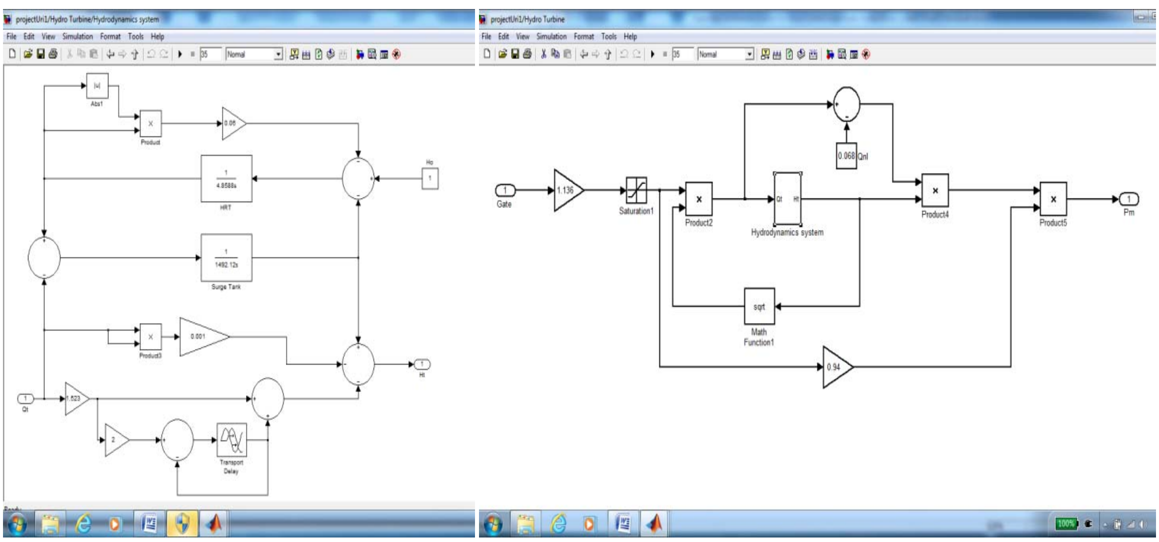

Figure 7: Simulation Model of Water Column System / Hydrodynamics System (HS) and Hydro Turbine in Matlab

V. RESULTS AND DISCUSSION

The simulation is started and the following figures are observed. Fig.8-9 shows frequency wave waveforms with time domain. Here frequency response is investigated for 1% step load disturbances by considering different water inertia time of penstock. In hydro plants with long supply conduits, it is common practice to use a surge tank. The purpose of the surge tank is to provide hydraulic isolation of the turbine from the headdeviations generated by transients in conduit. By considering the effect of elasticity and compressibility which leads to a travelling wave solution method is used in simulation for better performance. The frequency response with time domain for 1% step load is constantly stable after considering non-linear model of hydro turbine with elastic effect and surge tank application.

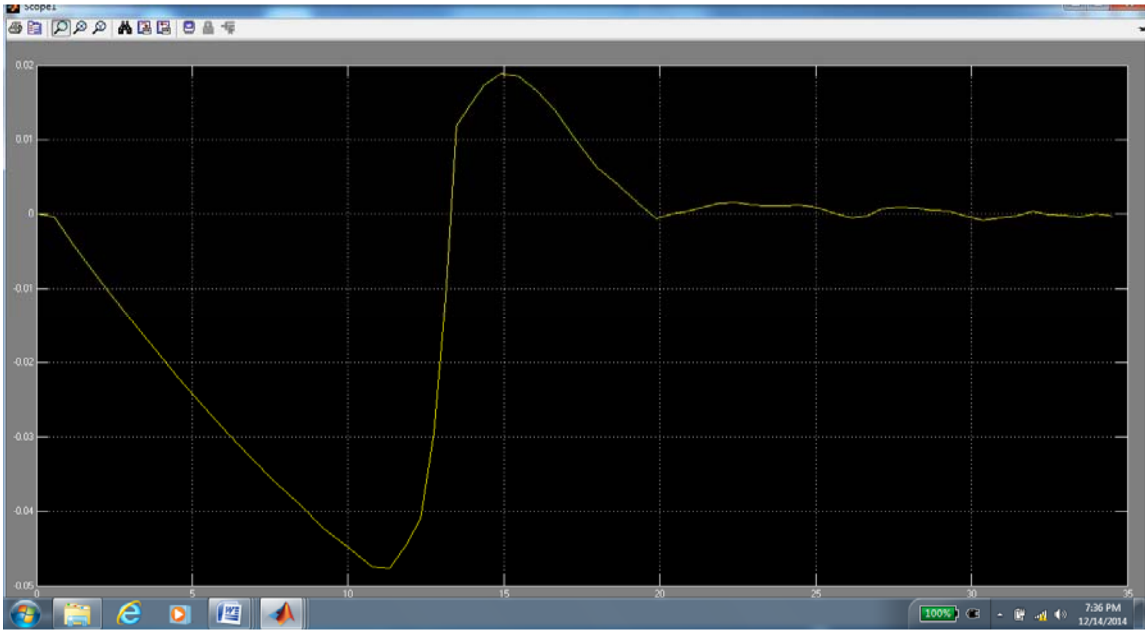

Figure 8: Time-Domain simulation of Uri-I Hydropower Plant to speed change at T_{wp} = 0.8 Sec

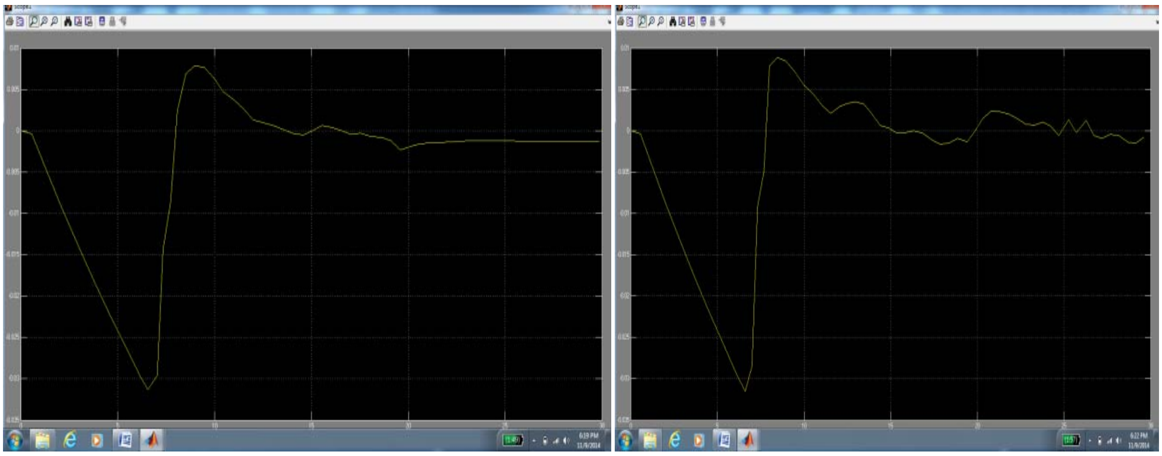

Figure 8: Time-Domain simulation of Uri-I Hydropower Plant to speed change at Twp = 1.2 Sec & 2.0 Sec

VI. CONCLUSION

This paper studies and demonstrates the procedures to develop the simulation system for hydraulic dynamics of hydro power plants in the MATLAB/ Simulink based software environment. Water inertia in penstock is the critical factor causing poorer dynamic performance on turbine speed as well as turbine water pressure .For better dynamics performance in generating unit, it becomes necessary to reduce the penstock water inertia by either increase in penstock cross-section area or decrease the penstock length. Oscillation amplitude would be reduced by increasing surge tank cross-section area to become a larger surge tank filling time constant. Wicket gate closing time of turbine is also a critical parameter. Longer closing time of wicket gate would result in a larger turbine speed but low in turbine water pressure. So, it becomes necessary to optimize the turbine wicket gate closing for large hydraulic transients.

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APPENDIX - A

NOMENCLATURE:

$\overline{H_{(t,r,l,l2,o)}}$	Head in (pu) [t: turbine, r: surge tank, l: loss in penstock, l2: loss in the HRT/tunnel, o: reservoir]	D	Tube/ pipe diameter (m)
$\overline{Q_{(r,p,t,s)}}$	Water flow in (pu) [r: turbine, p: penstock, t: HRT/tunnel, s: surge tank]	a	Pressure wave velocity (m/s)
T_w	The water inertia time or water starting time (s)	s	Laplace operator
T_{wp}, T_{wt}	Water starting time at rated or base load in (s) (WP: penstock, WT: HRT/ Tunnel	h	Water pressure relative deviation (pu)
T_S	Storage constant of Surge Tank (s)	q	Flow rate relative deviation (pu)
$f_{p1,p2,o}$	Head loss coefficients [p1: penstock, p2: HRT/ tunnel, o: surge tank orifice in (pu)	x	Displacement (m)
T_e	Elastic time in penstock (s)	T_r	Penstock reflection time (sec)
Z_p	Hydraulic surge impedance of penstock	H_f	Hydraulic frictional loss (m)
Q_r	The rated water flow (m^3/s)	m_t	Turbine torque relative deviations (pu)
H_r	The rated operated head (m)	q_t	Turbine flow rate relative deviations (pu)
l	Length of given portion of water column (m)	$\Delta\bar{H}$	Turbine water pressure relative deviations (pu)
g	The gravitational acceleration (m/s^2)	$\Delta\bar{\omega}$	Turbine speed relative deviations (pu)
A	The cross-sectional area of corresponding portion of water column (m^2)	M_t	Turbine torque (kNm)
$\Delta\overline{P_m}$	Perturbed turbine power	M_{tr}	Turbine rated torque (kNm)
$\Delta\bar{G}$	The ideal gate opening based on the change of real gate opening from no load to full load	n	Turbine speed (rpm)
A_t	Turbine gain	n_r	Turbine rated speed (rpm)
$\bar{g}$	Real gate opening (pu)	G	Wicket Gate opening (mm)
$\bar{g}_{FL}$	Gate opening at rated load	G_{max}	Maximum Wicket Gate opening (mm)
$\bar{g}_{NL}$	Gate opening at no load	H_t	Turbine water head (m)
Q	Flow rate (m^3/s)	H_{tr}	Turbine rated water head (m)
t	Time (sec)	Q_t	Turbine flow rate (m^3/s)
f	Friction coefficient	Q_{tr}	Turbine rated flow rate (m^3/s)