Modeling of Hydraulic turbine for analyzing effect of penstock parameter variation on mechanical power

Monika Soni, Simardeep kaur

Dept.of Electrical Engg.

Shri Shankaracharya Technical Campus

Bhilai, India

soni.monika03@gmail.com, simardeepkaur29@gmail.com

08982420037

Abstract—Modeling of hydraulic turbine is essential for analyzing the system response. In this paper nonlinear model of hydraulic turbine and long penstock is developed and it is linearized at an operating point considering non linear characteristics of turbine penstock and travelling wave effect. Hydroelectric power plants with long conduits have sever water hammer and stability problem. In this paper hydraulic turbine is modeled with penstock and turbine characteristics. Simulation model is developed using MATLAB SIMULINK. It was observed that with change in parameters of penstock response of system changed. At critical value of certain parameter like length, diameter or material of penstock system become unstable.

.**Keywords**— Turbine- penstock, Surge tank, Mechanical power,Mathematical mode,Mechanical power, water hammer, stability.

INTRODUCTION

The dynamic characteristics of hydraulic turbine and its governing system will affect the performance of the power system during change of load or in case of occurrence of fault. Modeling of system component like turbine and controller helps to study dynamic response. The non linear turbine model is useful for studies of large variation in power output and frequency.

For stability of power system it is necessary to minimize hydraulic transient. When there is load change in the system, change in mechanical power occur due to sudden opening of gate or due to sudden flow of water in the penstock. In order to reduce the transient in the mechanical power optimal value of penstock parameter is used. In this paper the effect of penstock parameter variation has been analyzed by developing the hydraulic turbine penstock transfer function.

The MATLAB Simulink and programming provides easy to use, versatile and powerful simulation environment for the dynamic research on hydropower plants. The linear model of hydraulic turbine and non elastic water hammer effect of pressure water supply penstock are considered in the modeling.

MATHEMATICAL MODEL OF HYDRAULIC TURBINE -PENSTOCK

The model consist of single penstock and turbine without surge tank effect. The performance of the hydro turbine system is changed by the effect of pipe wall elasticity, water inertia, water compressibility in penstock.

The basic equation of turbine penstock consist of the flow of water in penstock, turbine mechanical power and acceleration of the water in the penstock. For detailed study of hydraulic system first we have to develop the pressure flow wave equation in a closed conduit

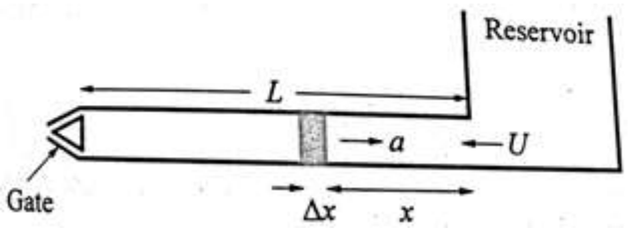

Fig. 1 Hydraulic system configuration

From Newton's second law;

$$\frac{\partial U}{\partial t} = -a_g \frac{\partial H}{\partial x} \qquad (1)$$

From continuity equation;

$$\frac{\partial U}{\partial x} = -\alpha \frac{\partial H}{\partial t} \qquad (2)$$

Where α isgiven by,

$$\alpha = \rho a_g \left(\frac{1}{K} + \frac{D}{Ef} \right)$$

Where x is distance and t is time.

By solving above two equation using Laplace transform we get,

$$H_2 = H_1 \sec h(T_e s) - Z_0 Q_2 \tanh(T_e s) \qquad (3)$$

$$Q_1 = Q_2 \cos h(T_e s) + \frac{1}{Z_0} H_2 \sinh(T_e s) \qquad (4)$$

1 and 2 is for upstream and downstream ends of the conduit, Expressing above in per unit dividing above by rated head H_r and rated flow Q_r we get

$$\overline{H_2} = \overline{H_1} \sec h(T_e s) - Z_n \overline{Q_2} \tanh(T_e s)$$

$$\overline{Q_1} = \overline{Q_2} \cos h(T_e s) + \frac{1}{Z_n} \overline{H_2} \sinh(T_e s)$$

Z_n= Normalized value of hydraulic surge impedance,

$$Z_n = Z_0 \frac{Q_r}{H_r}$$

$$\frac{Q}{Q_r} = \frac{AU}{AU_r}$$

Now above equation become,

$$\overline{H_2} = \overline{H_1}\sec h(T_e s) - Z_n\overline{U_2}\tanh(T_e s) - k_f\overline{U_2}\left|\overline{U_2}\right| \qquad (5)$$

Writing above equation in terms of head and velocity from steady state values,

Now equation become,

$$h_2 = h_1\sec h(T_e s) - Z_n u_2\tanh(T_e s) - \phi u_2 \qquad (6)$$

$$u_1 = u_2\cos h(T_e s) + \frac{1}{Z_n}h_2\sinh(T_e s) \qquad (7)$$

$h = (H - H_0)$ in p.u.

$u = (U - U_0)$ in p.u.

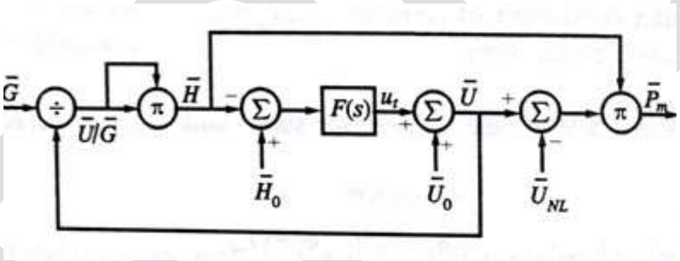

Fig.2 Non-Linear model of Hydropower plant

Now, from equation of velocity of water in the penstock is given by,

$$\overline{U_t} = \overline{G}\sqrt{\overline{H_t}} \qquad (8)$$

Turbine mechanical power is given by,

$$\overline{P}_{mech} = (\overline{U_t} - \overline{U}_{NL}).\overline{H}_t \qquad (9)$$

From fig.(3) we can write the equation

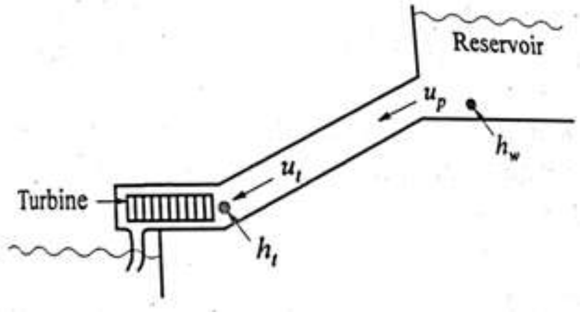

Fig.3 Hydro-turbine system

$$h_t=-Z_p u_t\tanh(T_{ep}s)-\phi_p u_t \qquad (10)$$

Since $h_w = 0$ deviation in head for large reservoir is zero

Transfer function relating head and flow at the turbine end of the penstock is written as,

$$F(s)=\frac{u_t}{h_t}=\frac{\overline{U}-\overline{U}_0}{\overline{H}-\overline{H}_0}=\frac{-1}{\phi_p+Z_p\tanh(T_{ep}s)} \qquad (11)$$

Now linearizing the above equation about an operating point

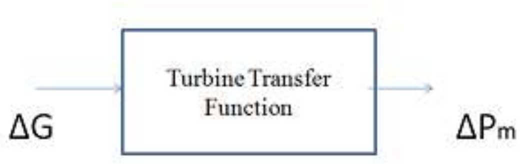

Fig.4 Linearized system

We know that,

$$\overline{\Delta U}=\frac{1}{2}\overline{\Delta H}+\overline{\Delta G} \qquad (12)$$

$$\frac{h_t(s)}{u_t(s)}=-Z_p\tanh(T_{ep}s)-\phi_p$$

Putting value of $\overline{\Delta U}$ in place of $u_t(s)$ and by solving we get,

$$h_t(s)\left[1+\frac{Z_p}{2}\tanh(T_{ep}s)+\frac{\phi_p}{2}\right]=\left[-Z_p\tanh(T_{ep}s)-\phi_p\right]\overline{\Delta G}$$

also we know that,

$$\overline{\Delta P_m}=3\overline{\Delta U}-2\overline{\Delta G}$$

From equation (12),

$$\overline{\Delta P_m}=\frac{3}{2}\overline{\Delta H}+\overline{\Delta G}$$

Now,

$$\Delta P_m = \frac{3}{2}\left[\frac{-Z_p \tanh(T_{ep}s) - \phi_p}{1 + \frac{Z_p}{2}\tanh(T_{ep}s) + \frac{\phi_p}{2}}\right]\Delta G + \Delta G$$

Finally linearized model of turbine-penstock transfer function is given by,

$$\frac{\Delta P_m}{\Delta G} = \frac{1 - Z_p \tanh(T_{ep}s) - \phi_p}{1 + \frac{Z_p}{2}\tanh(T_{ep}s) + \frac{\phi_p}{2}} \qquad (13)$$

H= total head

U= water velocity

A= area of conduit

f= thickness of conduit wall

a_g=acceleration due to gravity

h_w= reservoir head

h_t=turbine head

u_t= turbine water velocity

T_{wp}= water starting time of penstock

T_{ep}= penstock elastic time

METHODOLOGY

Assuming an ideal model and neglecting the hydraulic friction losses, equation (13) can be reduced as:

$$\frac{\Delta P_m}{\Delta G} = \frac{1 - Z_p \tanh(sT_{ep})}{1 + \frac{1}{2}Z_p \tanh(sT_{ep})} \qquad (14)$$

The representation of Equation (14) could alternatively be approximated as lumped parameter equivalent. Expanding the transfer function into a general nth order model by using the relationship:

$$\tanh(sT_{ep}) = \frac{1 - e^{-2sTep}}{1 + e^{-2sT_{ep}}} \qquad (15)$$

leads to the finite approximation:

$$\tanh(sT_{ep}) = \frac{sT_{ep}\prod_{n=1}^{n=\infty}\left[1 + \left(\frac{sT_{ep}}{n\pi}\right)^2\right]}{\prod_{n=1}^{n=\infty}\left[1 + \left(\frac{2sT_{ep}}{(2n-1)\pi}\right)^2\right]} \qquad (16)$$

For n=1 (i.e. with the fundamental component of the column represented), the Equation (14) become,

$$\frac{\Delta P_m}{\Delta G} = \frac{1 - sT_{wp} + \dfrac{4T_{ep}^2 s^2}{\pi^2} - \dfrac{T_{wp} T_{ep}^2 s^3}{\pi^2}}{1 + 0.5sT_{wp} + \dfrac{4T_{ep}^2 s^2}{\pi^2} + \dfrac{0.5T_{wp} T_{ep}^2 s^3}{\pi^2}}$$

For stable frequency regulation under isolated condition hydro turbine governors are designed to have large transient droop with long resettling time because change in gate position at the penstock may produce short term power change. Block diagram of a generating unit with hydraulic turbine is shown in fig.5

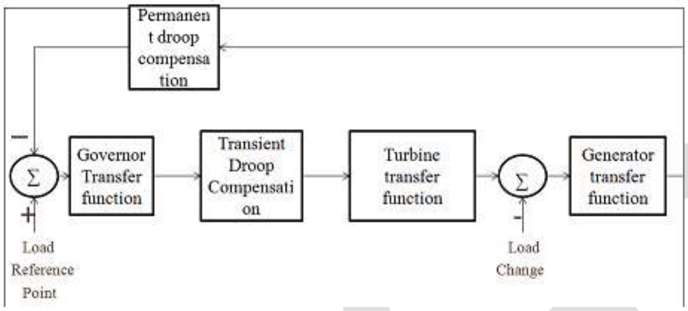

Fig. 5 Block Diagram of Hydraulic System

RESULT AND DISCUSSION

The dynamic behavior of hydropower plant must be known to understand the characteristics and stability of the system. In this paper static behavior of hydro plant is studied. The static behavior is studied by the relationship between the steady state value of gate position and turbine developed power. The hydraulic turbine generating unit was in standstill and ready to start up for initial. The simulation starts first then the turbine generating unit received signal after that.

Fig.6 shows the effect of water hammer on mechanical power and Fig.7 shows the change of speed of generator when critical value of diameter and length is not taken for the turbine penstock system hence in this case change in load at the generator side cause sudden opening or closing of gate due to water hammer effect since parameters are below critical value hence water hammer is not going to damp either continuous oscillation is going on or magnitude of mechanical power is increasing hence system become unstable.

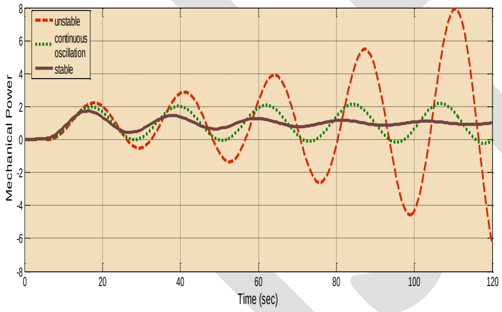

Fig.6 Effect on mechanical power with parameter variation

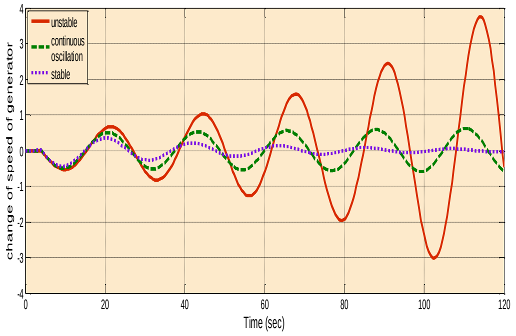

Fig.7 Effect on change of speed of generator

Also it is found that if value of diameter and length is taken above critical value and proper material is not used for penstock then also system oscillation is increasing and may cause destruction of the penstock. Effect of change of material in mechanical power is shown in Fig.8 and on change of speed of generator is shown in Fig 9.

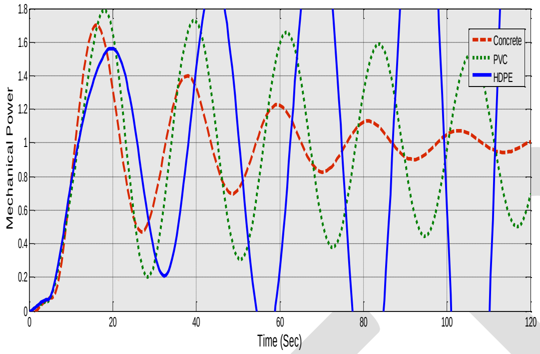

Fig. 8 Water hammer effect with change of material

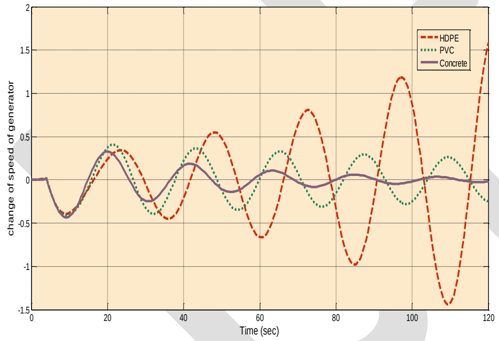

Fig.9 Change of speed of generator with material change

CONCLUSION

In this paper, non linear turbine penstock transfer function has been developed and then it is linearized about an point after that analysis of transfer function has been done for critical value of length and diameter of penstock. After that effect of material of penstock on the performance of the system is also studied. The simulation model and programming is done in MATLAB. The result has been obtain. This results shows that suitable length and diameter of penstock is must for system stability also material used for making penstock plays an important role hence material used for penstock should be proper.

That for a particular head an optimal length and diameter of the penstock must be considered for reducing the effect of the water hammer on the mechanical power. As well material used for penstock should be proper.

Appendix

Parameter of the system studied are as follows: Rp=0.05 T_G=0.2 sec, M=6.0 sec, R_T=0.38, T_R=5.0sec, D=1.0, H=264m, Q=76.67m^3/sec, E_{PVC}=1.5x10^9N/m^2, E_{HDPE} = 0.7x10^9N/m^2 $E_{concrete}$=48x10^9N/m^2, K=2.2x10^9N/m^2, ρ=997.296kg/m^3 L=410-420m, D=2.86-3.86,f=0.022m.

REFERENCES:

C.K. Sanathanan. Accurate low order model for hydraulic turbine penstock. IEEE Trans. Energy Conversion.1987.Vol.EC-2, No.2.pp. 196-200.

Ramey DG., Skoogland JW. Detailed Hydro Governor representation for system stability studies. IEEE Trans. 1970. Vol. PAS-89. No.2, pp.106-112.

Working group on Prime mover and Energy supply models for system Dynamic performance studies. Hydraulic Turbine control models for system dynamic studies. IEEE Trans. Power systems, 1992, Vol. 7, No.1 pp. 167-179.

P. Kundur. Power System Stability and Controls. Mc Graw-Hill, 1994.

Jiang J. Design an optimal robust governor for hydraulic turbine generating units. IEEE Transaction on EC.1995, Vol.10, pp.188-194.

F.R.Schleif, A.B.Wilbor. The coordination of hydraulic turbine governors for power system operation.IEEE Trans.1996.Vol.PAS-85,pp.750-758.

LN. Hannet, JW. Feltes, B.Fardanesh, W.Crean. Modeling and control tunning of a hydro station with units sharing a common penstock section. IEEE Trans Power System,1999,Vol.14.No.4,pp.1407-1414.

P.Oliver. Small hydro power: technology and current status. Renew.Sustain.Energy Rev.2002.Vol.6,pp.537-556.

P.M.Anderson and A.A.Fouad. Power System Control and stability 2nd Edition 2003.

F.Schwartz, F.R.Pegallapati, M.Shahiedehpour.Small Hydro as Green Power.In proc.IEEE Power Eng.Soc.General meeting.2005,pp.1883-1890.

N.Kishore, RP.Saini, SP.Singh. Simulation of reduced order hydro turbine models to study its hydraulic transient characteristics.9th International multitopic conference, IEEE INMIC 2005,pp.1-6.

Naidu BSK. Small Hydro: High-density, Non Conventional, Renewable energy source. National Power Training Institute, 1st edition(2005)

Sachin Mishra, S.K. Singal, D.K. Khatod . Effect of variation of penstock parameter on Mechanical power. International Journal of Energy Science, 2012. vol. 2 Iss.3, pp 110-114.

Nanaware R.A., Sawant S.R.,Jadhav B.T. Modeling of Hydraulic turbine and Governor for Dynamic studies of HPP. International Conference in Recent trends in Information technology and computer science . 2012, pp. 6-11