Modeling of Hydraulic Turbine and Governor for Dynamic Studies of HPP

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ABSTRACT
Accurate modeling of hydraulic turbine and its governor system is essential to depict and analyze the system response during an emergency. In this paper, both hydraulic turbine and turbine governor system are modeled. The hydro turbine model is designed using penstock and turbine characteristic equations and its governor system is modeled using PID controller. The simulation model is developed using MATLAB SIMULINK. The dynamic response of governing system to the disturbances such as load variation on the generator parameter is studied. The results graphically demonstrate the effect of load variation on generator parameters.

Keywords
Hydro power plant, Turbine Model, Penstock, PID, turbine governor.

1. INTRODUCTION
The dynamic characteristics of hydraulic turbine and its governor system affect Power system performance, during and following any disturbance, such as occurrence of a fault, rapid change of load. An accurate modeling of power system components, such as turbine and its governing system helps to study dynamic response. The non linear turbine model is more suitable for studies concerning large variation in power output and frequency. The several research articles [1-7] have presented the model structures for different types of governors and the hydraulic effects in the penstock.

The hydraulic dynamics in the penstock are also discussed in an IEEE working group [8] and Kundur [9]. The overall block diagram of the Hydraulic Turbine with governor [13, 15], servomotor and synchronous machine is shown in Fig. 1.

2. MODELING OF A HYDRAULIC TURBINE
The model is comprises of single penstock and turbine without surge tank. The hydro turbine model is designed from penstock and turbine characteristic differential equations [8, 10, 11, 12]. The performance of hydro turbine is influenced by the effects of pipe wall elasticity, water inertia, water compressibility in penstock. The basic equations relating to the flow of the water in penstock, turbine mechanical power and acceleration of the water defines the characteristics of turbine and penstock.

2.1 Modeling of Single penstock
The penstock is modeled assuming an incompressible fluid and a rigid conduit of length L and cross section A. From the low of momentum, the rate of change of flow in a single penstock is [10].

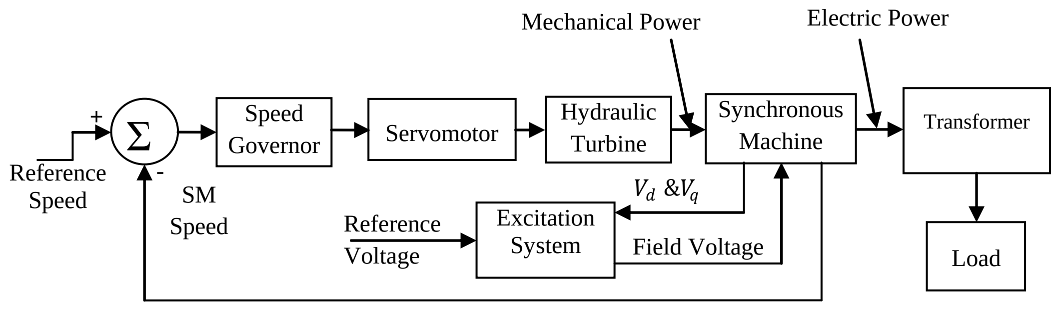

Fig 1: Block Diagram for Hydro power plant

$$\frac{d_q}{dt} = (h_s - h - h_I) g\, A/L \qquad (1)$$

Where,

q is the turbine flow, m^3/sec

h_s is the static head of the water column, m

A is the penstock cross section area, m^2

L is the length of penstock, m

g is acceleration due to gravity, m/sec^2

h is the head at turbine admission, m

h_I is the head loss due to friction in the conduit, m

The above equation (1) can be converted into per unit equation by dividing equation by its base quantity. Divide equation by q_{base} i.e. rated flow for rated output and rate head h_{base} we get.

$$\frac{dq/q_{base}}{dt} = \frac{d\bar{q}}{dt} = (h_s - h - h_I)\frac{gA}{Lq_{base}} \qquad (2)$$

By dividing the term $(h_s - h - h_I)$ by h_{base} and multiplying $\frac{gA}{Lq_{base}}$ by h_{base} we get

$$\frac{d\bar{q}}{dt} = \frac{(h_s - h - h_I)}{h_{base}} * \frac{h_{base}\ gA}{Lq_{base}} \qquad (3)$$

Here, h_{base} is difference between Lake Head and tail head. The q_{base} is nothing but maximum gate opening.

By putting $\frac{Lq_{base}}{h_{base}\ gA} = T_w$, we get

$$\frac{d\bar{q}}{dt} = (\bar{h}_s - \bar{h} - \bar{h}_I) * \frac{1}{T_w} \qquad (4)$$

Where,

$\bar{q}$ = the per unit water flow

$\bar{h}_s$ = per unit static head

$\bar{h}$ = per unit head at the turbine admission

$\bar{h}_I$ = per unit head loss due to friction

T_w = the water time constant or water starting time

2.2 Modeling of Turbine

The flow rate through turbine is a function of gate opening and head.

$$q = f\,(\text{gate, head}) \qquad (5)$$

The flow rate through turbine in per unit system is given by [12].

$$\bar{q} = \bar{G}\sqrt{\bar{h}} \qquad (6)$$

Where,

$\bar{q}$ = per unit water flow

$\bar{G}$ = per unit gate position

$\bar{h}$ = per unit head at the turbine admission

The turbine model is based on steady state measurements concerning output power with water flow. This is the relationship for the most part linear [12] and can be expressed as

$$P_m = A_t h(q - q_{nl}) \qquad (7)$$

Where,

Pm = per unit mechanical power

q = per unit water flow

A_t = turbine gain

q_{nl} = is per unit no load flow

$$A_t = \frac{1}{(\bar{G}_{max} - \bar{G}_{min})} \qquad (8)$$

Where,

$\bar{G}_{max}$ = Full load maximum per unit gate opening

$\bar{G}_{min}$ = No load per unit gate opening

Above equation is true for an ideal turbine, where mechanical power is equal to flow times head with appropriate conversion factor. But practical turbine has not 100% efficient. It has a small speed deviation damping effect due to the water flow in the turbine which can be expressed as function of gate opening [3, 10, 12].

The turbine generates the torque and the mechanical power would be given in the following

$$P_m = A_t h(q - q_{nl}) - \beta G \Delta w \qquad (9)$$

Where,

Δw = The speed deviation

β = proportionality constant

G = per unit gate position

The speed deviation Δw defines the deviation of the actual turbine-generator speed from the normal speed. The term $\beta G \Delta w$ represents speed deviation damping due to gate opening [6].

Equation 4, 6, 9 can be combined to produce the general dynamic characteristics of a hydraulic turbine with a penstock, unrestricted head and tail race [14] as shown in the block diagram in Fig. 2.

3. HYDRO POWER PLANT MODEL

The model of hydropower plant is developed by using MATLAB SIMULINK or POWER SYSTEM BLOCKSET [13, 14]. In designed model PID is used as turbine governor because this control has simple structure, stability, strong robustness and non steady state error [10]. In this simulation model, the measured synchronous machine speed is fed back to compare with the reference speed signal. The speed deviation produced by comparing reference and synchronous generator speed is used as a input for PID based speed governor. The governor produces the control signal, causing a change in the gate opening. The turbine then produces the torque, driving the synchronous machine generating the electrical power output. The speed governor continuously checks speed deviation to take action. The gains of PID controller are given in Table 1. Gain values are fixed by hand tuning according to the required response of control system.

Table -1.

Proportional Gain (Kp)	Integral Gain (Ki)	Derivative Gain (Kd)
0.5	0.5	0.5

For the simulation model **Excitation System Block** is taken from Power System Block set of MATLAB. **Excitation System** maintains the generator terminal o/p voltage at constant level.

In the developed model the effect of load variation on i) generator excitation system, ii)governor and iii) the synchronous generator is studied.

4. SYSTEM INITIALIZATION

Before running this system in steady state a initialization is required. In 'Load Flow and Machine Initialization', PV generator type Bus is used. It indicates that the load flow will be performed with the machine controlling the active power and its terminal voltage.

System is initialized with Active Power = 150MW, terminal voltage (Vrms) = 13800V. It also updates the phasors of AB and BC machine voltages as well as the currents flowing out of phases A and B.

It calculates the machine reactive power Q, mechanical power Pmec and field voltage Ef requested to supply the electrical power as Q = 3.4 Mvar, Pmec = 150.32 MW (0.7516 pu), Field voltage Ef = 1.291 pu.

The HTG and excitation Simulink unit are initialized according to the values calculated by the load flow. This initialization is automatically performed.

5. MODELVERIFICATION

The developed Model is verified and tested for load variations.

The test performed consists of three types

1) RLC Load Increase
2) RLC Load decrease
3) Three phase to ground fault

The model runs in steady state. Four scopes shown in fig. 3, 4, 5 shows the dynamic response of system. At the beginning , terminal voltage Va is 1.0 per unit (pu).

5.1 RLC Load Increase

The generation system runs in steady state. At t =5.0 the restive load is increased by 50 MW where capacitive reactive power and inductive reactive power, both are at 20 var . The effect of this load variation is shown if **Fig. 3**. At occurrence load variation, the speed of rotor decreases and excitation voltage increases. Here within 5 to 7 seconds generator Speed set at stable state to its initial level. The terminal voltage remains constant but the stator current shows small increment.

5.2 RLC Load Decrease

At t =5.0 the load is decreased by resistive active power 50 MW and capacitive reactive power and inductive reactive power 20 var each. The effect of this load variation is shown if **Fig. 4.** At occurrence load variation, the speed of rotor increases and excitation voltage decreases and set at its lower level. Both set at stable state within 5 to 7 seconds. The terminal voltage remains constant but the stator current slightly decreases and become stable as shown.

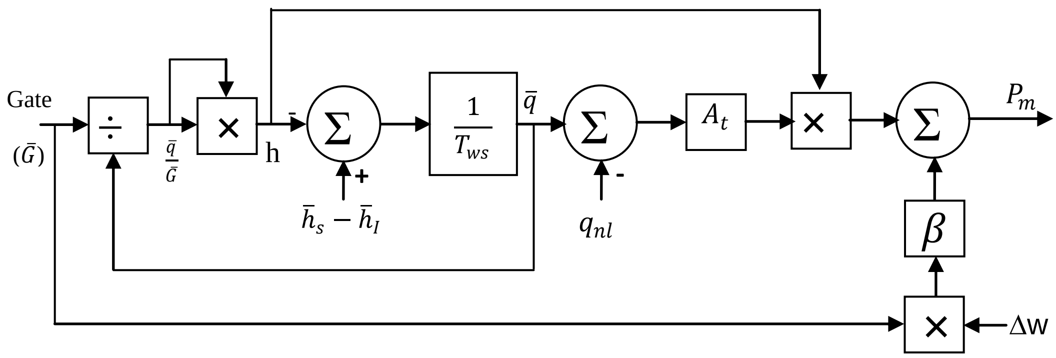

Fig 2: Mathematical Model for Penstock and Turbine

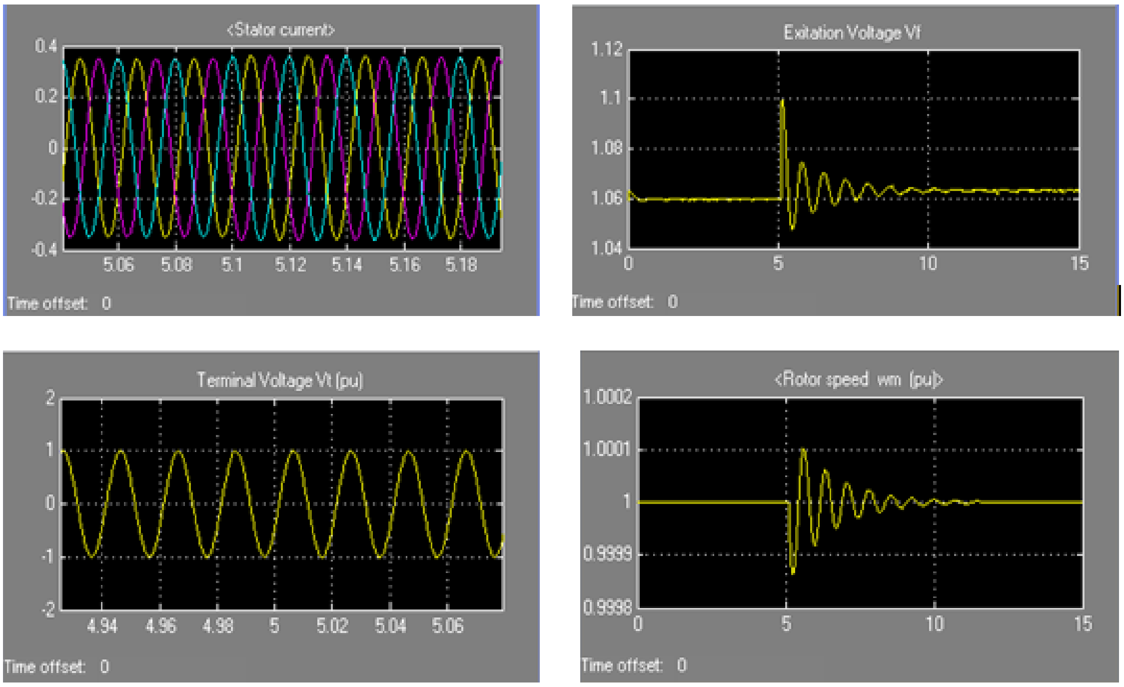

Fig 3: Results of RLC load Increase

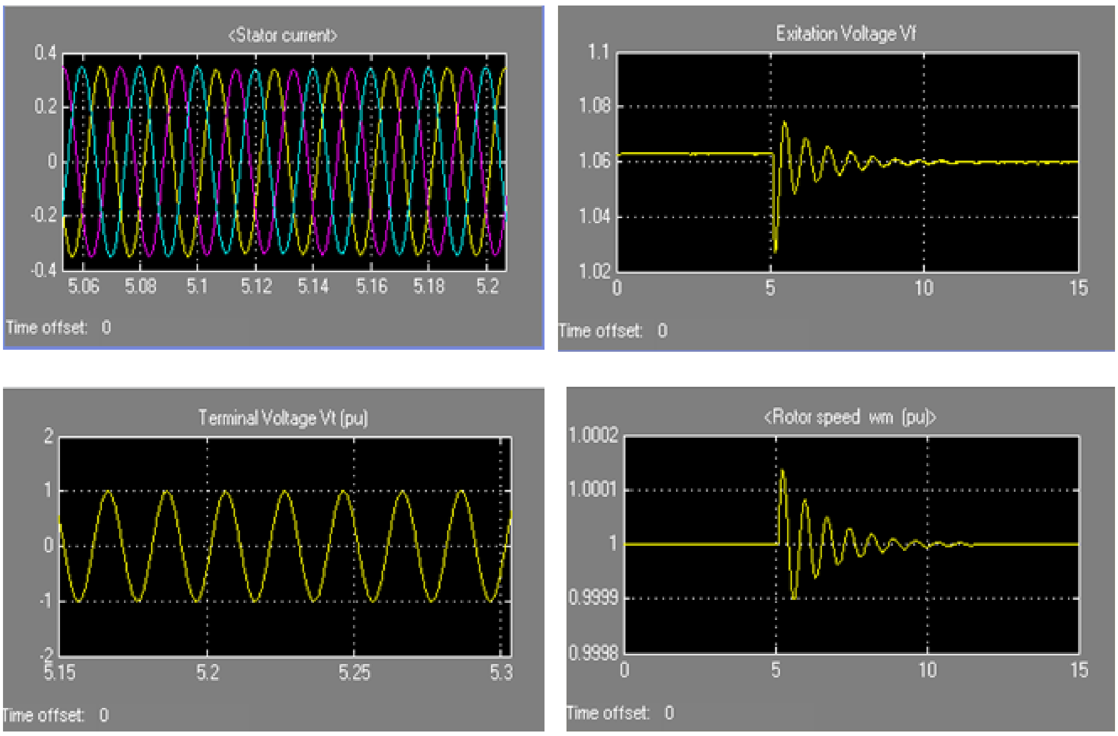

Fig 4: Results of RLC load Decrease

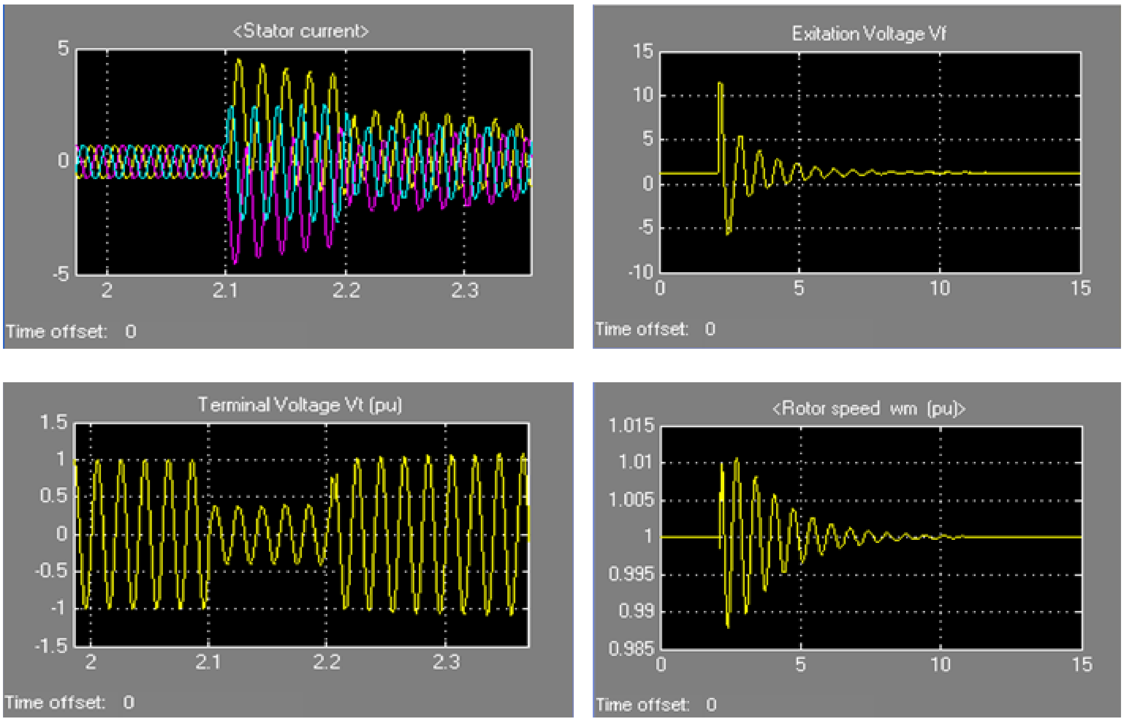

Fig 5: Results of Three phase to ground fault

5.3 Three phase to ground fault

Fig. 5 shows the result of three phase to ground fault i.e. short circuit. Fault occurs at t= 2.1 sec. Both, stator current and rotor speed shows the oscillations. Excitation voltage increases up to 11.5 per unit (pu). Fault clears after 6 cycles. Then rotor speed, excitation voltage, stator current and terminal voltage shows steady state after few seconds. The terminal voltage show quick response due to the fact that the Excitation System output Vf can go as high as 11.5 pu.

6. RESULT

The Fig. 4, 5, 6 shows the effect of load variation and effect of short circuit on generator parameter. The turbine governor system and excitation system brings the generation system to steady state within few seconds.

7. CONCLUSION

The general non-linear hydraulic turbine model has been given. This model is suitable for dynamic studies of hydro power plant. Severe disturbances are examined on dynamic model of power plants and power systems. Result shows sufficient accuracy of the model for the whole working range. The current turbine model with minor refinements will improve accuracy over the entire operating range.

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