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Modelling and Simulation of Low-Head Hydro Turbine for Small Signal Stability Analysis in Power System

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P A P E R I N F O

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A B S T R A C T

The hydro turbine dynamics have a considerable influence on the dynamic stability of power system. In the study of dynamic stability, the system is modeled by the linear differential equations (small signal analysis). Small signal stability of power systems is needed in all conditions and only is dependent on the conditions of power system performance before commotion occurrence. This paper provides an analysis of the small signal stability in a hydropower plant equipped with low head Kaplan turbine connected as single-machine infinite-bus (SMIB) power system. The dynamical behaviors with representative characteristics are identified and studied in details. The model of system is described by state-space equations. The eigenvalues analysis is used to show the effects of change in parameters for damping load angle and speed oscillations through the excitation and governor subsystems. Finally, results of theoretical analyses are verified by time-domain simulations under different system conditions and operating loads.

1. INTRODUCTION

Hydropower stations capture water flowing from height, either in rivers, water falls or artificial dams. It has now become the best source of electricity on earth and is the most important renewable energy converting industry. The most important advantage of hydropower is that it provides a clean and safe source of energy. They are self-sustaining. It doesn't contribute to global warming. Hydro-electric power is a flexible source of electricity since stations can be ramped up and down very quickly to adapt with changes of energy demands. It has been used since ancient times to grind flour and perform other tasks [1,2].

A turbine is a complex system in which, when the valve (steam or hydro) is opened wider, more steam or water will flow through the turbine and the mechanical power output at the shaft of the turbine will increase. Hydro turbines are easier and cheaper to control in comparison with steam turbines. Hydropower plant has environmental benefits and is economic and technical. Hydropower plants have essentially five major components. These are the storage reservoir, intake tunnel, surge tank, penstock, and water (hydro) turbine. Hydro-turbine governing system is one of the most important parts of hydropower plant [3,4]. They are multi-parameter, high dimension complex systems with time-variant, highly nonlinear and non-minimum phase characters [5,6].

Generally, the hydroelectric power plants based on the size of the head (head at the turbine inlet) can be divided into three broad groups: high-head (above 100m), medium-head (30m to 100m) and low-head (2m to 30m) plants [7,8]. In respect to flow path the classification of hydraulic turbines is as follows: axial flow hydraulic turbines, radial flow hydraulic turbines and mixed flow hydraulic turbines. In low-head hydro-electric power plants, Kaplan-type wheel reaction turbine is used. Kaplan Turbines have liquid flow in axial direction. In this turbine, the governor can change both the blade angle and the wicket gate opening [9,10]. Kaplan turbine has variable-pitch baled and high efficiency at all loads. There is a worldwide requirement of hydropower turbines for peak load operation at increasing heads and for low head turbines operating with large head variations.

In comparison with thermal units, hydropower plants are more robust. Hydropower plant can play an important role in infrastructure of intermittent energy sources production and has experienced strong growth in recent years. Many papers have been published considering applications of the hydro power system [11,12]. A model of hydro-turbine system with the

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effect of surge tank based on state-space equations to study the nonlinear dynamical behaviors of the system is presented in [13]. A design technique based on optimal pole shift theory for controlling a low-head hydro power plant connected as a SMIB power system is presented in [14], in which a state-space model with two-input and two-output variables is considered. A design technique of an adaptive optimal controller of the hydropower plant equipped with low head Kaplan turbine using artificial neural networks is presented in [15] to improve the generating unit transients through the exciter input, the guide vane position, and the runner blade position.

This paper provides an analysis of small signal stability in hydropower plant connected as single-machine infinite-bus (SMIB) power system. The nonlinear mathematical model is composed of electrical generator system, Kaplan turbine system, and governor system. The results of small signal stability analysis have been represented employing eigenvalue as well as time domain response. The proposed control scheme is demonstrated on normal, light and heavy load operating conditions. The organization of this paper is as follows: in section 2, a nonlinear dynamic mathematical model of a hydropower plant connected as SMIB power system is established. The structure of controller is show in section 3. The Section 4 gives formulation of the state space model for the power system. In section 5, the dynamical responses for three operating conditions (i.e., light, normal, heavy) are shown. Finally, the derived conclusions of this research are given in section 6.

2. SYSTEM METHEMATICAL MODEL

The main aim of electrical power systems is to provide the required power supply to customers with a given constant voltage and frequency. The block diagram of the single-machine infinite-bus power system is shown in Fig. 1, which is comprised of hydraulic turbine driving a synchronous generator. U_B and U_T are the voltages of the infinite bus and generator terminal bus, respectively [16]. An excitation system and automatic voltage regulator (AVR) are used to control the terminal voltage of the generator. The active power and frequency control are referred to as load frequency control (LFC) [17]. The synchronous generator is equipped with an IEEE type-DC1 exciter [18]. The output real power and terminal voltage at the generator terminals are measured and fed to the controller. The outputs of the controller (system control inputs) are fed into the generator-exciter and governor-valve.

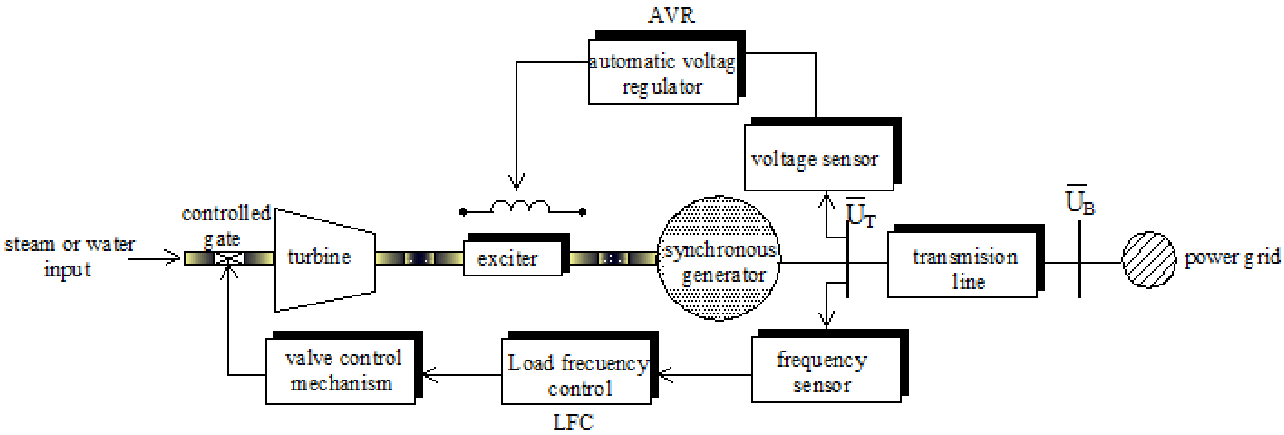


Figure 1. Control block diagram of the power system

The equations describing the hydro power plant behavior are summarized in this section. All variables are in per-unit deviations.

2.1. Excitation system

The IEEE Type DC1 excitation system is considered in this paper as shown in Fig. 2, where ΔU_R is the reference voltage deviation, ΔU_T is terminal voltage deviation, ΔE_F is the electrical field voltage deviation and ΔU_E is the error voltage deviation. $G_A(s)$, $G_S(s)$ and $G_U(s)$ are transfer function of the voltage regulator system, excitation system stabilizers and saturation, respectively. K_A, K_E and K_S are gains and T_A, T_E and T_S are time constants of the system exciter. The transfer function of excitation system is $G_V(s)$ and is given by:

$$G_V(s)=\frac{\Delta E_F(s)}{\Delta U_E(s)}=\frac{\Delta E_F(s)}{\Delta U_R(s)-\Delta U_T(s)}=\frac{G_A(s)G_U(s)}{1+G_A(s)G_U(s)G_S(s)} \qquad (1)$$

2.2. Turbine model

The power delivered by a generator is controlled by controlling the mechanical output power of a prime mover such as a water turbine or steam turbine. The mechanical output power is controlled by opening or closing valves adjusting the water or steam flow. The hydropower plant models based on the complexity of the equation involved in the modeling can be classified as the linear (non-elastic) models and nonlinear (elastic) models

[19]. The basic structure of the relationship between the different dynamics in a hydro power plant is shown in Fig. 3 [20].

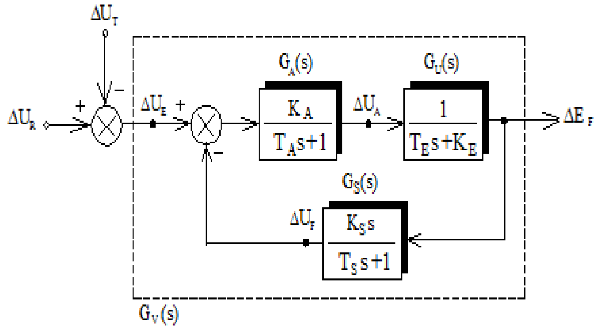


Figure 2. IEEE type-DC1 excitation system

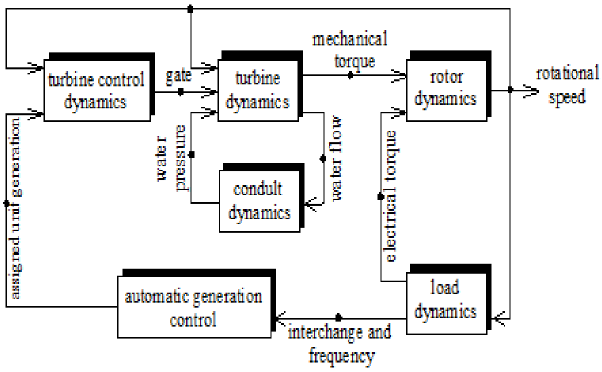


Figure 3. Functional block diagram of the hydro power generation and control system

The behavior of the turbine can be described by the variation in effective turbine head (h), water discharge flow (q), load torque (T_L), wicket gate position (g), mechanical rotate speed (ω_r), mechanical torque of the turbine (T_M), and turbine blade angular position (θ). The block diagram shown in Fig. 4 displays the relationships between the several dynamic elements present in a hydro power plant with low-head turbine.

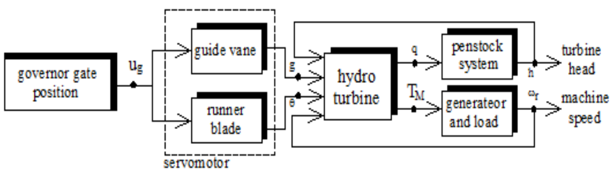


Figure 4. Functional block diagram of head-low turbine unit

The dynamic nonlinear characteristics of a Kaplan turbine are described by the water flow function (f_q) and torque function (f_t) as [21]:

$$\begin{cases} q = f_q(h, g, \omega_r, \theta) \\ T_M = f_t(h, g, \omega_r, \theta) \end{cases} \tag{2}$$

where, f_q and f_t are non-linear functions of h, g, ω_r, and θ.

The dynamics of the analyzed system in respect to the operating point can be observed by changing the operating point [22]. From a small-signal dynamics point of view, the linear first-order differential equation of the hydro-turbine governing system can be represented as [23]:

$$\begin{cases} q = q_h h + q_g g + q_w \omega_r + q_t \theta \\ T_M = m_h h + m_g g + m_w \omega_r + m_t \theta \end{cases} \tag{3}$$

The q_h, q_g, q_w, and q_r constants are partial derivatives of the water flow with respect to effective turbine head, gate opening, turbine speed, and turbine blade angular position, respectively. The m_h, m_g, m_w, and m_r constants are partial derivatives of the mechanical torque with respect to effective turbine head, gate opening, turbine speed, and turbine blade angular position, respectively [24]. These partial derivatives depend on machine loading and can be obtained from the characteristic curves of the hydro turbine at the operating point [25].

The water flow control in hydro-electric power plant equipped with a Kaplan turbine is performed by changing both the guide vane position and the runner blade position [26]. The water hammer equation in hydro unit with a low head turbine can be described as [27]:

$$h = -T_W \frac{d}{dt} q \tag{4}$$

Therefore, the dynamic characteristic of the penstock system is given by [28]:

$$\frac{d}{dt} q = \frac{1}{q_h T_W} (q_g g + q_w \omega_r - q + q_t \theta) \tag{5}$$

where, T_W is the water inertia time constant of the pressure diversion system. It varies with load and at full load lies between 0.5s and 5s.

The operation of Kaplan turbine involves control of the runner blades position and the wicket gates to adjust the water flow into the turbine. The corresponding servomotor equations are expressed as follows [29]:

$$\frac{d}{dt} g = \frac{1}{T_g} (u_g - g) \tag{6}$$

$$\frac{d}{dt} \theta = \frac{1}{T_r} (u_g - \theta) \tag{7}$$

where, u_g is governor gate position, T_g is wicket gate servomotor constant, and T_r is the runner blade servomotor constant. A typical block diagram of the hydro-turbine and penstock system is shown in Fig. 5.

2.3. Generator model

The conventional third-order model of synchronous machine is described by the electromechanical swing equation and the generator internal voltage equation. The dynamic of the generator can be expressed by the following differential equations [30,31]:

$$\frac{d}{dt}\delta = \omega_b(\omega_r - 1) \tag{8}$$

$$\frac{d}{dt}\omega_r = \frac{1}{J_M}[T_M - T_E - K_D(\omega_r - 1)] \tag{9}$$

$$\frac{d}{dt}E_q^{'} = \frac{1}{T_{do}^{'}}[E_F - E_q^{'} + (X_d^{'} - X_d)i_d] \tag{10}$$

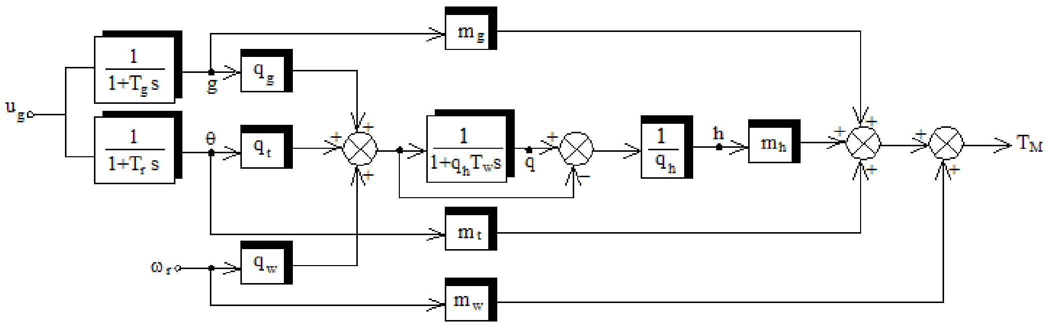


Figure 5. The linear model of the low-head hydro-turbine and penstock system

3. POWER SYSTEM STABILIZER

Nowadays, with the expansion of the transmission system and increase in power transfer through the transmission lines, maintaining the dynamic stability of the power system is important. Dynamic instability is created due to imbalance between the mechanical power input and electrical power output and lack of damping torque [32]. Power system stabilizer (PSS) provides an additional input signal to generate supplementary control signals for the excitation control system in order to damp the slow mode oscillations of the power system [33]. Some commonly used input signals are rotor speed deviation, accelerating power, and frequency deviation. The basic function of PSS is producing a component of electrical torque in phase with rotor speed deviations to increase the system positive damping. The transfer function of conventional lead-lag PSS (CPSS) as shown in Fig. 6 is given by the following [34]:

$$G_P(s) = K_Q\left(\frac{T_Q s}{1+T_Q s}\right)\left(\frac{1+T_1 s}{1+T_2 s}\right)\left(\frac{1+T_3 s}{1+T_4 s}\right) \tag{11}$$

where, T_Q is the washout time constant and K_Q is the PSS pure gain. T_1 and T_3 are the lead time constants, and T_2 and T_4 are the lag time constants. The selection of the T_Q value depends upon the type of mode under study.

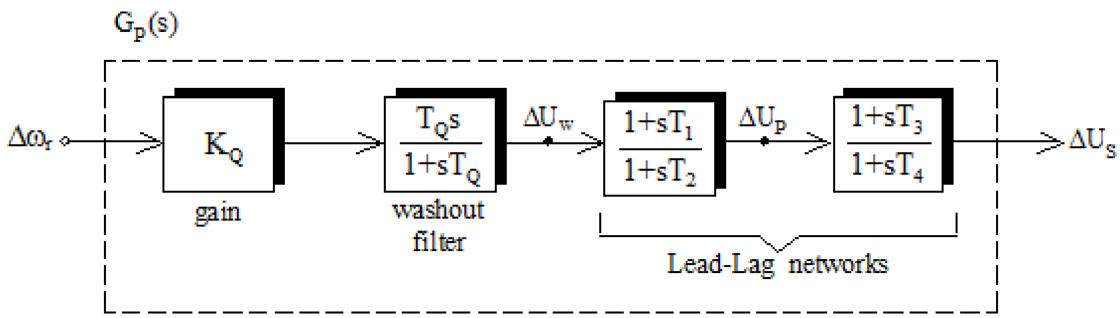


Figure 6. Strcture of power system stabilizer

4. STATE SPACE EQUATION

Small signal stability is best analyzed by linearizing the differential equations of hydro-turbine governing system about equilibrium operating point. The system has a multi-input multi-output structure and the use of state space models is a good approach for modeling and controlling. A simple state-space model of a hydro power plant connected as single-machine infinite-bus with nine state variables and two inputs is given as follows:

$$\frac{d}{dt}\Delta X = A\,\Delta X + B\,\Delta U \tag{12}$$

$$\Delta Y = C\,\Delta X \tag{13}$$

where, A and B are the system matrix and input matrix, respectively. The state vector (X) and input vector (U) are given by:

$$X = [\delta \ \omega_r \ E'_q \ E_F \ U_A \ U_F \ q \ g \ \theta \ U_W \ U_P \ U_S]^T \quad (14)$$

$$U = [U_R \quad U_g]^T \quad (15)$$

Fig. 7 shows the block diagram representation of the small-signal performance of the hydro power plant as SMIB power system, where $G_V(s)$, $G_P(s)$ and $G_R(s)$ are transfer function of the exciter system, the power system stabilizer and the voltage regulator system, respectively. U_E is the error voltage. The open loop equation describing it can be written in a state space as:

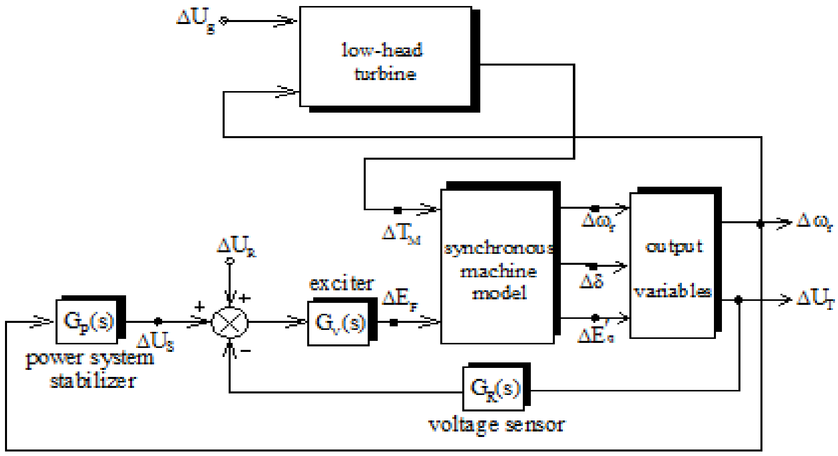


Figure 7. The block diagram of the plant model

$$\frac{d}{dt}\Delta\delta = \omega_b \Delta\omega_r \quad (16)$$

$$\frac{d}{dt}\Delta\omega_r = -\frac{K_1}{J_M}\Delta\delta - \frac{K_2}{J_M}\Delta E'_q + \frac{1}{J_M}\underbrace{(m_w - \frac{m_h q_w}{q_h})}_{K_7}\Delta\omega_r + \frac{m_h}{J_M q_h}\Delta q + \frac{1}{J_M}\underbrace{(m_g - \frac{m_h q_g}{q_h})}_{K_8}\Delta g + \frac{1}{J_M}\underbrace{(m_t - \frac{m_h q_t}{q_h})}_{K_9}\Delta\theta \quad (17)$$

$$\frac{d}{dt}\Delta E'_q = \frac{1}{T'_{do}}[\Delta E_F - \frac{1}{K_3}\Delta E'_q - K_4\Delta\delta] \quad (18)$$

$$\frac{d}{dt}\Delta E_F = -\frac{K_E}{T_E}\Delta E_F + \frac{1}{T_E}\Delta U_A \quad (20)$$

$$\frac{d}{dt}\Delta U_A = \frac{K_A}{T_A}\Delta U_R - \frac{K_A K_5}{T_A}\Delta\delta - \frac{K_A K_6}{T_A}\Delta E'_q - \frac{1}{T_A}\Delta U_A - \frac{K_A}{T_A}\Delta U_F \quad (21)$$

$$\frac{d}{dt}\Delta U_F = -\frac{K_S K_E}{T_S T_E}\Delta E_F + \frac{K_S}{T_S T_E}\Delta U_A - \frac{1}{T_S}\Delta U_F \quad (22)$$

$$\frac{d}{dt}\Delta g = \frac{1}{T_g}\Delta u_g - \frac{1}{T_g}\Delta g \quad (23)$$

$$\frac{d}{dt}\Delta\theta = \frac{1}{T_r}\Delta u_g - \frac{1}{T_r}\Delta\theta \quad (24)$$

$$\frac{d}{dt}\Delta q = \frac{q_g}{q_h T_W}\Delta g + \frac{q_w}{q_h T_W}\Delta\omega_r - \frac{1}{q_h T_W}\Delta q + \frac{q_t}{q_h T_W}\Delta\theta \quad (25)$$

$$\frac{d}{dt}\Delta U_W = -\frac{1}{T_Q}\Delta U_W + K_P\frac{d}{dt}\Delta\omega_r \quad (26)$$

$$\frac{d}{dt}\Delta U_P = -\frac{1}{T_2}\Delta U_P + \frac{1}{T_2}\Delta U_W + \frac{T_1}{T_2}\frac{d}{dt}\Delta U_W \quad (27)$$

$$\frac{d}{dt}\Delta U_S = -\frac{1}{T_4}\Delta U_S + \frac{1}{T_4}\Delta U_P + \frac{T_3}{T_4}\frac{d}{dt}\Delta U_P \quad (28)$$

The dynamic characteristics of the extended SMIB system are expressed in terms of constants K_1 to K_9. The K_1, K_2, K_3, K_4, K_5, and K_6 constants depend on the network parameters, the quiescent operating conditions, and the infinite bus voltage. The K_7, K_8, and K_9 constants are consequences of head, machine speed, wicket gate opening and runner blade position.

5. SIMULATION RESULTS

The parameters of the hydro power system are given in Table 1. The sensitivity constant of the model power system as a function load conditions is shown in Table 2. The effect of the AVR on damping torque is therefore primarily influenced by K_5 and $G_A(s)$. The constant K_5 can be either positive or negative. The effect of the

AVR is to decrease the damping torque, when K_5 is negative [35].

TABLE 1. Hydro power plant parameters

Generator synchronous	J_M=4.74, X'_d=0.254, X_d=1.7, X_q=1.64, T'_{do}=5.9, K_D=0, ω_b=120π
Exciter system	K_A=400, T_A=0.05, K_S=0.025, T_S=1, K_E=-0.17, T_E=0.95
Hydro turbine	q_h=0.3, q_z=0.82, q_w=0.387, q_t=0.41, m_h=1.276, m_z=0.839, m_w=-0.553, m_t=0.4725, T_g=0.5, T_r=1.4, T_W=2.23
Transmission line	R_E=0.02, X_E=0.4
Load conditions	Normal load (P_{EO}=1, Q_{EO}=0.62, U_{TO}=1.172) Heavy load (P_{EO}=1.4, Q_{EO}=1.1, U_{TO}=1.172) Light load (P_{EO}=0.3, Q_{EO}=0.1, U_{TO}=1.172)
Power system stabilizer	K_Q=0.0985, T_1=T_3=1.7454, T_2=T_4=0.0227, T_Q=10

TABLE 2. Constant K for different loading

Constant K / Loading conditions	K_1	K_2	K_3	K_4	K_5	K_6
Normal load	1.4462	1.3160	0.3072	1.8054	0.0293	0.5256
Heavy load	1.3709	1.3743	0.3072	1.8517	-0.0724	0.5174
Light load	0.9197	0.7096	0.3072	0.9716	0.1043	0.5984

5.1. Eigenvalues analysis

Table 3. summarizes the eigenvalues of the hydro-electric power plant with different load operations without controller. The values of damping coefficients and undamped natural frequency in electromechanical mode and electrical mode are represented in square bracket.

It is observed that the electromechanical mode for the open-loop system without controller which is characterized by the eigenvalues of -0.4670±10.7689, -0.2621±j10.1173 and -0.6108±j8.7264 is poorly damped. The participation matrix (magnitudes only) at normal load condition without controller is as:

$$P_{without-controller} = \begin{bmatrix} 0.5059 & 0.5059 & 0.0136 & 0.0136 & 0.0249 & 0.0142 & 0.0167 & 0 & 0 \\ 0.5041 & 0.5041 & 0.0140 & 0.0140 & 0.0336 & 0.0011 & 0.0070 & 0 & 0 \\ 0.0317 & 0.0317 & 0.3598 & 0.3598 & 3.3379 & 0.3919 & 1.2814 & 0 & 0 \\ 0.0157 & 0.0157 & 0.3621 & 0.3621 & 3.0578 & 0.3060 & 1.0817 & 0 & 0 \\ 0.0076 & 0.0076 & 0.8198 & 0.8198 & 0.1159 & 0.0012 & 0.0058 & 0 & 0 \\ 0.0138 & 0.0138 & 1.2987 & 1.2987 & 5.4459 & 1.0041 & 3.0466 & 0 & 0 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1 & 0 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0 & 1 \\ 0.0022 & 0.0022 & 0.0001 & 0.0001 & 0.0072 & 0.6797 & 0.3319 & 0 & 0 \end{bmatrix}$$

TABLE 3. Eigenvalues of power system without controller

Normal loading	Heavy loading	Light loading
-0.4670±j10.7689 [0.0433,10.7790]	-0.2621±j10.1173 [0.0259,10.1207]	-0.6108±j8.7264 [0.0698,8.7478]
-8.1378±j8.9779 [0.6716,12.1172]	-7.7646±j9.3219 [0.6400,12.1321]	-7.6556±j8.5991 [0.6649,1.8324]
-3.0569	-4.3994	-3.9556
-1.4658	-1.5084	-1.5240
-1.5991	-1.3704	-1.3190
-2.0000	-2.0000	-2.0000
-0.7143	-0.7143	-0.7143

From the participation matrix, we see that angular velocity change ($\Delta\omega_r$) and angle load change ($\Delta\delta$) have high participictions in the oscilliatory mode. Table 4. summarizes the eigenvalues of the hydro-electric power plant with different load operations with controller. The values of damping coefficients and undamped natural frequency in oscillation mode are represented in square bracket. The participation matrix (magnitudes only) at normal load condition with controller is:

$$P_{with-controller} = \begin{bmatrix} 0.0050 & 0.0050 & 0.2004 & 0.2004 & 0.4830 & 0.4830 & 0.0416 & 0.0000 & 0.0201 & 0.0136 & 0 & 0 \\ 0.0040 & 0.0040 & 0.1973 & 0.1973 & 0.4783 & 0.4783 & 0.0321 & 0.0000 & 0.0040 & 0.0006 & 0 & 0 \\ 0.1062 & 0.1062 & 0.3260 & 0.3260 & 0.5127 & 0.5127 & 2.9217 & 0.0000 & 1.3582 & 0.3810 & 0 & 0 \\ 0.1047 & 0.1047 & 0.3227 & 0.3227 & 0.5066 & 0.5066 & 2.6560 & 0.0000 & 1.1464 & 0.2973 & 0 & 0 \\ 0.1540 & 0.1540 & 0.3521 & 0.3521 & 0.1580 & 0.1580 & 0.0819 & 0.0000 & 0.0062 & 0.0011 & 0 & 0 \\ 0.0143 & 0.0143 & 0.2914 & 0.2914 & 0.6014 & 0.6014 & 4.8265 & 0.0000 & 3.2128 & 0.9745 & 0 & 0 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0 & 1 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0 & 1 \\ 0.0000 & 0.0000 & 0.0009 & 0.0009 & 0.0023 & 0.0023 & 0.0091 & 0.0000 & 0.3214 & 0.6918 & 0 & 0 \\ 0.0010 & 0.0010 & 0.0080 & 0.0080 & 0.0179 & 0.0179 & 0.0138 & 1.0001 & 0.0017 & 0.0003 & 0 & 0 \\ 0.3905 & 0.3905 & 0.2707 & 0.2707 & 0.2937 & 0.2937 & 0.0841 & 0.0000 & 0.0055 & 0.0008 & 0 & 0 \\ 0.4306 & 0.4306 & 0.0996 & 0.0996 & 0.0506 & 0.0506 & 0.0044 & 0.0000 & 0.0001 & 0.0000 & 0 & 0 \end{bmatrix}$$

TABLE 4. Eigenvalues of power system with controller

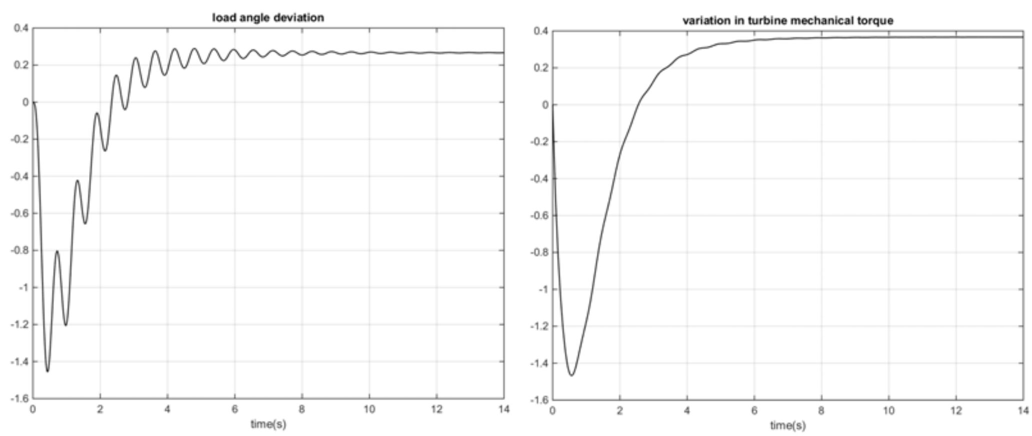
Normal loading	Heavy loading	Light loading
-2.1737±j7.3174 [0.2848,7.6334]	-1.4530±j7.1997 [0.1978,7.3449]	-1.4615±j7.0101 [0.2041,7.1608]
-3.4288±j15.7441 [0.2128,16.1131]	-3.6482±j15.8545 [0.2279,16.2680]	-5.1084±j12.9430 [0.3671,13.9146]
-47.1642±j11.3303 [0.9723,48.5061]	-47.2758±j11.5334 [0.9715,48.6623]	-46.0285±j8.8428 [0.9820,46.8702]
-2.8329	-3.8033	-3.5764
-0.1000	-0.1000	-0.1000
-1.6044	-1.5086	-1.5244
-1.4665	-1.3714	-1.3179
-2.0000	-2.0000	-2.0000
-0.7143	-0.7143	-0.7143

The PSS merely produces enough damping to compensate the negative damping due to AVR action. With the addition of the controller, the power system has become very stable.

5.2. Time-domain simulation

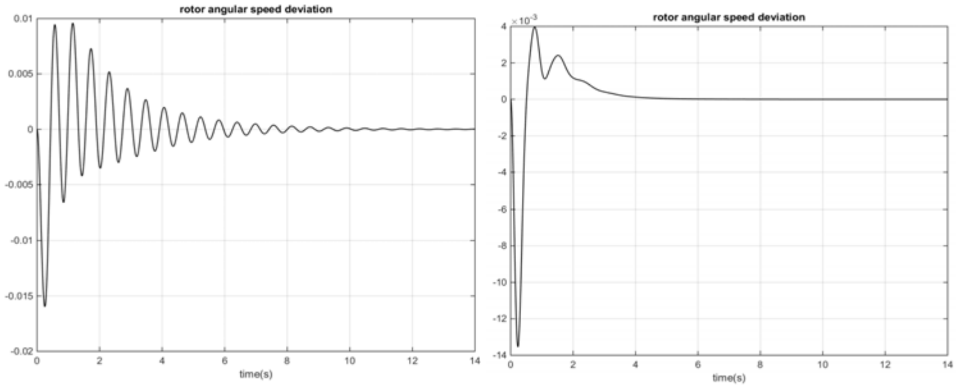
The dynamic responses of the power system without and with controller subjected to step change in governor gate position are presented in Figs. 8 and 9.

The dynamic responses of the power system without and with controller subjected to step change in load disturbance are presented in Figs. 10 and 11. The dynamic responses of the power system at heavy loading and light loading subjected to step change in load disturbance is presented in Figs. 12 and 13. From these figures, it is evident that the output response without controller is highly oscillatory which is not satisfactory.



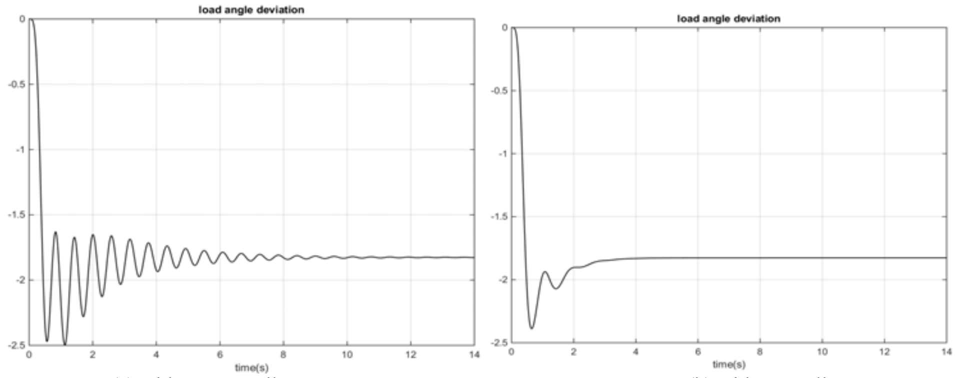
(a) without controller (b) with controller

Figure 8. Load angle deviations response at normal load operating point subjected to governor gate position



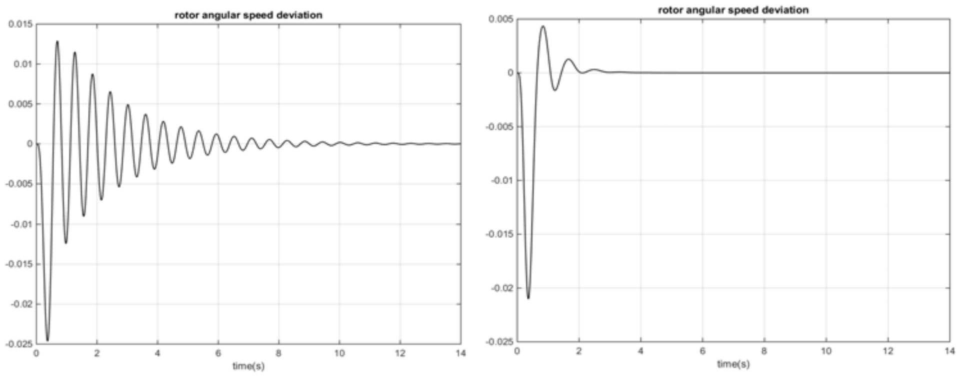
(a) without controller (b) with controller

Figure 9. Angular velocity deviation response at normal load operating point subjected to governor gate position



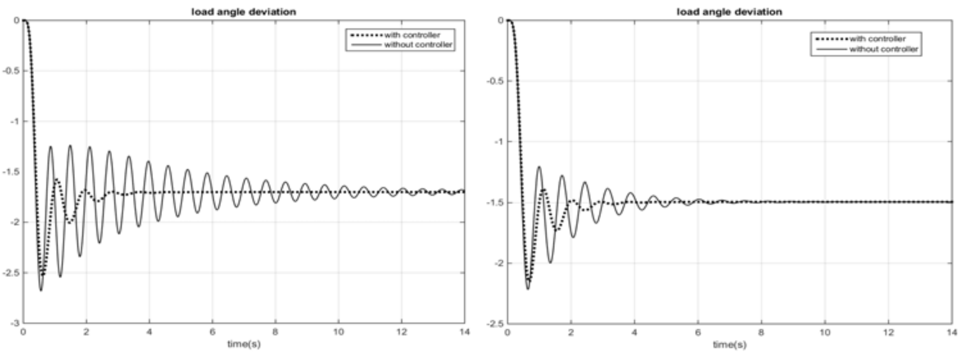
(a) without controller (b) with controller

Figure 10. Load angle deviations response at normal load operating point subjected to load disturbance



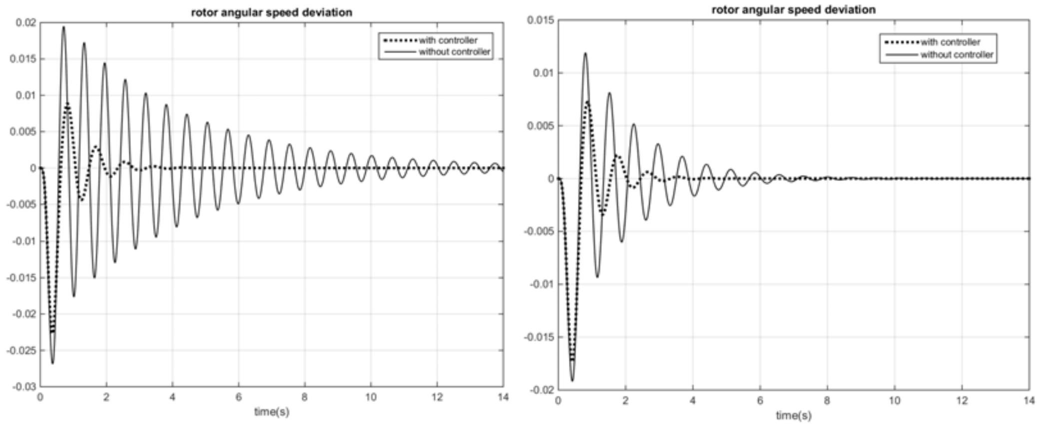
(a) without controller (b) with controller

Figure 11. Angular velocity deviation response at normal load operating point subjected to load disturbance



(a) at heavy load operating point (b) at light load operating point

Figure 12. Angular velocity deviation response subjected to load disturbance



(a) at heavy load operating point (b) at light load operating point

Figure 13. Angular velocity deviation response subjected to load disturbance

6. CONCLUSIONS

The low head hydro power plant as SMIB power system was studied in the paper. The considered plant is consisted of hydropower turbine connected to synchronous generator with excitation system, and the generator is connected to infinite-bus. The simulation results of the SMIB power system were demonstrated by considering three different loading conditions as normal load, heavy load, and light load. A linearized form of nonlinear model was used to design the controller in hydro turbine unit. The main aim in controlling the hydro-electrical power plants is maintaining stability and efficient performance over various load levels.

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