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# Steam Versus Hydraulic Power Plants For Frequency Stability Performance

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**ABSTRACT**
Load Frequency Control (LFC) is a primary control following disturbances such as faults and load disconnection. It is primitive for proper operation of the power system. It utilizes the real and virtual synchronous inertias for regulating the frequency. The objective of this control is to maintain the frequency within the acceptable limits. This article compares between the performances of conventional based power plant, steam, and hydro power plants. Different control techniques to regulate the frequency of these power systems are highlight, while revealing the promising performance indictor of each type. Optimal and zero steady-state frequency control approaches are investigated for these two systems. MATLAB simulation is used to simulate the dynamic performance of steam and hydraulic power plants. The results reveal the robustness and effectiveness of the proposed controller for reducing steady-state frequency error in relatively short time.
**Keywords -** Steam, Hydraulic, Disturbance, Load Frequency Control, Steady-State

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## I. INTRODUCTION

A mismatch between generation and demand results in large deviation in the operating frequency. This may be unacceptable for majority of loads, as it results in numerous problems, as saturation of power transformer core, tripping of circuit breakers and partial/full black out of the entire power system [1-4].

LFC recently becomes a fundamental control for reliable and secure operation of the power. The main objective of LFC is to minimize the transient variations following abnormal operating conditions; therefore, the system returns to its original frequency and schedules power [2-10].

LFC is extensively reported in the literature for single and multi-area power systems. Different control techniques are emerged and reported for implementing LFC, starting from simple proportional control to sophisticated lead-lag approaches. Different analysis methodologies are reported for analyzing the system under concern such as time-domain, S-domain and state-space [2-15]. However, a little is reported regarding the comparison between thermal power plants and hydro power stations. The comparison of the responses of these systems following severe disturbance is not clearly reported.

This article highlights the similarity and the difference in the performances of steam and hydro power plants following disturbances. Six distinct control approaches are investigated. These are Pole Placement (PP), Optimal Pole Shifting (OPS), Linear Quadratic Control (LQC), Proportional (P), Proportional Integral (PI) and Proportional Integral Derivative (PID). Additionally, this article studies the performance of these control techniques of LFC of the proposed studied system through developing a simulation model in the MATLAB software.

## II. THERMAL POWER PLANT

The thermal power plant utilizes fuel to turn the distilled water into super-heated steam. Recently, geothermal energy is defined as thermal plant [16-19]. The thermal power plant usually comprises from three main parts:

1. Generator-load
2. Prime mover
3. Governor

### A. Generator- Load Model

The swing equation of a synchronous machine is used to model the generator [16-19].

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = \Delta P_m - \Delta P_e \tag{1}$$

where H is per unit inertia constant, $\omega_s$ is the synchronous speed in rad/s, $\Delta P_m$ is the mechanical input power to the generator and $\Delta P_e$ is electrical output power from the generator, and $\delta$ is the angular position of the rotor.

The small single model of (1) is given by,

$$\frac{d\Delta \frac{\omega}{\omega_s}}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e) \tag{2}$$

where $\omega$ is the angular speed of the rotor.

The power system electrical load is frequency sensitive and non-frequency sensitive apparatus. Thus, electrical power is given by,

$$\Delta P_e = \Delta P_L - D\Delta\omega \tag{3}$$

### B. Prime mover model

The model of the turbine relates with the changes in the mechanical output power and the changes in the status of the valve. The model of the prime mover for the non-reheat steam turbine could be represented by,

$$\frac{\Delta P_m(s)}{\Delta P_v(s)} = \frac{1}{1+T_\tau s} \tag{4}$$

where $\Delta P_v$ is the change of the steam valve position and $T_\tau$ is turbine time constant.

### C. Governor speed model

The governor is used to sense the output frequency then control the steam valve position to balance the electric output power with mechanical input power. The governor model could be represented by the transfer function as [1, 16]:

$$\frac{\Delta P_v(s)}{\Delta P_g(s)} = \frac{1}{1+T_g s} \tag{5}$$

where $T_g$ is governor speed time constant and $\Delta P_g$ is the difference between reference set power and the power, $\frac{\Delta\omega}{R}$, where R is the speed regulation of the generator.

Equations (1)-(5) could be assembled either in a block diagram, Figure 1, or a state-space, (6).

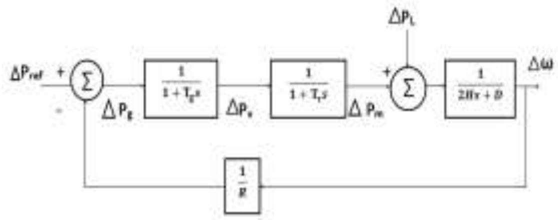


**Fig. 1** Block diagram model of the single area steam power plant

The state-space model is a mathematical representation for a system as a first order differential equations. These equations are function of the input, output and state variables. The state space model of the steam power plant is given as:

$$\begin{bmatrix} \Delta\dot{P}_v \\ \Delta\dot{P}_m \\ \Delta\dot{\omega} \end{bmatrix} = \begin{bmatrix} \frac{-1}{T_g} & 0 & \frac{-1}{RT_g} \\ \frac{1}{T_\tau} & \frac{-1}{T_\tau} & 0 \\ 0 & \frac{1}{2H} & \frac{-D}{2H} \end{bmatrix} \begin{bmatrix} \Delta P_v \\ \Delta P_m \\ \Delta\omega \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{-1}{2H} \end{bmatrix} \Delta PL \tag{6}$$

$$y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta P_v \\ \Delta P_m \\ \Delta\omega \end{bmatrix} \tag{7}$$

## III. HYDRAULIC POWER PLANT

### A. Hydraulic Turbine model

Many types of hydro-turbines are available. The selection of the specific turbine depends upon the flow rate and the head of the selected site to get the highest efficiency [17, 19]. Hydro-turbines are mainly categorized as impulse and reaction types. The water pressure response is inversely proportional with the position change of the gate after transient response.

For ideal hydro-turbine, the hydraulic systems dynamics are represented by the water velocity in the penstock, mechanical power of turbine, and water column acceleration.

The velocity of water in the penstock can be calculated as:

$$U = K_u G\sqrt{H_g} \tag{8}$$

where U represents the velocity of water, G is the gate position, $K_u$ is the proportionality constant of the flow equation and $H_g$ is the hydraulic head at the water valve.

The mechanical power of the hydro-turbine is proportional with the flow and pressure of the water:

$$P_m = K_p H_g U \tag{9}$$

$$\Delta\overline{P}_m = 3\Delta\overline{U} - 2\Delta\overline{G} \tag{10}$$

where η is the turbine efficiency, $K_u$ is the proportionality constant and ρ is the water density.

When the water comes from reservoir to turbine through gate and valve, its head changes at turbine and by applying the newton' second law we get:

$$T_w = \frac{LU_o}{a_g H_o} \tag{11}$$

where L represents the Length of conduit, $a_g$ is the acceleration due to gravity and $T_w$ is the water starting time from 0.5 to 4.0 s.

The controlling of the mechanical power in hydro-turbine is done by closing or opening valves regulation water flow. The transfer function of the ideal hydro-turbine is

$$\frac{\Delta P_m(s)}{\Delta G(s)} = \frac{-T_w s + 1}{0.5T_w + 1} \tag{12}$$

Where ΔG is the incremental change in gate position.

### B. Transient droop compensator

Hydraulic turbine has a different response due to the water inertia. The change in valve status produces a change in an initial turbine power. For the performance stability, large temporary transient droop is required with long resetting time. This is achieved by provide a transient gain reduction or a rate of feedback compensation. The feedback rate limits the movement of gate until the power output and water have time to reach the same equivalent value. This is modelled as a governor, which demonstrates a low gain for fast speed variations, and high gain in the steady state conditions. the transient droop compensator must be included in regulating the speed to improve the plant stability.

$$\frac{\Delta G(s)}{\Delta P_v(s)} = \frac{T_R s + 1}{T_R(\frac{R_T}{R})s + 1} \qquad (13)$$

where: $T_r$ is the reset time in second, $R$ is the permanent governor speed regulation parameter and $T_R$ is the reset time in second. $R_T$ is the temporary droop ranged between 0.01 and 1.2 and the value R is usually 0.05.

### C. Governor model

Governor in hydraulic system controls the flow of the water, which controls the speed of incoming water in order to control the hydraulic turbine speed, it can be represented as a time lag.

$$\frac{\Delta P_v(s)}{\Delta P_g(s)} = \frac{1}{1+sT_w} * \frac{1+T_R s}{1+s(\frac{R_T}{R})T_R} \qquad (14)$$

Equations (8) -(14) could be either assembled in a block diagram or state-space representation, similar to steam power plant. Figure2 shows the block diagram for hydraulic power system.

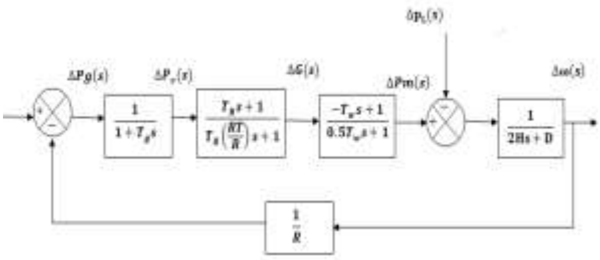


Fig. 2 Block diagram model of single area hydraulic power plant

The state-space model of the hydraulic power plant is given as:

$$\begin{bmatrix} \dot{\Delta\omega} \\ \dot{\Delta P_m} \\ \dot{\Delta P_v} \\ \dot{\Delta G} \end{bmatrix} = \begin{bmatrix} \frac{-D}{2H} & \frac{1}{2H} & 0 & 0 \\ \frac{1}{0.5T_g R_t} & \frac{-1}{0.5T_W} & \frac{-1}{0.5T_r(\frac{R_t}{R})} + \frac{1}{0.5T_g(\frac{R_t}{R})} & \frac{1}{0.5T_r(\frac{R_r}{R})} + \frac{1}{0.5T_w} \\ \frac{-1}{T_g R} & 0 & \frac{-1}{T_g} & 0 \\ \frac{-1}{T_g R_t} & 0 & \frac{-1}{T_r(\frac{R_t}{R})} + \frac{1}{T_g(\frac{R_t}{R})} & \frac{-1}{T_r(\frac{R_t}{R})} \end{bmatrix} \begin{bmatrix} \Delta\omega \\ \Delta P_m \\ \Delta P_v \\ \Delta G \end{bmatrix} + \begin{bmatrix} \frac{-1}{2H} \\ 0 \\ 0 \\ 0 \end{bmatrix} \Delta P_L \qquad (15)$$

$$y = [1 \quad 0 \quad 0 \quad 0] \begin{bmatrix} \frac{-1}{2H} \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (16)$$

## IV. CONTROL APPROACHES

### A. Pole placement control

Pole placement control is used to place the poles of the closed loop control system at any wanted locations by means of feedback through an appropriate feedback gain matrix, this can be achieved by direct substitution method [3]:

$$|SI - A + BK| = (s-u_1)(s-u_2)(s-u_3) \qquad (18)$$

where $I$ is the unit matrix, A is the state matrix, B is the input matrix, K is the desired gain matrix, and $\mu_1$, $\mu_2$ and $\mu_3$ are the desired closed loop pole.

### B. Optimal Pole Shifting

Optimal pole shifting is a method of shifting the real parts of the open loop poles to the desired location with the imaginary parts unchanged. This approach requires solving the linear matrix Lyapunov equations in order to shift two complex conjugate poles or one real pole. This method will yield a solution, which is considered as an optimal with respect to the performance index. The objective of this approach is to minimize transient deviation in frequency, and to result in a zero steady state errors. This method solved the problems without any nonlinear algebraic equations. The law of control consists on determining the feedback gain matrix. Then it was synthesized by multiplying the determined gain matrix and the state variables of the system. The gain matrix is calculated over wide range of the power system operating conditions [16-17].

$$(\wedge + \alpha I)\dot{v} + \dot{v}(\wedge^T + \alpha I) = \dot{H} \qquad (19)$$

where α is a positive scalar.

### C. Linear Quadratic Control

The regulator control problem defines the optimal trajectory for system departure from a point to another. This is realized via minimizing a given performance index. Selecting the performance index depends on the nature of control problem. The LQR aim is to reduce the error desired value and actual value in the present of the disturbance [16],

$$J = \int_0^\infty (x^T Q x + u^T R u)dt \qquad (20)$$

where J is the performance index, X is the state variables, Q, R is weighting matrices, U is the control low.

**D. Proportional Integral Derivative via Ziegler Nicholas**

If the mathematical model of the power plant could be derived, it is possible to use various control methods for calculating the control parameters that will satisfy the steady state and transient specifications of the closed loop control system. Ziegler-Nichols method of tuning the controller is a process of selecting the controller parameters to meet given performance specifications [10,19].

**Table 1** Ziegler–Nichols Tuning table

| Type of controller | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|
| P | $0.5K_{cr}$ | ∞ | 0 |
| PI | $0.45K_{cr}$ | $0.833P_{cr}$ | 0 |
| PID | $0.6K_{cr}$ | $0.5P_{cr}$ | $0.125P_{cr}$ |

## V. RESULTS AND DISCUSSIONS

In this paper, PP, OPS, LQR and PID of Ziegler-Nichols are applied for steam and hydraulic power plants. The parameters of steam and hydraulic power plants are respectively given in Tables 2 and 3.

**Table 2** Thermal power plant parameters

| | |
|---|---|
| Time constant of the Turbine | 0.5s |
| Time constant of the Governor | 0.2s |
| Inertia constant of the Governor | 5s |
| Speed regulation of the Governor | 0.05 pu |
| Load variation percent for percent change in frequency | 0.8 |

The isolated Hydro power plant has the following parameters.

**Table 3** Hydro power plant parameters

| | |
|---|---|
| Reset time constant | 5s |
| Temporary droop parameter | 0.01s |
| Governor time constant | 0.2s |
| Governor speed regulation | 0.05 pu |
| Load variation percent for percent change in frequency | 0.8 |

The rated mechanical input power is 250MW. 20% sudden increase of the load is used to investigate the effectiveness and validity of the proposed control approaches. The Matlab and Simulink dynamic platform are used for stimulating the systems under concerns with the control schemes.

**A. Thermal power plant**

The eigenvalues of the system state matrix without and with different controllers are given in Table 4.

**Table 4** closed loop poles of thermal power plant after using various controllers

| controller methods | System eigenvalues |
|---|---|
| System without control | -5.8863<br>-0.5968± j1.7825 |
| With PID controller | -5.244<br>-0.5341± j2.8016<br>-0.7672 |
| With linear quadratic control | -6.9149<br>-0.7485 ± j1.5701 |
| With pole placement control | -2±j6<br>-3 |
| With optimal pole shifting | -7<br>-2.5537 ± j 1.7825 |

**Figure 3** shows the response of thermal power plant if the load is increased by 20%.

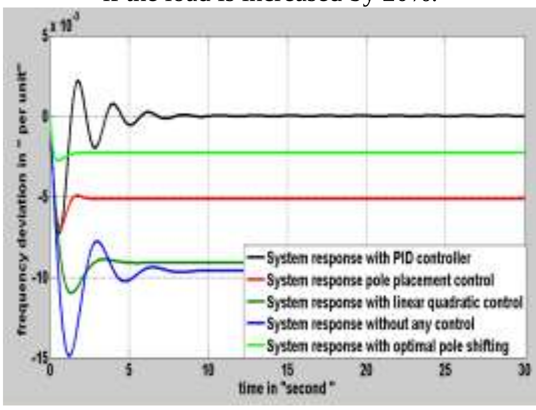


Fig. 3 Thermal power plant with various controller

Figure 3 shows that without control there are significant frequency drop. This could eventually resulted in tripping the power plant. The frequency of the system without control drops to 59.42 HZ. On the other hand, LQR control lead to a system with 59.46 HZ. The use of pole placement control with the poles shifted to 2+j6, -2-j6 and -3 leads to a better response with a frequency of 59.69 HZ. The OPS by solving first and second order Lyapunov equation results a frequency of 59.85 HZ. The poles of the system in OPS were shifted to -7, -2.5537+ j 1.7825 and -2.5537- j1.7825.

PID controller parameters given in Table 5, the system exhibits zero steady-state frequency response.

**Table 5** PID controller parameters for thermal power plant

| P | I | D |
|---|---|---|
| 27 | 16.36 | 13.32 |

**Figure 4** shows root locus of the system with PP, OPS, LQR, PID and without control for steam power plant.

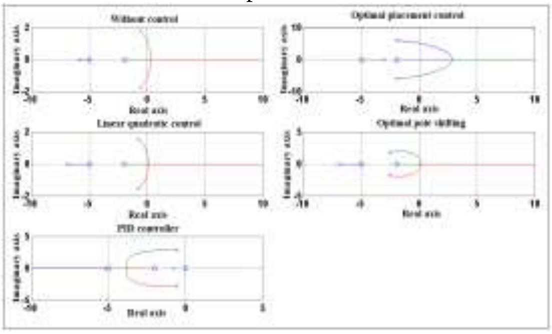

Fig. 4 root locus representation of thermal power plant

Figure 4 shows the original systems' poles, and linear quadratic controller poles after determined the Q and pole placement, poles that chose and determining the K matrix is k = [-0.0800 41.4400 99.2000]. Solving first and second order Lyapunov equation to shift real and complex poles. The gain matrix was calculated as K= [1.1137 5.6882 10.8019].

**B. Hydro power plant**

The eigenvalues of the system state matrix without and with different controllers for isolated hydro power plant are given in Table 6.

**Table 6** closed loop poles of hydraulic power plant after using various controllers

| **Control methods** | **Eigenvalues of hydro power plant** |
|---|---|
| System without control | -4.428<br>-0.389±j0.4817<br>-0.2727 |
| With PID controller | -2.5883<br>-0.4469 ±j0.9795<br>-0.2582<br>-0.0837 |
| With linear quadratic control | -4.5342<br>-0.4205 ±j0.5623<br>-0.4930 |
| With pole placement control | -2<br>-1±j<br>-0.5 |
| With optimal pole shifting | -8<br>-6<br>-0.9946 ±j0.4817 |

The response of the hydro power plant is illustrated in Fig. 5. The load is increased by 0.2 pu.

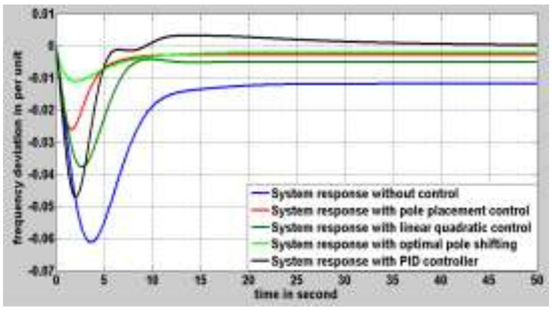


**Fig. 5** hydraulic power plant with various controller

Figure 5 shows there is a significant deviation in the frequency for 20% load increase. Comparing Figures 4 and 5 shows that steam power plant has better response than hydraulic power plant. In general, the hydro power plant requires longer time than thermal power plant to reach the steady-state. This is attributed to mechanism of hydro turbine, as it is governed by water speed not by super-heated steam as in thermal system.

Also, the again the response of the system without using control system was not the best, the new frequency of the system without control is 59.28 HZ. The linear quadratic control has a slower response with 59.7 HZ. the use of pole placement control with the poles shifted to –2, -1+j, -1-j and -0.5 leads to a better response with a frequency of 59.83 HZ. The optimal pole shifting which doesn't much differ from pole placement leads to a frequency of 59.88 HZ.

PID controller parameters given in Table 7, the system exhibits zero steady-state frequency response.

**Table 7** PID controller parameters for hydro power plant

| P | I | D |
|---|---|---|
| 13.8 | 2.36 | 12.07 |

Figure 6 shows root locus of the system with PP, OPS, LQR, PID and without control for hydro power plant.

For pole placement control the value of Q and R are equal to 1. The gain matrix of the optimal pole shifting was calculated as K= [-1.7394 -0.8806 1.1528 0.3114] and by solving louponov equation, K was calculated as, K = [5.7273 57.2112 98.1354 55.9556] for PID controller.

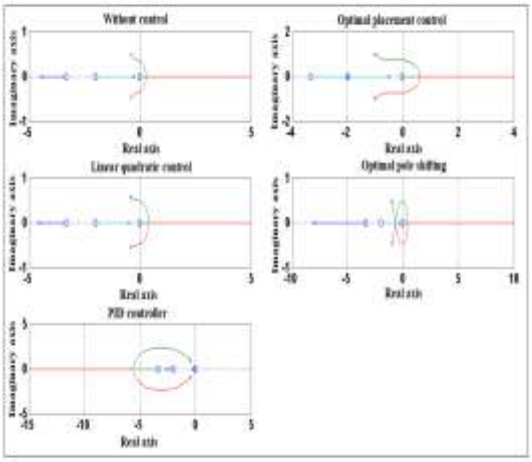


**Fig. 6** root locus representation with various controllers

## VI. CONCLUSION

This article addresses the application of different control techniques for steam and hydraulic power stations. Pole placement, optimal pole shifting and linear quadratic control are considered proportional type. Therefore, there is a steady-state frequency error. However, LQR produces the lowest steady-state frequency error either steam or hydraulic power plants.

The response of steam power plant following disturbance is much better than hydraulic power plant. This may be due to working principle of each.

The PID controller is efficient Automatic Generation Control (AGC) technique. As, it produces zero steady-state frequency error. However, the response speed is relatively slower. Moreover, PID involves higher overshoot and settling than LQR.

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