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Optimal Pole Shifting Technique Design Based on Single Area Load Frequency Controller

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Abstract

This paper presents the robust optimal shifting of eigenvalues control design and application for load frequency control. The optimal pole-shifting control is simple and applicable. Also, the proposed optimal pole-shifting is fast and robust than any other controller. A method for shifting the real parts of the open-loop poles to any desired positions while preserving the imaginary parts is constant. In each step of this approach, it is required to solve a first-order or a second-order linear matrix Lyapunov equation for shifting one real pole or two complex conjugate poles respectively. This presented method yields a solution, which is optimal with respect to a quadratic performance index. Load-frequency control (LFC) of a single and two area power systems are evaluated. The objective is to minimize transient deviation in frequency and tie-line power control and to achieve zero steady-state errors in these quantities. The attractive feature of this method is that it enables solutions to complex problem to be easily found without solving any non-linear algebraic Riccati Equation. The gain matrix is calculated one time only and it works over wide range of operating conditions. To validate the powerful of the proposed optimal pole shifting control, a linearized model of a single area load frequency control is simulated.

Keywords

Optimal Pole Shifting Controller, Load Frequency Control, Pole Placement Control

1. Introduction

Designing a feedback freedom may be used to achieve additional advantageous control properties. One of such

desirable properties for feedback is the optimally for a quadratic performance index. Robustness properties of this optimal feedback gain have been presented. A problem has been considered for converted into reduced-order linear problems. In each of these problems, a first-order or a second-order linear Lyapunov equation is to be solved for shifting one real pole or two complex conjugate poles, respectively [1]. Power system oscillation is usually in the range between 0.1 Hz to 2 Hz. Improved dynamic, stability of power system can be achieved through utilization of supplementary excitation control signal [2] [3]. The method is based on the mirror-image property. The problem of designing a feedback gain that shifts the poles of a given linear multivariable system to specified position has been studied extensively in the past decade. Many control strategies as fuzzy control [4] [5] have been proposed based on classical linear control theory. However, because of the inherent characteristics of the change loads, the operating point of a power system may change often during a daily cycle. The dynamic performance of power systems is usually affected by the influence of its control system [6]-[8]. It has been recognized that the complexity of a large electric power system has an adverse effect on the systems dynamic and transient stability, and its stability can be enhanced by using optimal pole shifting control. Further, the two area power system, composed of steam turbines controlled by integral control only, is sufficient for all load disturbances, and it does not work well. Also, the non-linear effect due to governor deadzones and generation rate constraint (GRC) complicates the control system design [9]-[11]. Further, if the two area power system contains hydro and steam turbines, the design of LFC systems is important. There are different control strategies that have been applied, depending on linear or non-linear control methods.

In this paper, a comparison between pole placement control and proposed optimal pole shifting controller is presented in single area load frequency control. This optimal pole shifting is fast response and simple implementation.

No eigenvalues should have a multiplicity greater than the number of inputs.

Calculate the feedback gain matrix K such that the single input system

$$\dot{X} = AX + BU \tag{1}$$

The feedback control law:

$$U = -K_{fb}X \tag{2}$$

Applied to Equation (1) a closed-loop system will be obtained in the form

$$\dot{X} = A_c X$$

with

$$A_c = A - BK_{fb} \tag{3}$$

Consider $S_i = R_e(s_i) + jIm(s_i)$ to be a closed-loop pole of Equation (3). And $\lambda_i = R_e(\lambda_i) + jLm(\lambda_i)$ is open-loop poles of Equation (1) for any S_i and λ_i, which satisfy the optimality condition of, α_i [1] can be given:

$$\alpha_i = \frac{-\left[R_e(s_i) + R_e(\lambda_i)\right]}{2} \tag{4}$$

where α_i is a positive real constant scalar.

R is a positive definite symmetric matrix. Then, for the following matrix algebraic equation:

$$P = (A + \propto I) + (A^T + \propto I)P - PBR^{-1}B^T P + Q = 0 \tag{5}$$

There exists a positive semi-definite real symmetric solution P satisfying

$$R_e(S_i) \le -\propto$$

Therefore, according to [1]:

$$(S_i + \propto)^2 = (\lambda_i + \alpha)^2$$

with $i = 1, 2, \cdots, n$ and $K_{fb} = R^{-1}B^T$. Further, the feedback control law.

$U = -K_{fb}X$ minimizes the following quadratic performance index:

$$\int_0^\infty \left(X^{\mathrm{T}}QX + U^{\mathrm{T}}RU \right)\mathrm{d}t$$

with $Q = 2\alpha P$

2. Single Area Load Frequency Control Model [9] [10]

The load-frequency control plays an important role in power system operation and control. It makes the generation unit supply sufficient and reliable electric power with good quality. **Figure 1** shows the block diagram of single area load frequency control. The model considered here can be written in state equations form as follows

$$\Delta \dot{f} = -\frac{1}{T_p}\Delta f + \frac{K_p}{T_p}\Delta P_g - \frac{K_p}{T_p}\Delta P_d$$

$$\Delta \dot{P}_g = -\frac{1}{T_t}\Delta P_g + \frac{1}{T_t}\Delta X_g$$

$$\Delta \dot{X}_g = -\frac{1}{RT_g}\Delta f - \frac{1}{T_g}\Delta X_g - \frac{1}{T_g}\Delta E + \frac{1}{T_g}U$$

$$\Delta \dot{E} = K_i\Delta f$$

3. Optimal Shifting of Eigenvalues Control [1]-[3] [11]

3.1. Shifting One Real Pole

A real pole $\lambda = \gamma$ is to be shifted to the new position $S = \sigma$ [3] which satisfies the optimality condition $|\sigma| > |\gamma_i|$. The first-order model to be used is defined by:

$$\Lambda = \lambda \quad \text{and} \quad G = C^{\mathrm{T}}B$$

where C^{T} is the left eigenvector of A associated with λ, if the positive scalar α is:

$$\alpha = \frac{-(\sigma + \lambda)}{2} \tag{6}$$

Then an explicit solution for the above reduced-other problem can be obtained by solution of the first-order Lyapunov Equation
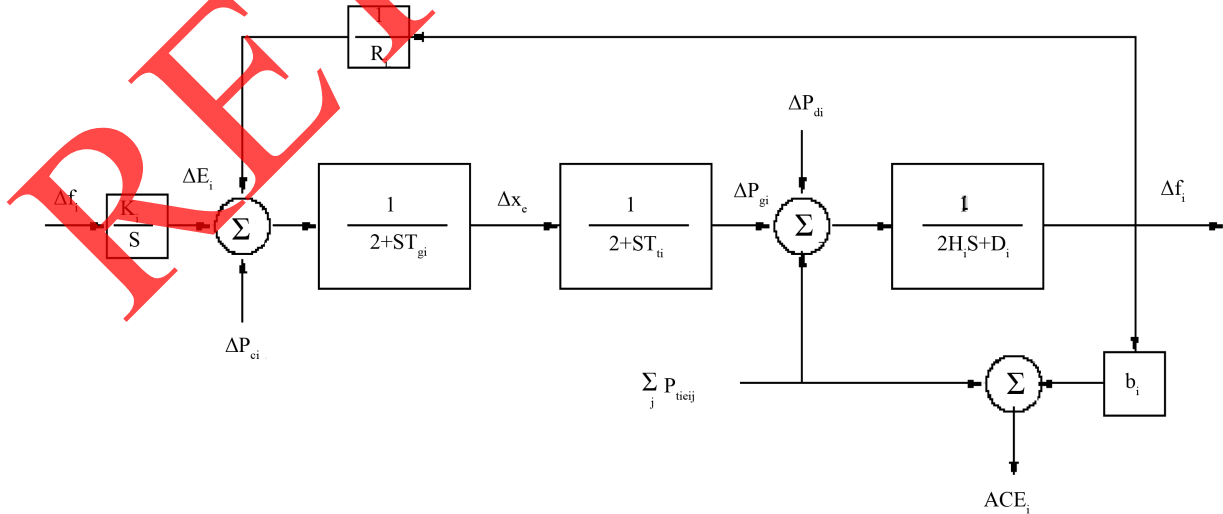
Figure 1. Block diagram of single area load frequency control.

$$(\sigma + \propto)\dot{V} + \dot{V}(\sigma + \propto) = \dot{H} \tag{7}$$

Is given by $\dot{V} = \dfrac{\dot{H}}{2(\sigma + \propto)}$ where:

$$\dot{H} = GR^{-1}G^{\mathrm{T}} \tag{8}$$

Then the required parameters $\dot{P}, \dot{Q}, \dot{K}$ can be calculated as $\dot{K} = R^{-1}G^{\mathrm{T}}\dot{P}\dot{Q} = 2 \propto \dot{P}$ and $\dot{P} = \dot{V}^{-1}$ then, the parameter rewritten as:

$$\dot{P} = 2\frac{(\sigma + \propto)}{\dot{H}}, \ \dot{Q} = \frac{4 \propto (\sigma + \propto)}{\dot{H}} \ \text{and} \ \dot{K} = \left[\frac{2(\sigma + \propto)}{\dot{H}}\right]R^{-1}G^{\mathrm{T}} \tag{9}$$

3.2. Shifting a Complex Pole

A complex conjugate pair of poles λ, $\dot{\lambda} = \gamma \pm j\beta$ of Equation (3) is to be shifted to the new positions S; $S = \sigma \pm j\beta$, which satisfy the optimality condition: $|\sigma| > |\gamma_i|$.

Let positive scalar α as: $\propto = \dfrac{-(\sigma + \lambda)}{2}$.

The second-order model Λ to be used is define

$$\Lambda = \begin{bmatrix} \gamma & -\beta \\ -\beta & \gamma \end{bmatrix}, \ G = C^{\mathrm{T}}B \ \text{and} \ C^{\mathrm{T}} = \begin{bmatrix} C_1^{\mathrm{T}} \\ C_2^{\mathrm{T}} \end{bmatrix} \tag{10}$$

where $\left(C_1^{\mathrm{T}} + jC_2^{\mathrm{T}}\right)$ is the left eigenvector of A associated with the pole $\lambda = \lambda + j\beta$ and the left eigenvector satisfied the equation:

$$C^{\mathrm{T}}A = \Lambda C^{\mathrm{T}} \tag{11}$$

By solving the following second-order linear Lyapunov Equation of Equation (7)

$$(\Lambda + \propto I)\dot{V} + \dot{V}(\Lambda^{\mathrm{T}} + \propto I) = \dot{H} \tag{12}$$

$$\dot{H} = GR^{-1}G^{\mathrm{T}}$$

The parameters $\dot{P}, \dot{Q}, \dot{K}$ of the second-order optimal problem are obtained

$$\dot{K} = R^{-1}G^{\mathrm{T}}\dot{P}, \ \dot{Q} = 2 \propto \dot{P} \ \text{and} \ \dot{P} = \dot{V}^{-1} \tag{13}$$

Therefore, the feedback controller K_{fb} can be calculated from:

$$K_{fb} = \dot{K}C^{\mathrm{T}} \tag{14}$$

where

$$P = C\dot{P}C^{\mathrm{T}} \tag{15}$$

$$Q = 2 \propto P \tag{16}$$

3.3. Shifting Several Poles

Problem of shifting several poles may be solved by the recursive applications of the following reduced order optimal shifting problem

$$\dot{Z}_i = \Lambda_i Z_i + G_i U_i \tag{17}$$

$$U = \dot{K}_i Z_i \tag{18}$$

$$\dot{J}_i = \int_0^\infty \left(Z_i^{\mathrm{T}}\dot{Q}_i Z_i + U_i^{\mathrm{T}}RU_i\right)\mathrm{d}t \tag{19}$$

with

$$C_i^{\mathrm{T}} A_i = \Lambda_i C_i^{\mathrm{T}}, \quad G_i = C_i^{\mathrm{T}} B \tag{20}$$

and

$$A_{i+1} = A_i - BK_i$$

$$k_i = \dot{K}_i C_i^{\mathrm{T}} \quad \text{and} \quad A_i = A \tag{21}$$

From Equation (18), the feedback matrix K can be constructed by the summation of the optimal feedback matrix K_i. Also the resulting matrices Q and P can be constructed as shown by the summation of the matrices Q_i and P_i, respectively [1]

$$P = \sum_i P_i, \quad Q = \sum_i Q_i \quad \text{and} \quad K_{fb} = \sum_i K_i \tag{22}$$

where:

$$k_i = \dot{K}_i C_i^{\mathrm{T}}, \quad P_i = C_i \dot{P}_i C_i^{\mathrm{T}} \quad \text{and} \quad Q_i = 2 \propto_i P_i$$

4. Pole Placement Control [6]-[8]

By using full-state feedback can shift the poles to the left hand side by (10% - 15%). We could use the Matlab function place to find the control vector gain K, which will give the desired poles.

$$K = \mathrm{place}(A, B, P) \tag{23}$$

where:

A: system matrix
B: input vector
P: pole shifting vector
K: control gain

A state feedback matrix K such that the eigenvalues of $A - B * K$ are those specified in vector P. The feedback law of $u = -kx$ has closed loop poles at the values specified in vector P.

$$\mathrm{Poles} = eig(A - B * K)$$

5. Digital Simulation Results

The normal parameters of single area power system are:

$$T_g = 0.2 \text{ sec}, \quad T_t = 0.5 \text{ sec}, \quad K_A = 1.25, \quad T_A = 12.5 \text{ sec}, \quad 1/R = 20, \quad K_p = 2, \quad T_p = 15 \text{ sec}.$$

The A and B matrices of single area model are calculated as:

$$A = \begin{bmatrix} -0.06 & 0.13 & 0 & 0 \\ 0 & -2.0 & 2.0 & 0 \\ -100 & 0 & -5 & -5 \\ 0.6 & 0 & 0 & 0 \end{bmatrix}$$

The dominant poles can be rewrite as:

$$-0.4752 \pm j2.1053$$

$$-\xi\omega_n \pm j\omega_n\sqrt{1-\xi^2} \tag{24}$$

where;

ξ: damping coefficient
ω_n: Frequency

$$\xi\omega_n = -0.478$$

$$j\omega_n\sqrt{1-\xi^2} = j2.053$$

$$\xi = 0.22$$

$$\omega_n = 2.1$$

The settling time $T_s = 72.7 \ \text{sec}$. the desired value of the damping coefficient can be choosing as $\zeta = 0.82$ to damping the oscillation of speed and constant imaginary part. The closed loop poles are specified as:

$$\zeta = 0.82 \quad \text{and} \quad j\omega_n\sqrt{1-\xi^2} = j2.05$$

From Equation (24), calculate the $\omega_n = 3.568$ the new dominant eigenvalues can be calculated as follows

$$-\xi\omega_n \pm j\omega_n\sqrt{1-\xi^2} = -2.92 \pm j2.053$$

The complete new poles are become as:

$$S_{1,2} = \sigma \pm j\beta = -2.92 \pm j2.053$$

$$S_3 = -6.08$$

$$S_4 = -0.0298$$

and calculate the settling time decreased (T_s) from 72.7 to 1 sec.

Shifting complex poles $\lambda_{1,2}$ to $S_{1,2}$, it can get:

$$\propto_1 = -\frac{(-0.4752 - 2.92)}{2} = 1.7040$$

C_1^T : left eigenvector which satisfy the Equation (10)

$$C_1^T = \begin{bmatrix} -7.27 & 0.23 & 0.195 & -0.35 \\ -11.07 & -0.64 & -0.198 & -0.55 \end{bmatrix}$$

Form Equation (10) $\Lambda = \begin{bmatrix} -0.478 & 2.05 \\ -2.05 & -0.478 \end{bmatrix}$

From Equations (11-12)

$$G_1 = \begin{bmatrix} 0.9706 \\ 1.4767 \end{bmatrix}$$

$$\dot{H}_1 = \begin{bmatrix} 0.94 & 1.433 \\ 1.433 & 2.18 \end{bmatrix}$$

Therefore, the solution of the corresponding second order Lyapunov Equation is found.

From Equation (12)

$$\dot{V} = \begin{bmatrix} 0.313 & 0.042 \\ 0.042 & 0.960 \end{bmatrix}$$

From Equation (13)

$$\dot{P} = \dot{V}_1^{-1} = \begin{bmatrix} 3.213 & -0.142 \\ -0.142 & 1.04 \end{bmatrix}$$

$$\dot{K}_1 = R^{-1}G_1^T\dot{P}_1 = \begin{bmatrix} 2.908 & 1.409 \end{bmatrix}$$

$$\dot{Q}_1 = 2\propto_1 \dot{P}_1 = \begin{bmatrix} 10.95 & -0.484 \\ -0.484 & 3.569 \end{bmatrix}$$

From Equations (14)-(16), the feedback controller gain matrix can be calculated as:

$$K_1 = \dot{K}C_1^T = \begin{bmatrix} -36.78 & -0.222 & 0.222 & -1.813 \end{bmatrix}$$

$$P_1 = C_1 \dot{P}_1 C_1^{\mathrm{T}} = \begin{bmatrix} 275.8500 & 1.6665 & -2.1656 & 13.6008 \\ 1.6665 & 1.6665 & -0.0013 & 0.0002 \\ -2.1656 & 0.3090 & 0.1749 & -0.1002 \\ 13.6008 & 0.0955 & -0.1002 & 0.6709 \end{bmatrix}$$

$$Q_1 = 2 \propto_1 P_1 = \begin{bmatrix} 940.09 & 5.6795 & -7.3805 & 46.3517 \\ 5.6795 & 2.2740 & 1.0531 & 0.3256 \\ -7.3805 & 1.0531 & 0.5959 & -0.3416 \\ 46.3517 & 0.3256 & -0.3416 & 2.2863 \end{bmatrix}$$

Also, another shifting real pole from −0.0296 to −15
Calculate K_2, P_2 and Q_2 as last.

$$K_2 = 1000 * \begin{bmatrix} -0.1123 & -0.0059 & -0.0032 & -1.4659 \end{bmatrix}$$

From Equation (23) the K total, P total and Q total are calculated as follows:
$K = K_1 + K_2$, $P = P_1 + P_2$, $Q = Q_1 + Q_2$ as follows:

$$P = 1.0e + 05 * \begin{bmatrix} 0.0112 & 0.0005 & 0.0002 & 0.1101 \\ 0.0005 & 0.0000 & 0.0000 & 0.0058 \\ 0.0002 & 0.0000 & 0.0000 & 0.0032 \\ 0.1101 & 0.0058 & 0.0032 & 1.4354 \end{bmatrix}$$

$$W = 1.0e + 06 * \begin{bmatrix} 0.0136 & 0.0007 & 0.0004 & 0.1653 \\ 0.0007 & 0.0000 & 0.0000 & 0.0087 \\ 0.0004 & 0.0000 & 0.0000 & 0.0048 \\ 0.1653 & 0.0087 & 0.0048 & 2.1573 \end{bmatrix}$$

The total control signal K is:

$$K_{\text{optimal pole-shifting}} = 1000 * \begin{bmatrix} -0.1491 & -0.0061 & -0.0030 & -1.4677 \end{bmatrix}$$

And also, the feedback control from the Pole Placement Control Design is the follows:
From Equation (23), desired vector P as: $P = \begin{bmatrix} -7.0811, -0.6780 + 2.0534i, -0.6780 - 2.0534i, -2.296 \end{bmatrix}$. The gain matrix $K = \text{place}(A, B, P)$

$$K_{\text{pole placement}} = \begin{bmatrix} -27.4982 & -1.1708 & -0.7619 & -95.9647 \end{bmatrix}$$

Figure 2 shows the frequency deviation response due to 10% load disturbance of single area with and without controller. The frequency is more damping in case of optimal pole shifting controller than other controller in all disturbance and any change in operating points. **Figure 3** depicts the frequency deviation response due to 10% load disturbance of single area with pole-placement and proposed optimal pole-shifting control. **Figure 4** displays the root-locus of the system without control. **Figure 5** shows the root-locus of the system with optimal pole-shifting control. **Figure 6** depicts the frequency deviation response due to 10% load disturbance of single area with pole-placement and proposed optimal pole-shifting control at 50% increase in Tt and Tg. Also, **Figure 7** shows the frequency deviation response due to 10% load disturbance of single area with pole-placement and proposed optimal pole-shifting control at 50% increase in Tp and Kp. **Table 1** displays the eigenvalues calculation with and without controller. **Table 2** depicts the settling time calculation at different load conditions.

From **Table 1**, the eigenvalues of the system in case of optimal pole-shifting controller is more damping than pole-placement control.

6. Conclusions

The present paper introduces a new controller for damping quickly the power system frequency. The problem of shifting the real parts of the open-loop poles to desired locations, while preserving the imaginary parts has been contributed. Load-frequency control (LFC) of single area systems is evaluated with two control strategies.
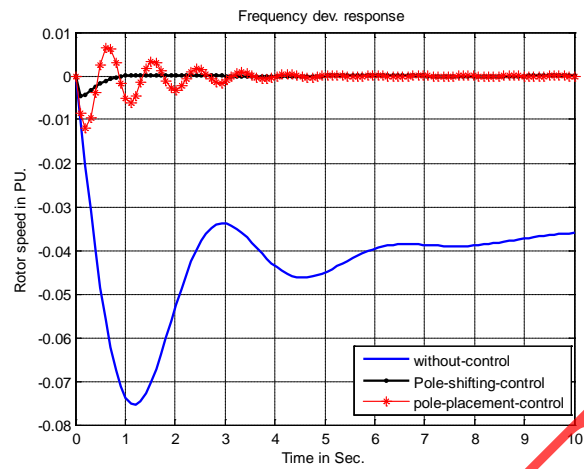
Figure 2. Frequency deviation response due to 10% load disturbance of single area with and without controller.

Figure 3. Frequency deviation response due to 10% load disturbance of single area with pole-placementand proposed optimal pole-shifting control.
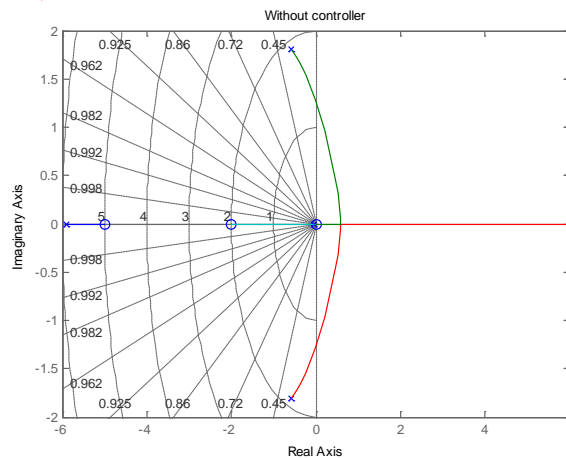

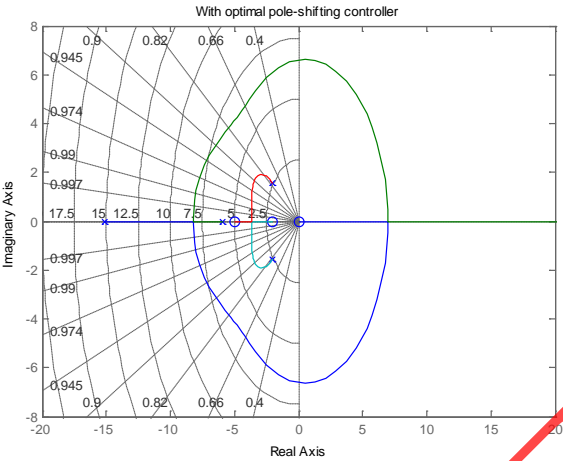**Figure 4.** Root-locus of the system without control.

Figure 5. Root-locus of the system with optimal pole-shifting control.

Figure 6. Frequency deviation response due to 10% load disturbance of single area with pole-placement and proposed optimal pole-shifting control at 50% increase in Tt and Tg.

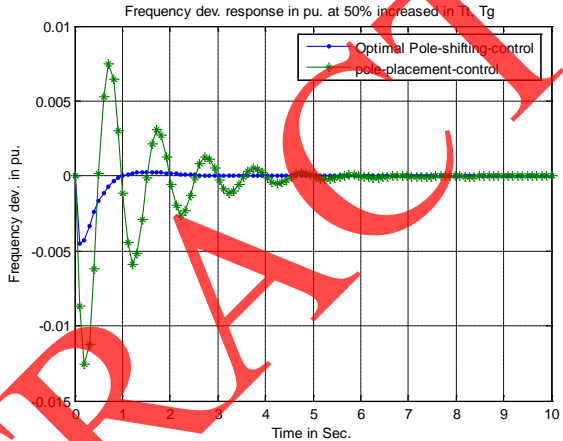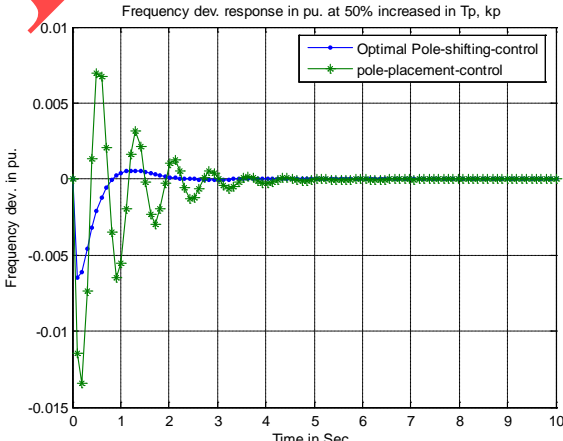**Figure 7.** Frequency deviation response due to 10% load disturbance of single area with pole-placement and proposed optimal pole-shifting control at 50% increase in Tp and Kp.

Table 1. Eigenvalues calculation with and without controller.

Operating point	Without controller	Pole-placement controller	Optimal pole-shifting
Normal condition	−6.0811 −0.4780 + 2.0534i −0.4780 − 2.0534i −0.0296	−7.0811 −0.6780 + 2.0534i −0.6780 − 2.0534i −2.2960	−20.9998 −6.0811 −2.3821 + 1.8658i −2.3821 − 1.8658i
Increased 50% of Tt, Tg	−4.2808 −0.2115 + 1.6617i −0.2115 − 1.6617i −0.0296	−5.3678 −0.7661 + 1.9001i −0.7661 − 1.9001i −1.4996	−20.1695 −5.0664 −2.1407 + 0.7094i −2.1407 − 0.7094i
Increased 50% of Tp, kp	−6.1699 −0.4252 + 2.1711i −0.4252 − 2.1711i −0.0298	−7.3832 −0.7409 + 2.1134i −0.7409 − 2.1134i −2.3099	−23.4841 −5.9806 −2.4271 + 1.8637i −2.4271 − 1.8637i

Table 2. Settling time calculation at different conditions.

	Case	Without control	Pole-placement controller	Optimal pole-shifting
	Normal condition	∞	7 Sec.	1.3 Sec.
Settling Time	Increased 50% of Tt, Tg	∞	6 Sec.	2 Sec.
	Increased 50% of Tp, kp	∞	5 Sec.	2 Sec.

It has been shown that the shift can be achieved by an optimal feedback control law with respect to a quadratic performance index. However, this has been done without any solving non-linear algebraic Riccati Equation. Moreover, the power system is subjected to different disturbances, and also, a comparison between the power system responses using the conventional pole-placement controller and the proposed optimal pole-shifting controller is presented and obtained.

The digital simulation result shows the powerful of the proposed optimal pole shifting controller than conventional pole-placement controller in sense of fast damping oscillation and small settling time. Moreover, the optimal pole shifting controller has less overshoot and under shoot than pole-placement control.

7. Discussions

Figures 2-7 show the frequency deviation response due to 10% load disturbance of single area with and without controller. All the response frequency is more damping in case of proposed optimal pole shifting controller than other pole-placement controller in all disturbance and any change in operating points. From **Table 1**, the eigenvalues are more shifting to left hand side in case of proposed optimal pole-shifting controller than pole-placement controller. Also, as shown in **Table 2** the settling time is less with optimal pole-shifting controller than other controller.

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