An analytical approach for LQR design for improving damping performance of multi-machine power system

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Article Info

Article history:

Received Jun 2, 2021
Revised Nov 24, 2021
Accepted Nov 27, 2021

Keywords:

Analytical approach
Low-frequency oscillations
LQR
Optimal control theory
Power system stabilizer

ABSTRACT

In a multi-machine environment, the inter-area low-frequency oscillations induced due to small perturbation(s) has a significant adverse effect on the maximum limit of power transfer capacity of power system. Conventionally, to address this issue, power systems were equipped with lead-lag power system stabilizers (CPSS) for damping oscillations of low-frequency. In recent years the research was directed towards optimal control theory to design an optimal linear-quadratic-regultor (LQR) for stabilizing power system against the small perturbation(s). The optimal control theory provides a systematic way to design an optimal LQR with sufficient stability margins. Hence, LQR provides an improved level of performance than CPSS over broad-range of operating conditions. The process of designing of optimal LQR involves optimization of associated state (Q) and control (R) weights. This paper presents an analytical approach (AA) to design an optimal LQR by deriving algebraic equations for evaluating optimal elements for weight matrix 'Q'. The performance of the proposed LQR is studied on an IEEE test system comprising 4-generators and 10-busbars.

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1. INTRODUCTION

To enhance the damping performance of an electrical power system against small disturbance(s), an excitation-based power system stabilizer (CPSS) is extensively used around the world. Although the CPSSs have been used widely for satisfactorily damping local-mode low-frequency oscillations, the outcome of CPSS may not be the best possible because of the intuitive nature of the tuning process and restrictive assumptions made. Later, the research was directed towards optimal control theory to develop an optimal state-variable feedback gain controller i.e. linear-quadratic-regultor (LQR) for stabilizing power systems against small perturbation(s). Consequently, reports [1]-[10] have appeared in the literature concerning the application of optimal LQR for stabilizing power systems.

In the referred papers [1]-[10], the design of LQR is based on the following sequential process: i) The control (*R*) and state (*Q*) weights are chosen as diagonal matrices; ii) The state weighing matrix *Q* is assigned numerical values arbitrarily by an iterative procedure; iii) Optimal LQR is determined; and

iv) Closed-loop performance of an electrical power system equipped with optimal LQR is investigated. If the system performance is not satisfactory, the entire process has to be repeated until satisfactory damping performance is obtained. This trial-and-error (T&E) method doesn't offer a systematic way of tuning Q; hence it is cumbersome, burdensome, and time-consuming.

On the other hand, in recent decades, other researchers had been developed evolutionary algorithms to design optimal LQR [11]-[17]. In the referred papers [11]-[17], different evolutionary algorithms such as genetic algorithm (GA), particle swam optimization (PSO), big bang-big crunch (BB-BC), ant colony optimization (ACO), real-coded genetic algorithm, differential evolution (D.E.) algorithm, and Jaya algorithm are reported to design optimal LQR. And in the references [18]-[25], Gbest-guided artificial bee colony algorithm, backtracking search algorithm, adaptive backstepping approach, Whale optimization algorithm, an improved whale optimization technique, modified shuffled frog leaping (MSFL) algorithm, model reference self-tuning Takaji-Sugeno fractional-order proportional-integral-derivative (TSMFOPID) control technique and evolutionary programming based optimisation technique respectively for tuning CPSS. But, the evolutionary techniques are i) highly dependent on evolutionary algorithms to optimize and ii) computation time is more; hence their use is restricted for solving optimization problems.

All these issues were addressed in this paper by proposing an analytical approach (AA) to tune LQR. The proposed technique of tuning LQR explores the correlation between the Lagrange-multiplier optimization technique and the algebraic-Riccati-equation (ARE). The proposed approach has the following advantages: i) It takes negligible time to tune LQR with the aid of derived algebraic equations; ii) It translates the performance objectives of the system from time-domain into cost-function; and iii) It enhances the robustness of the power system as Q varies in line with the operating condition. The proposed methodology explores its modular approach in tuning LQR. However, the design of a robust and decentralized LQR controller becomes impractical due to the non-availability of facilities to measure state variables (especially the rotor angle) in most multi-machine power systems (MMPS). This issue is addressed by considering the secondary voltage of transformer as a reference rather than infinite-bus voltage in modelling the power system [26].

2. MODELLING OF POWER SYSTEM

An IEEE test system comprising 4-generators and 10-busbars shown in Figure 1 is chosen for the study. This section deals with the modelling and stability analysis of electrical power system. The modelling of power system is done based on modified version of Heffron-Phillips model [26]. This facilitates the proposed optimal LQR more practical.

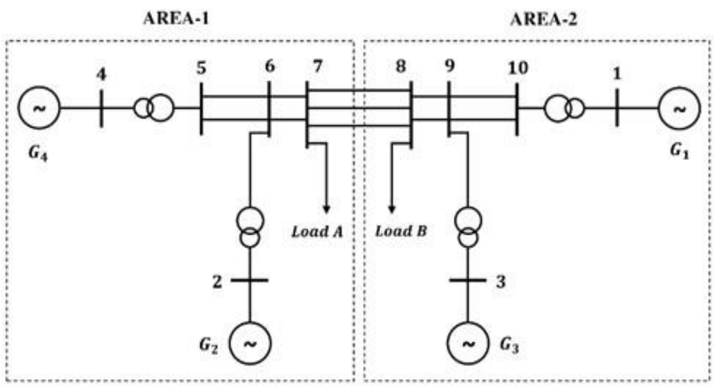

Figure 1. Single-line representation of 4-Generator and 10-Bus system

The linearized dynamic equations of an i^{th}-generator of power system are;

$$\Delta\dot{\delta}_{s_i} = (\omega_{B_i}\Delta S_{m_i} - \Delta\theta_{s_i}) \tag{1}$$

$$\Delta\dot{S}_{m_i} = \frac{1}{2H_i}(-G_{1_i}\Delta\delta_{s_i} - G_{2_i}\Delta E'_{q_i} - G_{v_{1_i}}\Delta V_{s_i} - D_i\Delta S_{m_i}) \tag{2}$$

$$\Delta\dot{E}'_{q_i} = \frac{1}{T'_{do_i}}\left\{\Delta E_{fd_i} - G_{4_i}\Delta\delta_{s_i} - G_{v_{2_i}}\Delta V_{s_i} - \frac{\Delta E'_{q_i}}{G_{3_i}}\right\} \tag{3}$$

$$\Delta\dot{E}_{fd_i} = \left\{\frac{K_{E_i}}{T_{E_i}}\left(\Delta V_{pss_i} - G_{5_i}\Delta\delta_{s_i} - G_{6_i}\Delta E'_{q_i} - G_{v_{3_i}}\Delta V_{s_i}\right) - \frac{\Delta E'_{q_i}}{T_{E_i}}\right\} \quad (4)$$

The state-space representation of (1)-(4) is;

$$\dot{x}_i = A_{g_i}x_i + B_{g_i}u_i + B_{1_i}u_{1_i} \quad (5)$$

$$y_i = C_{g_i}x_i + D_{g_i}u_i \quad (6)$$

Since the coefficients $G_{v_{1_i}}$, $G_{v_{2_i}}$, $G_{v_{3_i}}$are negligibly small, the (5) and (6) are reduced to;

$$\dot{x}_i = A_{g_i}x_i + B_{g_i}u_i \quad (7)$$

$$y_i = C_{g_i}x_i + D_{g_i}u_i \quad (8)$$

The Laplace's transformation of the state-space model of an i^{th}-generator is;

$$s\Delta E'_{q_i}(s) = -\frac{1}{G_{3_i}T'_{do_i}}\Delta E'_{q_i}(s) - \frac{G_{4_i}}{T'_{do_i}}\Delta\delta_{s_i}(s) + \frac{1}{T'_{do_i}}\Delta E_{fd_i}(s)` \quad (9)$$

$$s\Delta\delta_{s_i}(s) = \Delta\omega_i(s) \quad (10)$$

$$s\Delta\omega_i(s) = \left\{\frac{\omega_{B_i}}{2H_i}\Delta T_{m_i}(s) - \frac{\omega_{B_i}}{2H_i}\left[G_{1_i}\Delta\delta_{s_i}(s) + G_{2_i}\Delta E'_{q_i}(s)\right] - \frac{\omega_{B_i}}{2H_i}D_i\Delta\omega_i(s)\right\} \quad (11)$$

$$s\Delta E_{fd_i}(s) = \left\{-\frac{1}{T_{E_i}}\Delta E_{fd_i}(s) - \frac{K_{E_i}}{T_{E_i}}\left[G_{5_i}\Delta\delta_{s_i}(s) + G_{6_i}\Delta E'_{q_i}(s)\right] + \frac{K_{E_i}}{T_{E_i}}\Delta V_{ref_i}(s)\right\} \quad (12)$$

Under the assumption that, $\Delta V_{ref_i} = 0$; simplification of (9) and (12) yields (13);

$$\Delta E'_{q_i}(s) = -\frac{\left[G_{4_i}\left(1+sT_{E_i}\right) + K_{E_i}G_{5_i}\right]G_{3_i}}{\left[\left(1+sG_{3_i}T'_{do_i}\right)\left(1+sT_{E_i}\right) + K_{E_i}G_{6_i}G_{3_i}\right]}\Delta\delta(s) \quad (13)$$

The Laplace's transformation of electrical torque of an i^{th}-generator is;

$$\Delta T_{e_i}(s) = \left[G_{1_i}\Delta\delta_{s_i}(s) + G_{2_i}\Delta E'_{q_i}(s)\right] \quad (14)$$

By substituting (13) in (14) yields (15),

$$\Delta T_{e_i}(s) = \left\{G_{1_i} - \frac{\left[G_{4_i}\left(1 + sT_{E_i}\right) + K_{E_i}G_{5_i}\right]G_{3_i}G_{2_i}}{\left[\left(1 + sG_{3_i}T'_{do_i}\right)\left(1 + sT_{E_i}\right) + K_{E_i}G_{6_i}G_{3_i}\right]}\right\}\Delta\delta_{s_i}(s) = G_i(s) * \Delta\delta_{s_i}(s) \quad (15)$$

3. PROBLEM STATEMENT AND ANALYTICAL APPROACH OF DESIGNING LQR

This section explores the analytical approach of tuning state-weighing matrix (Q) associated with LQR. The feedback control law to minimize the cost function '$J(u)$' of linear-quadratic-regulator is given by (16).

$$u(t) = -Kx(t) \quad (16)$$

The cost function of LQR is given by (17).

$$J(u) = \int_0^\infty [x^T(t).Q.x(t) + u^T(t).R.u(t)]dt \quad (17)$$

The Lagrange-multiplier optimization technique for optimizing linear state feedback gain vector (K) is,

$$K = R^{-1}B^TP \quad (18)$$

where, P is the matrix solution to the following reduced algebraic-Reccati-equation (ARE).

$$A^TP + PA + Q - PBR^{-1}B^TP = 0 \quad (19)$$

The canonical form of electrical power system that is controllable [27] is given by;

$$\dot{x} = \hat{A}x + \hat{B}u \tag{20}$$

$$y = \hat{C}x + \hat{D}u \tag{21}$$

where,

$$\hat{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \tag{22}$$

$$\hat{B} = \begin{bmatrix} 0 & 0 & 0 & B_{41} \end{bmatrix}^T \tag{23}$$

$$\hat{C} = \begin{bmatrix} 0 & C_{12} & 0 & 0 \end{bmatrix} \tag{24}$$

$$\hat{D} = [0] \tag{25}$$

The (19) in accordance with controllable canonical form of power system becomes,

$$\hat{A}^T P + P\hat{A} + Q - P\hat{B}R^{-1}\hat{B}^T P = 0 \tag{26}$$

where Q, R and P are defined as (27)-(29).

$$Q = \begin{bmatrix} q_1 & 0 & 0 & 0 \\ 0 & q_2 & 0 & 0 \\ 0 & 0 & q_3 & 0 \\ 0 & 0 & 0 & q_4 \end{bmatrix} \tag{27}$$

$$R = [r] \tag{28}$$

$$P = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{12} & p_{22} & p_{23} & p_{24} \\ p_{13} & p_{23} & p_{33} & p_{34} \\ p_{14} & p_{24} & p_{34} & p_{44} \end{bmatrix} \tag{29}$$

The (18) in accordance with controllable canonical form of power system becomes,

$$K = R^{-1}\hat{B}^T P = \frac{B_{41}}{r}\begin{bmatrix} p_{14} & p_{24} & p_{34} & p_{44} \end{bmatrix} \tag{30}$$

For closed-loop systems, the actual characteristic equation is given by (31),

$$\left| sI - \hat{A} + \hat{B}K \right| = 0 \tag{31}$$

By substituting (22), (23) and (30) in (31) yields (32),

$$\left(s^4 + s^3\left(\frac{B_{41}^2 p_{44}}{r} - A_{44}\right) + s^2\left(\frac{B_{41}^2 p_{34}}{r} - A_{43}\right) + s\left(\frac{B_{41}^2 p_{24}}{r} - A_{42}\right) + \left(\frac{B_{41}^2 p_{14}}{r} - A_{41}\right)\right) = 0 \tag{32}$$

For 4th-order systems, the desired characteristic equation is (33),

$$(s^4 + 4\xi\omega_n s^3 + 2\omega_n^2(2\xi^2 + 1)s^2 + 4\xi\omega_n^3 s + \omega_n^4) = 0 \tag{33}$$

The 4th-row elements of matrix P are given by the following (34)-(37);

$$p_{14} = (\omega_n^4 + A_{41})\frac{r}{B_{41}^2} \tag{34}$$

$$p_{24} = (4\xi\omega_n^3 + A_{42})\frac{r}{B_{41}^2} \tag{35}$$

$$p_{34} = [2\omega_n^2(2\xi^2 + 1) + A_{43}]\frac{r}{B_{41}^2} \tag{36}$$

$$p_{44} = (4\xi\omega_n + A_{44})\frac{r}{B_{41}^2} \tag{37}$$

with the aid of ARE and (34)-(37) following equations are derived to get optimal Q.

$$\frac{q_1}{r} = \frac{1}{B_{41}^2}(\omega_n^8 - A_{41}^2) \tag{38}$$

$$\frac{q_2}{r} = \frac{1}{B_{41}^2}[2A_{41}A_{43} - A_{42}^2 + 4\omega_n^6(2\xi^2 - 1)] \tag{39}$$

$$\frac{q_3}{r} = \frac{1}{B_{41}^2}\{2[A_{41} + A_{42}A_{44} + 3\omega_n^4 + 8\omega_n^4\xi^2(\xi^2 - 1)] - A_{43}^2\} \tag{40}$$

$$\frac{q_4}{r} = \frac{1}{B_{41}^2}[4\omega_n^2(2\xi^2 - 1) - 2A_{43} - A_{44}^2] \tag{41}$$

The (38)-(41) are the outcome of proposed analytical approach for designing an optimal LQR for specified natural frequency (ω_n), damping ratio(ξ), and scalar quantity R.

4. DESCRIPTION OF POWER SYSTEM

The loads of the IEEE test system considered are modelled as constant impedances. The total connected load in the system is 2734 MW. The machine data, line data, load flow data, and automatic voltage regulator (AVR) & excitation-system data of the test system are taken from [28]. The symmetric base system consists of two identical areas connected through a relatively weak tie line. Each area comprises two generating units with equal power outputs. The electro-mechanical modes of oscillation present in the system are modes present with in the plant (inter-plant modes) and low frequency inter-area mode.

5. RESULTS AND DISCUSSION

Here, a comprehensive discussion is made on results obtained against small disturbances i) step change in the voltage, ii) step change in the electrical torque under different loading conditions nominal load, light load, and heavy load. The comparative damping performances of generators that are fitted with either LQR tuned through analytical approach or LQR tuned via trial and error method or CPSS are shown in Figures 2-4.

5.1. Case1: Nominal load

In this case, all the generators are assumed to be loaded with their respective nominal loads. The Figure 2 shows the variation in slip (S_m) for 10% step increase in torque at generator G_4 with tie-line power flow of 400 MW. It is observed that, the generator G_4 equipped with proposed LQR exhibits much superior damping performance than its counter parts. The same is in the case for generators G_1, G_2, and G_3. The settling times of generators noted from Figure 2 are tabulated in Table 1.

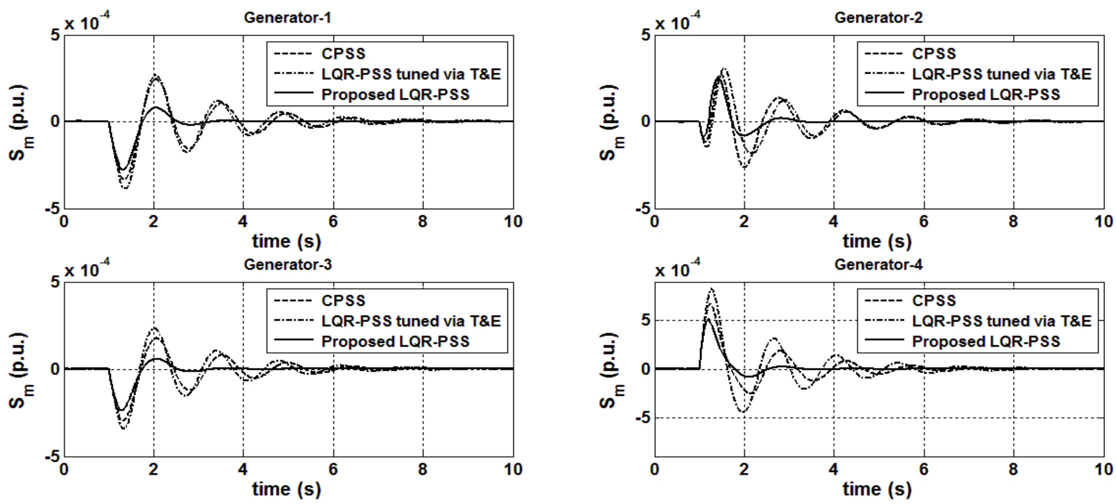

Figure 2. Variation in slip (S_m) when generator G_4 operating at nominal load is subjected to 10% increase in torque with tie line power flow of 400 MW

Table 1. Settling time: nominal load: 10% step increase in torque at generator G_4

Gen. No.	Settling time (Sec.) CPSS	LQR tuned via T&E method	Proposed LQR tuned via AA
G_1	8.6	8.6	2.6
G_2	8.6	8.6	2.6
G_3	8.6	8.6	2.6
G_4	8.6	8.6	2.6

5.2. Case2: Light load

Here, all the generators are assumed to be loaded to 80% of their respective nominal loads. The Figure 3 shows the variation in slip (S_m) for 10% step decrease in reference voltage at generator G_1 with tie-line power flow of 100 MW. The generator G_1 equipped with proposed LQR settles at 1.9 Sec. with negligible overshoot and no undershoots after the disturbance. The same is in the case for generators G_2, G_3, and G_4. The settling times of generators noted from Figure 3 are tabulated in Table 2.

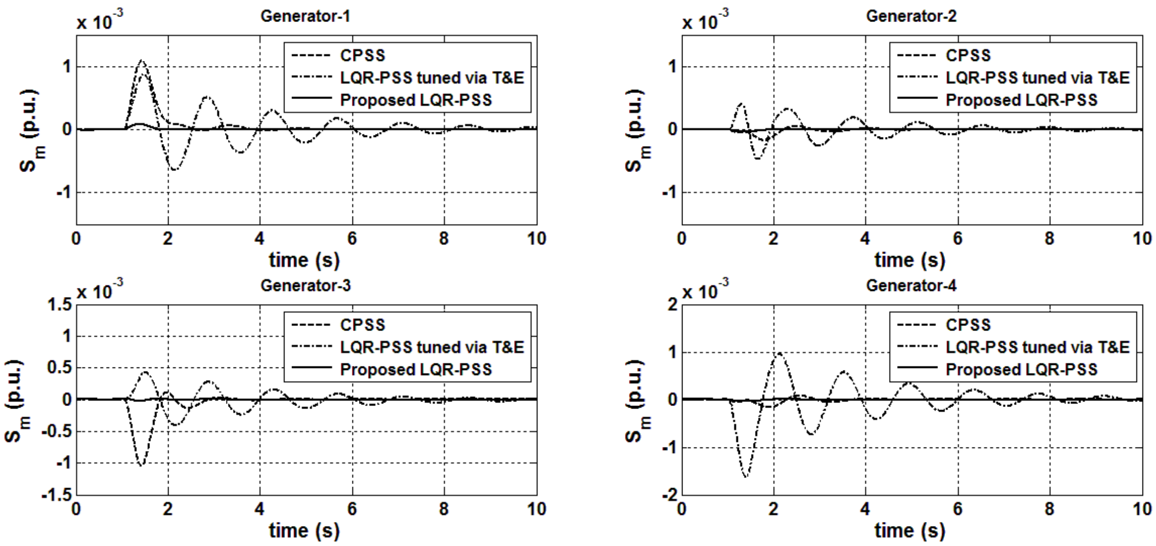

Figure 3. Variation in slip (S_m) when generator G_1 operating at 80% of nominal load is subjected to 10% decrease in voltage with tie line power flow of 100 MW

Table 2. Settling time: light load: 10% step decrease in reference voltage at generator G_1

Gen. No.	Settling time (Sec.) CPSS	LQR tuned via T&E method	Proposed LQR tuned via AA
G_1	4.2	10.4	1.9
G_2	4.2	10.4	1.9
G_3	4.2	10.4	1.9
G_4	4.2	10.4	1.9

5.3. Case3: Heavy load

In this case, all the generators are assumed to be loaded to 120% of their respective nominal loads. The Figure 4 shows the variation in slip (S_m) for 10% step increase in reference voltage at generator G_3 with tie line power flow of 400 MW. In this case; after the disturbance, the generator G_3 equipped with proposed LQR settles in 2.2 Sec. with no overshoot and negligible undershoot, whereas it is 10.6 Sec. and 8.8 Sec. when G_3 is equipped with CPSS and LQR tuned via trial-and error method respectively. The settling times of generators noted from Figure 4 are tabulated in Table 3.

Table 3. Settling time: heavy load: 10% step increase in reference voltage at generator G_3

Gen. No.	Settling time (Sec.) CPSS	LQR tuned via T&E method	Proposed LQR tuned via AA
G_1	10.6	8.8	2.2
G_2	10.6	8.8	2.2
G_3	10.6	8.8	2.2
G_4	10.6	8.8	2.2

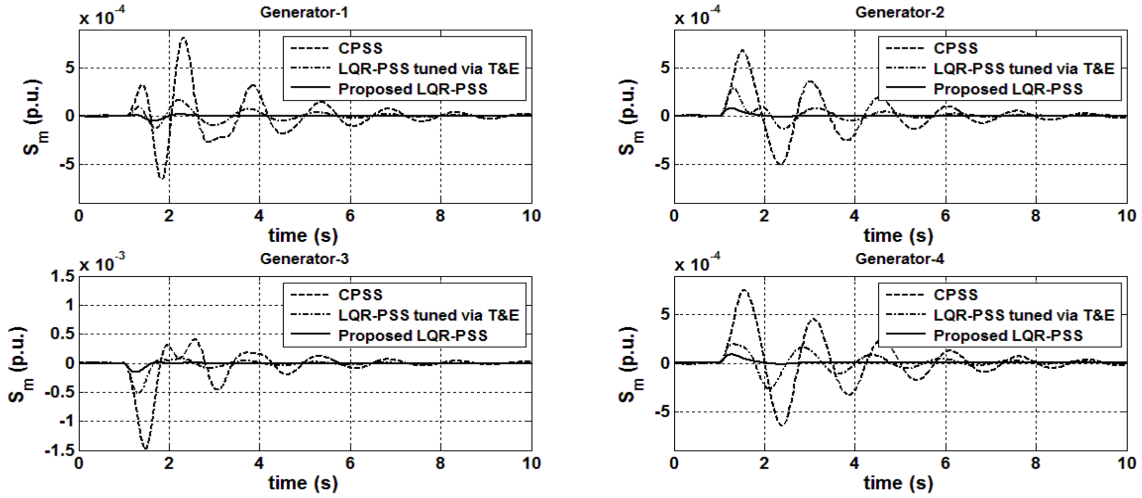

Figure 4. Variation in slip (S_m) when generator G_3 operating at 120% of nominal load is subjected to 10% increase in voltage with tie line power flow of 400 MW

6. CONCLUSION

In contrast with the LQR tuning via the trial-and-error approach, the LQR tuning via the proposed analytical approach leads to enhanced robustness of the power system as the state weighting matrix Q varies in line with the operating condition in the proposed methodology. The simulation results proved the superiority of the proposed optimal LQR in damping low-frequency electromechanical oscillations. It is observed that the proposed LQR improved the system dynamics by reducing the settling time and overshoots/undershoots.

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