Improving Rotor Angle Stability of the Multimachine Power System Using Constrained Optimal Control

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Abstract: This paper proposes a transient stability analysis of the multi-machine power systems. Rotor angle stability refers to the ability of synchronous machines to a power system to remain in synchronism after being subjected to a disturbance. It assumes a Single Machine Infinite Bus and two Machine Power System connected with a transmission line lossy are investigated. The linearized dynamical equations of the multi-machine power system are obtained near to an equilibrium point, and it can stabilize by using decentralized constrained optimal control. The relationship between the open-loop poles and the closed-loop poles that guarantee a positive regulator and quadratic is gaining stability. The feedback gains matrices can be achieved by applying the corresponding Riccati equations approach to each machine with bounded constraints. A successful strategy for control of large-scale power systems must satisfy these conditions to become robust and decentralized in terms of gain; phase margins and tolerance to the nonlinearity inside the subsystems. The numerical simulation test of the multi-machine power system showed the results. This study found that a decentralized control strategy that improves the rotor angle stability of the multi-machine power system is satisfied. The paper designed computation and simulation as a method to achieve the final results.

Keywords: Rotor angle, multimachine power systems, decentralized constrained optimal control, linear, quadratic regulator, subsystem.

1. Introduction

Interconnection has led to increased security since, and high systems efficiency since each generator could be utilized to a large extent. Rotor Angle Stability (RAS) refers to the ability of synchronous machines to remain in synchronism after being subjected to a disturbance [1] [2]. It is a dynamic phenomenon associated with changes in active power flows that create an angular separation between synchronous units in the systems. It has been a dominant stability problem in power systems. Hence, it becomes more challenging to assure the security of power systems [1]. RAS depends on the initial operating state because of the severity of the disturbance on the synchronous machine. RAS can be further divided into small stability and large-signal transient stability.

The leading cause of widespread blackouts is large rotor angle deviations. In some generators, it disturbs the balance between because of the complexity and nonlinearity of power overloads or any desperation in the system and oscillations in the rotor angle. The aim is to improve the RAS of the multimachine power system connected to keep the equipment operational after disturbances [1]. In interacting subsystems, it may not be workable to establish information flow between all control agents. For such systems, it is more desirable to have the same form of decentralization where each control input is constructed in terms of only those outputs available to the corresponding local control because of the communication and computational limitation [3] [4]. Based on inverse optimal control methods, strategies of these controls, and the perspective of the impact on the multimachine system and nonlinear behavior are examined.

Optimal control emerged as one of the fundamental design philosophies of modern control systems [5] [6]. The controller of a multivariable is said to be centralized if at least two of its outputs exchange information, otherwise, if there is no exchange of information, it is said to be decentralized control. The basic concept of the decentralized control is a local interaction between components of a system with the established order and coordination to achieve global goals without a central commanding influence, in another word, the overall system is no longer controlled by one controlled built by several independent local controllers incorporated in each component [7]. In the DC (decentralized control) solution, the goal is to achieve good performance by designing local feedback policies. Although the optimal control concept has many advantages, it is also a complex way of solving nonlinear problems.

Various methods have been used to improve RAS during the last decades. Karady and Mansour studied generator tripping based on a tracking rotor angle, where he used two algorithms to determine stability and operation conditions [8].
Rajapakse proposed RAS prediction using post-disturbance and enumerated estimation of the proximity of the post-fault and predicted stability status using the classifier [9]. Ahmed implemented generator RAS prediction using an adaptive artificial neural network for dynamic security assessment. He based his analysis on a prediction of each generator stability status under contingency to a certain level of load [10]. Jie monitored RAS in the wide-area proposed a phasor measurement unit online based on the maximal Lyapunov exponent [11].

Zairong designed a nonlinear decentralized controller using the Hamiltonian function method with a saturated steam valve and excitation controller in the power system [12]. Hongyin proposed a nonlinear robust decentralized by using a linear matrix inequality approach for different operating points and fault locations to operate cost performance by different operating points and fault locations [13]. Rotkowitz and Sanjay designed an optimal decentralized controller using convex problems to minimize closed-loop norms and feedback systems subjected to constraints [14]. Huang introduced quadratic invariance to preserve a general framework for both continuous and discrete-time for a stable or unstable system for any norm [13]. Qiang proposed a new nonlinear decentralized disturbance attenuation excitation control for MMPS (multimachine power system) based on a recursive design with linearization treatment, showed to improve the robustness system to dynamic uncertainties and also attenuates bounded exogenous disturbance on the power system to enhance transient stability [15].

Xuncheng designed a new model of excitation DCC (decentralized constrained controller) of MMPS based on the optimal feedback gain [15]. Elloumi compares two DC laws implemented MMPS, and it presented two aspects which are linear DC, the gains depend on the nonlinearity of the system and the successive approximation approach to determine two-point boundary value [16]. Hongshan proposes a fast excitation predictive control method for MMPS based on the dynamic model and some inequality constraints on state inputs and outputs in rolling optimization by using Gramian balanced reduction technique with improvement in the stability of PS (power system) [17]. Song reported a novel DC strategy for large PSS (power system stability) enhancement based on practical concepts that specific variable control needs only local information to improve the overall system performance [18]. Rim designed Takagi-Sugeno controller for a single machine infinite bus PS to analyze transient stability under severe disturbance, based on the linear fuzzy model, the feedback gain is determined by a linear-quadratic instructor [19]. Abouelsoud proposed a stabilizing controller for single machine power systems with a nonzero conductance of transmission line based on an observer to estimate power angle of the system, the stability of the reduced-order observer and closed-loop of the system incorporating using the Lyapunov direct method [20].

Vinodh and Jovitha presented an analytical approach for solving the weighting matrix, a selection problem of a Linear Quadratic Regulator for trajectory tracking application, chose LQR (linear, quadratic regulator) controller based on a trial-and-error approach to determine the optimum state feedback controller gains [21]. Karanjit proposed a novel decentralized dynamic output feedback controller to deal with the transient stability of a class of an MMPS. He uses local sliding mode observers to estimate the states of each local controller is obtained by solving two linear matrix inequalities [22]. Elkhateeb introduced a systematic optimization approach to find a constrained linear feedback state control to a linearized version of a lower power gas turbine model. It adopts the discretized model and constrained problem in the linear programming technique. The control law guarantees the positive invariance conditions of constraints polytope bounded along the trajectory of the closed-loop systems [23].

Hosni and Selwa investigated the problem of decentralized robust stabilizing control approach of a polynomial uncertain interconnected system associated with a quadratic approach, based on direct Lyapunov methods and Kronecker reduction production notation [24]. Lu designed a new approach for solving decentralized optimal control for large-scale PS, and each subsystem is controlled only by its variables. The cost function for each subsystem is minimized, and interacting effects between the subsystems are not ignored in driving the control strategy [25]. Jocic and Siljak proposed a multimachine model with non-uniform damping and transfer conductance. He pairwise decomposed it into many interconnected subsystems which each reference of the machine as a common part, based on Luré-Postkinov type of subsystem stability analysis and vector Lyapunov functions application to compute stability of region estimates for the overall multimachine model [4]. Ohtsuka proposed a method for MMPS, and the first step is to solve the corresponding centralized control system, LQR or H-infinity regulator applies to control the system. One can examine the relative effects of the control gains and eliminate those that are small [26]. Xuncheng proposed DC interconnected PS under the larger failure in real and reactive loads in the system model, based on the optimal damping ratio, he used left-half plane pole configuration to achieve a grid isolated DC which could suppress power oscillations effectively. Mahmud presented a robust nonlinear excitation controller design for synchronous generators in an MMPS to enhance the transient stability, based on the partial feedback linearization using reduced-order linear subsystems and autonomous subsystems [27].

Siljak presented past and present activities in large-scale interconnected systems, with an emphasis on dimensionality information structure constraints and uncertainty, based on the decomposition of a large-scale system and parallel computation using modern multi-processor architectures [29]. Mehdi and Nasser proposed Optimal Control of large-scale uncertain dynamic systems with time delays in states based on a two-level strategy. Proposed to decompose the large-scale system into several interconnected subsystems at the first level. Got by minimization of the convex performance indices in the presence of uncertainties and interaction, feedback, the solution is achieved by bounded data uncertainty problems, where the uncertainties, are only needed to be bounded, and it is not required to satisfy the so-called matching conditions. Second, a level substitution-type interaction prediction method is used to update the interaction parameters between subsystems [29]. Tao proposed an OC problem for large-scale systems with unknown parameters and dynamics. He used robust adaptive dynamic programming method, a decentralized optimal control with unmatched uncertainties, and the convergence of the robust adaptive dynamic programming algorithm and asymptotic stability of the closed-loop large-scale system to carry out the study [30].

2. Model and Problem Formulation

The model formulates multimachine power systems comprising generators interconnected through a transmission line, which is assumed to be lossy. The dynamics of the i[th] generators are described with excitation as presented by [32] [33].

$$\dot{\delta}_i = \omega_i$$

$$\dot{\omega}_i = -\frac{D_{mi}}{M_i} + \frac{\omega_0}{M_i}(P_{mi} - P_{ei}) \tag{1}$$

$$\dot{E}_i = \frac{1}{\tau_i}\left(-E_{qi} + E_{fi} + v_i\right), i \in \bar{N} := \{1, \dots \dots \dots \dots \dots \dots \dots \dots \dots N\}$$

The active P_{ei} and reactive Q_{ei} powers, as well as the voltage E_{qi}, are defined as:

$$P_{ei} = E_i I_{qi}$$

$$Q_{ei} = E_i I_{di}$$

$$E_{qi} = E_i + \left(x_{di} - x'_{di}\right) I_{di} = x_{adi} I_{fi} \tag{2}$$

The interconnects between machines are given by the currents:

$$I_{qi} = \sum_{j=1}^{N} E_j \left(G_{mij} \cos \delta_{ij} + B_{mij} \sin \delta_{ij}\right)$$

$$I_{di} = \sum_{j=1}^{N} E_j \left(G_{mij} \sin \delta_{ij} - B_{mij} \cos \delta_{ij}\right) \tag{3}$$

Where $\delta_{ij} = \delta_i - \delta_j$, G_{mij} is the conductance and B_{mij} is the susceptance both in p.u resulting from the computation of the network admittance matrix. Developing the sums when $i = j$ and recalling the identities [33] [34].

The network admittance through conductance and susceptance:

$$Y_{ij} = \sqrt{G_{mij}^2 + B_{mij}^2}$$

$$\alpha_{ij} = \tan^{-1}\left(\frac{G_{mij}}{B_{mij}}\right)$$

$$G_{mij} \cos \delta_{ij} + B_{mij} \sin \delta_{ij} = Y_{ij} \sin\left(\delta_{ij} + \alpha_{ij}\right)$$

$$G_{mij} \sin \delta_{ij} - B_{mij} \cos \delta_{ij} = Y_{ij} \cos\left(\delta_{ij} + \alpha_{ij}\right)$$

Yields

The current in quadratic and direct axis:

$$I_{qi} = G_{mii}E_i + \sum_{j=1}^{N} E_j \left(G_{mij}\cos\delta_{ij} + B_{mij}\sin\delta_{ij}\right)$$

$$I_{di} = -B_{mii}E_i + \textstyle\sum_{j=1}^{N} E_j \left(G_{mij}\sin\delta_{ij} - B_{mij}\cos\delta_{ij}\right) \tag{4}$$

Finally, combining results (1) and (4) in the well-known compact form.

The dynamic equation of the third-order model $\dot{\delta}_\iota, \dot{\omega}_\iota, \dot{E}_\iota$ becomes:

$$\dot{\delta}_\iota = \omega_i$$

$$\dot{\omega}_\iota = -D_i\omega_i + P_i - G_{ii}E_i^2 - d_iE_i\sum_{j=1}^{N} E_j\, Y_{ij}\sin\left(\delta_{ij} + \alpha_{ij}\right)$$

$$\dot{E}_\iota = -a_iE_i + b_i \textstyle\sum_{j=1}^{N} E_j\, Y_{ij}\cos\left(\delta_{ij} + \alpha_{ij}\right) + \frac{1}{\tau_i}\left(E_{fi} + v_i\right) \tag{5}$$

With the positive constants:

$$D_i = \frac{D_{mi}}{M_i},\ P_i = d_iP_{mi},\ G_{ii} = d_iG_{mii},\ d_i = \frac{\omega_0}{M_i}$$

$$a_i = \frac{1}{\tau_i}\left(1 - \left(x_{di} - x'_{di}\right)B_{mii}\right),\ \ b_i = \frac{1}{\tau_i}\left(x_{di} - x'_{di}\right)$$

Similarly, observe that $a_i,\ b_i > 0\ \ a_{ij} = \alpha_{ij}$, and that if$M_i = M_j, Y_{ij} = Y_{ji}$.

The paper assumes that the model with $u_i = 0$ has stable equilibrium points $\left(\dot{\delta_{\iota *}}, 0, \dot{E_{\iota *}}\right)$, and they find the control law u_i such that in closed-loop.

- Find the equilibrium point during the steady-state
- Constraints stability
- Closed-loop
- Decentralized control

3. Stabilization with state constraints

Let us consider a continuous-time Linear Time-Invariant system:

$$\dot{x} = Ax(t) + Bu(t) \tag{6}$$

$x \in \mathbb{R}^n$,$u \in \mathbb{R}^m$, (A, B) is controllable pair and symmetric constraint state and control sets [35] [35] [20].

$$S_x = \{x \in \mathbb{R}^n : -\omega_x \le G_x x \le \omega_x\} \tag{7}$$

$$S_u = \{x \in \mathbb{R}^n : -\omega_u \le G_x x \le \omega_u\} \tag{8}$$

$G_x \in \mathbb{R}^{s1\times n}$, $E_u \in \mathbb{R}^{r1\times n}$ are both full row rank, it considers the problem of designing a state feedback controller.

$$u = -Kx(t) \tag{9}$$

K is gain

Such that the closed-loop system

$$\dot{x} = A_c x(t) \tag{10}$$

Where $A_c = A - BK$ is asymptotically stable, and both the state and control constraints (7), (8) are satisfied. This implies that the state S_x is A_c invariant.

Where $A = \frac{\partial f}{\partial x}\Big|$ (11)

$$f = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} \tag{12}$$

$$\frac{\partial f}{\partial x} = \begin{bmatrix} \frac{\partial f_1}{\partial \delta} & \frac{\partial f_1}{\partial \omega} & \frac{\partial f_1}{\partial E} \\ \frac{\partial f_2}{\partial \delta} & \frac{\partial f_2}{\partial \omega} & \frac{\partial f_2}{\partial E} \\ \frac{\partial f_3}{\partial \delta} & \frac{\partial f_3}{\partial \omega} & \frac{\partial f_3}{\partial E} \end{bmatrix} \tag{13}$$

$$G = [1 \quad 1 \quad 1]$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$I = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

G assumed as C and the system become:

$$\begin{cases} \dot{x} = Ax + B \\ \quad y = Gx \end{cases} \tag{14}$$

$$-1 \leq \delta + \omega + E \leq 1$$

During equilibrium point ω_0=0

It means the constraints become

$$-1 \leq \epsilon\delta + E \leq 1$$

The gain K

$$K = (W_{1R} \quad W_{1I} \quad W_3)(V_{1R} \quad V_{1I} \quad V_3)^{-1} \tag{15}$$

4. Design Controller

The proposed controller is based on the algebraic Riccati equation for a stable regulator. Assumes that [A, B] is fully controllable and that B of full rank, the necessary and sufficient conditions for, $R = R^T > 0$ and $P = P^T \geqq 0$ are:

- A closed-loop system $A - BK$ is stable
- RBK is a symmetric matrix
- The matrix KB is positive definite

5. Simulation Results

The motion equation of the machine's rotor can be described by:

$$\dot{\delta} = \omega$$

$$\dot{\omega} = -D\omega + P_m - GE^2 - EY\sin(\delta + \alpha) \tag{16}$$

$$\dot{E} = -aE + b\cos(\delta + \alpha) + E_f + u$$

During the steady-state, all these parameters become as mentioned below to determine the equilibrium points:$\omega = 0$; $\delta = \delta_0$; $E = E_0$; $u = 0$;$G = 0$; $\alpha = 0$; $P_m = P$; δ_0 so that and E_0 to be known and then $f(x_0) = 0 <=> f(\delta_0, 0, E_0)$; the equation (23) becomes:

$$\begin{cases} P - E_0 Y \sin\delta_0 = 0 \\ -aE_0 + b\cos\delta_0 + E_f = 0 \end{cases} \tag{17}$$

$$E_0 = \frac{E_f}{a} + \frac{b}{a}\cos\delta_0 \tag{18}$$

$$P - \left(Y\frac{E_f}{a} + Y\frac{b}{a}\cos\delta_0\right)\sin\delta_0 \tag{19}$$

$\cos\delta_0 = \sqrt{1 - sin^2\delta_0}$; and $\sin\delta_0 = X$

$$P - \left(Y\frac{E_f}{a} + Y\frac{b}{a}\sqrt{1 - X^2}\right)X \tag{20}$$

$$P - Y\frac{E_f}{a}X = Y\frac{b}{a}X\sqrt{1 - X^2} \tag{21}$$

$$\left(P - Y\frac{E_f}{a}X\right)^2 = \left(Y\frac{b}{a}X\sqrt{1 - X^2}\right)^2 \tag{22}$$

$$Y^2\frac{b^2}{a^2}X^4 + X^2\left(\frac{{E_f}^2}{a^2}Y^2 - \frac{b^2}{a^2}Y^2\right) - 2\frac{PYE}{a}X + P^2 = 0 \tag{23}$$

Considering a power system network represented by two machines connected to a transmission line is lossy as Shown below:

$$\begin{aligned}
\dot{\delta_1} &= \omega_2 \\
\dot{\omega_1} &= -D_1\omega_1 + P_1 - G_{11}E_1^2 - YE_1E_2\sin(\delta_2 - \delta_1 + \alpha) \\
\dot{E_1} &= -a_1E_1 + b_1E_2\cos(\delta_1 - \delta_2 + \alpha) + E_{f1} + u_1 \\
\dot{\delta_2} &= \omega_2 \\
\dot{\omega_2} &= -D_2\omega_2 + P_2 - G_{22}E_2^2 - YE_1E_2\sin(\delta_1 - \delta_2 + \alpha) \\
\dot{E_2} &= -a_2E_2 + b_1E_1\cos(\delta_1 - \delta_2 + \alpha) + E_{f2} + u_2
\end{aligned} \tag{24}$$

It determines the equilibrium points by assuming: $\omega_1 = 0$; $\omega_2 = 0$; $u_1 = 0$; $u_2 = 0$

The computation of the parameters is: δ_{10} ; δ_{20} ; E_{10} ; E_{20}.

$$\begin{cases}
P_1 - G_{11}E_{10}^2 - YE_{10}E_{20}\sin(\delta_{10} - \delta_{20} + \alpha) = 0 \\
-a_1E_{10} + b_1E_{20}\cos(\delta_{10} - \delta_{20} + \alpha) + E_{f1} = 0 \\
P_2 - G_{22}E_{20}^2 + YE_{10}E_{20}\sin(\delta_{10} - \delta_{20} - \alpha) = 0 \\
-a_2E_{20} + b_2E_{10}\cos(\delta_{20} - \delta_{10} + \alpha) + E_{f2} = 0
\end{cases} \tag{25}$$

$$\sin(\delta_{10} - \delta_{20} + \alpha) = \frac{P_1 - G_{11}E_{10}^2}{YE_{10}E_{20}} \tag{26}$$

$$\cos(\delta_{10} - \delta_{20} + \alpha) = \frac{a_1E_{10} - E_{f1}}{b_1E_{20}} \tag{27}$$

$$E_{10} = \frac{P_1 - P_2 + G_{22}E_{20}^2}{G_{11}E_{10}} \tag{28}$$

$$E_{20} = \frac{b_2}{a_2 * b_1}\left[a_1 * E_{10} - E_{f1}\right] + \frac{E_{f2}}{a_2} \tag{29}$$

From (28) and (29) they obtain:

$E_{10} = x(1)$; $E_{20} = x(2)$

$$F(1) = P_1 - P_2 + G_{22}x^2(2) - G_{11}x^2(1) = 0 \tag{30}$$

$$F(2) = \frac{b_2}{a_2 * b_1}\left[a_1x(1) - E_{f1}\right] + \frac{E_{f2}}{a_2} - x(2) = 0 \tag{31}$$

These equations solved by iteration to get equilibrium points of each machine and control all the subsystems are achieved in the above order.

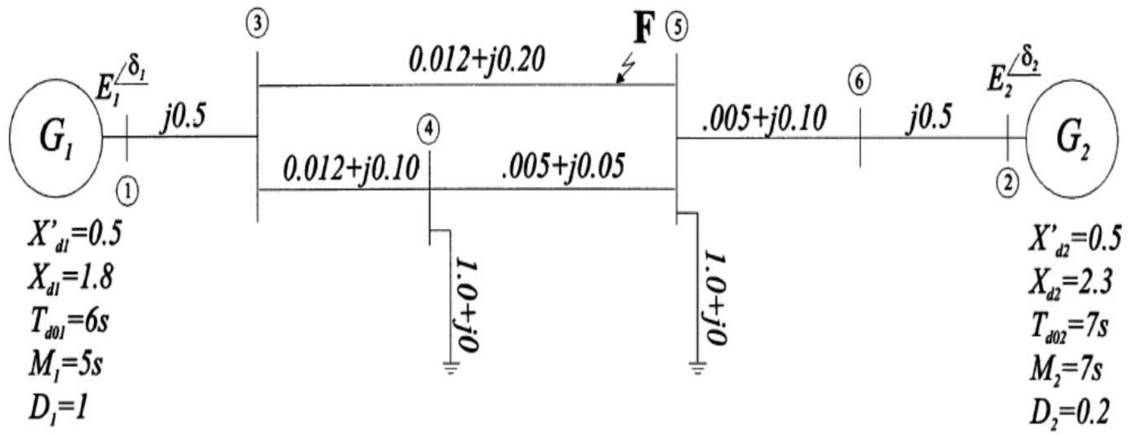

Fig. 1. Two machine systems [32]

6. Results and discussion

These results are compared and discussed in a numerical procedure for the multimachine power systems. A decentralized system is one of the most convenient designations for this control of a large-scale system. The results concerning the linear or nonlinear system have successfully solved such complex problems. The present numerical simulation of the Single Machine Infinite Bus System (SMIB) and the two-machine systems are presented.

6.1 Single Machine Infinite Bus

The simulations carried out for the SMIB with lossy transmission line and constrained with a decentralized controller is solved. A three-phase fault introduced at 1 second the transmission line assumed lossy. Clearing time after 1.5 seconds of opening the circuit breakers at both ends of the line. The fig. 2 plot their rotor angle of the machine and also shown the fig. 3 rotor speed of the machine and also plotted the fig. 4 excitation system of the machine. As a show, they should plot the dynamic equation of the third model rotor angle versus time, rotor speed versus time, and excitation system versus time as output results of the proposed decentralized control design. The table. 1 [32], as the data used for computing a single machine infinite bus and getting results to an equilibrium point in the table. 2 [32] as shown and compared for different cases of conductance.

The analysis assumes that when there are no losses, the conductance is null. The equilibrium points at the steady-state after the fault is $\left(\dot{\delta_{i*}}, 0, \dot{E_{i*}}\right) = (0.9211,0,0.888)$, which verifies the conditions of the Single Machine Infinite Bus in dynamical model.

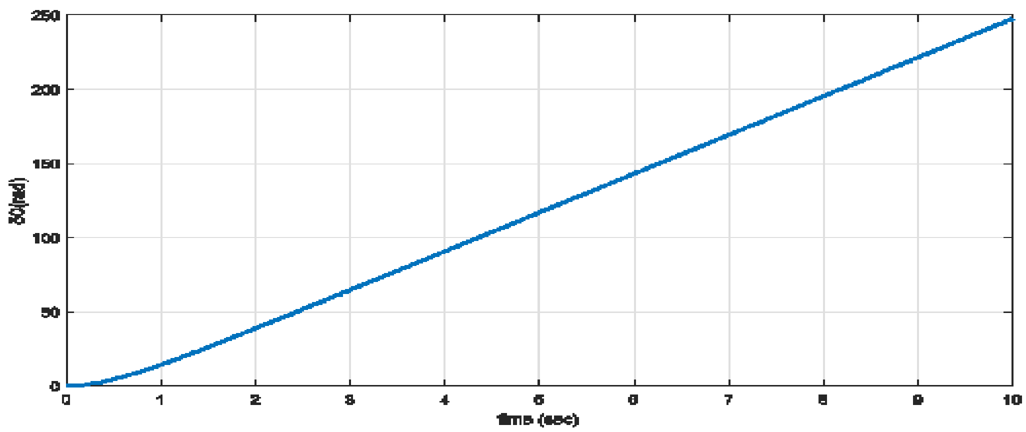

Fig.2. Rotor angle of the single machine

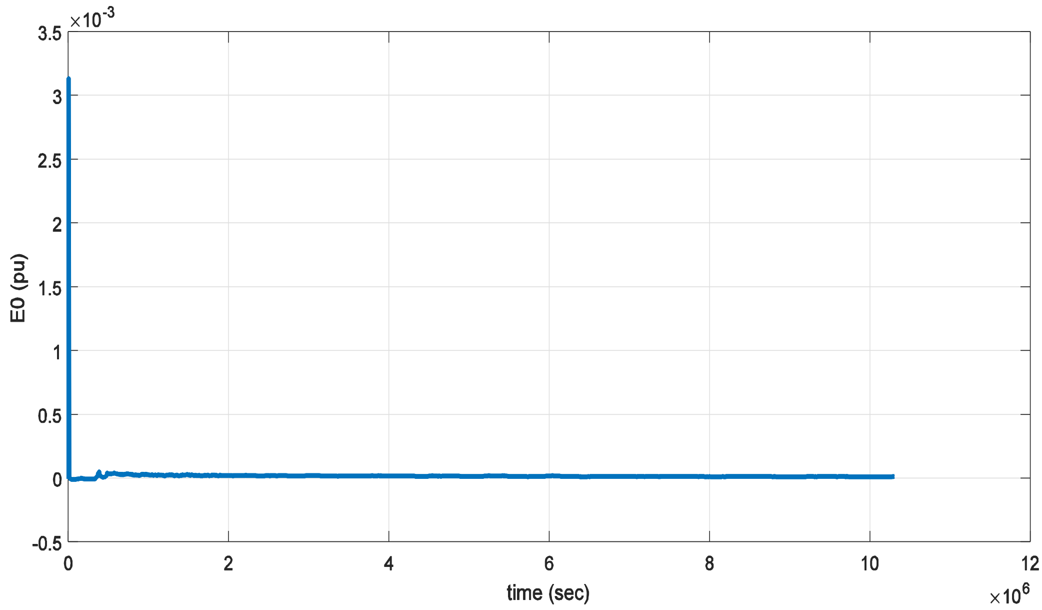

Fig.3. Excitation system of the single machine

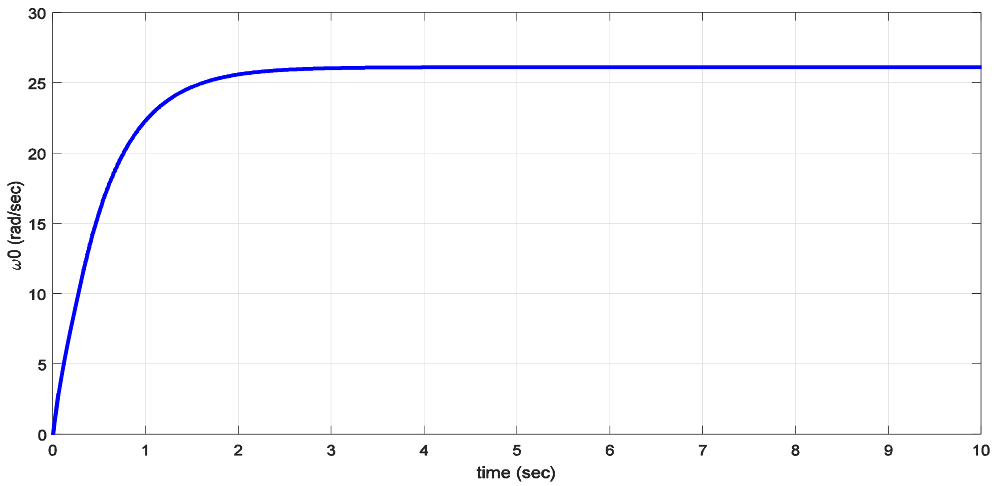

Fig.4. The rotor speed of the single machine

6. 2 Two machines System

In this subsection, the present simulation results of the two machine systems in fig. 1. [32]. Here, the disturbance is a three-phase fault in the transmission line that connects buses 3 and 5, cleared by isolating the faulty circuit simultaneously at both ends. This changes the topology of the network, which is a consequence induced by changes in the equilibrium points. This equilibrium got after solving the nonlinear equation iteratively presented as in: $(\dot{\delta_{1*}}, 0, \dot{E_{1*}}; \dot{\delta_{2*}}, 0, \dot{E_{2*}}) = (0.6105{,}0{,}1.0397; 0.8039{,}0{,}1.16)$, which verifies the conditions of the two machine power systems connected. It presents numerical results of the parameters of the model (24) as the equation presented $(\delta_1, \omega_1, E_1; \delta_2, \omega_2, E_2)$. The rotor angle of the machine number one in the fig. 5; the rotor speed of the machine number one in the fig. 6 and the excitation system of the machine number one in the fig. 7. They plot all versus times.

The rotor angle of machine number two in Fig. 8. Similarly, the rotor speed of machine number two in the fig. 9 and the excitation system of the machine number two in a fig. 10. The plot all those parameters versus times. They show it that the decentralized control system is appreciably more robust than the centralized control system, the deviation of the decentralized nearest to the optimal performance index. The table. 3 [32] used as data for the generators of two machine power systems.

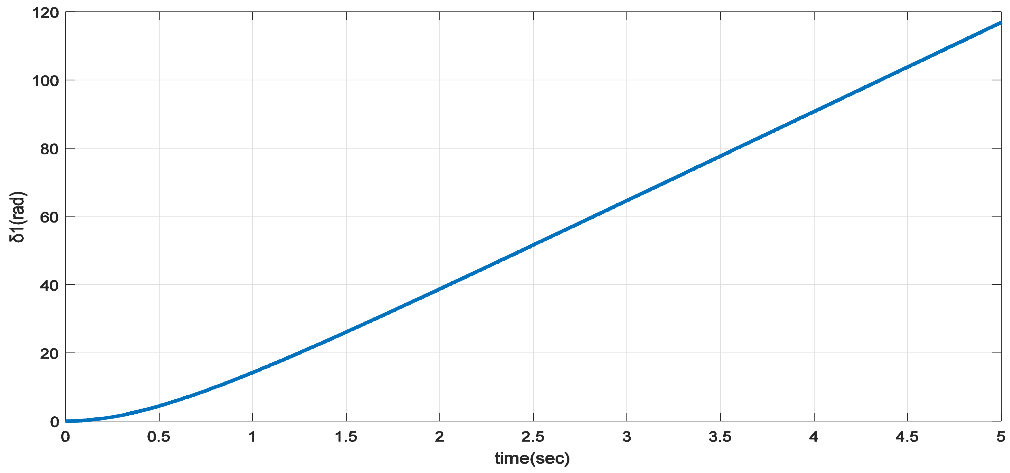

Fig.5. Rotor angle of machine #1

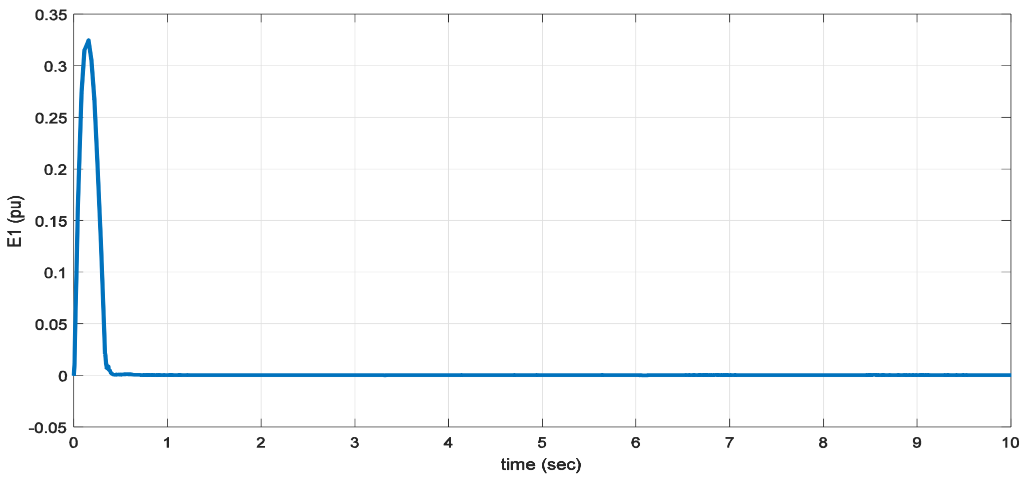

Fig.6. Excitation system of machine #1

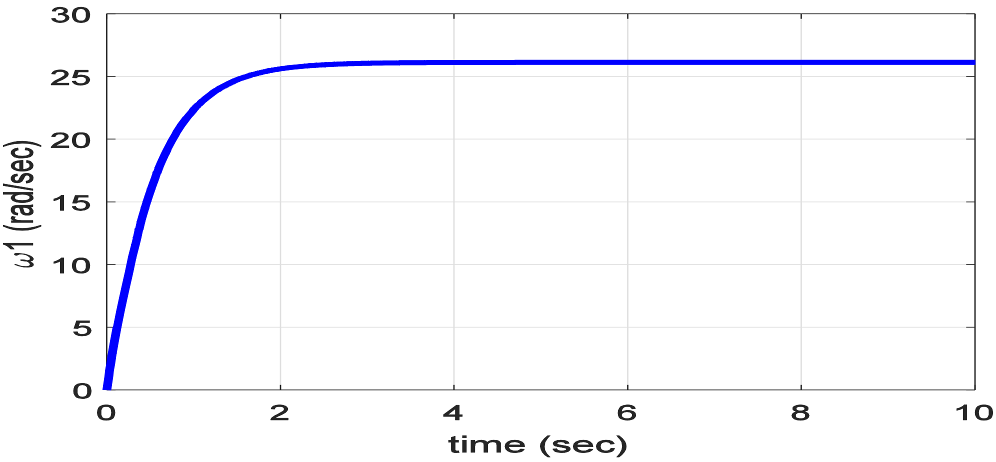

Fig.7. The rotor speed of machine #1

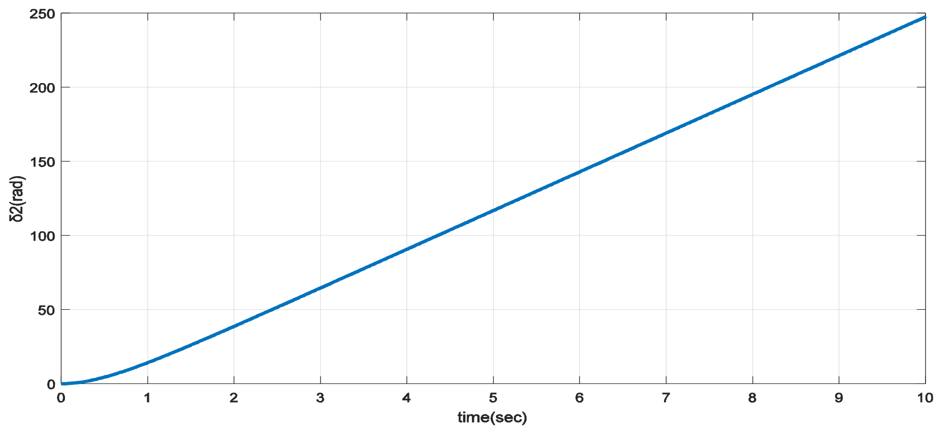

Fig.8. Rotor angle of machine #2

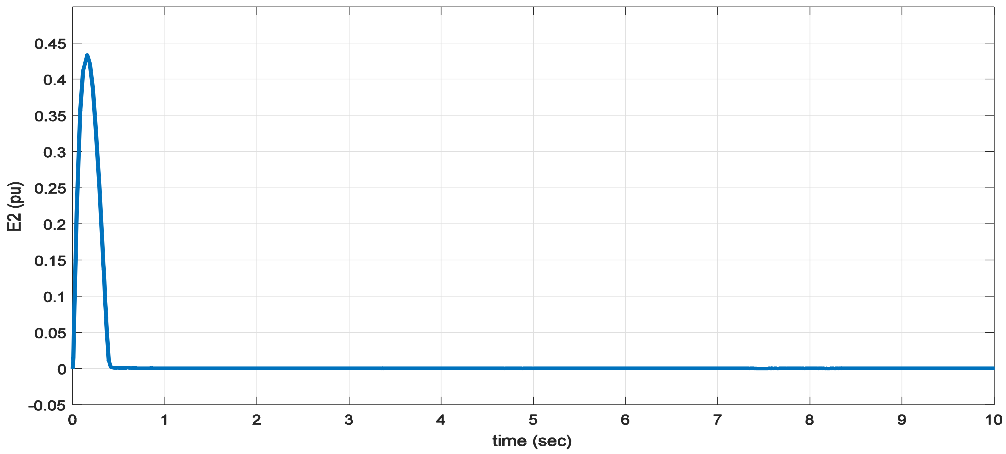

Fig.9. Excitation system of machine #2

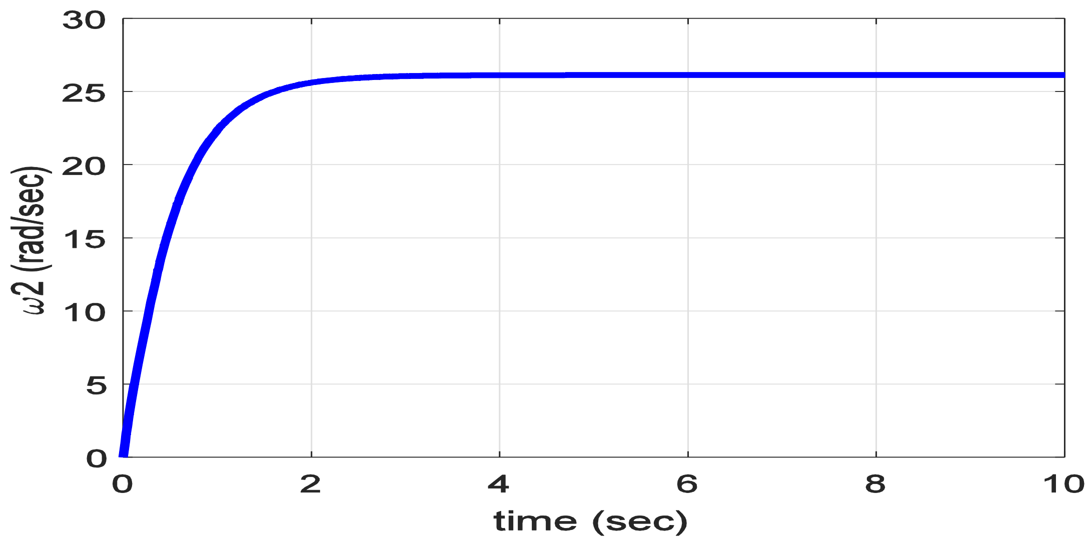

Fig.10. The rotor speed of machine #2

7. Analysis of the Results

This section analyzes the performance of the closed-loop systems, which is a three phase-fault considered on the line between bus 5 and 3 nearest bus 5. This is a great location of the fault in the transmission line system.

The fault is assumed to occur and cleared after 0.2 seconds, and 0.3 seconds it is known to be a conventional control system with: $u_0 = 0$; $u_1 = 0$; $u_2 = 0$, which cannot maintain the system stability if it clears the fault in 0.27 seconds after fault occurrence.

The optimal control decentralized feedback gain matrix K is given time response ofδ_0; δ_1; δ_2; ω_0; ω_1; ω_2; E_0; E_1; E_2. Are illustrated in the fig. 2 in the fig. 10 show the responses of the multimachine power system. The response curves in these figures show the advantage of the proposed control scheme. The simulation of the proposed control structure of the system under identical conditions leads to the following observations. The resulting rotor angles versus time, angular velocity versus time, and excitation system versus time are shown in fig .2 in Fig. 10. This control technique involves several independent local controllers decentralized through subsystem coordination. A local feedback controller is considered communicating among subsystems with constraint bounded. The advantage of a decentralized controller is reliable and expandable for each subsystem seems to achieve its objective. The decision is taken locally, and negotiation can take place in different actuators. They usually have different goals that are applied for the Single Machine System and Two Machine System.

8. Conclusion

This paper presents the improvement of the rotor angle stability for the multimachine power system. The main contribution and simulation results are based on the algebraic Riccati equation that uses the decentralized constraint optimal control to improve the stability of the multimachine power system. Regarding the different approaches, exploits, and computations, the following conclusion can be made.

First, the stability of multimachine power systems for state constraints with bounded and closed-loop systems are in the open left-half plane pole.

Second, the feedback state of each machine proposed the decentralized optimal controller to control itself. Keeping stability of the multimachine power systems considered lossy transmission line to measure and estimate its rotor angle. The stability of the overall closed-loop systems and the subsystem model results in local feedback matrices are determined only for subsystems. They have also shown that the proposed results yield necessary and sufficient conditions applied to constrain optimal control for a single and two machine power system and validating the results. It has not only stabilized the power system but also achieves the suboptimal control guaranteed, cost performance index for all parameters of generators.

References

[1] A.-A. A. Fouad and. M. . A. P, POWER SYSTEM CONTROL AND STABILITY, 2ND EDITION, New Jersey: Wiley and Sons, 2008.

[2] J. Machowski, B. Janusz, and R. B. James, Power system dynamics and stability, West Sussex: Wiley, 2008. ISBN: 0470725583,9780470725580,9780470714140

[3] J. H. Chow, F. W. Felix, and A. M. James, Applied Mathematics for Restructured Electric Power Systems, New York: Springer, 2005. ISBN: 0387234705,9780387234700

[4] Lj.B.Jocic and D. S. D, "Decomposition and Stability of Multimachine Power Systems," *IFAC*, vol. 11, no. 1, pp. 21-26, 1978. doi. 10.1016/s1474-6670(17)65922-6

[5] K. G. Vamvoudakis and SARANGAPANI Jagannathan, Control of Complex Systems: Theory and Applications, Cambridge: ELSEVIER, 2016. **ISBN:** 9780128052464

[6] D. D. Šiljak, Decentralized Control of Complex Systems, San Diego: Academic Press, 1991. **ISBN:** 9780080958712

[7] Y. Dai, J. Ziyan, S. Qi, C. Peizhang, W. Shiqiang and J. Yi, "A decentralized algorithm for optimal distribution in HVAC systems," *Elsevier*, vol. 95, p. 32, 2016.

[8] G. G. Karady and A. K. Mansour, "Improving transient stability using generator tripping based on tracking rotor-angle," *IEEE*, vol. 2, pp. 1113-1118, 2002. doi.org/10.1016/j.buildenv.2015.09.007

[9] A. Rajapakse, G. Francisco, N. Kasun, A. C. P and V. T. Vladimir, "Rotor Angle Instability Prediction Using Post-Disturbance Voltage Trajectories," *IEEE*, pp. 947 - 956, 2010. doi: 10.1109/PES.2010.5589386

[10] A. N. AL-MASRI, Z., A. A. K. Mohamed and H. Hashim, “A Novel Implementation for Generator Rotor Angle Stability Prediction Using an Adaptive Artificial Neural Network Application for Dynamic Security Assessment,” *IEEE*, vol. 28, no. 3, pp. 2516 - 2525, 2013. doi. 10.1109/TPWRS.2013.2247069

[11] J. Yan, L. Chen-Ching and. V. Umesh, "A PMU-based monitoring scheme for rotor angle stability," *IEEE*, vol. 26, no. 4, pp. 2125 - 2133, 2012. doi. 10.1109/TPWRS.2011.2111465

[12] Z. Xi, F. Gang, and C. Daizhan, "Nonlinear decentralized saturated controller design for power systems," *IEEE*, vol. 11, no. 4, pp. 539 - 547, 2003. doi.10.1109/TCST.2003.813404

[13] H. Li and W. Youyi, “Nonlinear robust decentralized control of multimachine power systems,” *IEEE*, p. 6, 2005. doi. 10.1109/IPEC.2005.207038

[14] M. Rotkowitz and L. Sanjay, "A Characterization of Convex Problems in Decentralized Control," *IEEE*, vol. 51, no. 2, pp. 1984-1996, 2006. doi. 10.1109/TAC.2005.860365

[15] Q. Lu, M. Shengwei, H. Wei, F. W. Felix, N. Yixin and S. Tielong, "Nonlinear decentralized disturbance attenuation excitation control via new recursive design for multi-machine power systems," *IEEE*, vol. 16, no. 4, pp. 729 - 736, 2001. doi. 10.1109/59.962419

[16] X. Huang, Q. Huang, Z. Xioapan, L. Lifang, and H. Yangyu, "Decentralized Control Model Research Power System Low Frequency Oscillation," *international Conference on Control, Automation and Systems Engineering*, pp. 108-111, 2013. doi. 10.2991/case-13.2013.27

[17] S.Elloumi, A. B and B. B. N, "On Decentralized Control of a Multimachine Power System: A Comparative study," *International Journal of Sciences and Techniques of Automatic control and Computer engineering*, vol. 7, no. 1, pp. 1816-1833, 2013. ISSN. 1737-7749

[18] H. Zhao, L. Xiaoming, and M. Zengqiang, "A Fast Multi-Step Prediction and Rolling Optimization Excitation Control Method for MultI-Machine Power System," *Technical Gazetta*, vol. 24, no. 6, pp. 1676-1677, 2017. doi.10.17599/tv-20160110060449

[19] Y.H.Song, T. J. A and M. X. Z, "Decentralized Optimal Control for Large Power Systems Stability Improvement," *IFAC Large Scale Systems*, pp. 169-172, 1995. doi.org/10.1016/S1474-6670(17)51512-8

[20] B. S. Rim, O. Kahouli and A. H. Hadj, "Stabilization of Single Machine Infinite Bus by Optimal Fuzzy Control," *IEEE*, pp. 409-413, 2016. doi. 10.1109/STA.2016.7952054

[21] A.A.Abouelsoud, I. A.-O. Abdullah and A. Hany, "Observer-Based Stabilizer of A single Machine Power System with Lossy Transmission Line," *WSEAS*, vol. 9, no. 2224-350X, pp. 462-468, 2014. ISSN 2224-350X

[22] V. K. E and J. Jovitha, "Algebraic Riccati equation based Qand R matrices selection algorithm for Optimal LQR Applied to track control of 3rd order magnetic levitation," *Archives of Electrical Engineering*, vol. 65, no. 1, pp. 151-168, 2016. doi.org/10.1515/aee-2016-0012

[23] K. Kalsi, L. Jianming and H. Z. Stanislaw, "Decentralized Control of Multimachine Power Systems," *American Control Conference*, pp. 2122-2127, 2009. doi. 10.1109/ACC.2009.5159812

[24] N.A.Elkhateeb, I. B. R and A. A. A, "Constrained Linear State Feedback Controller for a Low-Power Gas Turbine Model," *Journal of Control Engineering and Technology*, vol. 4, no. 1, pp. 66-75, 2014.

[25] H. RTIBI and E. Selwa, "Robust Decentralized Nonlinear Control for Multimachine Power Systems," *International Conference on Advanced Systems and Electric Technologies*, pp. 473-480, 2017. doi. 10.1109/ASET.2017.7983739

[26] Q. Lu, L. Jin, G. Jixang, K. Gordon and L. F, "Decentralized Control for Multimachine Power Systems," *Optimal Control and Application Methods,* vol. 10, pp. 53-64, 1989. doi.org/10.1002/oca.4660100105

[27] K.Ohtsuka, N. M, Y. K, T. H, and M. Y, "Decentralized controlof a multimachine power system," *IFAC,* p. 4, 1993. doi.org/10.1016/S1474-6670(17)48574-0

[28] X. Huang, Q. Huang, Z. Xiaopan, L. Lifang, and H. Yangyu, "Optimal feedback excitation decentralized coordinated control model of the multi-machine power system," *Applied Mechanics and Materials,* Vols. 433-435, pp. 1343-1346, 2013. doi.org/10.4028/www.scientific.net/AMM.433-435.1343

[29] D.D.Siljak, "Decentralized Control and Computations: Status and Prospects," *IFAC Large Scale Systems,* p. 11, 1995. doi.org/10.1016/S1367-5788(97)00011-4

[30] M. Rahmani and S. Nasser, "Robust Optimal Control for Large-Scale systems with state delay," *Transaction of the Instutute of Measurement and Control,* p. 8, 2013. doi.org/10.1177/0142331213511847

[31] T. Bian, J. Yu, and J. Zhong-Ping, "Decentralized Adapative Optimal Control of Large-Scale Systems with Application to Power Systems," *IEEE,* vol. 62, no. 4, pp. 2439-2447, 2015. doi. 10.1109/TIE.2014.2345343

[32] R. Ortega, G. Martha, A. Alessandro, S. Yuanzhang and S. Tielong, "Transient stabilization of multimachine power systems with nontrivial transfer conductances," *IEEE,* vol. 50, no. 0018-9286, pp. 60-75, 2005. doi. 10.1109/TAC.2004.840477

[33] A.A.Abouelsoud, "Global Stabilization of linear time-invariant systemssubject to state and control constraints," *The Mediterranean Journal of Measurement and Control,* vol. 3, no. 1743-9310, pp. 157-163, 2007. ISSN.1743-9310

[34] T.-T. Lee and L. Guang-Tsong, "The Inverse problem of linear optimal control for constant disturbance," *Taylor and Francis Journal of Control,* vol. 43, pp. 233-246, 2007. doi.10.1080/00207178608933460

[35] L. Fortuna and F. Mattia, Optimal and Robust Control Advanced Topiv with Matlab, Florida: CRC Press, 2012. doi.org/10.1201/b11660

[36] M. Galaz, O. Romeo, A. Alessandro, S. Yuanzhang and S. Tielong, "Transient stabilization of multimachine power systems," *Springer*, pp. 367-386, 2006.

[37] A.A.Abouelsoud, "Stabilizing output feedback controller of bilinear systems," *International Journal Modelling, Identification and Control,* vol. 6, no. 4, pp. 313-319, 209. doi.org/10.1504/IJMIC.2009.024738

[38] D. Langarica-Cordoba, O. Romeo and C. Daniele, "Transient stabilization of Multimachine power systems: Towards a decentralized global solution," *European Journal of Control,* p. 26, 2015. doi.org/10.1016/j.ejcon.2015.09.003

[39] A. Zecevic and D. Š. Dragoslav, Control of Complex Systems: Structural Constraints and Uncertainty, New York: Springer, 2010. ISBN. 1441912150,9781441912152

[40] M. Mahmud, J. H. M, R. P. H, and K. R. N, "Robust Nonlinear Excitation Controller Design for Multimachine Power Systems," *IEEE,* p. 6, 2014. doi. 10.1109/PESGM.2014.6938800

[41] P. Dorato, T. A. Chaouki, and C. Vito, Linear Quadratic Control: An Introduction, Malabar: KRIEGER Publishing Company, 2000. ISBN.1575241560 9781575241562

Appendix.

Table. 1 [32].

SMIB Parameters

P	Y	a	b	E_f
28.22	34.29	0.3341	0.1490	0.2405

Table. 2 [32]

System parameters for different values of G

G	Y	a	b	δ_*	E_*
0.01771	34.3046	0.02915	0.1490	0.9122	0.9824
0.0885	34.6526	0.1448	0.1506	0.4946	1.0815
0.1771	35.7184	0.2838	0.1552	0.0870	1.1528

Table. 3 [32]

Parameters of the post fault system

$Parameter$	$Gen\,1$	$Gen\,2$
a	16.7255	14.2937
b	11.1059	9.4147
Y	51.2579	36.6127
G_{ii}	28.9008	20.3936
α	0.5430	0.5430
E_f	5.8103	7.9279
P	52.2556	48.4902