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An Efficient Decentralized Control Strategy Applied to an Interconnected Multi-Machine Electric Power Grid

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Abstract

Background/Objectives: It is essential to design an efficient decentralized control strategy to deal with the stability against various disturbances in a practical electric power interconnection with nonlinearities and uncertainties. **Methods:** This paper presents theoretically a decentralized control strategy which is appropriately applied to an interconnected power system. Such an electric power grid is mathematically modeled first, then the design of an efficient control scheme for a stabilized solution will be presented. Finally, the feasibility and superiority of the proposed approach will be verified through various simulation cases using MATLAB/Simulink platform for a typical three-machine electric power system. **Findings:** It should be obviously found that a practical multi-area electric power network, which is considered to be a typical example of large-scale systems, composes of many synchronous generators. These machines are strongly interconnected via a number of nonlinearities such as parameters of transmission lines, thereby this feature brings a big challenge to the modeling of the network and the design of an efficient control strategy for an electric power interconnection in order to ensure its stability and reliability. Decentralized control strategies have been applied to be more suitable for tackling the stabilization problem of such an interconnected power grid in comparison with the centralized control scheme. In the present paper, an efficient linear decentralized control methodology based on a number of modified Riccati equations to calculate a proper feedback control law will be studied as a typically feasible candidate to this issue. The promising simulation results obtained in a three-machine interconnected power system model with various cases of initial conditions are quite able to demonstrate the superiority of the proposed control methodology. **Application/Improvements:** The proposed decentralized control strategy is successfully applied to a three-machine electric power interconnection model as a typical case study. Hence, this control methodology can afford to be efficiently adopted to a practical power network.

Keywords: Large-Scale System, Modeling, Decentralized Control Strategy, Multi-Machine Interconnected Power System, Stabilization Problem

1. Introduction

Large-scale systems, i.e. ecological networks (or ecosystems), water grids and traffic networks, normally compose of many subsystems with a numerous number of nonlinearities and uncertainties. This is because such systems have large dimension, high dynamic order, unknown parameters, restriction of information about the system behaviors, etc. Therefore, it is highly challenging to tackle the modeling and control of a large-scale system to ensure the quality, the stability as well as the reliability of the network[1,2].

As a typical case of the large-scale systems, a multi-machine electric power grid contains many subsystems, including synchronous generators, power stations, transmission lines and distribution networks. Furthermore, random disturbances, such as load variations and sudden phenomena, usually appear in an

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electric power interconnection. Together with inherent attributes, e.g., generation rate constraint and governor dead-band, these features cause a lot of difficulties with respect to an establishment for an optimal solution in regulation to the stabilization problem of the overall network against disturbances[3-10]. In this perspective, two control approaches have been taken into account. The first solution is to use a centralized control strategy. When applying this control approach, however, it might cope with a number of drawbacks, including the inadequate information of the entire system, the difficulty of the control design and the economic problem. Thus, a decentralized control methodology has been proposed as a perfect substitute for the centralized control method[11-14]. This control scheme is based upon a feedback control law to adapt to the nonlinear and complicated interactions among subsystems. It might not require complete information of the system, and thus it is able to simplify the control design. The decentralized methodology is quite capable of overcoming almost shortcomings resulting from the centralized solution. It is obvious that the decentralized strategy has been selected instead of the centralized method in the context of finding an efficient solution for the stabilization issue of a large-scale electric interconnection[15-18].

The objective of this paper is first to establish a mathematical model of large-scale interconnected power systems applying electrical and mechanical equations. Although this model has been successfully built by using a traditional approach, it is able to be efficiently adopted to design control strategies for the stabilization problem. The linear decentralized control strategy with the outstanding advantages as mentioned earlier is then studied generally and applied for a typical large-scale system. The idea of this approach is to establish and solve a number of modified algebraic Riccati equations. The results of these computations are then employed to calculate several gain vectors for the feedback control law. Eventually, the efficiency and superiority of the control method presented in this study will be testified in a three-machine interconnection network model. This model is quite able to be taken into a typical case study of multi-machine electric power grids. The promising simulation results obtained demonstrate the feasibility of the proposed solution; thus it can afford to guarantee the stability, the reliability and the economy of an interconnected electric power grid against the disturbances.

2. Modeling of an Interconnected Electric Power Grid

According to the aforementioned analyses, a practical electric power grid can be considered to be a typical example for the large-scale systems. It is the fact that such a practical electric interconnection usually consists of numerous power plants. These power plants are interconnected by transmission lines (or tie-line) for power exchanges. Naturally, an interconnected electric power network containing N generating stations is able to be described as a block diagram (Figure 1(a)). It is a complicated case of the electric power interconnections. In this context, each generating station is normally called an area or control area, which typically includes three basic units: a governor, a turbine (prime mover) and a generator as shown in Figure 1(b). Turbines including some kinds (i.e., hydraulic, reheat and non-reheat turbine) are employed to convert the natural energy into mechanical power. Thereafter, a synchronous generator connected with a turbine is adopted to convert such mechanical power into electric power. Finally, the electric power is able to be delivered to transmission lines to perform national generation scheduling.

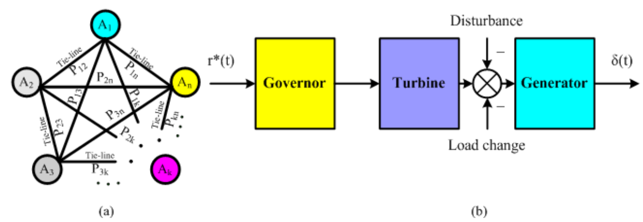

Figure 1. Structure of a multi-machine electric power system (a) N-area electric power system; (b) Three basic units of an area.

In such an area of the electric power interconnection, disturbances, such as load variations, usually appear from nowhere. These phenomena absolutely affect several parameters of an electric power grid such as the output revolution of a synchronous machine or the frequency of the network; thus they can cause a number of undesired influences for the normal operation of the system. Naturally, it is essential to find a qualified control methodology for solving the stability problem of an electric power system.

For designing such an efficient control methodology to the stability issue of an interconnected electric power network, we first need to establish a mathematical model of the system. Traditionally, mechanical and electrical equations are used here for the modeling. Considering each area of the power network with three basic components as shown in Figure 1(b), the mechanical and electrical equations built for the *i* th area can be obtained as follows. It should be noted that the nomenclature of the following equations can be found clearly in two reports[9,11].

The rotational angle and speed of the *i* th generator are described below:

$$\dot{\delta}_i = \omega_i, \tag{1}$$

$$\dot{\omega}_i = -\frac{D_i}{2H_i}\omega_i + \frac{\omega_0}{2H_i}\left(P_{mi} - P_{ei}\right) + d_i. \tag{2}$$

The electrical dynamics in such a generator should be expressed as:

$$\dot{E}'_{qi} = \frac{1}{T'_{doi}}\left(E_{fi} - E_{qi}\right). \tag{3}$$

Regarding the modeling of a turbine, a mathematical equation should be taken into account below:

$$\dot{P}_{mi} = -\frac{1}{T_{mi}}P_{mi} + \frac{K_{mi}}{T_{mi}}X_{ei}, \tag{4}$$

where, X_{ei} denotes the turbine valve opening, which is satisfying the equation below:

$$\dot{X}_{ei} = -\frac{K_{ei}}{T_{ei}R_i\omega_0}\omega_i - \frac{1}{T_{ei}}X_{ei} + \frac{1}{T_{ei}}P_{ci}, \tag{5}$$

Eventually, all electrical equations for such an electric power subsystem are presented below:

$$E_{qi} = E'_{qi} + \left(x_{di} - x'_{di}\right)I_{di}, \tag{6}$$

$$E_{fi} = k_{ci}u_{fi}, \tag{7}$$

$$P_{ei} = \sum_{j=1}^{N} E'_{qi}E'_{qj}B_{ij}\sin(\delta_i - \delta_j), \tag{8}$$

$$Q_{ei} = -\sum_{j=1}^{N} E'_{qi}E'_{qj}B_{ij}\cos(\delta_i - \delta_j), \tag{9}$$

$$I_{di} = -\sum_{j=1}^{N} E'_{qj}B_{ij}\cos(\delta_i - \delta_j), \tag{10}$$

$$I_{qi} = \sum_{j=1}^{N} E'_{qj}B_{ij}\sin(\delta_i - \delta_j), \tag{11}$$

$$E_{qi} = x_{adi}I_{fi}, \tag{12}$$

$$V_{ti} = \sqrt{\left(E'_{qi} - x'_{di}I_{di}\right)^2 + \left(x'_{di}I_{qi}\right)^2}, \tag{13}$$

The mathematical model as expressed in Equations (1)-(13), when applying the direct feedback linearization compensation law, can be briefly given below.

$$\dot{\delta}_i = \omega_i, \tag{14}$$

$$\dot{\omega}_i = -\frac{D_i}{2H_i}\omega_i - \frac{\omega_0}{2H_i}\Delta P_{ei} + d_i, \tag{15}$$

$$\Delta\dot{P}_{ei} = -\frac{1}{T'_{doi}}\Delta P_{ei} + \frac{1}{T'_{doi}}v_{fi} + \gamma_i(\delta,\omega), \tag{16}$$

where

$$\Delta P_{ei} = P_{ei} - P_{mi0}, \tag{17}$$

$$\gamma_i(\delta,\omega) = E'_{qi}.\sum_{j=1}^{N} E'_{qj}B_{ij}\sin(\delta_i - \delta_j) - E'_{qi}.\sum_{j=1}^{n} E'_{qj}B_{ij}\cos(\delta_i - \delta_j)\omega_j, \tag{18}$$

$$v_{fi} = I_{qi}k_{ci}u_{fi} - (x_{di} - x'_{di})I_{qi}I_{di} - P_{mi0} - T'_{doi}Q_{ei}\omega_i. \tag{19}$$

The equations given in (14)-(19) are able to be used to the modeling of an interconnected power system. Let us now consider a typical example of a three-interconnected-machine electric network model depicted in Figure 2. There are three generator units in this network, in which the third generator M_3 is interconnected with the other two machines (M_1 and M_2) through two infinite buses (Figure 2). In this context, we may only consider the dynamic responses of the first and second machines when the disturbances occur. It is obvious that the mathematical model of the interconnected electric power grid built above is rewritten as[13-16]:

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + \sum_{j=1, j\neq i}^{N} p_{ij}G_{ij}g_{ij}(x_i, x_j), \; i = 1,2,3,\ldots,N. \tag{20}$$

We define a state vector as follows:

$$x_i(t) = \left[\Delta\delta_i(t) \quad \Delta\omega_i(t) \quad \Delta P_{mi}(t) \quad \Delta X_{ei}(t)\right]^T \tag{21}$$

$$\text{Where}\begin{cases}\Delta\delta_i(t) = \delta_i(t) - \delta_{i0}\\ \Delta P_{mi}(t) = P_{mi}(t) - P_{mi0}\\ \Delta X_{ei}(t) = X_{ei}(t) - X_{ei0}\end{cases}$$

and

$$\begin{cases} A_i = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\dfrac{D_i}{2H_i} & -\dfrac{\omega_0}{2H_i} & 0 \\ 0 & 0 & -\dfrac{1}{T_{mi}} & \dfrac{K_{mi}}{T_{mi}} \\ 0 & -\dfrac{K_{ei}}{T_{ei}R_i\omega_0} & 0 & -\dfrac{1}{T_{ei}} \end{bmatrix}; B_i = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \dfrac{1}{T_{ei}} \end{bmatrix}; G_{ij} = \begin{bmatrix} 0 \\ \dfrac{\omega_0 E'_{qi} E'_{qj} B_{ij}}{2H_i} \\ 0 \\ 0 \end{bmatrix}; \\ g_{ij}(x_i, x_j) = \sin\left(\delta_i(t) - \delta_j(t)\right) - \sin\left(\delta_{i0} - \delta_{j0}\right). \end{cases} \tag{22}$$

Using the above mathematical model, we can design an efficient control strategy in dealing with the stability problem of the power network. The following section presents a linear decentralized control methodology which has been able to be successfully applied to large-scale systems, including an electric power interconnection.

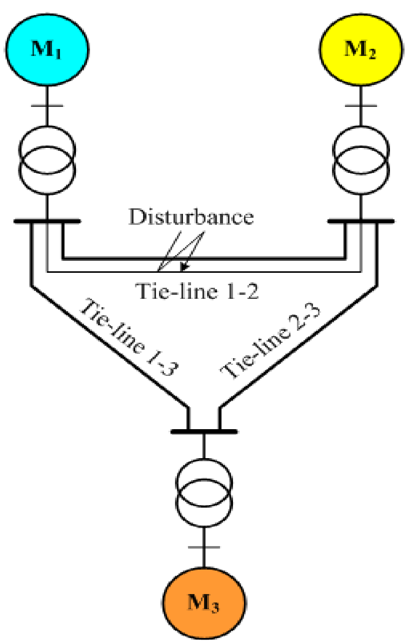

Figure 2. A three-machine electric power system model.

3. Control Solution for Stability Problem of an Interconnected Electric Power System

Since the interconnected power system presented in the previous section can be treated as a typical example of a large-scale system, to design an efficient control strategy applied to such a multi-machine electric interconnection, a model of large-scale systems should be taken into account. Assuming that this model consists of N subsystems, its corresponding mathematical representation is as follows[1]:

$$\begin{cases} \dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + f_i(t, x(t)), \text{ with } t > t_0 \\ x_i(t_0) = x_{i0}, \qquad i = 1,2,3,\dots,N \end{cases} \tag{23}$$

where, $f_i(t, x(t)) = f_i(x)$ denotes the interconnected components which represent all nonlinear characteristics of the ith subsystem. Such terms should satisfy the Lipshitz conditions as:

$$\begin{cases} \|f_i(x)\| \le c\|x\| \\ \|f_i(x) - f_i(y)\| \le h\|x - y\| \end{cases} \quad \forall x, y \in \mathbb{R}^n \tag{24}$$

where, c and h are two known positive constants.

As mentioned earlier, a decentralized control scheme is superior to a centralized control for realizing the stabilization of a nonlinear large-scale system. Therefore, it will be adopted in this study, particularly for the large-scale system described in (23) with the constraints (24). When applying the decentralized control strategy, the interconnection terms $f_i(x)$ should be rewritten as:

$$f_i(x) = \sum_{j=1, j\neq i}^{N} G_{ij} g_{ij}(x_i, x_j), \qquad i = 1,2,3,\dots,N. \tag{25}$$

In (25), $g_{ij}(x_i, x_j)$ is a nonlinear function, which must satisfy the following constraint:

$$\left\|g_{ij}(x_i, x_j)\right\| \le \left\|W_i x_i(t)\right\| + \left\|W_{ij} x_j(t)\right\|, \forall x_i \in \mathbb{R}^{n_i}, \forall x_j \in \mathbb{R}^{n_j} \tag{26}$$

where, W_i and W_{ij} denote two known and constant matrices.

According to the theory of the linear decentralized control strategy, it is necessary to linearize all nonlinear terms mentioned in (23). In particular, these nonlinear terms need to be employed to calculate control feedback gains for such a large-scale system. As presented in[1-2, 12-16], the authors suggested using a two-step method based on Riccati equations to establish the linear decentralized control law as follows.

Step 1: Establish the modified algebraic Riccati equations in a form as follows:

$$A_i^T P_i + P_i A_i + P_i\left(\sum_{j=1, j\neq i}^{N} p_{ij} G_{ij} G_{ij}^T\right) P_i - P_i B_i^T R_i^{-1} B_i P_i + \sum_{j=1, j\neq i}^{N} p_{ij}\left(W_i^T W_i + W_{ji}^T W_{ji}\right) + Q_i = 0. \tag{27}$$

where $R_i > 0$ and $Q_i(n_i \times n_i)$ and $P_i(n_i \times n_i)$ are defined matrices.

Step 2: Solve the above Riccati equations to find the control law as expressed in (28).

$$\begin{cases} u_i(t) = -K_i x_i(t) \\ K_i = R_i^{-1} B_i^T P_i \end{cases} \tag{28}$$

The feedback control law mentioned in (28) is capable of recovering the stability of a large-scale system after presence of disturbances. Hence, it is also applied to an interconnected electric power system, particularly the three-machine network as mentioned earlier. In this perspective, the corresponding control law can be given below:

$$\begin{cases} u_i(t) = -K_i x_i(t) \\ \quad = -K_{\delta i}\left[\delta_i(t) - \delta_{i0}\right] - K_{\omega i}\Delta\omega_i(t) - K_{Pi}\left[P_{mi}(t) - P_{mi0}\right] - K_{Xi}\left[X_{ei}(t) - X_{ei0}\right]. \\ K_i = R_i^{-1} B_i^T P_i \end{cases} \tag{29}$$

The effectiveness of this control law will be specifically demonstrated in the following section through a number of numerical simulations using MATLAB/Simulink package.

4. Numerical Simulation Results

Before starting the numerical simulation process using MATLAB/Simulink package, let us reconsider the three-machine electric interconnection model as mentioned in (20) and shown in Figure 2. With a number of necessary simulation parameters given in the reports[9,11], we can design the control methodology applying the decentralized method presented in the previous section. Specifically, the following three steps need to be executed:

Step 1: Design of the control plant, a typical example of an interconnected electric power grid.

From (22), using the simulation parameters given in the two reports[9,11], the following equations can be obtained for the first and second machines:

$$A_1 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -0.6250 & 39.2699 & 0 \\ 0 & 0 & -2.8571 & 2.8571 \\ 0 & -0.6366 & 0 & -10 \end{bmatrix}; A_2 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -0.2941 & 30.7999 & 0 \\ 0 & 0 & -2.8571 & 2.8571 \\ 0 & -0.6366 & 0 & -10 \end{bmatrix};$$

$$B_1 = B_2 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 10 \end{bmatrix}; \begin{cases} p_{12} = p_{21} = 1 \\ p_{13} = p_{31} = 1 \\ p_{23} = p_{32} = 1 \end{cases}$$

$$G_{ij} = \begin{bmatrix} 0 \\ \alpha_{ij} = \dfrac{\omega_0 E'_{qi} E'_{qj} B_{ij}}{2H_i} \\ 0 \\ 0 \end{bmatrix}, \text{with} \begin{cases} \alpha_{12} = \alpha_{13} = -27.49 \\ \alpha_{21} = \alpha_{23} = -23.10 \\ \alpha_{31} = \alpha_{32} = -23.10 \end{cases}$$

Step 2: Find the solution of the algebraic Riccati equations given in (27).

Using MATLAB environment, solving the Riccati equations presented in (27) with the given simulation parameters, the control law, especially the following two gain vectors (computed from (29)), can be obtained:

$$\begin{cases} K_1 = [K_{\delta_1} \ K_{\omega_1} \ K_{P_1} \ K_{X_1}] \\ \quad = [-174.7398 \ -42.2510 \ -10.7218 \ -5.2562] \\ K_2 = [K_{\delta_2} \ K_{\omega_2} \ K_{P_2} \ K_{X_2}] \\ \quad = [-174.2508 \ -29.2102 \ -10.7003 \ -5.4231] \end{cases}. \tag{30}$$

Step 3: Carry out the necessary numerical simulations to demonstrate the feasibility of the proposed control method.

In this step, we give two simulation cases with the initial conditions indicated in Table 1.

Table 1. Initial conditions for two simulation cases

Simulation case	$x_1^{(0)} = [\delta_{10}(rad)\ \omega_{10}(s^{-1})\ P_{m10}(p.u.)\ X_{e10}(p.u.)]^T$	$x_2^{(0)} = [\delta_{20}(rad)\ \omega_{20}(s^{-1})\ P_{m20}(p.u.)\ X_{e20}(p.u.)]^T$
Case 1	$[0.25 \quad 0.00 \quad 0.35 \quad 0.90]^T$	$[0.82 \quad 0.00 \quad 0.35 \quad 0.95]^T$
Case 2	$[0.10 \quad 0.15 \quad 0.20 \quad 0.50]^T$	$[0.82 \quad 0.20 \quad 0.50 \quad 1.05]^T$

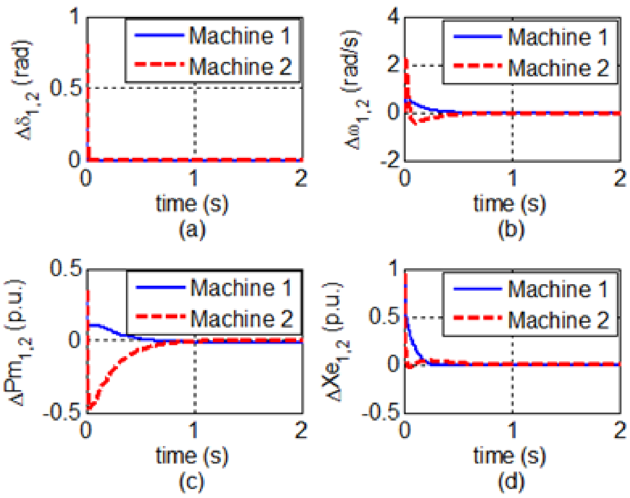

Figure 3. Dynamic responses of the first and second machines in the simulation case #1.

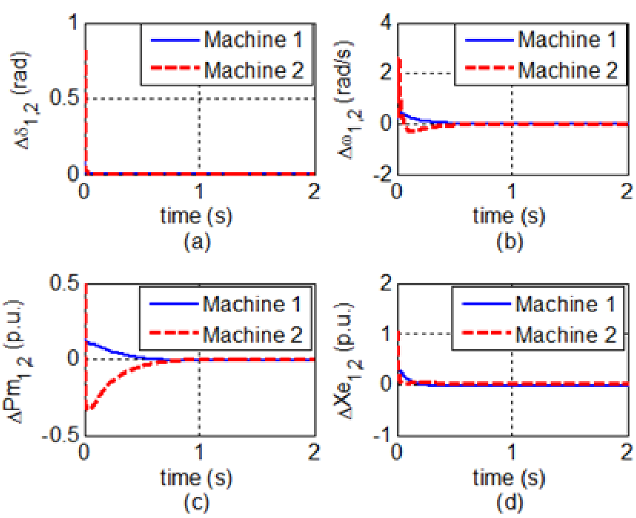

Figure 4. Dynamic responses of the first and second machines in the simulation case #2.

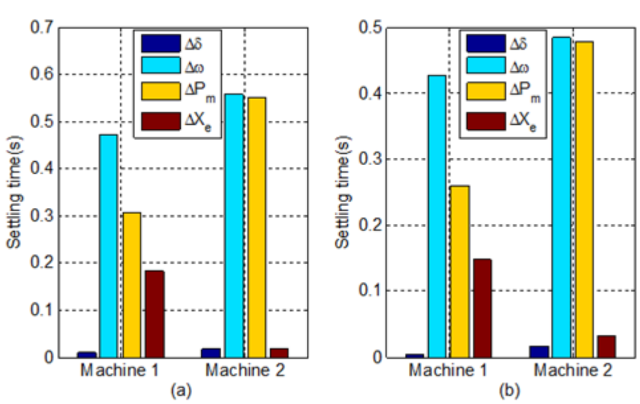

Figure 5. Comparative results of settling times for four state parameters. (a) Simulation case #1. (b) Simulation case #2.

Subsequently, numerical simulation results regarding the dynamic responses for the first and second machines are shown in Figure 3 and Figure 4. It can be said from these two Figures that all of four state parameters given in (21) are driven to zero very quickly, enhancing the control performances. It means that the stability of such two machines is able to be successfully recovered for this case. In order to observe clearly the efficiency, let us consider the most important parameter of the four state parameters, that is, the rotational speed change of two machines. This is an important parameter of the system because it directly affects the network frequency. It is found that the system frequency in a power network has a significant effect on equipment, such as transformers or AC motors. As a result, if the frequency variation can be damped quickly enough, the normal operation of the network is able to be assured and its stability is maintained. Figure 3(b) and Figure 4(b) describe this fast extinguishment, hence verifying the feasibility of the regulation method presented in this study to the stabilization problem.

Let us now give an acceptable tolerance of 5% to evaluate more specifically the efficiency of the proposed control method. In this case, two comparative graphs have been plotted (see Figure 5 (a) and Figure 5 (b)). It is obvious that all four settling times of the above four state parameters regarding two simulation cases are less than 0.6s; thus, the proposed control strategy is able to quickly bring the stability to the system after the disturbances. This proves the superiority and efficiency of the decentralized control methodology presented in this work.

5. Conclusions

This paper has studied an effective linear decentralized control strategy to find an optimal solution for the stabilization issue of the large-scale system. A three-machine electric interconnection model representing a typical case study of the large-scale systems has also been taken into account. First, this model is mathematically formulated then the linear decentralized control scheme is applied to recover the stability of the network after the presence of the disturbances. Numerical simulation results obtained have demonstrated the feasibility and superiority of the proposed control method. For future work, with the diversity and complexity of the practical electric power systems, modern control techniques, such as fuzzy logic and neural network should be considered to further improve the effectiveness of the studied regulation strategy. In this aspect, a robust control scheme can be built in an efficient integration with the decentralized control methodology proposed in the present paper.

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