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Accurate Decentralized H∞ Control for a Class of Generalized Power Systems

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Abstract: Aiming at the problem that it is difficult to control the system stability when the traditional controller method of centralized control is applied to the large-scale system, the accurate decentralized H∞ controller for a class of generalized power systems is studied. The mathematical model of generalized power system was established, the stability of the system was analyzed, the dimensionality reduction observer was designed, and the conditional inequality was solved by Lyapunov equation and Riccati equation. Based on H∞ loop forming and combined with decentralized control strategy, the design of an accurate decentralized H∞ controller is completed. By comparing the simulation experiments, it is verified that the power system equipped with an accurate decentralized H∞ controller can respond quickly to interference, that is, the proposed controller is more robust.

Keywords: Generalized power system; Observer; Accurate decentralized H∞ control; Lyapunov; Riccati

1. Introduction

The power system is a typical nonlinear system, and the generalized power system is a very complex dynamic system, which has the characteristics of wide range and complex structure. The generalized power system is usually composed of several subsystems which are interrelated, and the dynamic stability problem which is easy to occur after interconnection seriously affects the overall operation reliability of the power system. In recent years, with the development of smart grid, the structure of the power system is more complex, the stability is more difficult to control, and the control method and precision are required [1]. Therefore, for the complex generalized power system, improving the overall reliability of the system is the basic condition to ensure the normal operation of the system. In the traditional centralized control method based on fuzzy theory, the same controller is used to control the system. Although it can achieve a good control effect for the small system, when applied to the large system, the controller is not robust enough to realize the stability control of the generalized power system. As the preferred control method for stability control of generalized power system, decentralized control can quickly respond to the interference in each subsystem, which is conducive to the realization of system control [2].

The characteristic of decentralized control is that there is no unified controller. In this control mode, the output, input signals and system signals of each sub-operation are correlated with each other. The advantages of decentralized control are strong pertinence, high efficiency of information transmission and strong adaptability of the system. Although decentralized control has been applied in many industries such as transmission network, space system and economic system, the research results on decentralized control of generalized power system in China are not significant in recent years [3]. Based on the above analysis, this paper will study an accurate decentralized H∞ controller for a class of generalized power systems.

2. Accurate Decentralized H∞ Control for a Class of Generalized Power Systems

2.1. The mathematical model of generalized power system is established

The power system is a typical generalized system, which has both the characteristics of the general system and the basic characteristics of the generalized system. It can describe a wider range of systems than the normal system. With the complexity of the power system and the continuous expansion of the control area, the structure of the generalized power system becomes more and more complex, and the number of neutron systems in the system becomes more and more. The general model of generalized power system is usually a generalized interconnected system composed of several generalized subsystems, which can be expressed as:

$$\begin{aligned} E_{ii}\frac{dx_i}{dt} &= A_{ii}x_i + B_{ii}u_i + \sum_{j=1, j\neq i}^{N} A_{ij}x_j + G_{ii}\omega_{i1} \\ y_i &= C_{2ii}x_i + D_{2ii}\omega_{i2} \\ z_i &= C_{1ii}x_i + D_{1ii}u_i \end{aligned} \tag{1}$$

In formula (1), E_{ii} is the potential value of generalized power system; N is the number of subsystems of generalized power system; x_i is the system state variable; u_i is the control variable; $\sum_{j=1,j\neq i}^{N} A_{ij}x_j$ is the correlation measurement quantity of the system; ω_{i1} is the overall external disturbance to the power system; ω_{i2} is the disturbance to the output part of the power system; A_{ii}, B_{ii} and G_{ii} are constant matrices with appropriate dimensions; y_i is the feedback of generalized power system; z_i is the output of generalized power system; C_{2ii} and C_{1ii} are the parameters of the feedback and output state variables of the power system respectively; D_{1ii} is the parameter of the output of the power system; D_{2ii} is the feedback disturbance parameter of the power system [4]. Compared with general generalized systems, the system model is more complex by adding interconnected subsystems. Assuming that the matrices R_1 and R_2 are nonsingular, the two matrices are as follows:

$$\begin{cases} R_1 = D_{12i}^T D_{12i} \\ R_2 = D_{22i}^T D_{22i} \end{cases} \quad (2)$$

In formula (2), D_{12i} is the output variable parameter of the large system; D_{22i} is the output variable parameter of the subsystem. (E_0, A, C_2) can be detected and the pulse signal can be observed, in which E_0 is an infinite eigenvalue [5]. In the above system, there exists Riccati inequality that matrix P satisfies $E^T P = P^T E \geq 0$.

$$\begin{aligned} &P^T A + A^T P + \gamma^{-2} P^T G G^T + 2(P - P_D)^T BB^T (P - P_D) \\ &+ C_1^T C_1 - (B^T P + D_{12}^T C_1)^T (B^T P + D_{12}^T C_1) < 0 \end{aligned} \quad (3)$$

In formula (3), the matrix P is the n-order matrix; P_D is the diagonal matrix composed of diagonal elements in the matrix P. According to the above assumptions, the compact representation of the generalized power system composed of all subsystems is as follows [6]:

$$\begin{aligned} E\dot{x} &= Ax + Bu + G\omega \\ y &= C_2 x + D_2 \omega \\ z &= C_1 x + D_1 u \end{aligned} \quad (4)$$

After designing the mathematical model of the generalized power system, the controller with observer is used to obtain the approximate values of x_i and ω_{i1} states in the subsystem.

2.2. Design of dimensionless observer

The dimensional-reduction observer is used to observe the part of the state that cannot be directly observed from the output. It requires fewer integrators than the full-dimensional observer, and the overall feedback system is simple in structure and low in cost. In order to design a dimensions-reduction observer for system (1), the state matrix A and state matrix x are divided into blocks. If $C = [I_m \quad 0]$, then $y = Cx$. The sufficient conditions for the existence of dimensionality reduction observer in generalized power system are as follows [7]:

If $(A \quad C)$ can be seen, and the gain matrix P and X exist, the following linear matrix inequality is established:

$$\begin{bmatrix} A_{22}^T + A_{21}^T X^T + PA_{22} + XA_{12} + \gamma^2 I & X & P \\ X^T & -I & 0 \\ P & 0 & -I \end{bmatrix} < 0 \quad (5)$$

Then, Lyapunov function is used to obtain the asymptotically stable dimensional-reduction observer ($X = PL$) expression of the system (4) as follows:

$$\begin{aligned} \dot{x}_2 &= (A_{22} + LA_{12})\hat{x}_2 + (A_{22} + LA_{11}) y \\ &+ [\mathrm{L} \quad I_{n-m}] \Delta\phi - Ly \end{aligned} \quad (6)$$

In formula (6), $\Delta\phi$ is the dynamic error of the observer. The form of controller obtained by the observer designed above is as follows:

$$\begin{aligned} E_{ii}\dot{\xi}_i &= A_{ii}\xi_i + B_{ii}u_i + G_i\bar{\omega}_{i1} + L_i(y_i - C_{2i}\xi_i) \\ u_i &= K_i\xi_i \,(i = 1, 2, \cdots, N) \end{aligned} \quad (7)$$

In formula (7), ξ_i is the state estimation of i subsystem decentralized controller; $\bar{\omega}_{i1}$ is the estimation of system disturbance. After designing the dimensions-reduction observer and simplifying the expression of the generalized power system mathematical model by using the observer estimate, the H∞ loop is designed to stabilize the controller.

2.3. H∞ infinity loop takes shape

H∞ loop shaping is to describe the design objective of the closed loop system with the open loop transfer function. If the singular value of the nominal controlled object $G(s)/G_\tau(s)$ reaches the desired shape within the appropriate frequency range, select the pre-compensator $W_1(s)$ or the post-compensator $W_2(s)$ to shape it. In order to make the system better able to suppress interference, the gain of the open-loop transfer function $Gs(s)$ after shaping should be high enough in the low frequency band. At the same time, in order to ensure the robustness of the controller, the gain of open-loop transfer function $Gs(s)$ should be low enough in the high frequency band. In conclusion, to ensure good controller performance, the $Gs(s)$ must have the desired loop gain within the appropriate frequency range [8].

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The diagram below shows the design process of loop forming.

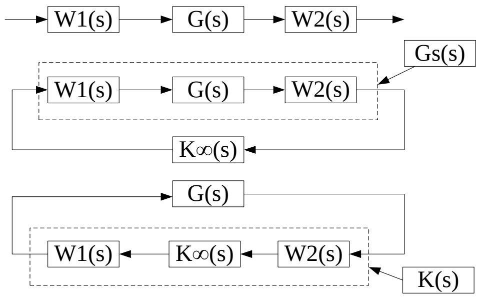

Figure 1. Circuit forming design process

After the H∞ loop is designed according to the process shown in the above figure, the H∞ control theory is combined with the decentralized control strategy to design an accurate decentralized controller for the generalized power system.

2.4. Design accurate dispersion controller

The accuracy of the decentralized controller was designed in this paper, using the structure of feedforward control, feedforward control is the basic principle of the system's external disturbance signals by another branch to the controller, the external signal through the impact of main channel and offset by the impact of feedforward control, so as to achieve the purpose of elimination of the influence of interference signals. The observer can be used to approximate the measured interference signal, so a feedforward channel is added, and the appropriate feedforward channel is selected to make the interference signal affect the system through the feedforward channel, which can exactly offset the influence of the interference signal on the output signal of the original system. The standard H∞ controller block diagram is shown below.

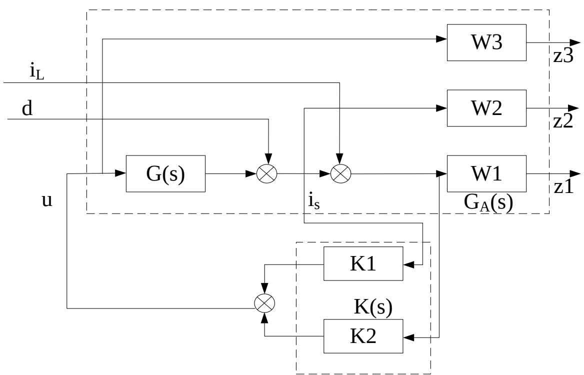

Figure 2. Standard H∞ controller block diagram

In the figure above, the weighted functions W_1, W_2 and W_3 correspond to controller input, controller output and evaluation output respectively. W_1 is a weighted function of the transfer function and represents the norm solution of additive perturbation. In transfer function, if the corresponding weighted function W_1 is introduced, the size of the control quantity u should be limited by selecting the size of the input weighted function to keep it within the allowable range of the system, so as to prevent the serious saturation phenomenon of the controller in the actual working process and the damage to the actuator caused by the excessive control quantity. From this point of view, and in order to ensure that the system has sufficient bandwidth, the static gain of W_1 should be appropriately small. W_2 plays a penalty function in the design of the controller. A larger W_2 results in a smaller controller gain. In addition, the reasonable choice of W_2 phase helps the controller to control the object from the right direction. Generally speaking, W_2 can be chosen as a smaller normal number, but it is also optional. W_3 is used to adjust the weakly damped poles of the open ring. If the controlled object has open loop weakly damped poles, these poles will become the poles of the closed-loop system after adding the controller closed loop, so that the designed controller cannot achieve a satisfactory effect. Therefore, the poles can be adjusted by W_3 [9].

Considering the generalized power system, for any $\gamma > 0$, the following equivalence relation exists [10]:

A. Function V in matrix X and C^{-1} satisfies $R^n \to R$:

$$\frac{dV}{dt} + \|y\|^2 - \gamma^2 \|u\|^2 < 0 \qquad (8)$$
$$E^T X = X^T E \geq 0$$

B. The matrix X satisfies this equation:

$$X^T A + A^T X + \gamma^{-2} X^T BB^{TX} + C^T C < 0 \qquad (9)$$

C. The matrix X is allowed with respect to (E, A), and $\|T(s)\|_\infty < \gamma$, $T(s) = C(sE - A)^{-1} B$.

In order to stabilize the closed-loop system, the decentralized controller constructed is:

$$u = -K_i x_i \qquad (10)$$

When the above conditions are met, the generalized power system can be controlled by H∞ accurately, and the control gain K of the generalized power system is as follows:

$$K = -R_1^{-\frac{1}{2}} \left(B^T P_D + D_{12}^T C_1 \right) \qquad (11)$$

So far, the design of H∞ controller for a class of generalized power system with accurate dispersion is completed, which makes up for the disadvantages of traditional controller design and makes the closed-loop control performance of generalized power system stable.

3. Simulation Results

In this paper, a class of H∞ controller for generalized power system is studied. To test the performance of the controller designed in this paper, a simulation experiment is carried out.

3.1. Experiment content

The simulation experiment was conducted by comparing the accurately distributed H∞ controller designed in this paper with the controller based on fuzzy theory. The experimental group was the accurately dispersed H∞ controller for the generalized power system studied in this paper, and the comparison group was the power system controller based on fuzzy theory. Experimental verification was carried out under two conditions, namely, changing the operating point of the system and power system failure. Experimental data of the two conditions were comprehensively analyzed, and the robustness of the controller was compared, and corresponding experimental conclusions were obtained.

3.2. Experimental preparation

This experiment takes the test system of 4 machines with two drives as an example for simulation analysis. The excitation system parameters of the four generators are all the same. 4. The analysis results of open loop eigenvalues of the machine system are shown in the following table.

Table 1. Analysis of open loop characteristic values of 4 machine systems

Model	1	2	3
Eigenvalue	-0.3647+j6.6075	-0.3563+j6.7433	0.1928+j3.5415
Damping ratio	0.0551	0.0528	-0.0543
Oscillation frequency /Hz	1.0516	1.0732	0.5636
The dominant unit	1#	3#	2#, 3#

The experimental group and the control group were used to control the four computer systems, and two experiments were carried out in the two experimental environments. Process and analyze experimental data and draw corresponding conclusions.

3.3. Experimental results

Firstly, the control effect of the control group and the control group on the experimental system was verified. The control effect of the two controllers is shown in the figure below.

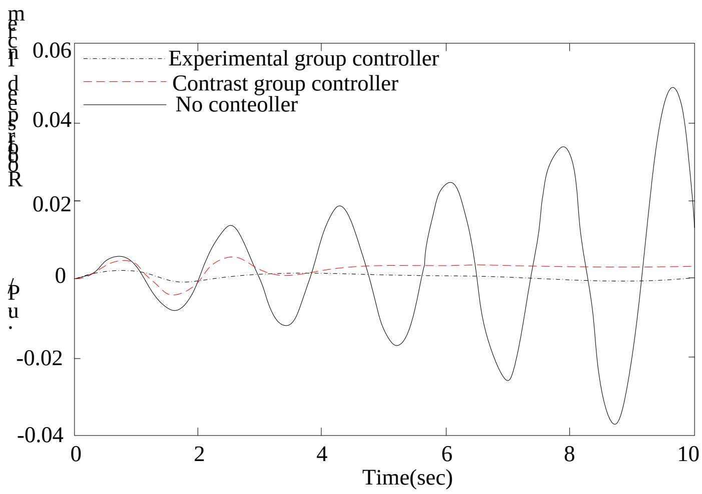

Figure 3. Comparison of controller effects

In order to illustrate the control effect of the controller on the experimental system, figure 3 compares the simulation curves of the system without control, the controller in the comparison group and the controller in the experimental group. It can be seen from the above figure that the system itself is unstable when the controller is not installed, and each generator shows an increasing oscillation. However, the stability of the system has been significantly improved after the controller is installed. Compared with the control group, the control group can better suppress the oscillation of the system.

Under the two experimental conditions of changing the operating point of the system and system failure, the response of the system after installing the controller in the experimental group and the control group was compared.

The response curve of the system is shown in the following figure.

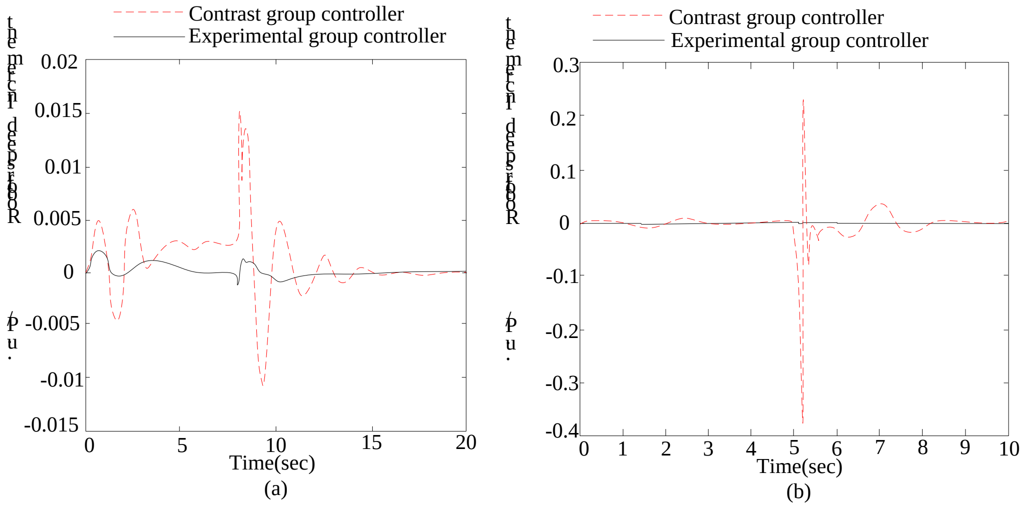

Figure 4. Comparison of response curves of the system under two experimental conditions

As can be seen from the above figure (a), the experimental system can run stably at the initial operating point. At 8 seconds, the system load is increased by 50MW, and the injected power of machine 1 is correspondingly increased by 50MW, thus obtaining the response curve of the system. As can be seen from figure 4 (a), when the operating point of the system changes, the response curve of the system after installing the controller of the experimental group fluctuates less and recovers quickly.

According to the above figure (b), the system had a three-phase short circuit failure at 5 seconds, and the system reclosed successfully after 0.2 seconds. During the system fault recovery period, the system response of the control group controller was greatly fluctuated, indicating that the controller did not get the timely response to the system control instructions. The response curve of the experimental group was almost unchanged, indicating that the controller could keep good control of the system in case of sudden failure.

To sum up, the accurate decentralized H∞ controller for a class of generalized power systems studied in this paper is more robust than the traditional fuzzy controller.

4. Conclusion

In this paper, a kind of generalized power system model is considered. Under the condition of observer, a system compact model composed of several generalized subsystems is established. Lyapunov function and Riccati inequality are used to solve the problem. Simulation results show that the proposed controller reduces the harmonic distortion rate of the power supply current, improves the compensation effect, improves the stability and robustness of the system, and improves the reliability of the dynamic operation of the generalized power system.

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