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Decentralized Robust Control for Multi-Machine Power System

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Abstract: This paper proposes a new decentralized output feedback control scheme for three-machine power system. The decentralized controller synthesis problem is formulated as a scaled H_∞ control problem, and an LMI-based algorithm is developed to synthesize the decentralized controller. The proposed controller provides robustness with regard to parametric uncertainties and also attenuates bounded exogenous disturbances in the sense of L_2-gain. Simulation results clearly show the effectiveness of the developed decentralized output feedback control scheme.

Keywords: Power system, decentralized output feedback control, nonlinearity, robustness, LMI.

1. INTRODUCTION

For large-scale power system, which commonly consists of interconnected subsystems, the centralized control system is expensive to implement because of high communication cost and computational burden.

On the contrary, in the decentralized control system, each local controller determines the control action based on the local measurement only. That is, the decentralized control is a more effective way to resolve issues of communication delay and data loss.

Recently, several decentralized control methods have been developed. Major ones are overlapping control (Suehiro et al, 2012) and homotopy (Chen et al, 2005) methods.

However, conventional methods are probably not suitable for large-scale power system because of nonlinear interconnections between subsystems.

This paper aims at developing a new decentralized output feedback control scheme for a three-machine power system with nonlinear interconnections. We formulate the synthesis problem as a scaled H_∞ control problem and propose a novel LMI-based algorithm to synthesize the decentralized static output feedback controller.

The proposed decentralized controller enhances the disturbance attenuation performance in the sense of L_2-gain.

The effectiveness of proposed method is verified by simulation results.

2. SYSTEM DESCRIPTION

We consider a power system shown in Fig. 1.

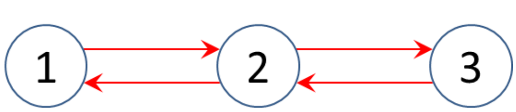

Fig. 1. A three-machine power system.

The swing equation for the i-th generator ($1 \le i \le 3$) is

$$\frac{2H_i}{f_s} \cdot \frac{\mathrm{d}\Delta f_i(t)}{\mathrm{d}t} + D_i \Delta f_i(t) = P_{mi}(t) - \left[\sum_{j=1,\, j\neq i}^{3} P_{tie,ij}(t)\right] - P_{Li}(t), \quad (1)$$

where P_{mi} is the mechanical input energy, P_{Li} is the load disturbance, $P_{tie,ij}$ is the tie line power flow directed from the i-th generator to the j-th generator ($1 \le j \le 3$, $j \ne i$), f_s is the nominal frequency, H_i is the inertia constant, D_i is the damping constant, Δf_i is the frequency deviation.

Assumption 1. Each H_i satisfies $0.8H_{i,0} \le H_i \le 1.2H_{i,0}$, where $H_{i,0}$ is the nominal value of H_i.

Neglecting the transmission loss, we can write the tie line power flow in the form

$$P_{tie,ij}(t) = E_i(t)\, E_j(t) \cdot B_{ij} \sin[\delta_i(t) - \delta_j(t)], \quad (2)$$

where δ_i and δ_j are power angles, E_i and E_j are terminal voltage magnitudes, B_{ij} denotes the susceptance between the i-th and j-th nodes.

Since small variations in load are expected during normal operation, we make the following assumption:

Assumption 2. Each E_i is close to its nominal value, that is, $E_i(t) \approx E_{i,0}$, where $E_{i,0}$ is the nominal value of E_i.

The expression for the reference value of $P_{tie,ij}$ is

$$P_{tie,ij,0} = k_{ij} \sin(\delta_{i,0} - \delta_{j,0}), \quad (3)$$

where $k_{ij} \triangleq E_{i,0}E_{j,0}B_{ij}$, $\delta_{i,0}$ represents the reference value of δ_i and $\delta_{j,0}$ represents the reference value of δ_j.

Under Assumption 2, the tie line power flow deviation can be approximated as $\Delta P_{tie,ij}(t) \approx k_{ij}h_{ij}(t)$, where

$$h_{ij}(t) = \sin[\delta_i(t) - \delta_j(t)] - \sin(\delta_{i,0} - \delta_{j,0}). \quad (4)$$

Theorem 1. The interconnection term h_{ij} can be bounded by a nonlinear function of power angle deviations:

$$|h_{ij}(t)|^2 \le |\Delta\delta_{ij}(t)|^2, \quad (5)$$

where $\Delta\delta_{ij}(t) = \Delta\delta_i(t) - \Delta\delta_j(t)$ with $\Delta\delta_i(t) = \delta_i(t) - \delta_{i,0}$ and $\Delta\delta_j(t) = \delta_j(t) - \delta_{j,0}$.

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Proof. We use trigonometric identities to express (4) as

$$h_{ij}(t) = 2\left[\cos\frac{\delta_{ij}(t)+\delta_{ij,0}}{2}\right]\cdot\left[\sin\frac{\Delta\delta_i(t)-\Delta\delta_j(t)}{2}\right],$$

where $\delta_{ij}(t) = \delta_i(t) - \delta_i(t)$ and $\delta_{ij,0} = \delta_{i,0} - \delta_{j,0}$.

From the inequality $\left|\sin\frac{\Delta\delta_i(t)-\Delta\delta_j(t)}{2}\right| \le \left|\frac{\Delta\delta_i(t)-\Delta\delta_j(t)}{2}\right|$, it is straightforward to show that h_{ij} satisfies (5).

Let $P_{Li,0}$ denote the nominal value of P_{Li}. By performing simple algebraic manipulations, we have

$$\begin{aligned}\frac{\mathrm{d}\Delta f_i(t)}{\mathrm{d}t} &= -\frac{f_s D_i}{2H_i}\Delta f_i(t) + \frac{f_s}{2H_i}\Delta P_{mi}(t)\\ &\quad -\frac{f_s}{2H_i}\left[\sum_{j=1,\, j\neq i}^{3} k_{ij}h_{ij}(t)\right] - \frac{f_s\rho_i}{2H_i}w_{pi}(t),\end{aligned}\tag{6}$$

where $\Delta P_{mi}(t) = P_{mi}(t) - P_{Li,0} - \sum_{j=1,\, j\neq i}^{3} P_{tie,ij,0}$ and $w_{pi}(t) = \frac{1}{\rho_i}w_i(t)$ with $w_i(t) = P_{Li}(t) - P_{Li,0}$, $\rho_i \in \mathbb{R}^+$.

Assumption 3. w_i and its variation rate are bounded.

The 3rd term on the right-hand side of (6) can be written in the compact form $\sum_{j=1,\, j\neq i}^{3} k_{ij}h_{ij}(t) = b_i^{\mathrm{T}} w_{qi}(t)$ with

$$b_1 = k_{12},\; w_{q1}(t) = h_{12}(t),\; b_2 = [k_{21}\;\; k_{23}]^{\mathrm{T}},$$
$$w_{q2}(t) = [h_{21}(t)\;\; h_{23}(t)]^{\mathrm{T}},\; b_3 = k_{32},\; w_{q3}(t) = h_{32}(t).$$

Let us introduce the new parameter $\theta_i = \frac{f_s}{2H_i}$. By choosing states for the i-th machine as

$$\begin{aligned}&[x_{i1}(t)\;\; x_{i2}(t)\;\; x_{i3}(t)\;\; x_{i4}(t)]^{\mathrm{T}}\\ &= [\Delta\delta_i(t)\;\; \Delta f_i(t)\;\; \Delta P_{mi}(t)\;\; \Delta P_{ti}(t)]^{\mathrm{T}},\end{aligned}$$

the dynamic model can be written in state-space form as

$$\begin{aligned}\dot{x}_{i1}(t) &= 2\pi\cdot x_{i2}(t),\\ \dot{x}_{i2}(t) &= (-D_i\theta_i)\,x_{i2}(t) + \theta_i x_{i3}(t)\\ &\quad + \left(-b_i^{\mathrm{T}}\theta_i\right)w_{qi}(t) + (-\rho_i\theta_i)\,w_{pi}(t),\\ \dot{x}_{i3}(t) &= (-T_{ti})^{-1}x_{i3}(t) + (T_{ti})^{-1}x_{i4}(t),\\ \dot{x}_{i4}(t) &= (-T_{gvi}R_i)^{-1}x_{i2}(t) + (-T_{gvi})^{-1}x_{i4}(t)\\ &\quad + (T_{gvi})^{-1}u_i(t),\end{aligned}\tag{7}$$

where ΔP_{ti} is the incremental change in value position, T_{ti} is the turbine time constant, R_i is the regulation constant, T_{gvi} is the governor time constant, u_i is the control input.

As illustrated in Fig. 2, we can obtain the augmented plant $G_{fi}(\theta_i)$ by connecting weight functions with $G_i(\theta_i)$ which represents the plant corresponding to (7).

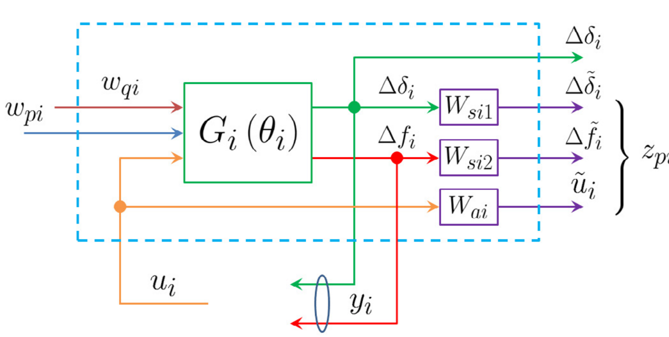

Fig. 2. Block diagram of the augmented plant $G_{fi}(\theta_i)$.

Definition 1. Θ_i is a convex polytope with 2 vertices, and is defined as

$$\Theta_i \triangleq \mathrm{Co}\{\theta_{i,1},\, \theta_{i,2}\},\; \theta_{i,1} = \frac{f_s}{2.4H_{i,0}},\; \theta_{i,2} = \frac{f_s}{1.6H_{i,0}}.$$

Then, we introduce new variables

$$\bar{z}_{pi}(t) = Q_i\Delta\delta_i(t),\; z_{qi}(t) = \bar{z}_{pi}(t) - \bar{w}_{pi}(t).\tag{8}$$

For the 1st machine, we select

$$Q_1 = I_1,\; \bar{w}_{p1}(t) = \Delta\delta_2(t),$$

such that $\bar{z}_{p1}(t) = \Delta\delta_1(t)$ and $z_{q1}(t) = \Delta\delta_{12}(t)$.

For the 2nd machine, we select

$$Q_2 = [I_1\;\; I_1]^{\mathrm{T}},\; \bar{w}_{p2}(t) = [\Delta\delta_1(t)\;\; \Delta\delta_3(t)]^{\mathrm{T}},$$

such that

$$\bar{z}_{p2}(t) = [\Delta\delta_2(t)\;\; \Delta\delta_2(t)]^{\mathrm{T}},\; z_{q2}(t) = [\Delta\delta_{21}(t)\;\; \Delta\delta_{23}(t)]^{\mathrm{T}}.$$

For the 3rd machine, we select

$$Q_3 = I_1,\; \bar{w}_{p3}(t) = \Delta\delta_2(t),$$

such that $\bar{z}_{p3}(t) = \Delta\delta_3(t)$ and $z_{q3}(t) = \Delta\delta_{32}(t)$.

The generalized plant $G_{pi}(\theta_i)$ is obtained from the interconnection of the augmented plant $G_{fi}(\theta_i)$ with (8).

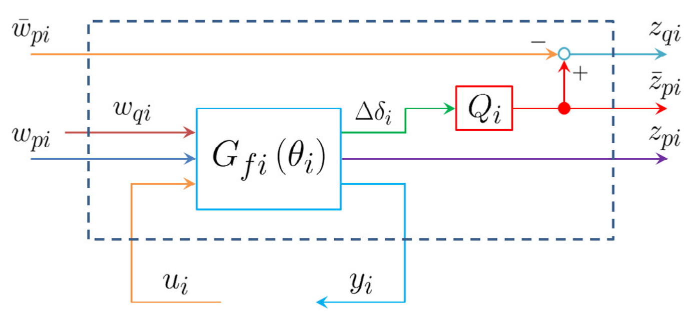

Fig. 3. Block diagram of the generalized plant $G_{pi}(\theta_i)$.

We express the generalized plant $G_{pi}(\theta_i)$ as

$$\begin{aligned}\dot{x}_i(t) &= A_i(\theta_i)\,x_i(t) + B_{1\eta,i}(\theta_i)\,w_{\eta i}(t)\\ &\quad + B_{1p,i}(\theta_i)\,w_{pi}(t) + B_{2i}u_i(t),\\ z_{\eta i}(t) &= C_{1\eta,i}x_i(t) + D_{11\eta,i}w_{\eta i}(t),\\ z_{pi}(t) &= C_{1p,i}x_i(t) + D_{12p,i}u_i(t),\; y_i(t) = C_{2i}x_i(t),\end{aligned}\tag{9}$$

where $x_i \in \mathbb{R}^7$ is the plant state vector and

$$y_i(t) = [x_{i1}(t)\;\; x_{i2}(t)]^{\mathrm{T}},\; z_{\eta i}(t) = \left[z_{qi}^{\mathrm{T}}(t)\;\; \bar{z}_{pi}^{\mathrm{T}}(t)\right]^{\mathrm{T}} \in \mathbb{R}^{n_i},$$
$$w_{\eta i}(t) = \left[w_{qi}^{\mathrm{T}}(t)\;\; \bar{w}_{pi}^{\mathrm{T}}(t)\right]^{\mathrm{T}} \in \mathbb{R}^{n_i}$$

with $n_1 = 2$, $n_2 = 4$ and $n_3 = 2$.

By normalization, θ_i can be written in the form

$$\theta_i = \theta_{i,0} + r_i\lambda_i(\theta_i),\tag{10}$$

where $\theta_{i,0} = \frac{5f_s}{9.6H_{i,0}}$, $r_i = \frac{f_s}{9.6H_{i,0}}$ such that $|\lambda_i(\theta_i)| \le 1$.

By substituting (10) into the matrix $A_i(\theta_i)$, and performing the matrix decomposition, we have

$$A_i(\theta_i) = A_{i,0} + B_{1\Delta,i}\cdot\Delta_i(\theta_i)\,C_{1\Delta,i},\tag{11}$$

where $A_{i,0}$ indicates the matrix with respect to $\theta_{i,0}$ and

$$\Delta_i(\theta_i) = \lambda_i(\theta_i)\,I_2.\tag{12}$$

Corollary 1. For all $q_i = 1, 2$,

$$A_i(\theta_{i,q_i}) = A_{i,0} + B_{1\Delta,i}\cdot\Delta_i(\theta_{i,q_i})\,C_{1\Delta,i},\tag{13}$$
$$\Delta_i^{\mathrm{T}}(\theta_{i,q_i})\,\Delta_i(\theta_{i,q_i}) = I_2.\tag{14}$$