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Decentralized Disturbance Attenuation Control for Multi-Machine Power System

Wei Wang * **Hiromitsu Ohmori** *

* *Department of System Design Engineering, Keio University, Kanagawa, Japan (e-mail: claudioceke@163.com; ohm@sd.keio.ac.jp).*

Abstract: This paper proposes a decentralized control scheme for multi-machine power system with nonlinear interconnections. The decentralized control law is constructed by a backstepping method. The proposed controller is robust with regard to the parameter uncertainties and also attenuates persistent disturbances in the sense of L_2-gain. Simulation results on a three-machine power system clearly show the effectiveness of the proposed decentralized control scheme.

Keywords: Decentralized control, power system, nonlinear system, backstepping.

1. INTRODUCTION

The large-scale power system consisting of interconnected subsystems prefers the decentralized control because of the low computational burden and communication cost.

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

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

This paper aims at developing a new decentralized control scheme for the multi-machine system based on a recursive algorithm without performing system linearization.

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

Moreover, parameter uncertainties are taken into account in the controller design to achieve robustness.

The proposed scheme is applied to a three-machine power system. It is confirmed by simulation results that a satisfactory performance has been achieved.

2. SYSTEM DESCRIPTION

In this section, we consider a power system consisting of n machines interconnected through a transmission network.

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

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

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 ($1 \le j \le n$, $j \neq i$), f_s is the nominal frequency, H_i is the inertia constant, D_i is the damping constant, Δf_i is the frequency deviation.

Remark 1. Generally speaking, the damping constant cannot be measured accurately.

Assumption 1. Each D_i satisfies

$$0.8D_{i,0} \le D_i \le 1.2D_{i,0},\ 1 \le i \le n,$$

where $D_{i,0}$ is the nominal value of D_i.

Neglecting the transmission loss, the tie line power can be written in the form

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

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

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

Assumption 2. $E_i(t) \approx E_{i,0}$ and $E_j(t) \approx E_{j,0}$, where $E_{i,0}$ and $E_{j,0}$ are reference values of E_i and E_j, respectively.

The power angle is related to Δf_i, and is given by

$$\delta_i(t) = 2\pi \int_0^t \Delta f_i(\tau)\, \mathrm{d}\tau + \delta_i(0). \tag{3}$$

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

$$P_{tie,ij,0} = P_{tie,ij,max} \cdot \sin(\delta_{i,0} - \delta_{j,0}), \tag{4}$$

where $P_{tie,ij,max} \triangleq E_{i,0}E_{j,0}B_{ij}$, $\delta_{i,0}$ and $\delta_{j,0}$ denote reference values of δ_i and δ_j, respectively.

Under Assumption 2, the tie line power flow deviation can be approximately expressed as

$$\Delta P_{tie,ij}(t) \approx P_{tie,ij,max} \cdot h_{ij}(t), \tag{5}$$

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

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

$$|h_{ij}(t)| \le |\Delta\delta_i(t)| + |\Delta\delta_j(t)|, \tag{6}$$

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

Proof. We can use the trigonometric identities to conveniently express h_{ij} as

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

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

From the inequality

$$\left|\sin \frac{\Delta\delta_i(t) - \Delta\delta_j(t)}{2}\right| \le \left|\frac{\Delta\delta_i(t) - \Delta\delta_j(t)}{2}\right|,$$

we have

$$|h_{ij}(t)| \le |\Delta\delta_i(t) - \Delta\delta_j(t)|. \quad (7)$$

It is straightforward to show that h_{ij} satisfies (6).

It is noted that $P_{tie,ij,max} = 0$ if the i-th machine has no connection with the j-th machine.

Hence the right side of (5) can be equivalently written as

$$P_{tie,ij,max} \cdot h_{ij}(t) = k_{ij}\sqrt{g_{ij}} h_{ij}(t), \quad (8)$$

where $k_{ij} = P_{tie,ij,max} \cdot \sqrt{g_{ij}} \ge 0$ and

$$g_{ij} \triangleq \begin{cases} 1 & \text{if the } i\text{-th machine has a connection with the } j\text{-th machine,} \\ 0 & \text{if the } i\text{-th machine has no connection with the } j\text{-th machine.} \end{cases}$$

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

$$\begin{aligned}\frac{\mathrm{d}\Delta f_i(t)}{\mathrm{d}t} &= -\frac{f_s D_i}{2H_i}\Delta f_i(t) + \frac{f_s}{2H_i}\Delta P_{mi}(t) \\ &- \frac{f_s}{2H_i}\left[\sum_{j=1,\, j\neq i}^{n} k_{ij}\sqrt{g_{ij}} h_{ij}(t)\right] - \frac{f_s}{2H_i} w_i(t),\end{aligned} \quad (9)$$

where $\Delta P_{mi}(t) = P_{mi}(t) - P_{Li,0} - \sum_{j=1,\, j\neq i}^{n} P_{tie,ij,0}$ and $w_i(t) = P_{Li}(t) - P_{Li,0}$.

The turbine is assumed to be of the non-reheat type, and is modeled as

$$\frac{\mathrm{d}\Delta P_{mi}(t)}{\mathrm{d}t} = -\frac{1}{T_{ti}}\Delta P_{mi}(t) + \frac{1}{T_{ti}}\Delta P_{ti}(t), \quad (10)$$

where T_{ti} is the turbine time constant, ΔP_{ti} is the incremental change in value position.

The mechanical-hydraulic governor can be represented as the 1st order system

$$\frac{\mathrm{d}\Delta P_{ti}(t)}{\mathrm{d}t} = \frac{1}{T_{gvi}}\left[-\Delta P_{ti}(t) - \frac{\Delta f_i(t)}{R_i} + u_i(t)\right], \quad (11)$$

where R_i and T_{gvi} are the regulation constant and governor time constant, u_i is the control input, respectively.

By setting the pre-feedback

$$u_i(t) = v_i(t) + \frac{\Delta f_i(t)}{R_i} + \Delta P_{ti}(t), \quad (12)$$

we have

$$\frac{\mathrm{d}\Delta P_{ti}(t)}{\mathrm{d}t} = \frac{1}{T_{gvi}} v_i(t). \quad (13)$$

Remark 2. The introduced variable v_i is regarded as the new control input of the i-th machine.

3. PROBLEM FORMULATION

We mainly concern the disturbance effects on power angle and frequency deviations.

Therefore, the controlled output vector is selected as

$$z_i(t) = \begin{bmatrix} z_{i1}(t) \\ z_{i2}(t) \end{bmatrix} = \begin{bmatrix} q_{i1}\Delta\delta_i(t) \\ q_{i2}\Delta f_i(t) \end{bmatrix},\ 1 \le i \le n,$$

where q_{i1} and q_{i2} are positive weighting factors.

The dynamic model of the i-th generator can be expressed in a compact form as

$$\begin{aligned}\frac{\mathrm{d}z_i(t)}{\mathrm{d}t} &= A_i(D_i) z_i(t) + B_i\Delta P_{mi}(t) \\ &- B_i w_i(t) - B_i\left[\sum_{j=1,\, j\neq i}^{n} k_{ij}\sqrt{g_{ij}} h_{ij}(t)\right],\end{aligned} \quad (14)$$

where

$$A_i(D_i) = \begin{bmatrix} 0 & \dfrac{2\pi q_{i1}}{q_{i2}} \\ 0 & -\dfrac{f_s D_i}{2H_i} \end{bmatrix},\ B_i = \begin{bmatrix} 0 \\ \dfrac{f_s q_{i2}}{2H_i} \end{bmatrix}.$$

Without loss of generality, we assume the following condition on the system (14).

Assumption 3. w_i and its variation rate are bounded, i.e. there exist known positive scalars d_i and v_i such that

$$\|w_i(t)\| \le d_i,\ \left\|\frac{\mathrm{d}w_i(t)}{\mathrm{d}t}\right\| \le v_i,$$

where $\|\cdot\|$ denotes the Euclidean norm of a vector.

Remark 3. The control task addressed in this paper is to construct the state feedback control law

$$v_i(t) = \alpha_i(z_i(t),\, \Delta P_{mi}(t),\, \Delta P_{ti}(t)),\ 1 \le i \le n,$$

for the system described by (10), (13) and (14), such that for a given positive value γ, the corresponding closed-loop interconnected system satisfies the dissipation inequality:

$$\frac{\mathrm{d}V}{\mathrm{d}t} \le -\|z(t)\|^2 + \gamma^2\|w(t)\|^2, \quad (15)$$

where V is a nonnegative storage function and

$$z(t) = \left[z_1^{\mathrm{T}}(t) \cdots z_n^{\mathrm{T}}(t)\right]^{\mathrm{T}},\ w(t) = [w_1(t) \cdots w_n(t)]^{\mathrm{T}}.$$

4. DECENTRALIZED CONTROLLER DESIGN

In this section, we will propose a backstepping method to construct a storage function V which satisfies (15).

The feedback control law will be achieved in the recursive design procedure. The design process involves five steps.

Step 1. Suppose for all $D_i \in \Theta_i$, there exists a symmetric positive definite matrix P_i such that

$$P_i A_i(D_i) + A_i^{\mathrm{T}}(D_i) P_i - 2\varepsilon_i P_i B_i B_i^{\mathrm{T}} P_i + \frac{1}{\mu_i} I_2 < 0, \quad (16)$$

where μ_i and ε_i are prescribed positive constant.

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

$$\Theta_i \triangleq \mathrm{Co}\left\{\underline{D}_i,\, \overline{D}_i\right\},\ \underline{D}_i = 0.8D_{i,0},\ \overline{D}_i = 1.2D_{i,0}.$$

By Schur complement, (16) is transformed equivalently to the following matrix inequality:

$$\Phi_i(D_i,\, P_i) = \begin{bmatrix} Q_i(D_i,\, P_i) & I_2 \\ I_2 & -\mu_i I_2 \end{bmatrix} < 0, \quad (17)$$