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Decentralized Disturbance Attenuation Control for Multi-machine Power System with Nonlinear Interconnections

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Abstract: This paper presents a novel decentralized control scheme for a multi-machine power system with nonlinear interconnections. We adopt a recursive backstepping method and develop a novel LMI-based algorithm to construct decentralized feedback control laws that improve the disturbance attenuation ability of the closed-loop interconnected system and do not require the online optimization. Simulation results show the effectiveness of our proposed control strategy.

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

1. INTRODUCTION

For a large-scale power system, which generally consists of interconnected subsystems, a centralized control system is extremely expensive and difficult to implement because of huge computational burden and high communication cost. On the contrary, the decentralized control is a more useful way to solve issues of data loss and communication delay.

As a result, the decentralized control has been a preferred strategy for large-scale power systems, because it does not require the communication between different subsystems.

Recently, several decentralized control methods have been developed and applied to the disturbance rejection control of complex power systems. Major ones are the distributed hierarchical control approach (Suehiro et al, 2012) and the homotopy method (Chen et al, 2005).

However, above-mentioned conventional schemes are probably not suitable for a large-scale power system because of the existence of nonlinear interconnections.

This paper deals with the decentralized disturbance attenuation control problem of the typical three-machine power system. We aim at developing a new decentralized control scheme without using the direct feedback linearization. To this end, we adopt a recursive backstepping approach and present a novel LMI-based iterative algorithm.

Constructed decentralized feedback control laws attenuate bounded exogenous disturbances in the sense of L_2-gain.

The effectiveness of our proposed control strategy is verified by simulation results.

2. SYSTEM DESCRIPTION

We deal with a typical three-machine power system which is shown in Fig. 1.

Definition 1. The point set $\mathcal{O}$ is defined as

$$\mathcal{O} \triangleq \{(\varpi, \varsigma) \mid \varpi \in \mathcal{N}, \varsigma \in \mathcal{N} \text{ and } \varpi \neq \varsigma\},$$

where the index set $\mathcal{N} \triangleq \{1, 2, 3\}$.

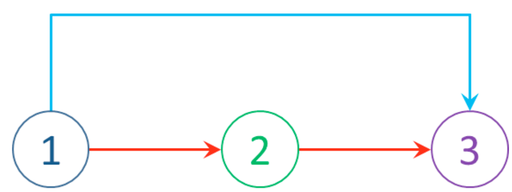

Fig. 1. A three-machine power system.

Definition 2. The rotor angle deviation is defined as

$$\Delta\delta_l(t) \triangleq \delta_l(t) - \delta_l^*, \forall l \in \mathcal{N},$$

where δ_l denotes the rotor angle of the l-th generator, in rad, and δ_l^* denotes the nominal value of δ_l.

Definition 3. For the l-th generator, z_{el} represents the incremental change in its quadrature-axis transient voltage, and is defined as

$$z_{el}(t) \triangleq E'_{ql}(t) - E'_{ql,0}, \forall l \in \mathcal{N},$$

where E'_{ql} denotes the quadrature-axis transient voltage of the l-th generator, in pu, $E'_{ql,0}$ is the nominal value of E'_{ql}.

The swing equation for the i-th ($i \in \mathcal{N}$) generator is

$$\frac{2H_i}{f_s} \cdot \frac{\mathrm{d}\Delta f_i(t)}{\mathrm{d}t} + D_i \Delta f_i(t) = P_{mi}(t) - P_{Li}(t) - P_{tie,i}(t), \quad (1)$$

where f_s is the nominal frequency, in Hz, and for the i-th generator, Δf_i is its frequency deviation, in Hz, P_{mi} is its mechanical input power, in pu, P_{Li} is its load disturbance, in pu, $P_{tie,i}$ is its total tie line power flow, in pu, D_i is its damping constant, in pu/Hz, H_i is its inertia constant, in sec. (Guo et al, 2000)

Ignoring line losses, the tie line power flow exported from the i-th generator to the j-th ($j \in \mathcal{N}$ and $j \neq i$) generator can be written in the form (Guo et al, 2000)

$$P_{tie,ij}(t) = E'_{qi}(t) E'_{qj}(t) \mathcal{B}_{ij} \sin \delta_{ij}(t), \quad (2)$$

where $\mathcal{B}_{ij} \in \mathbb{R}^+$ denotes the susceptance between i-th and j-th nodes, in pu, and $\delta_{ij}(t) = \delta_i(t) - \delta_j(t)$.

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Notice that each $P_{tie,ij}$ can be broken up as follows:

$$P_{tie,ij}(t) = \mathcal{B}_{ij}\bar{k}_{ij}(t) + k^*_{ij}\left[\sin\delta^*_{ij} + \varphi_{ij}(t)\right], \quad (3)$$

where for any $(i,j) \in \mathcal{O}$,

$$\bar{k}_{ij}(t) = \left[E'_{qi,0}z_{ej}(t) + E'_{qj,0}z_{ei}(t)\right]\sin\delta_{ij}(t) + z_{ei}(t)\,z_{ej}(t)\sin\delta_{ij}(t) \quad (4)$$

and $k^*_{ij} = E'_{qi,0}E'_{qj,0}\mathcal{B}_{ij} \in \mathbb{R}^+$, $\delta^*_{ij} = \delta^*_i - \delta^*_j$,

$$\varphi_{ij}(t) = \sin\delta_{ij}(t) - \sin\delta^*_{ij}. \quad (5)$$

Corollary 1. For any $(i,j) \in \mathcal{O}$,

$$\left|\bar{k}_{ij}(t)\right|^2 \le 1.5z^4_{ei}(t) + 3\left[E'_{qj,0}z_{ei}(t)\sin\delta_{ij}(t)\right]^2 + 1.5z^4_{ej}(t) + 3\left[E'_{qi,0}z_{ej}(t)\sin\delta_{ij}(t)\right]^2. \quad (6)$$

The sum of all tie line power flows exported from the i-th generator is computed as $P_{tie,i}(t) = \sum_{j=1,\,j\neq i}^{3} P_{tie,ij}(t) = P^*_{tie,i} + \Delta P_{tie,i}(t)$, where $P^*_{tie,i} = \sum_{j=1,\,j\neq i}^{3} k^*_{ij}\sin\delta^*_{ij}$.

From (3), it is clear that each $\Delta P_{tie,i}$ can be broken up as

$$\Delta P_{tie,i}(t) = \underbrace{\left[\sum_{j=1,\,j\neq i}^{3} k^*_{ij}\varphi_{ij}(t)\right]}_{b^{\mathrm{T}}_{qi,1}w_{qi,1}(t)} + \underbrace{\left[\sum_{j=1,\,j\neq i}^{3} \mathcal{B}_{ij}\bar{k}_{ij}(t)\right]}_{b^{\mathrm{T}}_{\kappa i}w_{\kappa i}(t)}. \quad (7)$$

Algebraic expressions of all $b_{qi,1}$ and $w_{qi,1}$ are

$$b_{q1,1}(t) = \left[k^*_{12}\ \ k^*_{13}\right]^{\mathrm{T}},\ w_{q1,1}(t) = \left[\varphi_{12}(t)\ \ \varphi_{13}(t)\right]^{\mathrm{T}},$$
$$b_{q2,1}(t) = \left[k^*_{21}\ \ k^*_{23}\right]^{\mathrm{T}},\ w_{q2,1}(t) = \left[\varphi_{21}(t)\ \ \varphi_{23}(t)\right]^{\mathrm{T}},$$
$$b_{q3,1}(t) = \left[k^*_{31}\ \ k^*_{32}\right]^{\mathrm{T}},\ w_{q3,1}(t) = \left[\varphi_{31}(t)\ \ \varphi_{32}(t)\right]^{\mathrm{T}},$$

while algebraic expressions of all $b_{\kappa i}$ and $w_{\kappa i}$ are

$$b_{\kappa 1}(t) = \left[\frac{\mathcal{B}_{12}}{\varrho_{12}}\ \ \frac{\mathcal{B}_{13}}{\varrho_{13}}\right]^{\mathrm{T}},\ w_{\kappa 1}(t) = \left[\varrho_{12}\bar{k}_{12}(t)\ \ \varrho_{13}\bar{k}_{13}(t)\right]^{\mathrm{T}},$$
$$b_{\kappa 2}(t) = \left[\frac{\mathcal{B}_{21}}{\varrho_{21}}\ \ \frac{\mathcal{B}_{23}}{\varrho_{23}}\right]^{\mathrm{T}},\ w_{\kappa 2}(t) = \left[\varrho_{21}\bar{k}_{21}(t)\ \ \varrho_{23}\bar{k}_{23}(t)\right]^{\mathrm{T}},$$
$$b_{\kappa 3}(t) = \left[\frac{\mathcal{B}_{31}}{\varrho_{31}}\ \ \frac{\mathcal{B}_{32}}{\varrho_{32}}\right]^{\mathrm{T}},\ w_{\kappa 3}(t) = \left[\varrho_{31}\bar{k}_{31}(t)\ \ \varrho_{32}\bar{k}_{32}(t)\right]^{\mathrm{T}},$$

where for any $(i,j) \in \mathcal{O}$, ϱ_{ij} is a positive weighting factor.

Let P^*_{Li} represent the nominal value of P_{Li}. For simplicity, we denote $w_i(t) = P_{Li}(t) - P^*_{Li}$ and $\theta_i = \frac{f_s}{2H_i}$.

Assumption 1. For any $i \in \mathcal{N}$, there exist known positive scalars d_i and v_i such that $|w_i(t)| \le d_i$ and $\left|\frac{\mathrm{d}w_i(t)}{\mathrm{d}t}\right| \le v_i$.

After performing simple algebraic manipulations, we have

$$\frac{\mathrm{d}\Delta f_i(t)}{\mathrm{d}t} = -D_i\theta_i\Delta f_i(t) + \theta_i x_{i3}(t) - b^{\mathrm{T}}_{qi,1}\theta_i w_{qi,1}(t) - \left[b^{\mathrm{T}}_{\kappa i}\ \ \rho_i\right]\theta_i w_{\sigma i}(t), \quad (8)$$

where for any $i \in \mathcal{N}$, $x_{i3}(t) = P_{mi}(t) - P^*_{Li} - P^*_{tie,i}$ and

$$w_{\sigma i}(t) = \left[w^{\mathrm{T}}_{\kappa i}(t)\ \ w_{pi}(t)\right]^{\mathrm{T}} \in \mathbb{R}^3 \quad (9)$$

with $w_{pi}(t) = \frac{1}{\rho_i}w_i(t)$, $\rho_i \in \mathbb{R}^+$. By choosing states as

$$x_{i1}(t) = \Delta\delta_i(t),\ x_{i2}(t) = \Delta f_i(t),\ x_{i4}(t) = \Delta P_{ti}(t),$$

the dynamic model of the i-th mechanical system can be written in a state-space form as (Kundur, 1994)

$$\begin{aligned}
\dot{x}_{i1}(t) &= 2\pi\cdot x_{i2}(t),\\
\dot{x}_{i2}(t) &= (-D_i\theta_i)\,x_{i2}(t) + \theta_i x_{i3}(t) + \left(-b^{\mathrm{T}}_{qi,1}\theta_i\right)\\
&\quad\cdot w_{qi,1}(t) + \left[-b^{\mathrm{T}}_{\kappa i}\theta_i\ \ -\rho_i\theta_i\right]w_{\sigma i}(t),\\
\dot{x}_{i3}(t) &= (-T_{ti})^{-1}x_{i3}(t) + (T_{ti})^{-1}x_{i4}(t),\\
\dot{x}_{i4}(t) &= (-T_{gvi}R_{gvi})^{-1}x_{i2}(t) + (-T_{gvi})^{-1}x_{i4}(t)\\
&\quad + (T_{gvi})^{-1}u_i(t),
\end{aligned} \quad (10)$$

where u_i denotes the control input of the i-th mechanical system, in pu, R_{gvi} denotes the regulation constant of the i-th governor, in Hz/pu, T_{gvi} denotes the time constant of the i-th governor, in sec, ΔP_{ti} is the incremental change in value position of the i-th turbine, in pu, and T_{ti} represents the time constant of the i-th turbine, in sec.

The electrical equation for the i-th generator is

$$T_{d0,i}\frac{\mathrm{d}E'_{qi}(t)}{\mathrm{d}t} = -E'_{qi}(t) + E_{ei}(t) - \left(x_{di} - x'_{di}\right)I_{di}(t) + \bar{w}_i(t), \quad (11)$$

where for the i-th generator, E_{ei} is its field voltage, in pu, x_{di} is its d-axis reactance, in pu, x'_{di} is its d-axis transient reactance, in pu, I_{di} is its d-axis current, in pu, $T_{d0,i}$ is its d-axis transient short-circuit time constant, in sec, and $\bar{w}_i$ is its electromagnetism disturbance, in pu. (Lu et al, 2001)

The expression for I_{di} is given by (Lu et al, 2001)

$$I_{di}(t) = -\left[\sum_{j=1,\,j\neq i}^{3} E'_{qj}(t)\,\mathcal{B}_{ij}\cos\delta_{ij}(t)\right] = I_{di,0} - \mathcal{I}_i(t), \quad (12)$$

where $I_{di,0} = -\left[\sum_{j=1,\,j\neq i}^{3} E'_{qj,0}\mathcal{B}_{ij}\cos\delta^*_{ij}\right]$ and

$$\begin{aligned}
\mathcal{I}_i(t) &= \sum_{j=1,\,j\neq i}^{3} \mathcal{B}_{ij}\left[E'_{qj}(t)\cos\delta_{ij}(t) - E'_{qj,0}\cos\delta^*_{ij}\right]\\
&= \underbrace{\left[\sum_{j=1,\,j\neq i}^{3} h^*_{ij}\mu_{ij}(t)\right]}_{\mathcal{M}_i(t)} + \underbrace{\left[\sum_{j=1,\,j\neq i}^{3} \mathcal{B}_{ij}\bar{h}_{ij}(t)\right]}_{\bar{\mathcal{H}}_i(t)}
\end{aligned} \quad (13)$$

with for any $(i,j) \in \mathcal{O}$, $h^*_{ij} = E'_{qj,0}\mathcal{B}_{ij} \in \mathbb{R}^+$ and

$$\mu_{ij}(t) = \cos\delta_{ij}(t) - \cos\delta^*_{ij}, \quad (14)$$

$$\bar{h}_{ij}(t) = z_{ej}(t)\cos\delta_{ij}(t). \quad (15)$$

Theorem 1. For any $(i,j) \in \mathcal{O}$, the interconnected term Γ_{ij} is bounded by

$$\Gamma_{ij}(t) \triangleq \varphi^2_{ij}(t) + \mu^2_{ij}(t) \le \left|\Delta\delta_{ij}(t)\right|^2, \quad (16)$$

where $\Delta\delta_{ij}(t) = \delta_{ij}(t) - \delta^*_{ij} = \Delta\delta_i(t) - \Delta\delta_j(t)$.

Proof. Use the trigonometric identity to express Γ_{ij} as

$$\Gamma_{ij}(t) = 2 - 2\cos\left[\delta_{ij}(t) - \delta^*_{ij}\right] = 4\left|\sin\frac{\Delta\delta_{ij}(t)}{2}\right|^2.$$

From the inequality $\left|\sin\frac{a}{2}\right| \le \left|\frac{a}{2}\right|$ $(a \in \mathbb{R})$, it is straightforward to show that (16) holds for any $(i,j) \in \mathcal{O}$.

Assumption 2. For any $i \in \mathcal{N}$, $\bar{w}_i(t) \approx \bar{w}_{i,0}$, where $\bar{w}_{i,0}$ is the nominal value of $\bar{w}_i$.

Under *Assumption 2*, and taking the first derivative of z_{ei} with respect to time, we have