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IFAC-PapersOnLine 49-4 (2016) 043–048

Decentralized Disturbance Attenuation Control for Large-Scale Power System

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Abstract: This paper proposes a novel decentralized control method for the large-scale power system with nonlinear interconnections. We develop a recursive design method to construct the decentralized feedback control law. The proposed feedback control law improves the disturbance attenuation ability of the corresponding closed-loop interconnected system and does not require the online optimization. Simulation results show the efficiency of our proposed control strategy.

Keywords: Decentralized disturbance attenuation control, power system, recursive design.

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 aims at developing a new decentralized control scheme for the interconnected large-scale power system. A recursive backstepping scheme is adopted to construct the decentralize feedback control law that attenuates bounded exogenous disturbances in the sense of L_2-gain.

Our proposed control strategy is tested on a four-machine power system. It is confirmed by simulation results that a satisfactory performance has been achieved.

2. SYSTEM DESCRIPTION

We consider a complex electric power system consisting of n generators ($n \in \mathbb{Z}^+$) interconnected through a transmission network.

Definition 1. $\mathcal{O}$ denotes a set of points, and is defined as

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

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

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)

The rotor angle deviation of the i-th generator is

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

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 $\mathcal{B}_{ij}$ (≥ 0) denotes the susceptance between i-th and j-th nodes, in pu, and $\delta_{ij}(t) = \delta_i(t) - \delta_j(t)$.

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

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

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

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

and $k_{ij}^* = E'_{qi,0} E'_{qj,0} \mathcal{B}_{ij} \geq 0$, $\delta_{ij}^* = \delta_i^* - \delta_j^*$,

$$g_{ij}(t) = \sin\left[\delta_i(t) - \delta_j^*\right] - \sin\delta_{ij}^*, \quad (4)$$

$$\bar{\ell}_{ij}(t) = \sin\delta_{ij}(t) - \sin\left[\delta_i(t) - \delta_j^*\right]. \quad (5)$$

10.1016/j.ifacol.2016.05.008

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

$$|g_{ij}(t)| \le |\Delta\delta_i(t)|, \tag{6}$$

while the interconnected term $\bar{\ell}_{ij}$ is bounded by

$$\left|\bar{\ell}_{ij}(t)\right| \le |\Delta\delta_j(t)|. \tag{7}$$

Proof. We use the trigonometric identity to conveniently express g_{ij} and $\bar{\ell}_{ij}$ as

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

$$\bar{\ell}_{ij}(t) = -2\left[\cos\frac{\delta_{ij}(t) + \delta_i(t) - \delta_j^*}{2}\right] \cdot \left[\sin\frac{\Delta\delta_j(t)}{2}\right].$$

From the inequality $\left|\sin\frac{\eta}{2}\right| \le \left|\frac{\eta}{2}\right|$ $(\eta \in \mathbb{R})$, it is straightforward to show that (6) and (7) hold for any $(i,j) \in \mathcal{O}$.

The sum of all tie line power flows exported from the i-th generator is calculated as $P_{tie,i}(t) = \sum_{j=1,\,j\ne i}^{n} P_{tie,ij}(t)$.

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

$$P_{tie,i}(t) = P_{tie,i}^* + \mathcal{G}_i(t) + \bar{\mathcal{L}}_i(t) + \sum_{j=1,\,j\ne i}^{n} \mathcal{B}_{ij}\bar{k}_{ij}(t), \tag{8}$$

where $P_{tie,i}^* = \sum_{j=1,\,j\ne i}^{n} k_{ij}^* \sin\delta_{ij}^*$ and

$$\mathcal{G}_i(t) = \sum_{j=1,\,j\ne i}^{n} k_{ij}^* g_{ij}(t),\ \bar{\mathcal{L}}_i(t) = \sum_{j=1,\,j\ne i}^{n} k_{ij}^* \bar{\ell}_{ij}(t).$$

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

$$\begin{aligned}\frac{\mathrm{d}\Delta f_i(t)}{\mathrm{d}t} =& -\frac{f_s D_i}{2H_i}\Delta f_i(t) + \frac{f_s}{2H_i}x_{i1}(t)\\ & - \frac{f_s}{2H_i}\mathcal{G}_i(t) - \frac{f_s}{2H_i}\bar{\mathcal{L}}_i(t) - \frac{f_s}{2H_i}w_i(t),\end{aligned} \tag{9}$$

where $x_{i1}(t) = P_{mi}(t) - P_{Li,0} - P_{tie,i}^*$ and $w_i(t) = \bar{w}_i(t) + \sum_{j=1,\,j\ne i}^{n} \mathcal{B}_{ij}\bar{k}_{ij}(t)$ with $\bar{w}_i(t) = P_{Li}(t) - P_{Li,0}$.

Without loss of generality, we assume the following condition on the load disturbance of the i-th generator.

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

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

Assumption 2. Each E'_{ql} is close to its nominal value, i.e.

$$z_{el}(t) \approx 0,\ \forall\, l \in \mathcal{N},$$

such that for any $i \in \mathcal{N}$, $w_i(t) \approx \bar{w}_i(t)$.

Generally, we concern disturbance effects on power angles and frequencies. Therefore, regulation outputs of the i-th subsystem are chosen as

$$z_{i1}(t) = \sqrt{q_{i1}}\Delta\delta_i(t),\ z_{i2}(t) = \sqrt{q_{i2}}\Delta f_i(t),$$

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

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

$$\begin{aligned}\frac{\mathrm{d}z_i(t)}{\mathrm{d}t} =& A_i z_i(t) + B_i x_{i1}(t)\\ & - B_i\mathcal{G}_i(t) - B_i\bar{\mathcal{L}}_i(t) - B_i w_i(t),\end{aligned} \tag{10}$$

where $z_i(t) = [z_{i1}(t)\ \ z_{i2}(t)]^{\mathrm{T}}$.

The i-th turbine is assumed to be of non-reheat type, and is modeled as (Kundur, 1994)

$$T_{ti}\frac{\mathrm{d}x_{i1}(t)}{\mathrm{d}t} = -x_{i1}(t) + x_{i2}(t), \tag{11}$$

where T_{ti} represents the time constant of the i-th turbine, in sec, and x_{i2} represents the incremental change in value position of the i-th turbine, in pu.

The i-th mechanical-hydraulic type governor can be modeled as the 1st order system (Kundur, 1994)

$$T_{gi}\frac{\mathrm{d}x_{i2}(t)}{\mathrm{d}t} = u_i(t) - x_{i2}(t) - \frac{1}{R_{gi}}\Delta f_i(t), \tag{12}$$

where T_{gi} is the time constant of the i-th governor, in sec, u_i is the control input of the i-th governor, in pu, and R_{gi} is the regulation constant of the i-th governor, in Hz/pu.

In (12), setting the pre-feedback $u_i(t) = v_i(t) + x_{i2}(t) + \frac{1}{R_{gi}}\Delta f_i(t)$ leads to

$$\frac{\mathrm{d}x_{i2}(t)}{\mathrm{d}t} = \frac{1}{T_{gi}}v_i(t). \tag{13}$$

Problem 1. The problem that we have to address is how to construct the decentralized state feedback control law

$$v_i(t) = \alpha_i[z_i(t), x_{i1}(t), x_{i2}(t)],\ \forall\, i \in \mathcal{N},$$

so that for a given $\gamma \in \mathbb{R}^+$, the corresponding closed-loop interconnected system satisfies the dissipation inequality

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

where V is a Lyapunov function to be constructed, and

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

3. DECENTRALIZED CONTROLLER DESIGN

To solve the problem mentioned in the previous section, a backstepping approach will be adopted. As a consequence, a desirable decentralized state feedback control law will be achieved in the recursive design procedure.

The general design procedure involves five steps.

Step 1. Suppose for any $i \in \mathcal{N}$, there exists $\mu_i \in \mathbb{R}^+$ and $\mathbb{P}_i \in \mathbb{S}_{++}^2$ such that

$$\Psi_i(\mathbb{P}_i, \mu_i) = \begin{bmatrix} A_i\mathbb{P}_i + \mathbb{P}_i A_i^{\mathrm{T}} - 2\varphi_i B_i B_i^{\mathrm{T}} & \mathbb{P}_i \\ \mathbb{P}_i & -\mu_i I_2\end{bmatrix} < 0, \tag{14}$$

where φ_i is a prescribed positive constant.

Definition 4. The set of $\beta \times \beta$ symmetric positive definite matrices is denoted by $\mathbb{S}_{++}^{\beta}$, where $\beta \in \mathbb{Z}^+$.

The LMI optimization problem to be solved is

$$\begin{aligned}&\text{minimize} \quad \mu_i\\ &\text{subject to} \ \ \mathbb{P}_i = \mathbb{P}_i^{\mathrm{T}} > \frac{1}{\theta_i}I_2,\ \Psi_i(\mathbb{P}_i, \mu_i) < 0.\end{aligned}$$

Remark 1. For any $i \in \mathcal{N}$, θ_i is a known positive constant, and the first constraint implies $\mathbb{P}_i^{-1} \in \mathbb{S}_{++}^2$ and $\mathbb{P}_i^{-1} < \theta_i I_2$.

The set of optimal solutions is denoted by

$$\mu_i = \tilde{\mu}_i \in \mathbb{R}^+,\ \mathbb{P}_i = \tilde{\mathbb{P}}_i \in \mathbb{S}_{++}^2.$$