

Decentralized Load-Frequency Control of Large-Scale Nonlinear Power Systems: Fuzzy Overlapping Approach

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Abstract – This paper develops a design methodology of a decentralized fuzzy load-frequency controller for a large-scale nonlinear power system with valve position limits on governors. The concerned system is locally exactly modeled in Takagi–Sugeno’s form. Sufficient design condition for uniform ultimate boundedness of the closed-loop system is derived based on the overlapping decomposition. Convergence of all incremental frequency deviations to zero is also investigated. A simulation result is provided to visualize the effectiveness of the proposed technique.

Keywords: Load-frequency control, Valve position limits, Large-scale power system, Takagi–Sugeno fuzzy model-based control, Overlapping decomposition.

1. Introduction

Advent of a deregulated power market has re-attracted attentions to load-frequency control from two theoretical standpoints: (i) Frequent on-off controls of large capacity load in an individual area may cause long-lasting large overshoot in ΔX_{G_k} [1]. Thus limits on ΔX_{G_k} due to its mechanical restriction may not guarantee linearity of the system. The linear model that has commonly been adopted may no longer be valid for controller design [2, 3]. (ii) Deregulation policy makes the conventional centralized load-frequency control strategies based on full information in the entire power system [1, 4, 5] be impractical [6]. Rather, decentralized approach that a control unit is in charge of an area is more appealing, which provokes structurally overlapping constraint on control gain matrices [7, 8]. However, high dimensionality of a large-scale power system weighs down their synthesis.

In this paper, a decentralized load-frequency controller design technique is developed for a large-scale nonlinear power system with consideration of valve position limits. To tackle the difficulties mentioned above, we apply the Takagi–Sugeno (T–S) fuzzy model-based scheme that is widely recognized as a powerful resolution to nonlinear control problems [9], together with the overlapping decomposition technique that is found to provide efficient solutions to the high dimensionality issue in large-scale control systems [10, 11].

The system of interest is first locally exactly represented by a T–S fuzzy model, with $P_{T_{kl}}$ being overlapping parts between areas. We then expand this large-scale model into a larger one by using the overlapping decomposition,

where the small-scale sub-models (each representing an area) appear as disjoint and the gain matrices become block-diagonal. Design condition so that the expanded closed-loop system is uniformly ultimately bounded is derived. The designed (block-diagonal) gains are contracted to the original (overlapping) ones. It is shown that the resulting controller preserves the stability property of the expanded closed-loop system. We also investigate the convergence of all Δf_k s to zero. A numerical example is included to convincingly demonstrate the effectiveness of the proposed method.

2. Fuzzy Modeling

Assuming that all generators are of non-reheat type, the overall generator-load model of the power equilibrium in Area k with an integral control, connected with Area l via $\Delta P_{T_{kl}}$, is given in the following form [5]:

$$\begin{aligned}\dot{\Delta f}_k &= -\frac{1}{T_{P_k}}\Delta f_k + \frac{K_{P_k}}{T_{P_k}}\Delta P_{G_k} - \frac{K_{P_k}}{T_{P_k}}\Delta P_{D_k} - \frac{K_{P_k}}{T_{P_k}}\Delta P_{T_{kl}} \\ \dot{\Delta P}_{G_k} &= -\frac{1}{T_{T_k}}\Delta P_{G_k} + \frac{1}{T_{T_k}}\Delta X_{G_k} \\ \dot{\Delta X}_{G_k} &= -\frac{1}{R_k T_{G_k}}\Delta f_k - \frac{1}{T_{G_k}}\Delta X_{G_k} - \frac{1}{T_{G_k}}\Delta E_k + \frac{1}{T_{G_k}}\Delta P_{C_k} \\ \dot{\Delta E}_k &= K_{E_k}\Delta f_k + K_{E_k}\Delta P_{T_{kl}} \\ \dot{\Delta P}_{T_{kl}} &= T_{kl}\Delta f_k - T_{kl}\Delta f_l.\end{aligned}\tag{1}$$

Assumption 1: Assume that ΔP_{D_k} lives in \mathcal{L}_∞ . Thus there exists $\xi \in \mathbb{R}_{\geq 0}$ such that $\|\Delta P_{D_k}\|_{\mathcal{L}_\infty} < \xi$. The same applies to other areas.

The linear model in (1) may be valid, only when it is exposed to small ΔP_{D_k} . If large ΔP_{D_k} occurs under the deregulated environment, adequate large amount of steam flow should be provided, which is proportional to ΔX_{G_k} .

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However, due to the mechanical structure of the piston-like steam valve in the governor shown in Fig. 1, there are open and close limits on ΔX_{G_k} , denoted by $\Delta X_{G_k}^O$ and $\Delta X_{G_k}^C$, respectively. This constrained incremental change in the governor valve position can be expressed as the following nonlinear function:

$$\xi_k(\Delta X_{G_k}) := \begin{cases} \Delta X_{G_k}^C, & \text{if } \Delta X_{G_k} \leq \Delta X_{G_k}^C \\ \Delta X_{G_k}, & \text{if } \Delta X_{G_k}^C \leq \Delta X_{G_k} \leq \Delta X_{G_k}^O \\ \Delta X_{G_k}^O, & \text{otherwise.} \end{cases}$$

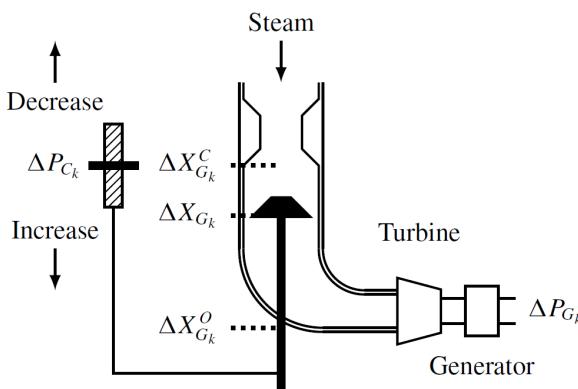


Fig. 1. Typical mechanical structure of governor.

Thus, (1) is no longer a good model for the power system when the valve position limits are taken into account.

For brevity of discussion, we consider a single-generator two-area power system considering the valve position limits on each governor shown in Fig. 2. Let the state, the control, and the disturbance be

$$x := (\Delta f_k, \Delta P_{G_k}, \Delta X_{G_k}, \Delta E_k, \Delta P_{T_{kl}}, \Delta f_l, \Delta P_{G_l}, \Delta X_{G_l}, \Delta E_l)$$

$$u := (\Delta P_{C_k}, \Delta P_{C_l})$$

$$w := (\Delta P_{D_k}, \Delta P_{D_l}).$$

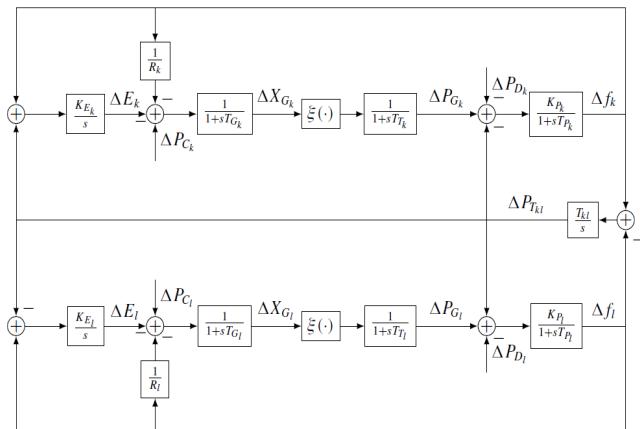


Fig. 2. Single-generator two-area power system considering the valve position limits on each governor.

Then, the state-space model of the concerned system is represented as

$$\begin{aligned} \dot{x}_1 &= -\frac{1}{T_{P_k}} x_1 + \frac{K_{P_k}}{T_{P_k}} x_2 - \frac{K_{P_k}}{T_{P_k}} x_5 - \frac{K_{P_k}}{T_{P_k}} w_1 \\ \dot{x}_2 &= -\frac{1}{T_{T_k}} x_2 + \frac{1}{T_{T_k}} \xi_k(x_3) \\ \dot{x}_3 &= -\frac{1}{R_k T_{G_k}} x_1 - \frac{1}{T_{G_k}} x_3 - \frac{1}{T_{G_k}} x_4 + \frac{1}{T_{G_k}} u_1 \\ \dot{x}_4 &= K_{E_k} x_1 + K_{E_k} x_5 \\ \dot{x}_5 &= T_{kl} x_1 - T_{kl} x_6 \\ \dot{x}_6 &= \frac{K_{P_l}}{T_{P_l}} x_5 - \frac{1}{T_{P_l}} x_6 + \frac{K_{P_l}}{T_{P_l}} x_7 - \frac{K_{P_l}}{T_{P_l}} w_2 \\ \dot{x}_7 &= -\frac{1}{T_{T_l}} x_7 + \frac{1}{T_{T_l}} \xi_l(x_8) \\ \dot{x}_8 &= -\frac{1}{R_l T_{G_l}} x_6 - \frac{1}{T_{G_l}} x_8 - \frac{1}{T_{G_l}} x_9 + \frac{1}{T_{G_l}} u_2 \\ \dot{x}_9 &= -K_{E_l} x_5 + K_{E_l} x_6. \end{aligned} \quad (2)$$

We seek to cast (2) into a T-S fuzzy model on the domain of interest $\mathcal{B}_{\Delta_x} := \{x : \|x\| \leq \Delta_x\}$ with some $\Delta_x \in \mathbb{R}_{\geq 0}$. To that end, we need to represent ξ_k and ξ_l as the following convex combinations:

$$\begin{aligned} \xi_k(x_3) &= \tilde{\theta}_1 \tilde{\alpha}_1 x_3 + \tilde{\theta}_2 \tilde{\alpha}_2 x_3, \quad 1 = \tilde{\theta}_1 + \tilde{\theta}_2 \\ \xi_l(x_8) &= \tilde{\theta}_3 \tilde{\alpha}_3 x_8 + \tilde{\theta}_4 \tilde{\alpha}_4 x_8, \quad 1 = \tilde{\theta}_3 + \tilde{\theta}_4. \end{aligned}$$

Solving the equations for $\tilde{\theta}_1$, $\tilde{\theta}_2$, $\tilde{\theta}_3$, and $\tilde{\theta}_4$ yields

$$\begin{aligned} \tilde{\theta}_1 &= \frac{\frac{\xi_1(x_3)}{x_3} - \tilde{\alpha}_2}{\tilde{\alpha}_1 - \tilde{\alpha}_2}, \quad \tilde{\theta}_2 = 1 - \tilde{\theta}_1 \\ \tilde{\theta}_3 &= \frac{\frac{\xi_2(x_8)}{x_8} - \tilde{\alpha}_4}{\tilde{\alpha}_3 - \tilde{\alpha}_4}, \quad \tilde{\theta}_4 = 1 - \tilde{\theta}_3 \end{aligned}$$

where setting $\tilde{\alpha}_1, \tilde{\alpha}_2, \tilde{\alpha}_3, \tilde{\alpha}_4 \in \mathbb{R}$ as

$$\begin{aligned} \tilde{\alpha}_1 &:= \sup_{x \in \mathcal{B}_{\Delta_x}} \left\{ \frac{\xi_1(x_3)}{x_3} \right\}, \quad \tilde{\alpha}_2 := \inf_{x \in \mathcal{B}_{\Delta_x}} \left\{ \frac{\xi_1(x_3)}{x_3} \right\} \\ \tilde{\alpha}_3 &:= \sup_{x \in \mathcal{B}_{\Delta_x}} \left\{ \frac{\xi_2(x_8)}{x_8} \right\}, \quad \tilde{\alpha}_4 := \inf_{x \in \mathcal{B}_{\Delta_x}} \left\{ \frac{\xi_2(x_8)}{x_8} \right\} \end{aligned}$$

guarantees $\tilde{\theta}_1, \tilde{\theta}_2, \tilde{\theta}_3, \tilde{\theta}_4 \in \mathbb{R}_{[0,1]}$, as shown in Fig. 3, which are adopted as membership functions. Now the T-S fuzzy model for (2) is constructed in the following form

$$\mathcal{S} : \dot{x} = \sum_{i=1}^4 \theta_i A_i x + B u + D w \quad (3)$$

on \mathcal{B}_{Δ_x} , where $\theta_1 = \tilde{\theta}_1 \tilde{\theta}_3$, $\theta_2 = \tilde{\theta}_1 \tilde{\theta}_4$, $\theta_3 = \tilde{\theta}_2 \tilde{\theta}_3$, and the system matrices are

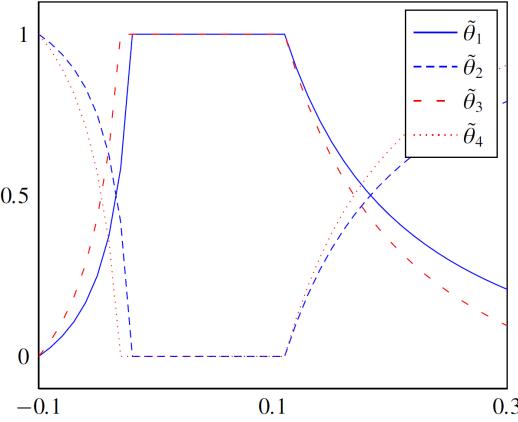


Fig. 3. Membership functions.

$$A_i = \begin{bmatrix} A_{i11} & A_{i12} & 0 \\ A_{i21} & A_{i22} & A_{i23} \\ 0 & A_{i32} & A_{i33} \end{bmatrix}, \quad B = \begin{bmatrix} B_{11} & 0 \\ B_{21} & B_{22} \\ 0 & B_{32} \end{bmatrix}$$

$$D = \begin{bmatrix} D_{11} & 0 \\ D_{21} & D_{22} \\ 0 & D_{32} \end{bmatrix}$$

where

$$A_{i11} = \begin{bmatrix} -\frac{1}{T_{P_k}} & \frac{K_{P_k}}{T_{P_k}} & 0 & 0 \\ 0 & -\frac{1}{T_{T_k}} & \frac{1}{T_{T_k}}\alpha_{k_i} & 0 \\ -\frac{1}{R_k T_{G_k}} & 0 & -\frac{1}{T_{G_k}} & -\frac{1}{T_{G_k}} \\ K_{E_k} & 0 & 0 & 0 \end{bmatrix}$$

$$A_{i12} = \begin{bmatrix} -\frac{K_{P_k}}{T_{P_k}} \\ 0 \\ 0 \\ K_{E_k} \end{bmatrix}, \quad A_{i21} = [T_{kl} \ 0 \ 0 \ 0], \quad A_{i22} = 0$$

$$A_{i23} = [-T_{kl} \ 0 \ 0 \ 0], \quad A_{i32} = \begin{bmatrix} \frac{K_{P_l}}{T_{P_l}} \\ 0 \\ 0 \\ -K_{E_l} \end{bmatrix}$$

$$A_{i33} = \begin{bmatrix} -\frac{1}{T_{P_l}} & \frac{K_{P_l}}{T_{P_l}} & 0 & 0 \\ 0 & -\frac{1}{T_{T_l}} & \frac{1}{T_{T_l}}\alpha_{l_i} & 0 \\ -\frac{1}{R_l T_{G_l}} & 0 & -\frac{1}{T_{G_l}} & -\frac{1}{T_{G_l}} \\ K_{E_l} & 0 & 0 & 0 \end{bmatrix}$$

$$B_{11} = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_{G_k}} \\ 0 \end{bmatrix}, \quad B_{21} = B_{22} = 0, \quad B_{32} = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_{G_l}} \\ 0 \end{bmatrix}$$

$$D_{11} = \begin{bmatrix} -\frac{K_{P_k}}{T_{P_k}} \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad D_{21} = D_{22} = 0, \quad D_{32} = \begin{bmatrix} -\frac{K_{P_l}}{T_{P_l}} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

where $\alpha_{k_1} = \alpha_{k_2} = \tilde{\alpha}_1$, $\alpha_{k_3} = \alpha_{k_4} = \tilde{\alpha}_2$, $\alpha_{l_1} = \alpha_{l_3} = \tilde{\alpha}_3$, and $\alpha_{l_2} = \alpha_{l_4} = \tilde{\alpha}_4$.

Remark 1: The T-S fuzzy model (3) does not have modeling error of (2) at any operating point over \mathcal{B}_{Δ_v} .

3. Controller Design

We employ a fuzzy load-frequency controller for (3) in the form of

$$\mathcal{K} : u := \sum_{i=1}^4 \theta_i K_i x. \quad (4)$$

Assumption 2: Area k uses its own local information $(\Delta f_k, \Delta P_{G_k}, \Delta X_{G_k}, \Delta E_k, \Delta P_{T_k})$ for load-frequency control. The same applies to Area l .

Deliberating Assumption 2, the gain matrix in (4) is not of full nonzero pattern but of the following overlapping structure

$$K_i = \begin{bmatrix} K_{i11} & K_{i12} & 0 \\ 0 & K_{i22} & K_{i23} \end{bmatrix} \quad (5)$$

where the partitioned matrices in K_i are compatible with those in A_i and B . The closed-loop system with (3) and (4) is written as

$$\dot{x} = \sum_{i=1}^4 \theta_i (A_i + BK_i)x + Dw =: \mathcal{F}(x). \quad (6)$$

Example 1 (Motivation): Consider the parameters in Table 1 and let $(\tilde{\alpha}_1, \tilde{\alpha}_2, \tilde{\alpha}_3, \tilde{\alpha}_4) := (1, 0.2, 1, 0.3)$ for (3). We attempt to design the decentralized fuzzy load-frequency controller (4) by the method in [4], with (5), a decay rate $\gamma = 0.1$, and a Lyapunov matrix $P := \text{diag}\{P_1, P_2, P_3\}$ compatible with A_i . However we fail to find any feasible solutions for (5), owing to the large scale of the power system.

Table 1. Parameters of the power system.

Parameter	Area k	Area l
T_{P_k}	20 s	22 s
T_{T_k}	0.3 s	0.2 s
T_{G_k}	0.08 s	0.1 s
K_{P_k}	120 Hz/p.u MW	125 Hz/p.u MW
R_k	2.4 Hz/p.u MW	2.5 Hz/p.u MW
K_{E_k}	0.423 MW	0.5 MW
T_{kl}	0.545 MW	0.545 MW
$\Delta X_{G_k}^C$	-0.02 p.u	-0.03 p.u
$\Delta X_{G_k}^O$	0.11 p.u	0.11 p.u

We seek to design (4) with (5) using the overlapping decomposition [10]. Consider the linear maps

$$\tilde{x} = \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix} := Vx, \quad x := U\tilde{x} \quad (7)$$

through the full-rank transform matrices

$$V := \left[\begin{array}{cc|c} I & 0 & 0 \\ 0 & 1 & 0 \\ \hline 0 & 1 & 0 \\ 0 & 0 & I \end{array} \right], \quad U := \left[\begin{array}{cc|c} I & 0 & 0 & 0 \\ 0 & \frac{1}{2} & \frac{1}{2} & 0 \\ \hline 0 & 0 & 0 & I \end{array} \right]$$

which are compatible with $\tilde{x}_1 := (x_1, x_2, x_3, x_4, x_5)$ and $\tilde{x}_2 := (x_5, x_6, x_7, x_8, x_9)$, and $UV = I$. Then (3) is expanded to

$$\tilde{\mathcal{S}} : \dot{\tilde{x}} = \sum_{i=1}^4 \theta_i \tilde{A}_i \tilde{x} + \tilde{B} u + \tilde{D} w \quad (8)$$

where by an explicit algebraic relation $\tilde{A}_i V = V A_i$ of (7), we obtain

$$\begin{aligned} \tilde{A}_i &= \begin{bmatrix} A_{i_{11}} & A_{i_{12}} & 0 & 0 \\ A_{i_{21}} & A_{i_{22}} & 0 & A_{i_{23}} \\ A_{i_{21}} & 0 & A_{i_{22}} & A_{i_{23}} \\ 0 & 0 & A_{i_{32}} & A_{i_{33}} \end{bmatrix} \\ \tilde{B} = VB &= \begin{bmatrix} B_{11} & 0 \\ B_{21} & B_{22} \\ B_{21} & B_{22} \\ 0 & B_{32} \end{bmatrix}, \quad \tilde{D} = VD = \begin{bmatrix} D_{11} & 0 \\ D_{21} & D_{22} \\ D_{21} & D_{22} \\ 0 & D_{32} \end{bmatrix}. \end{aligned}$$

The controller for (8) to be identical to (4) is taken as

$$\tilde{\mathcal{H}} : u := \sum_{i=1}^4 \theta_i \tilde{K}_i \tilde{x} \quad (9)$$

where \tilde{K}_i is of the following block-diagonal form:

$$\tilde{K}_i = \begin{bmatrix} K_{i_{11}} & K_{i_{12}} & 0 & 0 \\ 0 & 0 & K_{i_{22}} & K_{i_{23}} \end{bmatrix}.$$

The expanded closed-loop system is written as

$$\tilde{\mathcal{S}}_K : \dot{\tilde{x}} = \sum_{i=1}^4 \theta_i (\tilde{A}_i + \tilde{B} \tilde{K}_i) \tilde{x} + \tilde{D} w =: \tilde{\mathcal{F}}(\tilde{x}). \quad (10)$$

Theorem 1 (Design): Given $\gamma \in \mathbb{R}_{>0}$, if there exist matrices $P = P^T \succ 0$ and

$$M_i := \begin{bmatrix} M_{i_{11}} & M_{i_{12}} & 0 & 0 \\ 0 & 0 & M_{i_{22}} & M_{i_{23}} \end{bmatrix}$$

such that the following linear matrix inequalities are

satisfied for $i \in \{1, 2, 3, 4\}$

$$\begin{bmatrix} G^T (\tilde{A}_i P + \tilde{B} M_i + P \tilde{A}_i^T + M_i^T \tilde{B}^T + \gamma P) G & * \\ \tilde{D}^T G & -I \end{bmatrix} \prec 0 \quad (11)$$

then the expanded closed-loop system (10) is uniformly ultimately bounded, where $\tilde{K}_i = M_i P^{-1}$, $G \in \mathbb{R}^{10 \times 9}$ is given satisfying $P^{-1}V = GN$ for some nonsingular $N \in \mathbb{R}^{9 \times 9}$, and $*$ denotes the transposed entry in symmetric positions.

Proof: Choose a Lyapunov function $W(\tilde{x}) := \tilde{x}^T P^{-1} \tilde{x}$. Then, we readily compute as

$$\begin{aligned} \dot{W}(\tilde{x})|_{(10)} &= \tilde{\mathcal{F}}(\tilde{x})^T P^{-1} \tilde{x} + \tilde{x}^T P^{-1} \tilde{\mathcal{F}}(\tilde{x}) \\ &= \sum_{i=1}^4 \theta_i \begin{bmatrix} P^{-1} \tilde{x} \\ w \end{bmatrix}^T \\ &\quad \times \begin{bmatrix} \tilde{A}_i P + \tilde{B} M_i + P \tilde{A}_i^T + M_i^T \tilde{B}^T + \gamma P & * \\ \tilde{D}^T & -I \end{bmatrix} \\ &\quad \times \begin{bmatrix} P^{-1} \tilde{x} \\ w \end{bmatrix} - \gamma \tilde{x}^T P^{-1} \tilde{x} + w^T w \\ &= \sum_{i=1}^4 \theta_i \begin{bmatrix} N U \tilde{x} \\ w \end{bmatrix}^T \\ &\quad \times \begin{bmatrix} G^T (\tilde{A}_i P + \tilde{B} M_i + P \tilde{A}_i^T + M_i^T \tilde{B}^T + \gamma P) G & * \\ \tilde{D}^T G & -I \end{bmatrix} \\ &\quad \times \begin{bmatrix} N U \tilde{x} \\ w \end{bmatrix} - \gamma \tilde{x}^T P^{-1} \tilde{x} + w^T w \end{aligned}$$

where NU is of full rank. If (11) is true, we have

$$\dot{W} \leq -\gamma \lambda_{\min}(P^{-1}) \|\tilde{x}\|^2 + 2\xi^2$$

under Assumption 1. Define

$$\tilde{c} := \sqrt{\frac{2\xi^2}{\gamma \lambda_{\min}(P^{-1})}}.$$

One can easily agree that $\dot{W}(\tilde{x}) < 0$ as long as $\tilde{x} \notin \mathcal{B}_{\tilde{c}}$, where $\mathcal{B}_{\tilde{c}} := \{\tilde{x} : \|\tilde{x}\| \leq \tilde{c}\}$ is a compact set. According to the standard Lyapunov theorem, there exists a finite time $t_1 \in \mathbb{R}_{>0}$ such that \tilde{x} enters $\mathcal{B}_{\tilde{c}}$ at $t = t_1$ and remains for all $t \in \mathbb{R}_{>t_1}$. This implies that \tilde{x} is bounded and ultimately converges to $\mathcal{B}_{\tilde{c}}$.

After design, \tilde{K}_i is contracted to $K_i = \tilde{K}_i V$ due to the identity of (4) and (9).

Theorem 2 (Stability Preservation): Uniform ultimate boundedness of the expanded closed-loop system (10) implies that of the original closed-loop system (6).

Proof: Manipulating (6) with (10) yields

$$\begin{aligned}\dot{W}(x)|_{(6)} &= \frac{\partial W}{\partial \tilde{x}} \frac{\partial \tilde{x}}{\partial x} \mathcal{F}(x) \\ &= \frac{\partial W}{\partial \tilde{x}} V \left(\sum_{i=1}^4 \theta_i ((A_i + BK_i)x + Dw) \right) \\ &= \frac{\partial W}{\partial \tilde{x}} \tilde{\mathcal{F}}(\tilde{x}) \\ &= \dot{W}(\tilde{x})|_{(10)}.\end{aligned}$$

Further, we know from (7) that $\|\tilde{x}\| \leq \|V\| \|x\|$. Hence $\dot{W}(x)|_{(10)} < 0$ holds outside $\mathcal{B}_c := \{x : \|x\| \leq c\}$ where $c := \tilde{c}/\|V\|$. Thus, (6) preserves the stability of (10).

Remark 2: Let

$$G^T := \begin{bmatrix} 1 & \cdots & 0 & \beta_1 & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 1 & \beta_5 & 0 & \cdots & 0 \\ 0 & \cdots & 0 & \beta_6 & 1 & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \beta_9 & 0 & \cdots & 1 \end{bmatrix}$$

where $\beta_j = \mathbb{R}$, $j \in \{1, \dots, 9\}$, are appropriately chosen. Then by the constraint $P^{-1}V = GN \Rightarrow G^T P = N^{-T}V^T$, P must be in the form of $P = P_1 + P_2 p_{66}$ [11], where

$$P_1 = \begin{bmatrix} P_{111} & * & * \\ 0 & 0 & * \\ 0 & 0 & P_{133} \end{bmatrix}$$

and

$$P_2 = \begin{bmatrix} 0 & * & * & * & * & * & * & * \\ \vdots & \ddots & * & * & * & * & * & * \\ 0 & \cdots & 0 & * & * & * & * & * \\ \beta_1 & \cdots & \beta_4 & \beta_5 & * & * & * & * \\ 0 & \cdots & \cdots & 0 & 1 & * & * & * \\ \vdots & \ddots & & \vdots & -\beta_6 & 0 & * & * \\ \vdots & \ddots & & \vdots & \vdots & \vdots & \ddots & * \\ 0 & \cdots & \cdots & 0 & -\beta_9 & 0 & \cdots & 0 \end{bmatrix} p_{66}$$

where $P_{111}, P_{133} \in \mathbb{R}^{4 \times 4}$, and $p_{66} \in \mathbb{R}$ are decision variables for (11). Hence, P is structurally same to that in Example 1.

The following assumption is conventionally conjectured in the load-frequency control related context.

Assumption 3: In addition to Assumption 1, ΔP_{D_k} is modeled by a step function. Then we have a useful result.

Theorem 3 (Convergence of Δf_k s to Zero): The decentralized fuzzy load-frequency controller (4) drives Δf_k and Δf_l to zero.

Proof: Let $\phi(w)$ be a solution to $\mathcal{F}(x) = 0$. Since

$\dot{w} = 0$ from Assumption 3, $W(x)|_{(6)}$ keeps decreasing outside \mathcal{B}_c until $\dot{W}(x)|_{(6)} = 0$ at $x = \phi(w)$, because

$$\frac{\partial W}{\partial x} \mathcal{F}(x)|_{x=\phi(w)} = 0$$

but

$$\frac{\partial W}{\partial x} = 2x^T V^T P V \neq 0$$

for all $x \neq 0 \in \mathbb{R}^9$ due to

$$\text{rank}(V^T P V) = 9 \Rightarrow \mathcal{N}((V^T P V)^T) = \{0\}.$$

Therefore, x uniquely converges to $\phi(w)$. From $\mathcal{F}(\phi(w)) = 0$ and (2), we know that $\phi_1 + \phi_5 = 0$, $\phi_1 - \phi_6 = 0$, $-\phi_5 + \phi_6 = 0$, concluding $\Delta f_k = \phi_1 = 0$ and $\Delta f_l = \phi_6 = 0$.

The design procedure is summarized as follows:

Step 1) Expand the given system \mathcal{S} with V into $\tilde{\mathcal{S}}$.

Step 2) Make a closed-loop system with the controller $\tilde{\mathcal{K}}$ in a block-diagonal form.

Step 3) Choose β s appropriately to construct G and P_2 .

Step 4) Solve (11).

Step 5) Contract $\tilde{\mathcal{K}}$ with V into the original controller \mathcal{K} to implement in practice.

4. Numerical Simulation

We use the parameters same to Example 1, where the nominal frequency in each area is $f_0 = 60$ Hz. We set large $(\Delta P_{D_k}, \Delta P_{D_l}) := (0.1, 0.1)$ activated at $t = 0$. It satisfies Assumption 3. To highlight the advantage of the developed technique, we compare it with the standard linear quadratic regulation (LQR) method [5] and the conventional integral control scheme. It is noted that the integral control in the load-frequency context refers to ΔE_{ks} with all zero- $P_{C_{ks}}$ [6], which is regarded as a basic control unit in real power systems even in multi-machine multi-area network case [8].

Similarly in Example 1, the LQR technique does not find any gain in the form of (4) with (5) (considering Assumption 2) based on (3). Instead we apply the LQR scheme to design a centralized control gain of full nonzero pattern (ignoring Assumption 2), which is carried out based on the linear model without taking into account the valve position limits— (A_1, B) in our T-S fuzzy model. To that end, from the discussion in [5], the weighting matrices for the cost function $J = \int_0^\infty (x^T Q x + u^T R u) d\tau$ in our state space become $Q = \text{diag}\{1, 0, 0, 1, 1, 1, 0, 0, 1\}$ and $R = \text{diag}\{1, 1\}$ to produce

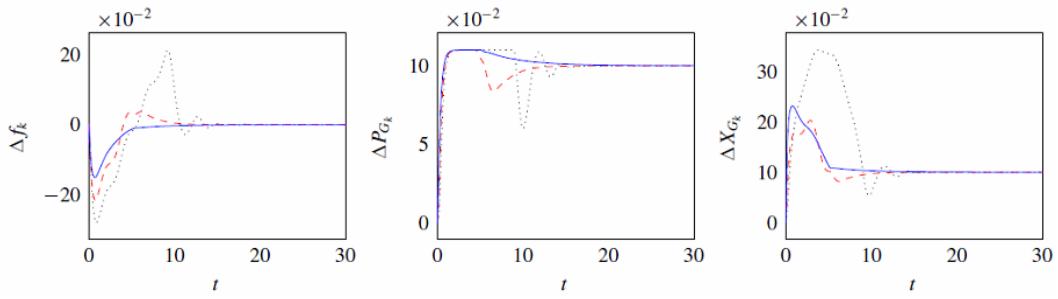


Fig. 3. Time responses in Area k : proposed (solid); LQR (dashed); integral control (dotted).

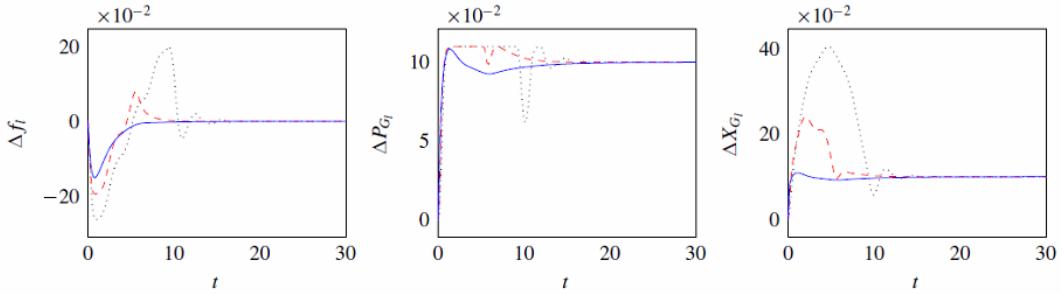


Fig. 4. Time responses in Area l : proposed (solid); LQR (dashed); integral control (dotted).

$$K_{\text{LQR}} = \begin{bmatrix} -0.779 & -1.146 & -0.269 & -0.414 \\ 0.020 & 0.033 & 0.005 & 0.0024 \\ 1.042 & -0.0253 & 0.011 & 0.006 & -0.002 \\ -0.816 & -0.8334 & -0.855 & -0.362 & -0.414 \end{bmatrix}$$

On the other hand, by applying Theorem 1 to (8) and contracting \tilde{K}_i s, we have the overlapping K_i s as

$$\begin{aligned} K_1 &= \left[\begin{array}{ccccc} -16.40 & -22.33 & -2.18 & -16.22 & 9.10 \\ 0 & 0 & 0 & 0 & | 12.22 \\ 0 & 0 & 0 & 0 & \\ -46.96 & -74.92 & -8.74 & -34.84 & \end{array} \right] \\ K_2 &= \left[\begin{array}{ccccc} -16.38 & -22.36 & -2.17 & -16.20 & 9.08 \\ 0 & 0 & 0 & 0 & | 2.47 \\ 0 & 0 & 0 & 0 & \\ -11.88 & -19.90 & -1.54 & -8.21 & \end{array} \right] \\ K_3 &= \left[\begin{array}{ccccc} -1.74 & -3.83 & 0.50 & -1.16 & 2.57 \\ 0 & 0 & 0 & 0 & | 12.19 \\ 0 & 0 & 0 & 0 & \\ -46.92 & -74.85 & -8.72 & -34.80 & \end{array} \right] \\ K_4 &= \left[\begin{array}{ccccc} -1.74 & -3.88 & 0.50 & -1.17 & 2.56 \\ 0 & 0 & 0 & 0 & | 2.46 \\ 0 & 0 & 0 & 0 & \\ -11.88 & -19.90 & -1.54 & -8.21 & \end{array} \right]. \end{aligned}$$

Three simulations are performed with the nonlinear model (2). The initial state is set as $x(0) = 0$. As Figs. 3 and 4 depict the time responses, the compared methods generate large overshoots on all Δf_k s as well as ΔX_{G_k} s. The main reason is that they do not theoretically handle the

valve position limits. As a result, ΔP_{G_k} s undergo severe saturations thus the load-frequency control performances are degraded. Contrary to this, all Δf_k s are directly guided to zero against the valve position limits caused by the large ΔP_{D_k} s. Furthermore, all system variables are ultimately bounded by the proposed method.

5. Conclusions

In this paper, we have presented the decentralized fuzzy controller design for the load-frequency control of the large-scale nonlinear power system, based on the overlapping decomposition technique. Simulation result convincingly demonstrated that the effectiveness of the developed technique over the existing design schemes.

Nomenclature

- ΔE_k : Incremental frequency deviation in Area k
- Δf_k : Incremental frequency deviation in Area k
- ΔP_{C_k} : Incremental change in speed changer position in Area k
- ΔP_{D_k} : Incremental change in load demand in Area k
- ΔP_{G_k} : Incremental change in generator output in Area k
- $\Delta P_{T_{kl}}$: Incremental tie-line flow between Areas k and l
- ΔX_{G_k} : Incremental change in governor valve position in Area k
- $\Delta X_{G_k}^C$: Close limit in ΔX_{G_k} in Area k
- $\Delta X_{G_k}^O$: Open limit in ΔX_{G_k} in Area k
- K_{E_k} : Integral control gain in Area k
- K_{P_k} : Plant gain in Area k

l	: Area l when typed as a (sub-)subscript
R_k	: Speed regulation parameter in Area k
T_{Gk}	: Time constant of governor in Area k
T_{kl}	: Maximum tie-line flow between Areas k and l
T_{P_k}	: Time constant of plant in Area k
T_{T_k}	: Time constant of turbine in Area k

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