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

Ho Jae Lee* and Do Wan Kim†

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 $\Delta X_G$, [1]. Thus limits on $\Delta X_G$ 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 $P_{hi}$ 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 $\Delta f_k$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 $\Delta P_{li}$, is given in the following form [5]:

$$
\begin{align*}
\Delta f_k &= -\frac{1}{T_f} \Delta f_k + \frac{K_p}{T_p} \Delta P_{Gi} - \frac{K_p}{T_p} \Delta P_{Gi} - \frac{K_p}{T_p} \Delta P_{Gi} \\
\Delta P_{Gi} &= -\frac{1}{T_i} \Delta P_{Gi} + \frac{1}{T_f} \Delta X_{Gi} \\
\Delta X_{Gi} &= -\frac{1}{R_i T_i} \Delta X_{Gi} - \frac{1}{T_f} \Delta X_{Gi} - \frac{1}{T_f} \Delta X_{Gi} - \frac{1}{T_f} \Delta X_{Gi} \\
\Delta E_k &= K_e \Delta f_k + K_e \Delta P_{hi} \\
\Delta P_{hi} &= T_s \Delta f_k - T_s \Delta f_k.
\end{align*}
$$

(1)

Assumption 1: Assume that $\Delta P_{hi}$ lives in $L_\infty$. Thus there exists $\zeta \in \mathbb{R}_{>0}$ such that $\|\Delta P_{hi}\|_{L_\infty} < \zeta$. The same applies to other areas.

The linear model in (1) may be valid, only when it is exposed to small $\Delta P_{hi}$. If large $\Delta P_{hi}$ occurs under the deregulated environment, adequate large amount of steam flow should be provided, which is proportional to $\Delta X_{Gi}$.
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 \( \Delta X_{Gi} \), denoted by \( \Delta X_{Gi}^O \) and \( \Delta X_{Gi}^C \), respectively. This constrained incremental change in the governor valve position can be expressed as the following nonlinear function:

\[
\xi_k(\Delta X_{Gi}) := \begin{cases} 
\Delta X_{Gi}^C, & \text{if } \Delta X_{Gi} < \Delta X_{Gi}^C \\
\Delta X_{Gi}, & \text{if } \Delta X_{Gi}^C < \Delta X_{Gi} < \Delta X_{Gi}^O \\
\Delta X_{Gi}^O, & \text{otherwise.}
\end{cases}
\]

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

\[
\begin{align*}
x & := (\Delta f_k, \Delta P_{Gk}, \Delta X_{Gk}, \Delta P_{Gk}, \Delta f_k, \Delta P_{Gk}, \Delta X_{Gk}, \Delta E_k) \\
u & := (\Delta P_{Gk}, \Delta P_{Gk}) \\
w & := (\Delta P_{Dk}, \Delta P_{Dk}).
\end{align*}
\]

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

\[
\begin{align*}
\dot{x}_1 & = -\frac{1}{T_{p1}} x_1 + \frac{K_{p1}}{T_{p1}} x_2 - \frac{K_{p1}}{T_{p1}} x_5 - \frac{K_{p1}}{T_{p1}} w_1 \\
\dot{x}_2 & = -\frac{1}{T_{p2}} x_2 + \frac{1}{T_{p2}} \xi_k(x_3) \\
\dot{x}_3 & = -\frac{1}{R_{i1} T_{Gi}} x_1 - \frac{1}{T_{Gi}} x_3 - \frac{1}{T_{Gi}} x_4 + \frac{1}{T_{Gi}} u_1 \\
\dot{x}_4 & = K_{Ei} x_1 + K_{Ex} x_5 \\
x_5 & = T_{li} x_1 - T_{li} x_6 \\
\dot{x}_6 & = \frac{K_{p1}}{T_{p1}} x_5 - \frac{1}{T_{p1}} x_6 + \frac{K_{p1}}{T_{p1}} x_7 - \frac{K_{p1}}{T_{p1}} w_2 \\
\dot{x}_7 & = -\frac{1}{T_{l2}} x_7 + \frac{1}{T_{l2}} \xi(x_8) \\
\dot{x}_8 & = -\frac{1}{R_{i1} T_{Gi}} x_6 - \frac{1}{T_{Gi}} x_8 - \frac{1}{T_{Gi}} x_9 + \frac{1}{T_{Gi}} u_2 \\
x_9 & = -K_{Ei} x_5 + K_{Ex} x_6.
\end{align*}
\]

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

\[
\begin{align*}
\xi_k(x_1) & = \tilde{\theta}_1 \tilde{\alpha}_1 x_1 + \tilde{\theta}_2 \tilde{\alpha}_2 x_3, \\
\xi_l(x_8) & = \tilde{\theta}_3 \tilde{\alpha}_3 x_8 + \tilde{\theta}_4 \tilde{\alpha}_4 x_8,
\end{align*}
\]

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

\[
\begin{align*}
\tilde{\theta}_1 &= \frac{\xi_k(x_1)}{\tilde{\alpha}_1 - \tilde{\alpha}_2}, \quad \tilde{\theta}_2 = 1 - \tilde{\theta}_1 \\
\tilde{\theta}_3 &= \frac{\xi_l(x_8)}{\tilde{\alpha}_3 - \tilde{\alpha}_4}, \quad \tilde{\theta}_4 = 1 - \tilde{\theta}_3
\end{align*}
\]

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

\[
\begin{align*}
\tilde{\alpha}_1 & := \sup_{x_1 \in \mathcal{B}_x} \left\{ \frac{\xi_k(x_1)}{x_1} \right\}, \quad \tilde{\alpha}_2 := \inf_{x_1 \in \mathcal{B}_x} \left\{ \frac{\xi_k(x_1)}{x_1} \right\} \\
\tilde{\alpha}_3 & := \sup_{x_8 \in \mathcal{B}_x} \left\{ \frac{\xi_l(x_8)}{x_8} \right\}, \quad \tilde{\alpha}_4 := \inf_{x_8 \in \mathcal{B}_x} \left\{ \frac{\xi_l(x_8)}{x_8} \right\}
\end{align*}
\]

guarantees \( \tilde{\theta}_1, \tilde{\theta}_2, \tilde{\theta}_3, \tilde{\theta}_4 \in [0,1] \), 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

\[
\mathcal{F} : \dot{x} = \sum_{i=1}^{4} \theta_i A_i x + B u + D w
\]

on \( \mathcal{B}_x \), where \( \theta_1 = \tilde{\theta}_1 \tilde{\beta}_1, \theta_2 = \tilde{\theta}_1 \tilde{\beta}_2, \theta_3 = \tilde{\theta}_3 \tilde{\beta}_3, \) and \( \theta_4 = \tilde{\theta}_4 \tilde{\beta}_4 \), and the system matrices are
Decentralized Load-Frequency Control of Large-Scale Nonlinear Power Systems: Fuzzy Overlapping Approach

where \( \alpha_k = \alpha_k, \, \alpha_1 = \alpha_k = \tilde{\alpha}_2, \, \alpha_1 = \alpha_1 = \tilde{\alpha}_3, \) and \( \alpha_1 = \alpha_1 = \tilde{\alpha}_4. \)

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

### 3. Controller Design

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

\[
\mathcal{X} : u := \sum_{i=1}^{4} \theta_i K_i x. \tag{4}
\]

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

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

\[
K_i = \begin{bmatrix} K_{i11} & K_{i12} & 0 \\ 0 & K_{i22} & 0 \end{bmatrix} \tag{5}
\]

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

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

**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 \( A_1. \) However we fail to find any feasible solutions for (5), owing to the large scale of the power system.

<table>
<thead>
<tr>
<th>Table 1. Parameters of the power system.</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>-----------</td>
</tr>
<tr>
<td>( T_{f_k} )</td>
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<tr>
<td>( T_{f_l} )</td>
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<tr>
<td>( T_{E_k} )</td>
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<tr>
<td>( K_{R_k} )</td>
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<tr>
<td>( R_k )</td>
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<tr>
<td>( K_{E_k} )</td>
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<tr>
<td>( T_{33} )</td>
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<tr>
<td>( \Delta X'_{G} )</td>
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<tr>
<td>( \Delta X''_{G} )</td>
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</tbody>
</table>
We seek to design (4) with (5) using the overlapping decomposition [10]. Consider the linear maps

\[ \tilde{x} = \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix} := Vx, \quad x := U\tilde{x} \tag{7} \]

through the full-rank transform matrices

\[ V := \begin{bmatrix} I & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad U := \begin{bmatrix} I & 0 & 0 \\ 0 & \frac{1}{2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

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

\[ \tilde{\mathcal{J}} : \dot{\tilde{\tilde{x}}} = \sum_{i=1}^{4} \theta_i \tilde{A}_i \tilde{x} + \tilde{B}u + \tilde{D}w \tag{8} \]

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

\[ \tilde{A}_i = \begin{bmatrix} A_{i11} & A_{i12} & 0 & 0 \\ A_{i12} & A_{i22} & 0 & A_{i23} \\ A_{i21} & 0 & A_{i22} & A_{i23} \\ 0 & 0 & A_{i32} & A_{i33} \end{bmatrix}, \quad \tilde{B} = VB = \begin{bmatrix} B_{11} & 0 \\ B_{21} & B_{22} \\ B_{23} & B_{32} \\ 0 & B_{32} \end{bmatrix}, \quad \tilde{D} =VD = \begin{bmatrix} D_{11} & 0 \\ D_{21} & D_{22} \\ 0 & D_{32} \end{bmatrix}. \]

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

\[ \tilde{\mathcal{J}} : \dot{\tilde{\tilde{x}}} = \sum_{i=1}^{4} \theta_i \tilde{K}_i \tilde{x} \tag{9} \]

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

\[ \tilde{K}_i = \begin{bmatrix} K_{i11} & K_{i12} & 0 & 0 \\ 0 & 0 & K_{i32} & K_{i33} \end{bmatrix}. \]

The expanded closed-loop system is written as

\[ \tilde{\mathcal{J}} : \dot{\tilde{x}} = \sum_{i=1}^{4} \theta_i (\tilde{A}_i + \tilde{B}\tilde{K}_i) \tilde{x} + \tilde{D}w =: \tilde{\mathcal{J}}(\tilde{x}) \tag{10} \]

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

\[ M_i := \begin{bmatrix} M_{i11} & M_{i12} & 0 & 0 \\ 0 & 0 & M_{i22} & M_{i23} \end{bmatrix} \]

such that the following linear matrix inequalities are satisfied for \( i \in \{1, 2, 3, 4\} \)

\[ \begin{bmatrix} G^T(\tilde{A}_i P + \tilde{B}M_i + P\tilde{A}_i^T + M_i^T \tilde{B}^T + \gamma P)G & * \\ \tilde{D}^T G & -I \end{bmatrix} < 0 \tag{11} \]

then the expanded closed-loop system (10) is ultimately uniformly 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

\[ \dot{W}(\tilde{x})_{(10)} = \tilde{\mathcal{J}}(\tilde{x})^T P^{-1} \tilde{x} + \tilde{x}^T P^{-1} \tilde{\mathcal{J}}(\tilde{x}) \]

\[ = \sum_{i=1}^{4} \theta_i \left[ \begin{bmatrix} P^{-1} \tilde{x} \\ w \end{bmatrix} \right]^T \left[ \begin{bmatrix} \tilde{A}_i P + \tilde{B}M_i + P\tilde{A}_i^T + M_i^T \tilde{B}^T + \gamma P \\ \tilde{D}^T G \end{bmatrix} \right] \left[ \begin{bmatrix} P^{-1} \tilde{x} \\ w \end{bmatrix} \right] - \gamma \tilde{x}^T P^{-1} \tilde{x} + w^T w \]

\[ = \sum_{i=1}^{4} \theta_i \left[ NU \tilde{x} \right]^T \left[ \begin{bmatrix} G^T(\tilde{A}_i P + \tilde{B}M_i + P\tilde{A}_i^T + M_i^T \tilde{B}^T + \gamma P)G \\ \tilde{D}^T G \end{bmatrix} \right] \left[ NU \tilde{x} \right] - \gamma \tilde{x}^T P^{-1} \tilde{x} + w^T w \]

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

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

under Assumption 1. Define

\[ \tilde{\zeta} := \sqrt{\frac{2\zeta^2}{\gamma \lambda_{\min}(P^{-1})}}. \]

One can easily agree that \( \dot{W}(\tilde{x}) < 0 \) as long as \( \tilde{x} \notin \mathcal{B}_t \), where \( \mathcal{B}_t := \{ \tilde{x} : \| \tilde{x} \| \leq \tilde{\zeta} \} \) 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 \( \mathcal{B}_t \) 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 \( \mathcal{B}_t \).

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

\[
\dot{W}(x)_{(10)} = \frac{\partial W}{\partial \tilde{x}} \frac{\partial \tilde{x}}{\partial x} \mathcal{F}(x) = \frac{\partial W}{\partial \tilde{x}} V \left( \sum_{i=1}^{4} \theta_i ((A_i + BK_i)x + Dw) \right) = \frac{\partial W}{\partial \tilde{x}} \mathcal{F}^T(\tilde{x}) = W(\tilde{x})|_{(10)}.
\]

Further, we know from (7) that \(\|\tilde{x}\| \leq \|x\| \leq c\) where \(c := \hat{c}/\|V\|\). Thus, (6) preserves the stability of (10).

Remark 2:

Let

\[
G^T :=
\begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\beta_1 & 0 & -\beta_0 & -\beta_0 & -\beta_0 & -\beta_0 & -\beta_0 & -\beta_0 & -\beta_0 & -\beta_0
\end{bmatrix}
\]

where \(\beta_j = \mathbb{R}, j \in \{1, \ldots, 9\}\), 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

\[
P_1 =
\begin{bmatrix}
P_{11} & * & * & * & * & * & * & * & * & * \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

and

\[
P_2 =
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\beta_1 & -\beta_4 & -\beta_5 & -\beta_0 & -\beta_0 & -\beta_0 & -\beta_0 & -\beta_0 & -\beta_0 & -\beta_0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

where \(P_{11}, P_{33} \in \mathbb{R}^{4 \times 4}\), 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, \(\Delta P_D\) is modeled by a step function. Then we have a useful result.

Theorem 3 (Convergence of \(\Delta f_i\) to Zero): The decentralized fuzzy load-frequency controller (4) drives \(\Delta f_i\) and \(\Delta f_j\) to zero.

Proof: Let \(\phi(w)\) be a solution to \(\mathcal{F}(x) = 0\). Since \(\dot{W} = 0\) from Assumption 3, \(W(x)|_{(10)}\) keeps decreasing outside \(\mathcal{B}_r := \{x : \|x\| \leq c\}\) due to

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

but

\[
\frac{\partial W}{\partial x} = 2x^T V^T PV \neq 0
\]

for all \(x \neq 0 \in \mathbb{R}^q\) due to

\[
\text{rank} (V^T PV) = 9 \Rightarrow \mathcal{N} ((V^T PV)^T) = \{0\}.
\]

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 \(\Delta f_i = \phi_i = 0\) and \(\Delta f_j = \phi_j = 0\).

The design procedure is summarized as follows:

- Step 1) Expand the given system \(\mathcal{F}\) with \(V\) into \(\mathcal{F}\).
- Step 2) Make a closed-loop system with the controller \(\mathcal{K}\) in a block-diagonal form.
- Step 3) Choose \(\beta\)s appropriately to construct \(G\) and \(P_2\).
- Step 4) Solve (11).
- Step 5) Contract \(\mathcal{K}\) 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 \((\Delta P_D, \Delta P_B) := (0.1, 0.1)\) 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 the developed fuzzy model in our T–S fuzzy model. To that end, from the discussion in [5], the weighting matrices for the cost function \(J = \int_{0}^{\infty} (x^T Q x + u^T R u) dt\) in our state space become \(Q = \text{diag}\{1, 0, 0, 1, 1, 0, 0, 0\}\) and \(R = \text{diag}\{1, 1\}\) to produce...
441

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

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

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

$$K_1 = \begin{bmatrix} -16.40 & -22.33 & -2.18 & -16.22 & 9.10 \\ 0 & 0 & 0 & 0 & 12.22 \\ 0 & 0 & 0 & 0 & -46.96 \\ -74.92 & -8.74 & -34.84 & 0 & 0 \\ -16.38 & -22.36 & -2.17 & -16.20 & 9.08 \\ 0 & 0 & 0 & 0 & 2.47 \\ -11.88 & -19.90 & -1.54 & -8.21 & 0 \end{bmatrix}$$

$$K_2 = \begin{bmatrix} -1.74 & -3.83 & 0.50 & -1.16 & 2.57 \\ 0 & 0 & 0 & 0 & 12.19 \\ 0 & 0 & 0 & 0 & -46.92 \\ -74.85 & -8.72 & -34.80 & 0 & 0 \\ -1.74 & -3.88 & 0.50 & -1.17 & 2.56 \\ 0 & 0 & 0 & 0 & 2.46 \\ -11.88 & -19.90 & -1.54 & -8.21 & 0 \end{bmatrix}$$

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 $\Delta f_k$s as well as $\Delta X_{G_k}$. The main reason is that they do not theoretically handle the valve position limits. As a result, $\Delta P_{G_k}$s undergo severe saturations thus the load-frequency control performances are degraded. Contrary to this, all $\Delta f_k$s are directly guided to zero against the valve position limits caused by the large $\Delta P_{D_k}$. 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**

- $\Delta E_k$: Incremental frequency deviation in Area $k$
- $\Delta f_k$: Incremental frequency deviation in Area $k$
- $\Delta P_{G_k}$: Incremental change in speed changer position in Area $k$
- $\Delta P_{D_k}$: Incremental change in load demand in Area $k$
- $\Delta P_{G_l}$: Incremental change in generator output in Area $k$
- $\Delta P_{D_l}$: Incremental tie-line flow between Areas $k$ and $l$
- $\Delta X_{G_k}$: Incremental change in governor valve position in Area $k$
- $\Delta X_{C_k}$: Close limit in $\Delta X_{G_k}$ in Area $k$
- $\Delta X_{O_k}$: Open limit in $\Delta X_{G_k}$ in Area $k$
- $K_{E_k}$: Integral control gain in Area $k$
- $K_{P_k}$: Plant gain in Area $k$
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