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Load Frequency Control of a Multi-Area Power System: An Adaptive Fuzzy Logic Approach

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***Abstract*—In this paper, a new load frequency control (LFC) for multi-area power systems is developed based on the direct–indirect adaptive fuzzy control technique. LFCs for each area are designed based on availability of frequency deviation of each area and tie-line power deviation between areas. The fuzzy logic system approximation capabilities are exploited to develop suitable adaptive control law and parameter update algorithms for unknown interconnected LFC areas. An H_∞ tracking performance criterion is introduced to minimize the approximation errors and the external disturbance effects. The proposed controller guarantees stability of the overall closed-loop system. Simulation results for a real three-area power system prove the effectiveness of the proposed LFC and show its superiority over a classical PID controller and a type-2 fuzzy controller.**

***Index Terms*—Adaptive control, adaptive fuzzy control, fuzzy approximation, GDB, GRC, load frequency control (LFC), multi-area.**

Nomenclature

Variable	Definition
Δf_i	Frequency deviation.
ΔP_{t1i}	Mechanical power deviation of gas turbine.
ΔP_{g1i}	Governor (gas turbine) power deviation.
ΔP_{t2i}	Mechanical power deviation of steam turbine.
ΔP_{ri}	Power deviation in steam reheater.
ΔP_{g2i}	Governor (steam turbine) power deviation.
ΔP_{tiei}	Deviation in net tie-line power.
D_i	Load damping coefficient.
K_{ri}	Reheater gain.
M_i	Inertia constant.
R_i	Governor speed regulation.
T_{t1i}	Gas Turbine time constant.
T_{g1i}	Governor time constant.
T_{t2i}	Steam Turbine time constant.
T_{g2i}	Governor time constant.
T_{ri}	Reheater time constant.
T_{ij}	Synchronizing power coefficient.

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I. Introduction

CLASSICAL control techniques of power systems are based on mathematical models. These techniques have difficulties in achieving the control objectives in the presence of uncertainties, changing of operating points under which the mathematical model is derived, and worn out of system components. In order to overcome these limitations, applications of intelligent technologies such as fuzzy systems, artificial neural networks, and genetic algorithms have been investigated. In the last two decades, applications of such intelligent techniques to various aspects of power systems, such as operation, planning, control, and management have witnessed increasing attention [1].

The load frequency control (LFC) of a multi-area power system is the mechanism that balances between power generation and the demand regardless of the load fluctuations to maintain the frequency deviations within acceptable limits. The basic means of controlling prime-mover power to match variations in system load is through control of the load reference set-points of selected generating units [2].

Various types of LFC schemes have been developed recently (see [3]–[6] and references therein). A survey of different control schemes of LFC and strategies of automatic generation control (AGC) can be found in [7], [8]. A unified PID LFC controller tuning using internal model control is presented in [8]. A new systematic tuning method with a new structure to design a robust PID load frequency controller for multimachine power systems based on maximum peak resonance specification is presented in [10]. Based on the active disturbance rejection control concept, a robust decentralized LFC scheme is proposed in [11] for an interconnected three-area power system. A decentralized LFC synthesis is formulated in [12] as an H_∞-control problem and solved using an iterative linear matrix inequalities algorithm to design robust PI controllers in the multi-area power systems. The simultaneous presence of system nonlinearities such as governor dead band (GDB) and generation rate constraint (GRC) deteriorate the LFC system performance [13]. This problem has been dealt with by considering known saturation nonlinearity for GRC and known dead band for the GDB [13], [14]. Implementation of the aforementioned LFC requires accurate information about the control area parameters, which are usually imprecisely modeled or varying due to wearing out of the components or due to changing of operating points. Moreover, the GRC and GDB nonlinearities have to be exactly known.

In the past decade, different adaptive fuzzy logic LFC techniques have been developed (e.g., [16]–[22]). An adaptive fuzzy gain scheduling scheme for conventional PI and optimal load frequency controllers has been proposed in [16] where a Sugeno type fuzzy inference system is used to find the gains of fuzzy controller based on scheduling the controller gains for different operating conditions. A control scheme based on artificial neuro-fuzzy inference system (ANFIS) is proposed in [17] to optimize and update the control gains for automatic generation control (AGC) according to load variations. A fuzzy system is used in [18] to determine adaptively the proper gains of a PI controller according to the area-control error and its change for LFC. The LFC for power system subject to nonlinearities in valve position limits and parametric uncertainties is developed using Takagi-Sugeno (T-S) fuzzy system [21]. The work in [22] proposed a fuzzy PI LFC where a genetic algorithm and particle swarm optimization are incorporated to ease the controller design. The aforementioned results and most of the adaptive fuzzy logic LFC schemes available in the literature are based on availability of if-then rules for the control actions or on T-S modeling of the power system.

The approximation capabilities of the fuzzy logic systems [23] are exploited in the present work to design an adaptive fuzzy logic LFC. An approximation-based adaptive fuzzy logic control scheme is developed for LFC of a multi-area power system. The multi-area power system under study has the characterizations of unknown parameters (due to wearing out of components or variation of operating points), unknown interconnection among subsystems (due to unknown or variations in synchronizing power coefficients), and unknown nonlinearities. In the controller design, fuzzy logic systems are used to construct the control law. The proposed controller of each area depends on the local states, namely, the frequency and tie-line power deviations and the tracking error. The key idea is to utilize the fuzzy logic systems to develop a control law capable to achieve the LFC objectives and ensure global stability of the overall closed-loop system in the presence of unknown system parameters and unknown nonlinearities. The proposed controller consists of three parts, namely, a primary control, an auxiliary control, and a third term introduced to approximate the unknown interconnections among subsystems and the unknown nonlinearities. The auxiliary control is incorporated to attenuate the effects of the approximation errors, and the external disturbances in an H_∞ sense.

The main contributions of this paper can be summarized as follows: 1) the proposed controller can achieve the LFC objectives in the presence of unknown parameters and nonlinearities; 2) by introducing an auxiliary control part to satisfy the H_∞ tracking performance, the controller achieves nearly perfect tracking for both the frequency and tie-line power deviations; 3) the controller does not rely on the availability of if–then fuzzy rules; and 4) to the best of the authors' knowledge, to date, no attempt has been made in designing LFC using direct-indirect adaptive fuzzy logic control technique with consideration of GRC and GDB as unknown nonlinearities.

The paper is organized as follows. The Introduction is given in Section I, and the dynamic model of the multi-area power system is presented in Section II. The proposed direct–indirect adaptive fuzzy logic control design and closed-loop stability are highlighted in Sections III and IV, respectively. Simulation results of the proposed controller applied to a real three-area power system are provided in Section V along with comparison with the classical PID and type-2 fuzzy controller. The conclusion is given in Section VI.

II. Dynamic Model of a Multi-Area Power System

Consider a power system consisting of N LFC areas, each area has a number of generators. All generators in one area are simplified as an equivalent generator unit [2]. Moreover, each area is assumed to have a number of gas turbines of simple cycle and combined cycle types and a number of steam turbines of reheat type. Without loss of generality, it is assumed that the controller to be proposed is installed to the gas turbines while the steam turbines have no control on the reference set-point. The nonlinearities of the GRC and the GDB are incorporated in the model as nonlinear functions $\overline{v}_i(\Delta P_{t1i}, \Delta P_{g1i})$, and $\overline{\beta}_i(\Delta P_{g1i})$, respectively. The block diagram of the ith LFC area in a multi-area system is shown in Fig. 1. The dynamic model of each area can be written as [24]

$$\begin{aligned}\dot{\overline{x}}_i &= \overline{A}_{ii}\overline{x}_i + \overline{B}_i\overline{u}_i + \overline{E}_i\Delta\overline{r}_i \\ &\quad + \sum_{j=1}^{N}\overline{A}_{ij}\overline{x}_j + \overline{\mathrm{g}}_{1\mathrm{i}} + \overline{\mathrm{g}}_{2\mathrm{i}} - \overline{F}_i\Delta P_{di} \qquad (1)\\ y_i &= \overline{C}_i\overline{x}_i \qquad (2)\end{aligned}$$

where the control area matrices are given by

$$\overline{A}_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & 0\\ -2\pi T_{ij} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\begin{aligned}\overline{B}_i &= \begin{bmatrix} 0 & 0 & \frac{1}{T_{g1i}} & 0 & 0 & 0 & 0\end{bmatrix}^T\\ \overline{F}_i &= \begin{bmatrix} \frac{1}{M_i} & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}^T\\ \overline{E}_i &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 0\end{bmatrix}^T\\ \overline{\mathrm{C}}_{\mathrm{i}} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}\\ \overline{\mathrm{g}}_{1\mathrm{i}} &= \frac{1}{M_i}\begin{bmatrix} \overline{\nu}_i(\overline{x}_i) & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}^T\end{aligned}$$

and $\overline{x}_i$ and $\overline{A}_{ii}$, shown at the bottom of the following page. $\overline{\mathrm{g}}_{2\mathrm{i}} = (1/T_{t1i})[0\ \overline{\beta}_i(\overline{x}_i)\ 0\ 0\ 0\ 0\ 0]^T$ and $\Delta\overline{r}_i$ is the change in

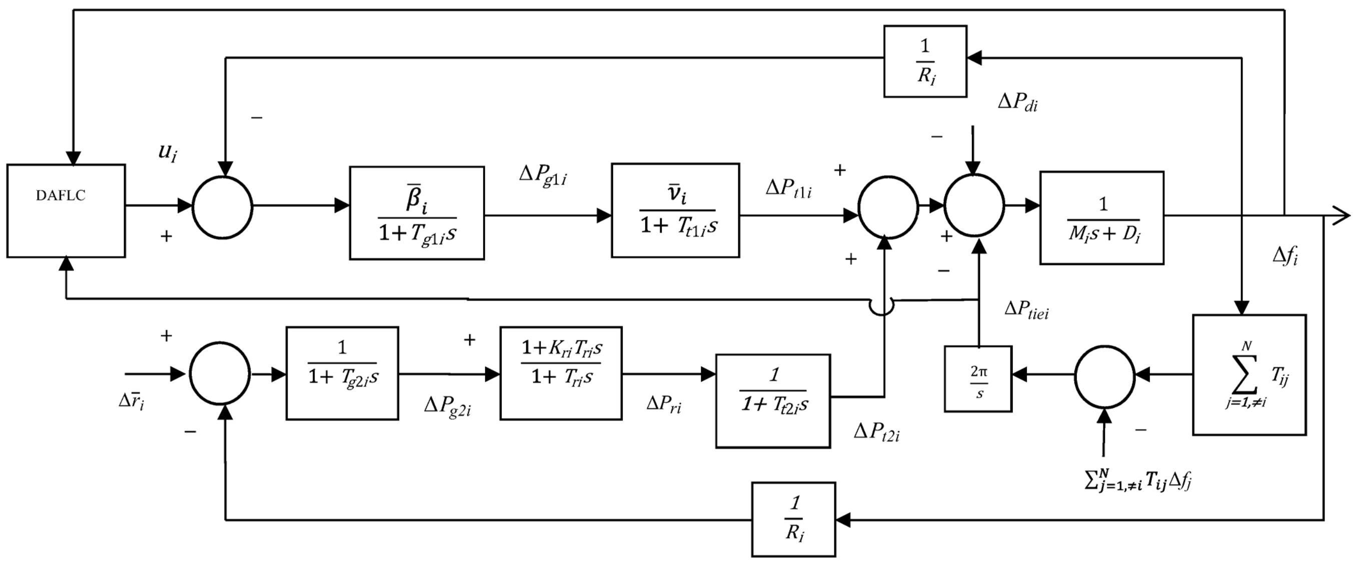

Fig. 1. Dynamic model of the ith area in a multi-area power system

reference set-point of the steam turbine (assumed zero), ΔP_{di} is the load change, $T_{ij} = T_{ji}$, and $\alpha = (-(K_{ri}/T_{g2i}) + (1/T_{ri}))$.

The parameters of each control area, the tie-line power between each area, and the functions $\bar{v}_i(x_2, x_3)$ and $\bar{\beta}_i(x_3)$ are assumed unknown. To facilitate the design of a local adaptive fuzzy controller, model (1) is transformed to the controller canonical from as

$$\begin{aligned}\dot{x}_i &= A_{ii}x_i + B_i u_i + \sum_{j=1, j\neq 1}^{N} A_{ij}x_j + \mathrm{g_{1i}}(x_i)\\ &\quad + g_{2i}(x_i) - F_i\Delta P_{di} \qquad (3)\\ y_i &= C_i x_i \qquad (4)\end{aligned}$$

where $A_{ii} = S_i^{-1}\overline{A}_{ii}S_i$, $B_i = S_i^{-1}\overline{B}_i$, $F_i = S_i^{-1}\overline{F}_i$, $A_{ij} = S_i^{-1}\overline{A}_{ij}S_j$, $C_i = \overline{C}_i S_i$, $\mathrm{g_{1i} = S_i^{-1}\overline{g}_{1i}}$, $\mathrm{g_{2i} = S_i^{-1}\overline{g}_{2i}}$ and S_i is the similarity transformation matrix [25]. Equation (3) can be written in the following form:

$$\dot{x}_i = A_{ii}x_i + B_i u_i + \mathrm{D}_i(X) + \mathcal{G}_{1i}(x_i) + \mathcal{G}_{2i}(x_i) - \mathcal{F}_i \qquad (5)$$

where $\mathrm{D}_i^T(X) = [\mathrm{D}_{1i}(X)\ldots\mathrm{D}_{7i}(X)]$ accounts for the interconnections between the ith area and other areas [26], $\mathcal{G}_{1i}^T(x_i) = [\mathcal{G}_{11i}(x_i)\ldots\mathcal{G}_{71i}(x_i)]$ and $\mathcal{G}_{2i}^T(x_i) = [\mathcal{G}_{12i}(x_i)\ldots\mathcal{G}_{72i}(x_i)]$ represent the GRC and GDB nonlinearities, $\mathcal{F}_i^T(x_i) = [\mathcal{F}_{1i}\ldots\mathcal{F}_{7i}]$ represents the load disturbance terms, and the vector $X = [x_1\ x_2 \ldots \mathrm{x_N}]$ is the composite state vector. The ith isolated and undisturbed LFC area of the model (5) without consideration of GDB and GRC nonlinearities is given by

$$\dot{x}_i = A_{ii}x_i + B_i u_i \qquad (6)$$

where the transformed matrices A_{ii}, B_i and C_i have the forms

$$A_{ii} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0 & 1 & 0 & 0\\ 0 & 1 & 0 & 0 & 0 & 1 & 0\\ 0 & 1 & 0 & 0 & 0 & 0 & 1\\ -a_{0i} & -a_{1i} & -a_{2i} & -a_{3i} & -a_{4i} & -a_{5i} & -a_{6i} \end{bmatrix}$$

$$\begin{aligned}B_i^T &= [0\quad 0\quad 0\quad 0\quad 0\quad 0\quad 1]\\ C_i &= [C_{0i}\quad C_{1i}\quad C_{2i}\quad C_{3i}\quad C_{4i}\quad 0\quad 0].\end{aligned}$$

$$\overline{x}_i = [\Delta f_i \quad \Delta P_{t1i} \quad \Delta P_{g1i} \quad \Delta P_{t2i} \quad \Delta P_{ri} \quad \Delta P_{g2i} \quad \Delta P_{tiei}]$$

$$\overline{A}_{ii} = \begin{bmatrix} -\frac{D_i}{M_i} & \frac{1}{M_i} & 0 & \frac{1}{M_i} & 0 & 0 & -\frac{1}{M_i}\\ 0 & -\frac{1}{T_{t1i}} & \frac{1}{T_{t1i}} & 0 & 0 & 0 & 0\\ -\frac{1}{R_i T_{g1i}} & 0 & -\frac{1}{T_{g1i}} & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & -\frac{1}{T_{t2i}} & \frac{1}{T_{t2i}} & 0 & 0\\ -\frac{K_{ri}}{R_i T_{g2i}} & 0 & 0 & 0 & -\frac{1}{T_{ri}} & \alpha & 0\\ -\frac{1}{R_i T_{g2i}} & 0 & 0 & 0 & 0 & -\frac{1}{T_{g2i}} & 0\\ \sum_{j=1, j\neq 1}^{N} 2\pi T_{ij} & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The entries of the last row of A_{ii} denoted by $a_i = [-a_{ji}]$, $j = 0, \ldots 6$, and $i = 1, \ldots N$, are negative and dependent on system parameters. The transfer function of (6) is given by

$$H_i(s) = \frac{c_{4i}s^4 + c_{3i}s^3 + c_{2i}s^2 + c_{1i}s + c_{0i}}{s^7 + a_{6i}s^6 + a_{5i}s^5 + a_{4i}s^4 + a_{3i}s^3 + a_{2i}s^2 + a_{1i}s + a_{0i}} = \frac{N_i(s)}{D_i(s)}. \tag{7}$$

Upon repetitive differentiation of (4) and using (6) until the input appears, one can obtain

$$\dddot{y}_i = C_i A_{ii}^3 x_i + C_i A_{ii}^2 B_i u_i \tag{8}$$

where $C_i A_{ii}^3 x_i = c_{4i} a_i x_i + [0\ 0\ 0\ c_{0i}\ c_{1i}\ c_{2i}\ c_{3i}]^T x_i$ and $C_i A_{ii}^2 B_i u_i = c_{4i} u_i$, $c_{4i} \neq 0$. Equation (8) indicates that the relative degree of each subsystem is 3. This means that its zero dynamics is of order 4. In fact the poles of reciprocal of the polynomial $N_i(s)$ represents the zero dynamics which is stable provided that $c_{ki} > 0$, $k = 0, \ldots 4$. If the parameters of subsystem (4) and (6) are precisely known, the ideal local control u_i^* can be written as

$$u_i^* = \frac{1}{c_{4i}} \left(\dddot{y}_{ri} + K_i^T \underline{e}_i - C_i A_{ii}^3 x_i \right) \tag{9}$$

where y_{ri} is a reference signal, assumed to have bounded derivatives (up to 3). The control law (9) will force the error vector $\underline{e}_i = [e_i\ \dot{e}_i\ \ddot{e}_i]^T$ to converge to zero where $e_i = y_{ri} - y_i$ provided $K_i = [K_{0i}\ K_{1i}\ K_{2i}]^T$ is chosen such that all of the roots of the characteristic equation $s^3 + K_{2i}s^2 + K_{1i}s + K_{0i} = 0$ are in the open left half of the S-plane

III. Proposed Adaptive Fuzzy Logic LFC

In this paper adaptive fuzzy logic control (AFLC) is used to design the LFC. Generally speaking, the AFLC schemes are classified as direct and indirect [23]. In the direct adaptive fuzzy logic control (DAFLC), a fuzzy logic system is used to generate the control signal whereas in the indirect adaptive fuzzy logic control (IAFLC), a fuzzy logic system is used to approximate unknown functions of the plant. A direct–indirect adaptive fuzzy logic LFC is proposed where fuzzy logic systems are employed for each area to construct the primary control part and to approximate the unknown interconnection terms and the unknown nonlinearities due to GDB and GRC. The controller parameters are updated to reduce the error between the subsystem output and a given reference signal.

To develop a direct-indirect adaptive fuzzy logic control (DIAFLC), a fuzzy system having a center-average defuzzifier, product inference, and singleton fuzzifier is considered. This type of fuzzy logic system is given by

$$\mathrm{q}(x_i) = \frac{\sum_{l=1}^{M} \bar{h}^l \left(\Pi_k^{n_i} \mu_{F_k^l}(x_k) \right)}{\sum_{l=1}^{M} \left(\Pi_k^{n_i} \mu_{F_k^l}(x_k) \right)} \tag{10}$$

where M is the number of fuzzy if–then rules having the form: if x_1 is F_1^l, x_2 is F_2^l, and $\ldots x_{n_i}$ is $F_{n_i}^l$, then h is G^l for $l = 1, 2, \ldots M$, where F_k^l and G^l are fuzzy sets with membership functions $\mu_{F_k^l}$ and μ_{G^l}, respectively, and h is the linguistic variable which can be considered as output of the fuzzy logic system. The parameter $\bar{h}^l$ is the point at which $\mu_{G^l}(h)$ achieves its maximum value where $\mu_{G^l}(h) = 1$. Equation (10) can be rewritten in terms of the fuzzy basis functions (FBF)

$$\ell_{\mathrm{k}}(\mathrm{x_i}) = \frac{\Pi_k^{n_i} \mu_{F_k^l}(x_k)}{\sum_{l=1}^{M} \left(\Pi_k^{n_i} \mu_{F_k^l}(x_k) \right)} \tag{11}$$

as

$$q(x_i|\theta_i) = \theta_i^T \ell(x_i) \tag{12}$$

where $\theta_i = [\theta_{i1} \ldots \theta_{iM}]^T$ is a vector of adjustable parameters and $\ell(x_i) = [\ell_1(x_i) \ldots \ell_M(x_i)]^T$.

In the presence of unknown subsystem parameters and unknown nonlinear functions, a local DIAFLC is designed as [26]

$$u_i = u_{ip}(x_i|\theta_i) - u_{ia} - \mathcal{H} \tag{13}$$

where $u_{ip}(x_i|\theta_i)$ is the primary control, u_{ia} is an attenuation control term introduced to achieve an H_∞ tracking performance [28], [29], and $\mathcal{H} = (-\hat{d}_i(X|\theta_{di}) - \hat{g}_{1i}(x_i|\phi_i) - \hat{g}_{2i}(x_i|\Theta_i))$ represents the fuzzy approximations of unknown interconnections and unknown nonlinear functions of GDB and GRC.

The fuzzy system (12) is used to determine the primary control and the fuzzy approximations as

$$u_{ip}(x_i|\theta_i) = \theta_i^T \xi(x_i) \tag{14}$$

$$\hat{d}_i(X|\theta_{di}) = \theta_{di}^T \eta(X) \tag{15}$$

$$\hat{g}_{1i}(x_i|\phi_i) = \phi_i^T \rho(x_i) \tag{16}$$

$$\hat{g}_{2i}(x_i|\Theta_i) = \Theta_i^T \zeta(x_i) \tag{17}$$

where $\xi(x_i) = [\xi_1(x_i) \ldots \xi_{\mathrm{M}}(x_i)]^T$, $\eta(X) = [\eta_1(X) \ldots \eta_{\mathrm{M}}(X)]^T$, $\rho(x_i) = [\rho_1(x_i) \ldots \rho_{\mathrm{M}}(x_i)]^T$, $\zeta(x_i) = [\zeta_1(x_i) \ldots \zeta_{\mathrm{M}}(x_i)]^T$, and $\eta_{\mathrm{k}}(X)$, $\rho_{\mathrm{k}}(x_i)$, and $\zeta_{\mathrm{k}}(x_i)$ are FBF in the form of (11) and the vectors $\theta_i = [\theta_{i1} \ldots \theta_{iM}]^T$, $\theta_{di} = [\theta_{di1} \ldots \theta_{diM}]^T$, $\phi_i = [\phi_{i1} \ldots \phi_{iM}]^T$, and $\Theta_i = [\Theta_{i1} \ldots \Theta_{iM}]^T$ are the vectors of adjustable parameters whose updating laws are to be determined later.

Define the following minimum approximation errors:

$$\omega_{1i} = c_{4i} \left(u_i^* - u_{ip} \left(x_i | \theta_i^* \right) \right) \tag{18}$$

$$\omega_{2i} = c_{4i} d_i \left(X | \theta_{di}^* \right) - C_i A_{ii}^2 \mathrm{D}_i(X) \tag{19}$$

$$\omega_{3i} = c_{4i} \hat{g}_{1i} \left(x_i | \phi_i^* \right) - C_i A_{ii}^2 G_{1i}(x_i) \tag{20}$$

$$\omega_{4i} = c_{4i} \hat{g}_{2i} \left(x_i | \Theta_i^* \right) - C_i A_{ii}^2 G_{2i}(x_i) \tag{21}$$

where θ_i^*, θ_{di}^*, ϕ_i^*, and Θ_i^* are the optimum values of the adaptive parameter vectors defined by

$$\theta_i^* = \arg \min_{\theta_i \in \Omega_1} \left[\sup_{x \in U_c} \left| u_i^* - (u_{ip}(x_i|\theta_i)) \right| \right]$$

$$\theta_{di}^* = \arg \min_{\theta_{di} \in \Omega_2} \left[\sup_{x \in U_c} \left| c_{4i} \hat{d}_i(X) \left| \theta_{di} \right) - C_i A_{ii}^2 D_i(X) \right| \right]$$

$$\phi_i^* = \arg \min_{\phi_i \in \Omega_3} \left[\sup_{x \in U_c} \left| c_{4i} \hat{g}_{1i}(x_i|\phi_i) - C_i A_{ii}^2 G_{1i}(x_i) \right| \right]$$

$$\Theta_i^* = \arg \min_{\Theta_i \in \Omega_4} \left[\sup_{x \in U_c} \left| c_{4i} \hat{g}_{2i}(x_i|\Theta_i) - C_i A_{ii}^2 G_{2i}(x_i) \right| \right]$$

and the sets Ω_1, Ω_2, Ω_3, and Ω_4 denote the desired bounds of the parameters θ_i, θ_{di}, ϕ_i, and Θ_i, respectively, and U_c is the controllability region [23].

IV. Closed-Loop Stability Analysis

Closed-loop stability of the interconnected and disturbed subsystem dynamics in the presence of GRC and GDB nonlinearities is studied in this section. Using (4) and (5), it is straightforward to write the third derivative of the output of each subsystem as

$$\dddot{y}_i = C_i A_{ii}^3 x_i + c_{4i} u_i + C_i A_{ii}^2 M_i \tag{22}$$

where $M_i = \mathrm{D}_i(X) + \mathcal{G}_{1i}(x_i) + \mathcal{G}_{2i}(x_i) - \mathcal{F}_i$.

Substituting (13) into (22) and adding and subtracting $(c_{4i} u_i^*)$, we obtain

$$\begin{aligned}\dddot{e}_i = &\left[-K_i^T \underline{e}_i + c_{4i}\left(u_i^* - u_{ip}(x_i|\theta_i)\right)\right.\\ &\left.+c_{4i} u_{ia} + c_{4i}\mathcal{H} - C_i A_{ii}^2 M_i\right].\end{aligned} \tag{23}$$

Equation (23) in state space form will be

$$\begin{aligned}\dot{\underline{e}}_i = &\left[A_{ci}\underline{e}_i + c_{4i}\left(u_i^* - u_{ip}(x_i|\theta_i)\right) B_i + c_{4i} u_{ia} B_i\right.\\ &\left.+\left(c_{4i}\mathcal{H} - C_i A_{ii}^2 M_i\right) B_i\right]\end{aligned} \tag{24}$$

where $A_{ci} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -K_{0i} & -K_{1i} & -K_{2i} \end{bmatrix}$.

Upon substituting (14)–(17) in (24), the following error equation is obtained:

$$\begin{aligned}\dot{\underline{e}}_i = &\left[A_{ci}\underline{e}_i + \omega_{\mathrm{T}i} B_i + c_{4i} u_{ia} B_i\right.\\ &\left.+c_{4i} B_i\left(\varphi_{1i}^T \xi(x_i) - \varphi_{2i}^T \eta(X) - \varphi_{3i}^T \rho(x_i) - \varphi_{4i}^T \zeta(x_i)\right)\right]\end{aligned} \tag{25}$$

where $\varphi_{1i}^T = (\theta_i^* - \theta_{\mathrm{i}})^T$, $\varphi_{2i}^T = (\theta_{di}^* - \theta_{di})^T$, $\varphi_{3i}^T = (\phi_i^* - \phi_i)$, and $\varphi_{4i}^T = (\Theta_i^* - \Theta_i)$ are the parameter errors and $\omega_{Ti} = (\omega_{1i} + \omega_{2i} + \omega_{3i} + \omega_{4i} + C_i A_{ii}^2 \mathcal{F}_i)$ denotes the fuzzy approximation error and the external disturbance.

The effect of the term ω_{Ti} on the tracking performance can be attenuated by the auxiliary control u_{ia}. Therefore, the control design problem is to find adaptive laws for the parameter vectors θ_i, θ_{di}, ϕ_i, Θ_i, and u_{ia} in order to achieve the following H_∞ tracking performance [28], [29]:

$$\begin{aligned}\int_0^T \underline{e}_i^T Q_i \underline{e}_i dt \leq &\underline{e}_i^T(0) P_i \underline{e}_i(0) + \frac{1}{\gamma_{1i}}\varphi_{1i}^T(0)\varphi_{1i}(0)\\ &+\frac{1}{\gamma_{2i}}\varphi_{2i}^T(0)\varphi_{2\mathrm{i}}(0)\\ &+\frac{1}{\gamma_{3i}}\varphi_{3i}^T(0)\varphi_{3\mathrm{i}}(0) + \frac{1}{\gamma_{4\mathrm{i}}}\varphi_{4i}^T(0)\varphi_{4\mathrm{i}}(0)\\ &+\rho_i^2 \int_0^T \omega_{Ti}^2 dt\end{aligned} \tag{26}$$

for positive definite symmetric matrices Q_i, P_i, positive parameters γ_{i1}, γ_{i2}, and a desired attenuation level ρ_i.

In order to study the closed-loop stability of the overall system, the following positive definite Lyapunov function V_i is considered:

$$\begin{aligned}V_i(\underline{e}_i, \varphi_i, t) = &\frac{1}{2}\underline{e}_i^T P_i \underline{e}_i + \frac{1}{2\gamma_{1i}}\varphi_{1i}^T \varphi_{1i} + \frac{1}{2\gamma_{2i}}\varphi_{2i}^T \varphi_{2\mathrm{i}}\\ &+\frac{1}{2\gamma_{3i}}\varphi_{3i}^T \varphi_{3\mathrm{i}} + \frac{1}{2\gamma_{4i}}\varphi_{4i}^T \varphi_{4\mathrm{i}}\end{aligned} \tag{27}$$

where $\varphi_i^T = [\varphi_{1i}\ \varphi_{2i}\ \varphi_{3i}\ \varphi_{4i}]^T$. The time derivative of V_i along the trajectory (25) is determined as

$$\begin{aligned}\dot{V}_i = &\frac{1}{2}\underline{e}_i^T\left(A_{ci}^T P_i + P_i A_{ci}\right)\underline{e}_i + (c_{4i} u_{ia} + \omega_{Ti})\underline{e}_i^T P_i B_i\\ &+T_1 + T_2 + T_3 + T_4\end{aligned} \tag{28}$$

where $T_1 = c_{4i}\xi^T(x_i)\varphi_{1i}\underline{e}_i^T P_i B_i - (1/\gamma_{1i})\varphi_{1i}^T\dot{\theta}_i$, $T_2 = c_{4i}\eta^T(X)\varphi_{2i}\underline{e}_i^T P_i B_i + (1/\gamma_{2i})\varphi_{2i}^T\dot{\theta}_{di}$, $T_3 = c_{4i}\rho^T(x_i)\varphi_{3i}\underline{e}_i^T P_i B_i + (1/\gamma_{3i})\varphi_{3i}^T\dot{\phi}_i$, and $T_4 = c_{4i}\zeta^T(x_i)\varphi_{4i}\underline{e}_i^T P_i B_i + (1/\gamma_{4i})\varphi_{4i}^T\dot{\Theta}_i$.

If the updating laws for the parameter vectors are chosen as

$$\dot{\theta}_i = (\gamma_{1i} c_{4i})\underline{e}_i^T P_i B_i \xi(x_i) \tag{29}$$

$$\dot{\theta}_{di} = -(\gamma_{2i} c_{4i})\underline{e}_i^T P_i B_i \eta(X) \tag{30}$$

$$\dot{\phi}_i = -(\gamma_{3i} c_{4i})\underline{e}_i^T P_i B_i \rho(x_i) \tag{31}$$

$$\dot{\Theta}_i = -(\gamma_{4i} c_{4i})\underline{e}_i^T P_i B_i \zeta(x_i) \tag{32}$$

then the terms T_i, $i = 1 \ldots 4$, vanish, and (28) becomes

$$\dot{V}_i = \frac{1}{2}\underline{e}_i^T\left(A_{ci}^T P_i + P_i A_{ci}\right)\underline{e}_i + (c_{4i} u_{ia} + \omega_{Ti})\underline{e}_i^T P_i B_i. \tag{33}$$

Now, if the auxiliary control u_{ia} is chosen as

$$u_{ia} = -\frac{1}{c_{4i}\sigma_i}\underline{e}_i^T P_i B_i \tag{34}$$

then (33) becomes

$$\dot{V}_i = -\frac{1}{2}\underline{e}_i^T Q_i \underline{e}_i + \omega_{Ti}\underline{e}_i^T P_i B_i - \frac{1}{2\rho_i^2}\underline{e}_i^T P_i B_i B_i^T P_i \underline{e}_i \tag{35}$$

where P_i is the solution of the following Riccati-like equation:

$$A_{ci}^T P_i + P_i A_{ci} - P_i B_i\left(\frac{2}{\sigma_i} - \frac{1}{\rho_i^2}\right)B_i^T P_i = -Q_i \tag{36}$$

for $0 < \sigma_i \leq 2\rho_i^2$.

Assumption: There exists a constant $\delta > 0$, such that $\int_0^T \omega_T^T \omega_T dt \leq \delta$, where $\omega_T^T = [\omega_{T1} \ldots {}_{TN}]$.

Theorem: For each interconnected and disturbed LFC area (5), the proposed DIAFLC given by (13)–(17) and (34) along with the adaptation laws (29)–(32) ensures that the tracking error and the parameter error of the closed-loop LFC area are bounded and achieves the H_∞ tracking performance (26) with desired attenuation level.

Proof: Equation (35) can be rewritten as

$$\dot{V}_i = -\frac{1}{2}\underline{e}_i^T Q_i \underline{e}_i + \frac{1}{2}\rho_i^2\omega_{Ti}^2 - \frac{1}{2}\varepsilon_i^T \varepsilon_i \tag{37}$$

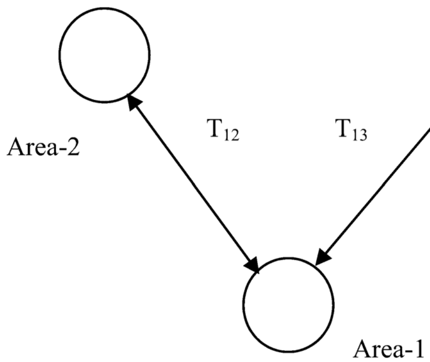

Fig. 2. Three-area system.

TABLE I
SYSTEM PARAMETERS

Parameter	Area-1	Area-2	Area-3
D	0.24	0.11	0.046
K_r	0.3	0.3	
M	167	89.5	23.25
R	0.04	0.04	0.04
T_{t1}	0.4	0.4	0.1
T_{g1}	0.1	0.1	0.4
T_{t2}	1.0	1.0	
T_{g2}	0.1	0.1	
T_{ri}	1.0	1.0	
T_{12}=T_{21}	8.4	8.4	
T_{13}=T_{31}	2.3		2.3

where $\varepsilon_i = ((1/\rho_i)\mathrm{B}_i^{\mathrm{T}}\mathrm{P}_i\underline{\mathrm{e}}_i - \rho_i\omega_{Ti})$. Using the fact that the last term of (37) is negative, then it becomes

$$\dot{V}_i \leq -\frac{1}{2}\underline{e}_i^T Q_i \underline{e}_i + \frac{1}{2}\rho_i^2\omega_{Ti}^2 \tag{38}$$

Integrating (38) from 0 to t, we obtain

$$V_i(t) - V_i(0) \leq -\frac{1}{2}\int_0^t \underline{e}_i^T Q_i \underline{e}_i dt + \frac{1}{2}\rho_i^2 \int_0^t \omega_{Ti}^2 dt \tag{39}$$

Since $V_i(t) \geq 0$, inequality (39) implies that

$$\int_0^t \underline{e}_i^T Q_i \underline{e}_i dt \leq 2V_i(0) + \rho_i^2 \int_0^t \omega_{Ti}^2 dt \tag{40}$$

This equation is the H_∞ tracking performance with desired attenuation level given by (26). Moreover, the boundedness of the tracking error and the approximation errors can be shown from (39) which can be rewritten as

$$V_i(\underline{e}_i, \varphi_i, t) - V_i(\underline{e}_i(0), \varphi_i(0), 0) \leq \frac{1}{2}\rho_i^2 \int_0^t \omega_{Ti}^2 dt \tag{41}$$

Using the above assumption, (41) becomes

$$V_i(\underline{e}_i, \varphi_i, t) - V_i(\underline{e}_i(0), \varphi_i(0), 0) \leq \infty \tag{42}$$

This implies that $\underline{e}_i$ and φ_i are all bounded for $0 \leq \mathrm{t} \leq \infty$.

TABLE II
CONTROLLER PARAMETERS

Area	DAFLC	PID
1	γ_1=50, γ_2=2.5, Q=1.5 I, ρ=0.85, r =1	K_p=64.8, K_I= 5.02, K_D = 62.7
2	γ_1=10, γ_2=2.5, Q=.01 I, ρ=0.85, r=1	K_p=0.36, K_I= 0.011, K_D = 4.5
3	γ_1=25, Q=0.5 I, ρ=0.85, r=1	K_p= 0.8, K_I= 5.02, K_D =0.006

TABLE III
IF–THEN RULES FOR THE TYPE-2 FUZZY CONTROLLER

AĊE \ ACE	N	Z	P
N	P	N	N
Z	N	P	P
P	N	N	N

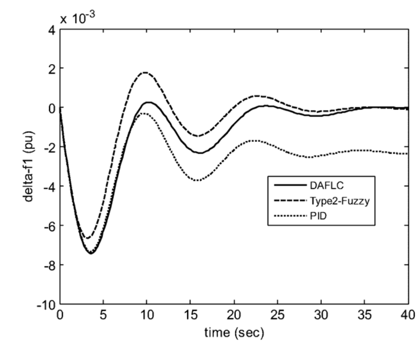

Fig. 3. Frequency deviation in area-1 (case I-A).

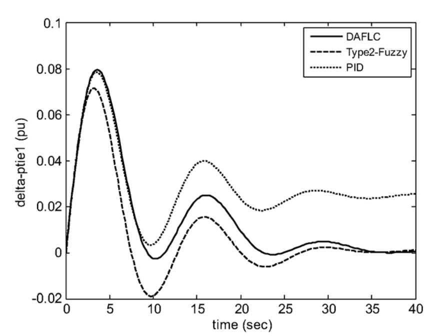

Fig. 4. Tie-line power deviation to area-1 (case I-A).

Now consider the composite system Lyapunov function candidate $V = \sum_{i=1}^{N} V_i$ and denoting $P = \mathrm{diag}(P_i)$, $Q = \mathrm{diag}(Q_i)$, $\rho = \mathrm{diag}(\rho_i)$, and $\underline{e}^T = [\underline{e}_1 \ldots \underline{e}_N]$, one can write for the composite system the following inequality:

$$\lambda_Q \|\underline{e}\|_2^2 \leq 2V(0) + \frac{1}{2}\rho^2\delta \tag{43}$$

from which one concludes that the overall system tracking error is contained in a bounded set $\Omega_{\underline{e}}$ defined by $\Omega_{\underline{e}} = \{\underline{e} : \|\underline{e}\|_2^2 \leq (1/\lambda_Q)(2V(0) + (1/2)\rho^2\delta)\}$ where λ_Q is the real part of the eigenvalues of Q with minimum magnitude. This concludes the proof.

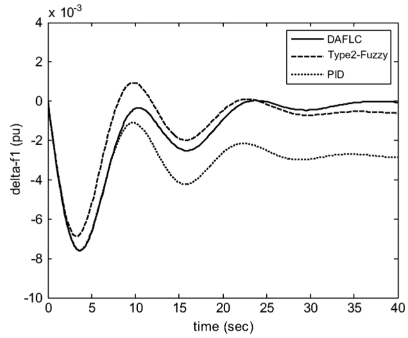

Fig. 5. Frequency deviation in area-1 (case I-B).

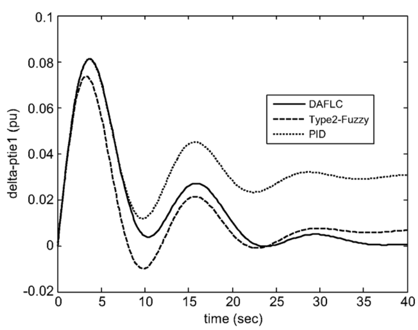

Fig. 6. Tie-line power deviation to area-1 (case I-B).

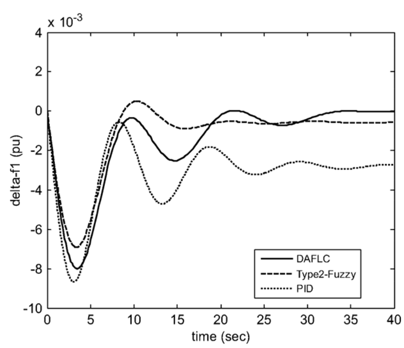

Fig. 7. Frequency deviation in area-1 (case II-A).

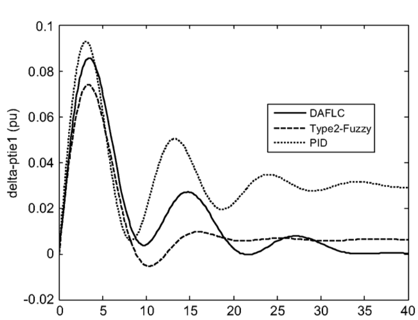

Fig. 8. Tie-line power deviations to area-1 (case II-A).

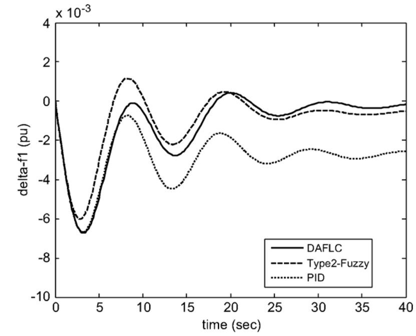

Fig. 9. Frequency deviation in area-1 (case II-B).

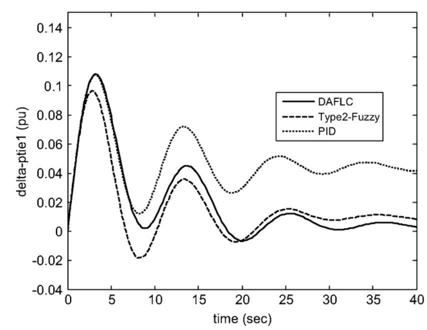

Fig. 10. Tie-line power deviations to area-1 (case II-B).

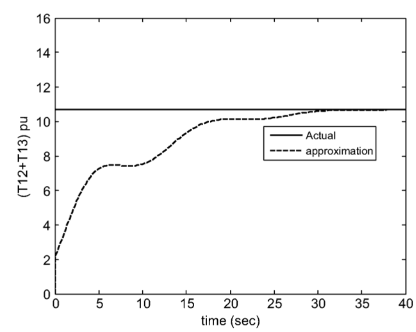

Fig. 11. Actual and approximated value of synchronizing power.

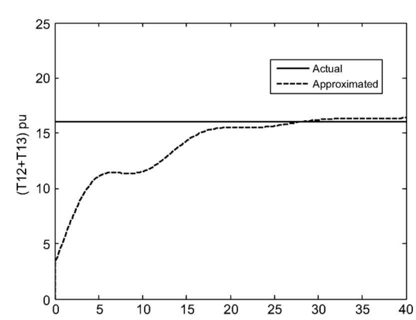

Fig. 12. Actual (off-nominal 50%) and approximated value of synchronizing power coefficients $(\mathrm{T}_{12} + \mathrm{T}_{13})$.

V. Simulation Results

A real three-area interconnected power system existing in the gulf region is considered as a simulation example to investigate the effectiveness of the proposed DIAFLC given by (13)–(17), (29)–(32), and (34). The three-area system is shown in Fig. 2.

Area-1 has 49 gas turbine-machines and seven steam turbine-machines while area-2 has 48 gas turbine-machines and 40 steam turbine machines. Area-3 has 28 gas turbine-machines only. The system parameters are given in Table I. Five Gaussian membership functions are chosen for the frequency and the tie-line power deviations in each area. It is assumed that no

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TABLE IV
PERFORMANCE COMPARISON BETWEEN THE DIAFLC, TYPE-2 FUZZY, AND PID CONTROLLERS

Case	$\lvert\Delta f_{1ss}\rvert$ (10^{-3})			$\lvert\Delta f_{1max}\rvert$ (10^{-3})			$\lvert\Delta P_{tie1ss}\rvert$ (10^{-3})			$\lvert\Delta P_{tie1max}\rvert$ (10^{-3})		
	DIAFLC	Type-2 Fuzzy	PID	DIAFLC	Type-2 Fuzzy	PID	DIAFLC	Type-2 Fuzzy	PID	DIAFLC	Type-2 Fuzzy	PID
Case IA	0	0	2	8	6.5	8	0	0	25	80	70	80
Case IB	0	1	3	8	7	8	0	7.5	30	80	70	80
Case IIA	0	1	3	8	7	9	0	10	30	85	70	90
Case IIB	0	1	3	7	6	7	0	10	40	95	85	95

fuzzy control rules are available for the proposed DIAFLC. Comparisons between simulation results of the proposed controller and those of a PID classical controller, designed using Ziegler-Nichols method, and a type-2 fuzzy decentralized LFC (Type-2 Fuzzy) [30] are carried out in the presence of GRC and GDB. The parameters of the proposed DIAFLC and the PID controller are tabulated in Table II and the "If-then" rules for the Type-2 fuzzy controller are given in Table III.

Two different simulation cases are considered. In case I, the nominal parameters of the system are used, and two simulation tests are carried out, namely, a load disturbance of 300 MW (0.3 p,u,) is assumed to take place in area-1 (case I-A) and load disturbances of 0.3, 0.1, and 0.01 p.u. are assumed to occur in areas 1, 2, and 3, respectively (case I-B). The off-nominal parameters are considered in case II. In this case, two simulation sets of results are obtained. In the first set a mismatch of 50% in both the inertia constant and load damping coefficient is assumed [31] (case II-A). The second set where the tie-line synchronizing power coefficient has a mismatch of 50% [12] is considered (case II-B). Simulation results of the frequency and the tie-line power deviations of area 1 for case I-A are shown in Figs. 3 and 4. Frequency and tie-line power deviations of area 1 for case I-B are shown in Figs. 5 and 6. Simulation results for cases II-A and II-B are given in Figs. 7–10, respectively. The approximated value of the interconnection terms $(\mathrm{T}_{12}+\mathrm{T}_{13})$ for the nominal and off-nominal cases are shown in Figs. 11 and 12, respectively.

A summary of simulation performance in terms of the steady-state ($|\Delta \mathrm{f}_{1\mathrm{ss}}|$) and maximum overshoot ($|\Delta \mathrm{f}_{1\,\mathrm{max}}|$) of frequency deviation for area 1 and the steady-state ($|\Delta \mathrm{P}_{\mathrm{tie1ss}}|$) and maximum overshoot ($|\Delta \mathrm{P}_{\mathrm{tie1\,max}}|$) of tie-line power deviation for area 1 of the three controllers is shown in Table IV. As another performance measure, the integral of time-weighted absolute error (ITAE) defined as $\int_0^{T_f} t|\Delta f(t)|dt$, where T_f is the final simulation time, is evaluated for the three controllers, and the results are shown in Table V. In the presence of parameters mismatch, the type-2 fuzzy and PID controllers show nonzero steady-state frequency and tie-line power deviations while the proposed controller shows zero steady state deviations. Moreover, the ITAE performance index is much smaller for the proposed controller as compared with the other two.

It is clear that the proposed controller achieves the LFC objectives even in the presence of parameter uncertainties and unknown saturation and dead band of GRC and GDB. It is worth-noting to mention that the advantage of the proposed controller is that it does not need any set of "if-then" rules in contrast to the type-2 fuzzy controller and it can cope with parameter variation and the unknown nonlinearities. However, from the comparison table, $|\Delta \mathrm{f}_{1\,\mathrm{max}}|$ and $|\Delta \mathrm{P}_{\mathrm{tie1\,max}}|$ of the proposed

TABLE V
ITAE PERFORMANCE INDEX

Case	ITAE		
	DIAFLC	Type-2 Fuzzy	PID
Case IA	0.151	0.351	1.893
Case IB	0.171	0.56	2.294
Case IIA	0.168	0.52	2.292
Case IIB	0.162	0.451	2.197

controller is higher than those of the PID and Type-2 Fuzzy controllers.

VI. CONCLUSION

The paper presents a new load frequency controller for multi-area power system having unknown parameters. The proposed controller is developed using DIAFLC technique. Four fuzzy logic systems with center average defuzzifier and singleton fuzzifier are used to design the primary control signal, to approximate the unknown functions of the GRC and GDB nonlinearities and to approximate the unknown interconnections. An auxiliary control signal is designed to compensate for the fuzzy approximation errors and to achieve an H_∞ tracking performance. A composite Lyapunov function is used to show the boundedness of the closed-loop system tracking error. A realistic three-area power system is used as a validation example. Simulation results show that the developed DIAFLC is able to achieve the LFC objectives in terms of zero steady-state frequency and tie-line deviations. Superiority of the developed DIAFLC over a Type-2 fuzzy and a classical PID controller is illustrated.

REFERENCES

[1] H. Bevrani and T. Hiyama, *Intelligent Automatic Generation Control*. Boca Raton, FL, USA: CRC press, 2011.
[2] P. Kundur, *Power System Stability and Control*. New York, NY, USA: Mc-Graw Hill, 1994.
[3] C. Zhang, L. Jiang, Q. H. Wu, Y. He, and M. Wu, "Delay-dependent robust load frequency control for time delay power systems," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 2192–2201, Aug. 2013.
[4] H. Trinh, T. Fernando, H. H. C. Iu, and K. P. Wong, "Quasi-decentralized functional observers for the LFC of interconnected power systems," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3513–3514, Aug. 2013.
[5] S. Saxena and Y. V. Hote, "Load frequency control in power systems via internal model control scheme and model-order reduction," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 2749–2757, Aug. 2013.
[6] H. Bevrani and T. Hiyama, "On load-frequency regulation with time delays: Design and real-time implementation," *IEEE Trans. Energy Convers.*, vol. 24, no. 1, pp. 292–300, Mar. 2009.
[7] H. Shayeghi, H. A. Shayanfar, and A. Jalili, "Load frequency control strategies: A state-of-the-art survey for the researcher," *Energy Convers. Manag.*, vol. 50, pp. 344–353, 2009.

[8] Ibraheem, P. Kumar, and D. P. Kothari, "Recent philosophies of automatic generation control strategies in power systems," *IEEE Trans. Power Syst.*, vol. 20, no. 1, pp. 346–357, Feb. 2005.

[9] W. Tan, "Unified tuning of PID load frequency controller for power systems via IMC," *IEEE Trans. Power Systems*, vol. 25, no. 1, February 2010.

[10] A. Khodabakhshian and M. Edrisi, "A new robust PID load frequency controller," *Control Eng. Practice*, vol. 16, pp. 1069–1080, 2008.

[11] L. Dong, Y. Zhang, and Z. Gao, "A robust decentralized load frequency controller for interconnected power systems," *ISA Trans.*, vol. 51, pp. 410–419, 2012.

[12] H. Bevrani, Y. Mitani, and K. Tsuji, "Robust decentralised load-frequency control using an iterative linear matrix inequalities algorithm," *Proc. Inst. Electr. Eng.—Gener., Transm. Distrib.*, vol. 151, no. 3, May 2004.

[13] S. Velusami and I. A. Chidambaram, "Decentralized biased dual mode controllers for load frequency control of interconnected power systems considering GDB and GRC non-linearities," *Energy Convers. Manag.*, vol. 48, pp. 1691–1702, 2007.

[14] R. Arivoli and I. A. Chidambaram, "CPSO based LFC for a two-area power system with GDB and GRC nonlinearities interconnected through TCPS in series with the tie-line," *Int. J. Comput. Applications*, vol. 38, no. 7, pp. 1–10, Jan. 2012.

[15] N. Hoonchareon, C. Ong, and R. A. Kramer, "Implementation of an ACE1 decomposition method," *IEEE Trans. Power Syst.*, vol. 17, no. 3, pp. 757–761, Aug. 2002.

[16] J. Talaq and F. Al-Basri, "Adaptive fuzzy gain scheduling for load frequency control," *IEEE Trans. Power Syst.*, vol. 14, no. 1, pp. 145–150, Feb. 1999.

[17] A. Abdennour, "Adaptive optimal gain scheduling for the load frequency control problem," *Electr. Power Compon. Syst.*, vol. 30, pp. 45–56, 2002.

[18] I. Kocaarslan and E. Cam, "Fuzzy logic controller in interconnected electrical power systems for load-frequency control," *Electr. Power Energy Syst.*, vol. 27, pp. 542–549, 2005.

[19] H. Bevrani and P. R. Daneshmand, "Fuzzy logic-based load-frequency control concerning high penetration of wind turbines," *IEEE Syst. J.*, vol. 6, no. 1, pp. 173–180, Mar. 2012.

[20] S. H. Hosseini and A. H. Etemadi, "Adaptive neuro-fuzzy inference system based automatic generation control," *Electr. Power Syst. Res,*, vol. 78, pp. 1230–1239, 2008.

[21] H. J. Lee, J. B. Park, and Y. H. Joo, "Robust load-frequency control for uncertain nonlinear power systems: A fuzzy logic approach," *Inf. Sci.*, vol. 176, pp. 3520–3537, 2006.

[22] C.-F. Juang and C.-F. Lu, "Load-frequency control by hybrid evolutionary fuzzy PI controller," *Proc. Inst. Electr. Eng.—Gener., Transm. Distrib.*, vol. 153, no. 2, pp. 196–204, 2006.

[23] L. X. Wang, *Fuzzy System and Control: Design and Stability Analysis*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1994.

[24] L. Jiang, W. Yao, Q. H. Wu, J. Y. Wen, and S. J. Cheng, "Delay-dependent stability for load frequency control with constant and time-varying delays," *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 932–941, May 2012.

[25] R. L. Williams II and D. A. Lawrence, *Linear State-Space Control Design*. Hoboken, NJ, USA: Wiley, 2007.

[26] H. Yousef, M. Hamdy, D. Eteim, and E. El-Madbouly, "Adaptive fuzzy semi-decentralized control for a class of large-scale nonlinear systems with unknown interconnections," *Int. J. Robust Nonlinear Control*, vol. 16, pp. 687–708, 2006.

[27] H. Yousef, M. Hamdy, and E. El-Madbouly, "Robust adaptive fuzzy semi-decentralized control for a class of large-scale nonlinear systems using input-output linearization concept," *Int. J. Robust Nonlinear Control*, vol. 20, pp. 27–40, 2010.

[28] Y. C. Chang, "Adaptive fuzzy-based tracking control for nonlinear SISO systems via VSS, H^{-} approaches," *IEEE Trans. Fuzzy Syst.*, vol. 9, pp. 728–742, 2001.

[29] B. S. Chen, T. S. Lee, and J. H. Feng, "A nonlinear H_{-} control design in robotic systems under parameter perturbations and external disturbance," *Int. J. Control*, vol. 59, pp. 439–461, 1994.

[30] K. R. Sudha an and R. V. Santhi, "Robust decentralized load frequency control of interconnected power system with generation rate constraint using type-2 fuzzy approach," *Electr. Power Energy Syst.*, vol. 33, pp. 699–707, 2011.

[31] H. Shayeghi and H. A. Shayanfar, "Automatic generation control of interconnected power system using ANN technique based on μ-synthesis," *J. Electr. Eng.*, vol. 55, no. 11–12, pp. 306–313, 2004.

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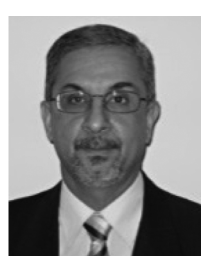

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