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Glocal Control of Load Frequency for Electrical Power Networks with Multiple Shared Model Set

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Abstract – **Load frequency control of electrical power networks to balance the demand and supply based on automatic generation control (AGC) has been widely studied for years. As the power networks become more complex, we face the essential issue: How to design the load frequency control systematically to assure the stability of the overall system while optimizing the global/local control performances? To this end, in this paper, we propose a framework for glocal (global/local) control of load frequency. The command to each local governor includes two signals: the local signal through the corresponding area-control error (ACE) in the lower-layer, and the global signal distributed from the upper-layer by controlling the average frequency aggregation. We will clarify the role-sharing of the upper and lower layers via two model sets which are shared in both control layers. Finally, we demonstrate the trade-off between upper and lower performances through the volumes of model sets, and verify the effectiveness of the proposed method by simulations.**

I. Introduction

In the electrical power networks, load frequency control (LFC) is the very fundamental function to balance the demand-supply, and maintain the system frequency at the nominal values [1]. After more than four decades, many control strategies has been proposed. Among them, centralized control [2] is no longer of interest since it is unsuitable for the very complex power system in the future, especially when various renewable sources are integrated. Thus, completely decentralized control [3~6] or hierarchically decentralized control [7~11] has been much attracted in control community in recent years. However, a systematic method to assure the stability of the overall load frequency control system is still a challenge issue. The power network can be seen as a large scale system of N local areas, and the most difficult challenge in stability analysis is the interconnection between local areas represented by the synchronizing torque coefficient matrix T of size $N\times N$. Define $\Psi(s) = det(I_N + diag\{\Phi_i(s)\}T/s)$ where $\Phi_i(s)$ is the transfer function of ith local subsystem including the local plant and local controller. In [6], Tan states that the decentralized LFC system is stable if $\Psi(s)$ is stable. However, it is not easy to assure the stability of $\Psi(s)$, especially when N is a big number and uncertainties are introduced. When tuning any ith controller, it is necessary to know the details of not only matrix T but also other N-1 controllers. Thus, this type of decentralized control is unsuitable for large scale power networks. In [7] and [8], Andreasson *et al* propose a hierarchical control structure such that the mechanical power for each local area is obtained by two control layers: the proportional (P) control of local frequency ω_i in the lower-layer, and in the upper-layer the integral (I) control of the average frequency $\varpi = (\omega_1 + \omega_2 +\ldots+ \omega_N)/N$. According to [8], the overall LFC system is stable if the P gains and I gains are both positive. However, this proposition is only applicable to the simplified power networks that neglecting the dynamics of turbines and governors. By selecting the same control gains for the heterogeneous local areas, the authors cannot discuss the control performance of two control layers. Moreover, the control of tie-line power is neglected by this strategy. In [10], Shiltz *et al* propose excellent integration of AGC and demand response. However, the stability of the overall system is examined by a centralized way as follows. Let z is the vector includes the state of the total system, the dynamics of the overall system is $z[k+1] = A\cdot z[k]$ where matrix A is established from system dynamics and the controllers. Considering the large scale power networks, it is quite complex to select the control gains such that A is Schur stable. In summary, we need a systematic design procedure that assuring the stability of the overall system, and enabling control performance analysis.

Considering the above issues, the inspiration of our works is based on the glocal (global/local) concept in which the control actions are restricted locally while the purposes are to attain both the local and global behaviors [12]. Firstly, we show that, similarly to the electric vehicles [13], the load frequency dynamics can be modelled hierarchically with global/local generalized plants by aggregation; and the physical interaction can be treated in the upper-layer. Then, we propose a hierarchically decentralized LFC including the upper-layer controller C_g and N lower-layer controllers $C_{l,i}$ (Fig. 1). In our original works, only one "global/local shared model set" is shared by the upper-layer and lower-layer [14]. In this paper, this idea is utilized in a new way. We notice that there exist two channels connecting the control layers, namely, *Channel 1* for the control distribution from the upper-layer, and *Channel 2* for the physical interaction between interconnected areas. The upper-layer expects that the transfer functions of the local subsystem in *Channels 1* and *2* belong to the model set $\mathcal{M}_{\delta1}$ and $\mathcal{M}_{\delta2}$, respectively. The model sets including perturbation can be expressed as

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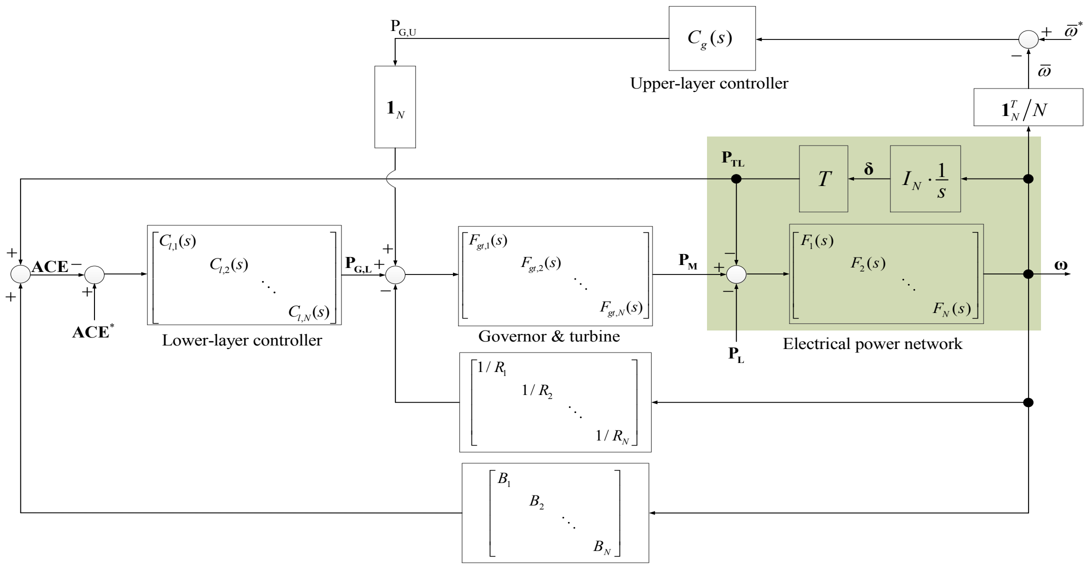


Fig.1. Hierarchically decentralized control system of load frequency.

follows: $\mathcal{M}_{\delta j} = \{\mathcal{F}_l(M_{oj}, \Delta_j) : \|\Delta_j\|_\infty \leq \delta_j\}$ where $j = \{1,2\}$. Thus, each $C_{l,i}$ is designed to optimize the local objective with the additional model matching conditions. From the global controller point of view, the lower-layer becomes a plant including the physical interaction channel and uncertainty channels $\mathcal{M}_{\delta j}$. Thus, we only have to solve a standard robust control problem to design C_g, and the number of local areas is no longer a big issue. Since the control performances are functions of the volumes δ_j, we can clarify the trade-off between two layers.

II. MODELING

A. Modeling of the power networks

The power network includes N local are shown in Fig. 1 [15]. Let $t_{ij} = t_{ji}\ \forall\ i \neq j$ is the synchronizing torque coefficient between ith area and jth area. The symmetric matrix T is expressed as

$$T = \begin{bmatrix} \sum_{j\neq 1} t_{1j} & -t_{12} & \cdots & -t_{1N} \\ -t_{21} & \sum_{j\neq 2} t_{2j} & \cdots & -t_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ -t_{N1} & -t_{N2} & \cdots & \sum_{j\neq N} t_{Nj} \end{bmatrix} \quad (1)$$

B. Modeling of the proposed LFC system

We propose the hierarchically decentralized control system for load frequency as in Fig. 1. In the lower-layer, $C_{l,i}(s)$ is to control the corresponding ACE to follow the reference ACE*. In the upper-layer, $C_g(s)$ is to control the average frequency. The command to each governor is the summary of the local control signal, and the global control signal distributed from the upper-layer.

TABLE I
NOMENCLATURE

Symbol	Meaning
ϖ	Average aggregation of frequency deviation
$\mathbf{1}_N$	All-one column vector of size N
$\boldsymbol{\omega}$	Vector of frequency deviation
$\mathbf{P_M}$	Vector of mechanical power deviation
$\mathbf{P_L}$	Vector of load power deviation
$\mathbf{P_{TL}}$	Vector of tie-line power deviation
$F_i(s)$	Transfer function of generator in the ith area
$F_{gt,i}(s)$	Transfer function of governor & turbine in ith area
R_i	Droop characteristics for ith area
B_i	Frequency bias setting of ith area
T	Synchronizing torque coefficient matrix
ACE	Vector of area control error
$C_{l,i}(s)$	Transfer function of the ith lower-layer controller
$C_g(s)$	Transfer function of the upper-layer controller
$\mathbf{P_{G,L}}$	Vector of local control signal
$P_{G,U}$	Global control signal

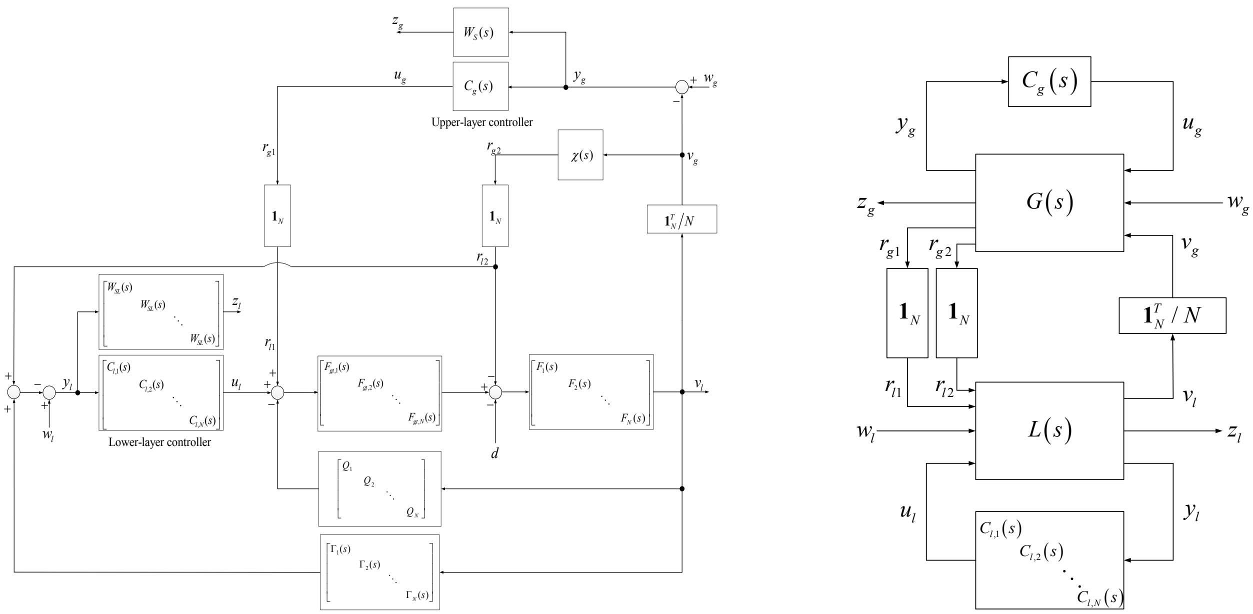
III. GLOCAL CONTROL APPROACH

A. Problem Setting

In this study, we consider a class of power system including N interconnected areas such that the synchronizing torque coefficients are homogeneous ($t_{ij} = t\ \forall\ i \neq j$), which fairly fits to the situation where all the generators are located in a certain compact region, such as an island-grids. We take this idealized assumption for the sake of simplicity in demonstrating the fundamental characteristics of electric power network with hierarchical structure. Then, we have

$$T = diag\{Nt\} - \mathbf{1}\cdot\mathbf{1}^{\mathbf{T}} t \quad (2)$$

Thanks to (2), the LFC system in Fig. 1 can be equivalently represented as in Fig. 2(a). To apply the framework of glocal control [14], we name the signals as follows: w_l is the reference value of the ACE, and w_g is the reference value of ϖ; y_l and y_g are the control errors of two control layers; z_l and z_g are the signals for evaluating the control performances of the lower-layer and upper-layer,



(a) (b)

Fig.2. Representation of LFC system in case of homogeneous synchronizing torque coefficient.

obtaining via the weighting functions $W_{SL}(s)$ and $W_S(s)$, respectively. In the channel from lower-layer to upper-layer, v_l is the vector of frequency deviation and v_g is the average frequency deviation. The control signals of two layers are u_l and u_g. The upper-layer connects to the lower-layer via the control signal distribution channel between r_{g1} and r_{l1}, and the physical interaction channel between r_{g2} and r_{l2}. The gain $Q_i = 1/R_i$, and other transfer functions in Fig. 2(a) are

$$\chi(s) = \frac{Nt}{s},\ H_i(s) = \frac{F_i(s)}{1+F_i(s)\chi(s)},\ \Gamma_i(s) = B_i + \chi(s)$$

B. Glocal Framework

The system in Fig. 2(a) can be expressed by the glocal control framework shown in Fig. 2(b) where the block matrices are expressed as (3). In the following, we remove "s" in the transfer function expressions for simplicity.

$$G = \begin{bmatrix} 0 & 1 & -1 \\ 0 & W_S & -W_S \\ 1 & 0 & 0 \\ 0 & 0 & \chi \end{bmatrix},\ L = \begin{bmatrix} L_{vr1} & L_{vr2} & L_{vw} & L_{vu} \\ L_{zr1} & L_{zr2} & L_{zw} & L_{zu} \\ L_{yr1} & L_{yr2} & L_{yw} & L_{yu} \end{bmatrix} \quad (3)$$

where $L_{*\#} = diag\left\{L_{*\#}^{(i)}\right\}$ and

$$L^{(i)} = \begin{bmatrix} \dfrac{H_i}{1+Q_iF_{gt,i}H_i} & \dfrac{F_{gt,i}H_i}{1+Q_iF_{gt,i}H_i} & 0 & \dfrac{F_{gt,i}H_i}{1+Q_iF_{gt,i}H_i} \\ \dfrac{-W_{SL}\Gamma_iH_i}{1+Q_iF_{gt,i}H_i}+W_{SL} & \dfrac{-W_{SL}F_{gt,i}H_i}{1+Q_iF_{gt,i}H_i} & W_{SL} & \dfrac{-W_{SL}F_{gt,i}H_i}{1+Q_iF_{gt,i}H_i} \\ \dfrac{-\Gamma_iH_i}{1+Q_iF_{gt,i}H_i}+1 & \dfrac{-F_{gt,i}H_i}{1+Q_iF_{gt,i}H_i} & 1 & \dfrac{-F_{gt,i}H_i}{1+Q_iF_{gt,i}H_i} \end{bmatrix}$$

C. Global and Local Performance

The condition for ACE tracking control can be expressed as $\left\|\eta_{l,i}W_{SL}S_{l,i}\right\|_\infty \le 1$ where $\eta_{l,i}$ represents the local control performance to be maximized, and the sensitivity function is

$$S_{l,i} = \frac{\Gamma_iC_{l,i}F_{gt,i}H_i}{1+\left(Q_i+\Gamma_iC_{l,i}\right)F_{gt,i}H_i}$$

On the other hand, the condition for the upper-layer is $\left\|\eta_gW_SS_g\right\|_\infty \le 1$ where η_g represents the global control performance to be maximized, and S_g is the sensitivity function from w_g to y_g. It is a very complex high order function which depends on both the upepr and lower blocks. Considering the large scale power networks, our interests are as follows: (1) How to reduce the computational effort to optimize η_g and stabilize the overall system? (2) Does the trade-off between η_g and $\eta_{l,i}$ exists?

D. Idea of Shared Model Sets

For any local subsystem we have

$$v_{l,i} = \Phi_{1,i}r_{l1,i} + \Phi_{2,i}r_{l2,i} \quad (4)$$

where $\Phi_{1,i} = \dfrac{F_{gt,i}H_i}{1+\left(Q_i+\Gamma_iC_{l,i}\right)F_{gt,i}H_i}$, $\Phi_{2,i} = \dfrac{\left(C_{l,i}F_{gt,i}+1\right)H_i}{1+\left(Q_i+\Gamma_iC_{l,i}\right)F_{gt,i}H_i}$

Let M_{1o} and M_{2o} be the nominal models. We can define the multiplicative model matching errors as

$$\Delta_{1,i} = \frac{\Phi_{1,i}-M_{1o}}{M_{1o}},\ \Delta_{2,i} = \frac{\Phi_{2,i}-M_{2o}}{M_{2o}} \quad (5)$$

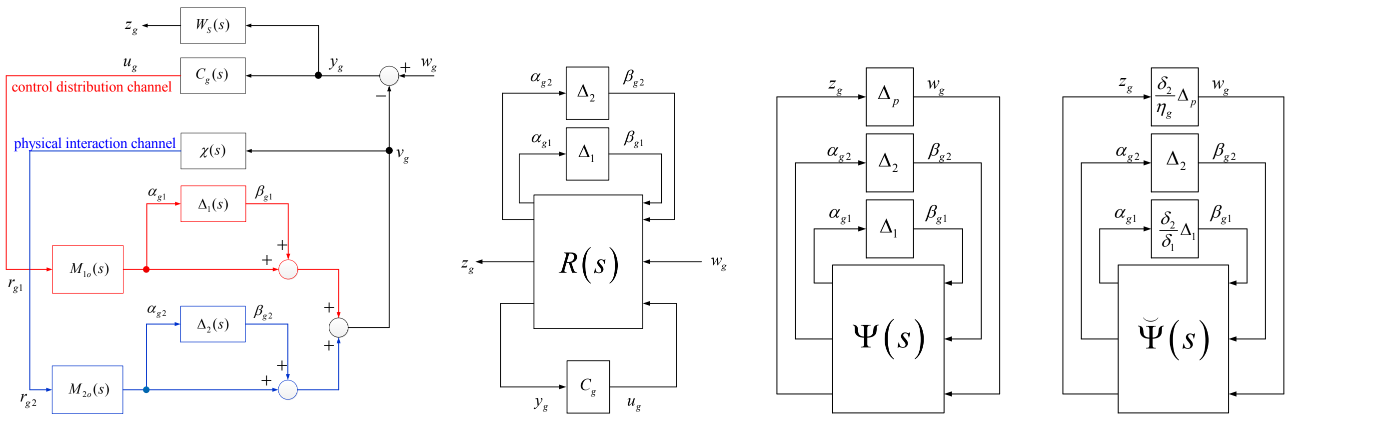


Fig. 3. Representation of the overall system with nominal models and perturbations.

If the above errors satisfy $\|\Delta_{1,i}\|_\infty \le \delta_1$ and $\|\Delta_{2,i}\|_\infty \le \delta_2\ \forall\, i$, the overall system can be expressed as in Fig. 3(a) where the channels from r_{g1} and r_{g2} to v_g can be represented by the nominal models with the perturbation Δ_1 and Δ_2 satisfying

$$\|\Delta_1\|_\infty = \left\|\frac{1}{N}\sum_{i=1}^{N} k_i\Delta_{1i}\right\|_\infty \le \delta_1,\ \|\Delta_2\|_\infty = \left\|\frac{1}{N}\sum_{i=1}^{N}\Delta_{2i}\right\|_\infty \le \delta_2 \quad (6)$$

The system in Fig. 3(a) can be transformed to the system in Fig. 3(b). To represent the global control performance, we define the perturbation Δ_p such that $\|\Delta_p\|_\infty \le \eta_g$. The system in Fig. 3(b) is again transformed to the system in Fig. 3(c). The block matrices R and Ψ are obtained as

$$R = \begin{bmatrix} 0 & 0 & 0 & M_{1o} \\ \dfrac{\chi M_{2o}}{1-\chi M_{2o}} & \dfrac{\chi M_{2o}}{1-\chi M_{2o}} & 0 & \dfrac{\chi M_{2o} M_{1o}}{1-\chi M_{2o}} \\ \dfrac{-W_S}{1-\chi M_{2o}} & \dfrac{-W_S}{1-\chi M_{2o}} & W_S & \dfrac{-W_S M_{1o}}{1-\chi M_{2o}} \\ \dfrac{-1}{1-\chi M_{2o}} & \dfrac{-1}{1-\chi M_{2o}} & 1 & \dfrac{-M_{1o}}{1-\chi M_{2o}} \end{bmatrix}$$

$$\Psi = \begin{bmatrix} \dfrac{-C_g M_{1o}}{1-\chi M_{2o}+C_g M_{1o}} & \dfrac{-C_g M_{1o}}{1-\chi M_{2o}+C_g M_{1o}} & \dfrac{(1-\chi M_{2o})C_g M_{1o}}{1-\chi M_{2o}+C_g M_{1o}} \\ \dfrac{\chi M_{2o}}{1-\chi M_{2o}+C_g M_{1o}} & \dfrac{\chi M_{2o}}{1-\chi M_{2o}+C_g M_{1o}} & \dfrac{\chi M_{2o} C_g M_{1o}}{1-\chi M_{2o}+C_g M_{1o}} \\ \dfrac{-W_S}{1-\chi M_{2o}+C_g M_{1o}} & \dfrac{-W_S}{1-\chi M_{2o}+C_g M_{1o}} & \dfrac{W_S(1-\chi M_{2o})}{1-\chi M_{2o}+C_g M_{1o}} \end{bmatrix}$$

We finally transform the system shown in Fig. 3(c) to the system in Fig. 3(d) where

$$\breve{\Psi} = \begin{bmatrix} \dfrac{\delta_1}{\delta_2}\Psi_{11} & \dfrac{\delta_1}{\delta_2}\Psi_{12} & \dfrac{\delta_1}{\delta_2}\Psi_{13} \\ \Psi_{21} & \Psi_{22} & \Psi_{23} \\ \dfrac{\eta_g}{\delta_2}\Psi_{31} & \dfrac{\eta_g}{\delta_2}\Psi_{32} & \dfrac{\eta_g}{\delta_2}\Psi_{33} \end{bmatrix}$$

Accordingly, the combined perturbation in Fig. 3(d) is

$$\breve{\mathbf{\Delta}} = diag\left\{\frac{\delta_2}{\delta_1}\Delta_1, \Delta_2, \frac{\delta_2}{\eta_g}\Delta_p\right\} \quad (7)$$

Since $\|\Delta_1\|_\infty \le \delta_1$, $\|\Delta_2\|_\infty \le \delta_2$, and $\|\Delta_p\|_\infty \le \eta_g$, it is transparent that $\left\|\breve{\mathbf{\Delta}}(s)\right\|_\infty \le \delta_2$. We name $\{M_{jo}, \delta_j\}$ ($j = 1, 2$) as the model set to be shared between two control layers. Thanks to the model sets, the upper-layer control design becomes a standard robust control problem with the block diagram shown in Fig. 3(d). A popular way to design the system in Fig. 3(d) is μ-synthesis proposed by Zhou and Doyle [16].

IV. Glocal Control Design

Following the idea of shared model sets presented in the previous Section, we propose the following procedure to clarify the independent design of local and global.

Step 1: Model set selection

Select the model sets $\{M_{jo}, \delta_j\}$ ($j = 1, 2$).

Step 2-L: Lower-layer design

Each local controller $C_{l,i}$ is designed to satisfy

(i)Model matching condition

$$\left\|\frac{\Phi_{1,i}-M_{1o}}{M_{1o}}\right\|_\infty \le \delta_1,\quad \left\|\frac{\Phi_{2,i}-M_{2o}}{M_{2o}}\right\|_\infty \le \delta_2 \quad (8)$$

(ii)ACE tracking condition

$$\left\|\eta_{l,i} W_{SL} S_{l,i}\right\|_\infty \le 1 \quad (9)$$

Step 2-G: Upper-layer design

Following the μ-synthesis [16], the global controller is design to satisfy

$$\sup_\omega \mu_{\breve{\Delta}}\left(\breve{\Psi}(j\omega)\right) \le \frac{1}{\delta_2} \quad (10)$$

where $\mu_{\breve{\mathbf{\Delta}}}\left(\breve{\Psi}\right)=\dfrac{1}{\min\left\{\bar{\sigma}\left(\Delta\right):\Delta\in\breve{\mathbf{\Delta}},\ \det\left(I-\breve{\Psi}\Delta\right)=0\right\}}$

V. ILLUSTRATIVE EXAMPLE

A. A Three-Area-Power System and Design Setting

In this paper, we consider a three-area power system discussed in [4~6]. The transfer functions of this system are expressed as follows

$$F_{gt,i}(s)=\frac{1}{\left(T_{g,i}s+1\right)\left(T_{t,i}s+1\right)},\ F_i(s)=\frac{K_{p,i}}{T_{p,i}s+1}\quad (i=1,2,3) \qquad (11)$$

where $T_{g,i}$ is the time constant of the governor; $T_{t,i}$ is the time constant of the turbine; $K_{p,i}$ and $T_{p,i}$ are the gain and time constant of the generator, with t_{ij} = 0.5 $\forall\ i\neq j$ and other parameters are

$$T_{g,1}=0.08,\ T_{t,1}=0.3,\ T_{p,1}=20,\ K_{p,1}=120,\ R_1=2.4,\ B_1=0.4$$
$$T_{g,2}=0.072,\ T_{t,2}=0.33,\ T_{p,2}=25,\ K_{p,2}=112.5,\ R_2=2.7,\ B_2=0.4$$
$$T_{g,3}=0.07,\ T_{t,3}=0.35,\ T_{p,3}=20,\ K_{p,3}=115,\ R_3=2.5,\ B_3=0.4$$

In this paper, we consider the integral controllers in both layers, or $C_{l,i}(s)$ = $K_{l,i}/s$ and $C_g(s)$ = K_g/s. The weighting functions are assumed to be the 1st oders functions $W_{SL}(s)$ = $1/(s+\lambda_l)$ and $W_S(s)$ = $1/(s+\lambda_g)$.

B. Controller Design

Selection of nominal model:

We select the 5th order nominal models as

$$M_{1o}(s)=\frac{K_{po}s^2}{L_o(s)},M_{2o}(s)=\frac{K_{po}s\left[\left(T_{go}s+1\right)\left(T_{to}s+1\right)+K_{lo}\right]}{L_o(s)} \qquad (12)$$

where N = 3 and

$$L_o(s)=s\left(T_{go}s+1\right)\left(T_{to}s+1\right)\left(T_{po}s^2+s+K_{po}Nt\right)$$
$$+K_{po}\left(Q_os^2+B_oK_{lo}s+NtK_{lo}\right)$$

We select K_{lo} = 0.5 and $\{T_{go}, T_{to}, T_{po}, K_{po}, Q_o, B_o\}$ as the averages of the corresponding values in three areas.

Lower-layer design:

Substitute $\Phi_{1,i}(s)$, $\Phi_{2,i}(s)$ and the nominal models to the model matching condition (8) and replace "s" by "$j\omega$", the available set of the local control gain can be expressed as $\left\{K_{l,i}\right\}=\left\{K_{l,i}:g_{1,i}(\omega)\leq\delta_1^2\ \&\ g_{2,i}(\omega)\leq\delta_2^2\quad\forall\omega\geq0\right\}$. On the other hand, substitute $S_{l,i}(s)$ and $W_{SL}(s)$ to (9), the local control performance must satisfy $\eta_{l,i}^2\leq f_i\left(\omega\right)\quad\forall\omega\geq0$. Due to the limitation of paper space, we neglect to show the details of $g_{1,i}(\omega)$, $g_{2,i}(\omega)$, and $f_i(\omega)$ in this paper. The optimal local control performance is obtained as

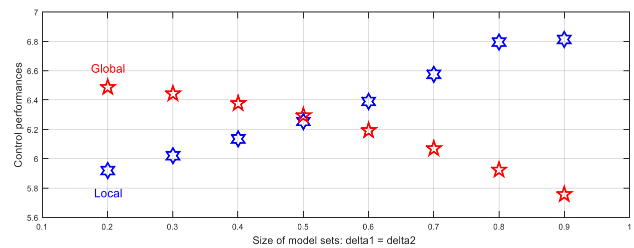


Fig. 4. Trade-off between the global and local performances.

$$\eta_{l,i}^*=\sqrt{\max_{\{K_{l,i}\}}\min_{\omega\geq0}f_i(\omega)} \qquad (13)$$

Upper-layer design:

Since it is very complex to calculate the μ value directly, the standard scheme is to approximate μ by its upper-bound [16], and the design condition can be reduced to

$$\sqrt{\sum_i\sum_j\left|\Psi_{ij}\right|^2\frac{d_i^2}{d_j^2}}\leq\frac{1}{\delta_2^2}\quad\forall\omega\geq0 \qquad (14)$$

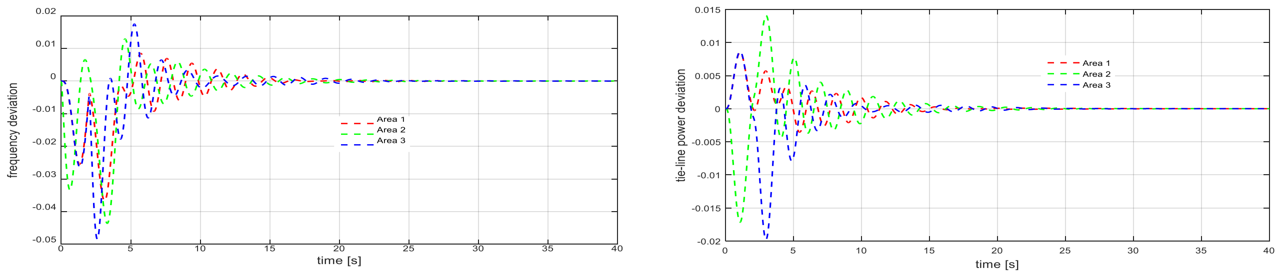
where d_i is the scaling, i from 1 to 3, and d_3 can be set to unit without loss of generality. The optimal global control performance can be obtained using D-K algorithm [16].

C. Trade-off between Global and Local Performance

In this paper, due to the complexity of the power network, it is impossible to obtain the analytical expression of the control performances as in our previous works [13]. In stead, we solve the optimization (13) and (14) by numerical methods at some discrete values of $\{\delta_1,\ \delta_2\}$. We define $\eta_l^*=\min_i\{\eta_{l,i}^*\}$, and summary the results in Fig. 4 considering the case that δ_1 = δ_2. We can see that η_l^* is an increasing function of δ_1 and δ_2. In contrast, η_g^* is shown to be the decreasing functions of both δ_1 and δ_2. Thus, there exists the trade-off between the global and local control performances.

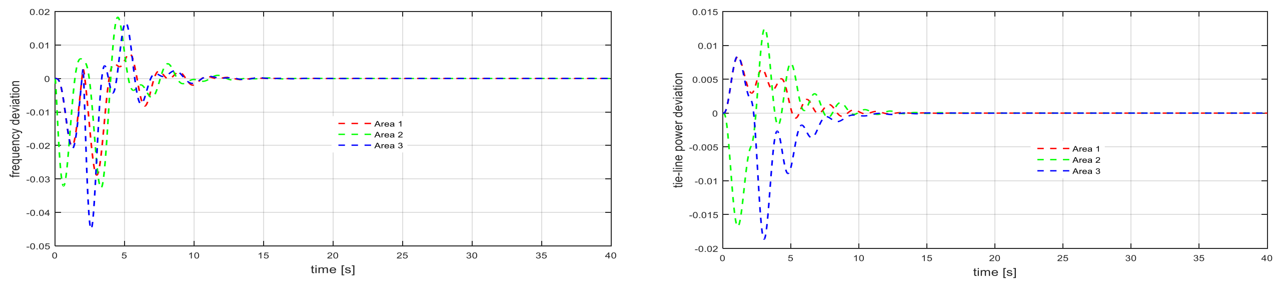
D. Numerical Simulation

We conduct numerical simulation in Matlab/Simulink with the step load $P_{l,1}$ = 0.01, $P_{l,2}$ = 0.02, and $P_{l,3}$ = 0.03. Two tests are performed for comparison. In test A (Fig. 5), each local area is provided with the local controller $C_{l,i}(s)$ = $K_{l,i}/s$. In test B (Fig. 6), the secondary control action is generated by both $C_{l,i}(s)$ = $K_{l,i}/s$ and $C_g(s)$ = K_g/s. To design the control gains, we select the size of the model sets as $\{\delta_1$ = δ_2 = $0.5\}$ which almost balances the global and local control performances. Thanks to the global control signal based on average aggregation, the deviations of frequencies and tie-line powers in Test B attain faster consensus to zero with less vibration. The hierarchically decentralized control strategy, therefore, can not only assure the stability of the overall system, but also improve the performance of load frequency control.



(a) Frequency deviation (b) Tie-line power deviation

Fig. 5. Test A: LFC by completely decentralized control.



(a) Frequency deviation (b) Tie-line power deviation

Fig. 6. Test B: LFC by hierarchically decentralized control.

VI. Conclusions

Utilizing the glocal control theory with the idea of global/local shared model sets, we propose a novel load frequency control system for electrical power networks. The design procedure has two main merits. Firstly, it considerably reduces the design effort since any design step is a standard robust control problem. Secondly, it preserves the independence between two layers, and between the local areas. When we design the upper-layer, we do not need to know the details of the lower-layer which includes a huge numbers of generators, turbines, and governors. When we design any local area, we only need to optimize the local objective without any information from the other areas. Besides that, based on the shared model sets, we clarify the role-sharing between the upper-layer and lower-layer, and demonstrate their trade-off. For the next steps, we will develop the design strategy for the general power networks with heterogeneous synchronizing torque coefficient and various types of generation including renewable sources.

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