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Designing Intelligent Load-Frequency Controllers for Large-Scale Multi-Control-Area Interconnected Power Systems

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Abstract—**This work concentrates on designing an effectively intelligent control methodology to maintain the network frequency against load variations in a multi-control-area interconnected power system. Since conventional controllers (e.g., Integral, PI and PID) have only obtained poor control performances, such as high overshoots and long settling times, they should be replaced with the intelligent regulators using modern control techniques. Fuzzy logic-based control strategy, which has been one of the most effectively intelligent methodologies, is able to perfectly substitute for such conventional controllers when dealing with the network frequency stabilization problem. This paper proposes a type of PD-based fuzzy logic controllers with the proper 49-rule base in order to solve thoroughly the load-frequency control issue. The effectiveness and outperformance of such intelligent load-frequency controller over conventional regulators will be verified through numerical simulation processes. Such simulation processes are performed in a five-control-area non-reheat thermal electric power grid model, a typical case study of the large-scale interconnected power networks, using MATLAB/Simulink package version 2013a.**

Keywords—***Load-frequency control, tie-line bias control strategy, conventional regulator, intelligent controller, PD-based FLC***

Symbols

i	control-area order, $i = 1, 2, 3, 4, 5$
f	network frequency, Hz
f_n	nominal network frequency, $f_n = 50Hz$
$P_{tie,i}$	tie-line power, $p.u.$
$\Delta P_{D,i}$	load variation, $p.u.$
Δf_i	change of the network frequency, $p.u.$
$T_{g,i}$	governor time constant, s
$T_{t,i}$	non-reheat thermal turbine time constant, s
$K_{p,i}$	generator-load unit coefficient, $Hz/p.u.MW$
$T_{p,i}$	generator-load unit time constant, s
T_{ij}	tie-line synchronizing factor, s

$\Delta P_{tie,i}$	tie-line power deviation, *p.u.*
B_i	bias factor of frequency, *MW/p.u.Hz*
M_i	generator inertia constant, *p.u.*
D_i	load damping factor, *p.u. MW/Hz*
R_i	speed regulation, *Hz/MW*

I. Introduction

Load in large-scale interconnected electric power grids, depending upon customers, is changing continually over time (Hadi 2010; Bevrani & Hiyama 2011). This leads to the energy imbalance between the generation and load, causing the deviation of system frequency from its nominal value (50Hz or 60Hz) (Wood et al. 2013; Kundur 1994; Richard 2001). Due to the proportional relationship between the working frequency and active power in an electric power grid, such deviation usually causes the change of the generation demand. As a result, it is highly necessary to design robust and effective Load-Frequency Control (LFC) strategies to automatically control the electric generation for the grid. The control strategy, especially in a large-scale multi-area power system, is usually called as Automatic Generation Control (AGC) (Chongxin et al. 2013; Ibrabeem et al. 2005). As an important part of the AGC scheme, the LFC therefore aims to protect both the working frequency as well as the power interchange of the tie-lines in accordance with the scheduled dispatch, ensuring the stability, reliability and economy of an electric power grid. To obtain the objectives of the LFC strategy, the transient oscillations of both the system frequency bias and tie-line power change, which affect all power system devices, need to be damped efficiently enough to recover quickly the steady-state of the network after load variations (Shayeghi et al. 2009). As a result, designing an effective LFC strategy plays an important role on the successful operation, stability and reliability of large-scale interconnected power networks in reality.

When conducting the LFC problem, based on the tie-line bias control strategy, two categories of controllers have been applied recently, including conventional and intelligent regulators (Kundur 1994; Richard 2001; Shashi et al. 2013; Hamed et al. 2013). Basically, the conventional control methodologies employing traditional regulators (i.e., Integral, PI or PID), have been initially adopted to extinguish the transient oscillations of both the network frequency and tie-line power deviations. Nevertheless, when applying these controllers, a large-scale power network, which can be considered as a nonlinear-complicated control system, has only obtained highly poor performances, such as large overshoots and long settling times. These undesirable control indices may strongly affect the operation and stability of an electric power grid (Shayeghi et al. 2009; Hamed et al. 2013; Tan 2010).

In order to overcome the above drawbacks, intelligent controllers using modern control techniques, e.g., fuzzy logic (FL), have widely been investigated recently. Fuzzy logic controllers (FLCs), which have been applied efficiently in many control systems, can be employed to carry out the LFC strategy due to the following reasons (Shashi et al. 2013; Hassan et al. 1993; Chown et al. 1998):

(a) FL is a thinking process of users incorporated in control strategy, and hence it is not necessary to know clearly and fully parameters of the control system,
(b) FLCs can utilize efficiently the incomplete information to make a good control decision which only depends on the knowledge of experts, and
(c) with FL rules, it is able to set up successfully an HMI (Human Machine Interface) which is highly useful for the interaction property of a modern control scheme.

Obviously, the most dominant advantage of the FLCs is that the control parameters can be changed fast enough to respond well to the dynamic variations of the system. This is because none of parameters may be needed to estimate according to the working principle of the FL architecture. As a result, by applying the FL-based LFC controllers, the main characteristics as mentioned earlier can be significantly improved in order to achieve efficiently the objectives of the control strategy (Santos et al. 2004; Demiroren & Yesil 2004; Subbaraj et al. 2007).

This paper will investigate four categories of controllers, namely Integral (I), PI, PID, and PD-type FLC based on the tie-line bias control strategy to conduct the LFC problem. The first three load-frequency regulators are candidates of conventional methods. The last control architecture based on FL technique will be proposed in an effort to further improve the control quality of the LFC solution. In this study, a five-area non-reheat electric power grid model based on the tie-line bias control strategy is built first to implement such four LFC controllers. Subsequently, a numerical simulation process applying different LFC strategies to such interconnected electric power grid model will be realized to validate the robustness as well as the effectiveness of the proposed control architecture. The results obtained from the simulation processes demonstrate the outperformance of the intelligent PD-type FL control strategies over the conventional controllers when dealing with the LFC issue.

The present paper is arranged as follows. Section II will focus on designing a model of five-control-are interconnected thermal power system, which is chosen as a typical case study of a large-scale practical electric grid. Section III then describes the principle and design of two LFC architectures, namely conventional and intelligent methodologies. Section IV will realize the numerical simulation processes to evaluate the effectiveness of such two categories of LFC controllers. Finally, conclusions and future work will be deduced in Section V.

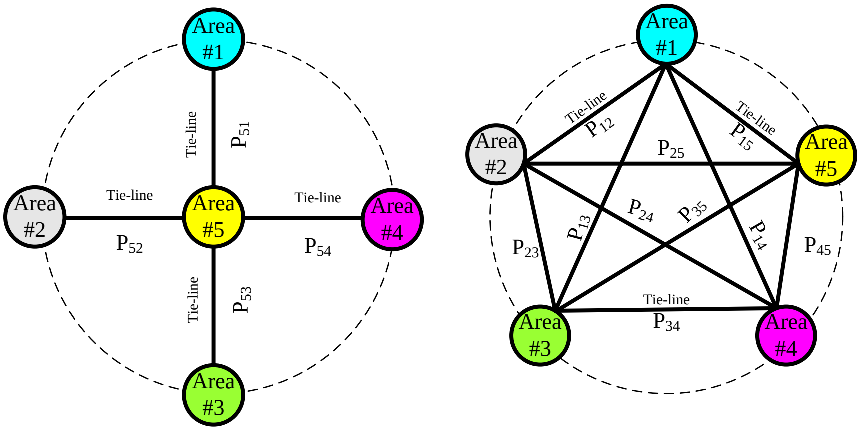
II. Modeling a Five-Control-Area Interconnected Electric Power Grid

It is the fact that the multi-control-area interconnected power systems are highly complicated, depending upon the construction plans of each country. Despite the complexity and diversity, each control-area of an interconnected power grid always composes of three basic units, namely governor, turbine and generator, to generate the electric energy from the other sources (e.g., hydro and thermal energy). In this paper, a five-area interconnected thermal network will be selected as a candidate of the large-scale power systems to conduct the LFC problem. Fig. 1 shows two simple architectures of such a five-area electric power grid. For the first architecture, only the 5^{th} area is interconnected with each other area to exchange the power. In the second case, an area is interconnected with each other one, so that the load variation can appear randomly at any area, affecting both the system frequency and the tie-line power flows of the net. Therefore, the frequency and tie-line power deviations resulting from this phenomenon need to be reduced by applying effective controllers in each area. In this work, tie-line bias control based controllers are used for each control-area to solve the LFC problem (Hadi 2010). For the typical case study, the second architecture indicated in Fig. 1 (b) is chosen. Thereafter, a simulation model, which is built in MATLAB/Simulink environment, can be shown in Fig. 2. In order to build this model, the transfer functions of a governor, a non-reheat turbine and a generator-load unit are formulated respectively as follows (Kundur 1994; Tan 2010):

$$G_{g,i}(s) = \frac{1}{s.T_{g,i} + 1} \tag{1}$$

$$G_{t,i}(s)=\frac{1}{s.T_{t,i}+1} \tag{2}$$

$$G_{P,i}(s)=\frac{K_{p,i}}{s.T_{P,i}+1}. \tag{3}$$



(a) (b)

Fig. 1. Five-area interconnected power system models.

(a) Area #5 is interconnected with each other area

(b) An area is interconnected with each other area

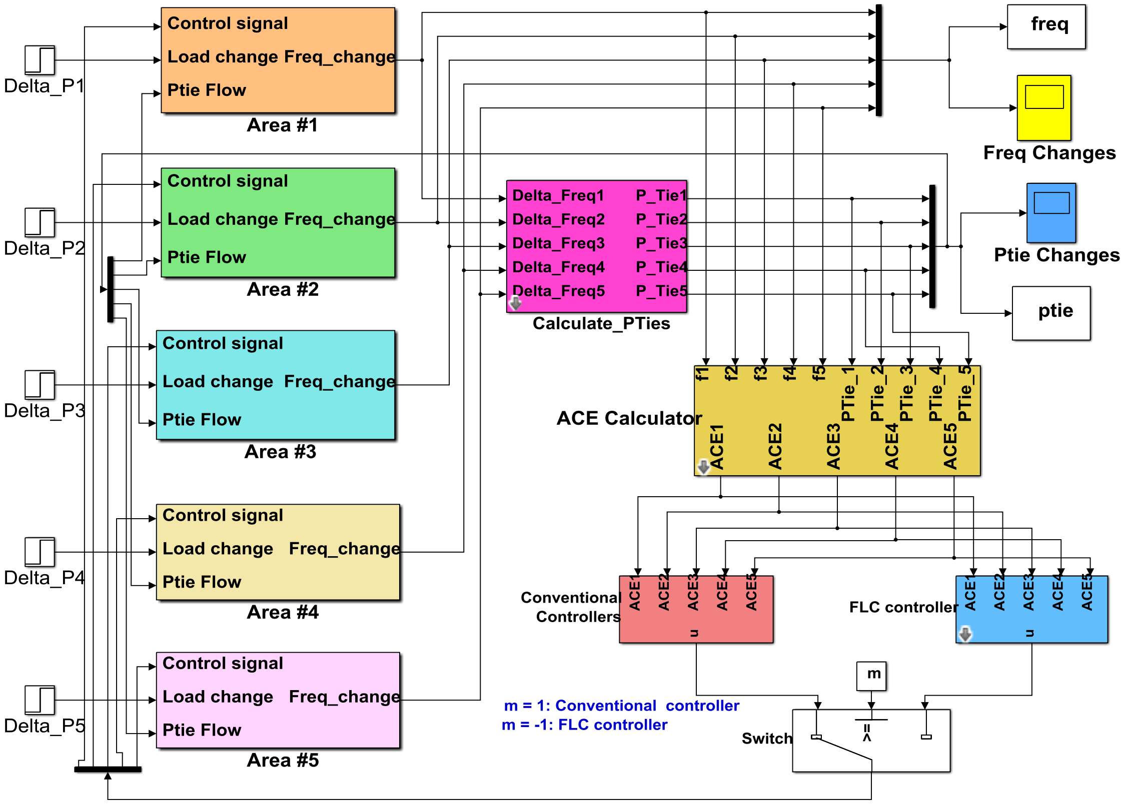


Fig. 2. A five-control-area non-reheat interconnected power system model in MATLAB/Simulink environment

The simulation parameters used in the above expressions can be found clearly in Appendix of this paper. The state-space model for such power system model can be described below

$$\dot{X} = AX + BU + FD \tag{4}$$

where, $X^T = [\Delta f_i \; \Delta P_{Gi} \;\; \Delta P_{Vi} \;\; \Delta P_{tie,i}]$ is the static variable vector, $U^T = [\Delta P_{C1} \;\; \Delta P_{C2} \;\; \Delta P_{C3} \, \Delta P_{C4} \, \Delta P_{C5}]$ is the control variation, and vector $D^T = [\Delta P_{D1} \;\; \Delta P_{D2} \;\; \Delta P_{D3} \, \Delta P_{D4} \, \Delta P_{D5}]$ denotes the load disturbance variable for all areas. Here, the tie-line power flow bias can be calculated from the system frequency changes of the interconnected control areas. A typical expression to compute the tie-line power deviation can be given as follows (Kundur 1994):

$$\Delta P_{tie,i}(s) = \frac{2\pi}{s} \sum_{\substack{j=1 \\ j \neq i}}^{5} T_{ij} \left(\Delta F_i(s) - \Delta F_j(s) \right) \tag{5}$$

where, T_{ij} and $\Delta F_i(s)$ are the synchronizing factor of the tie-line and the deviation of the frequency of the i^{th} control-area in the Laplace domain, respectively.

Applying the tie-line bias control technique, the input signal of the corresponding LFC controller used for the control-area #*i* is computed relying upon the definition of Area Control Error (ACE) as shown below:

$$ACE_i(s) = \Delta P_{tie,i}(s) + B_i . \Delta F_i(s) \tag{6}$$

where, $\Delta P_{tie,i}(s)$ and $\Delta F_i(s)$ are the tie-line power change and the net frequency deviation in the Laplace domain, respectively. Using the definition expressed in (6), it is the fact that only one controller is needed to minimize the deviations of the net frequency as well as the tie-line power interchange in accordance with the principle of the tie-line bias control strategy. This enables to simplify the design and reduce the calculating process of the control architecture. This is also the most important reason why such a method is applied in the present study in order to maintain the power system frequency. The following section will describe two LFC methodologies based on the bias control strategy.

III. Tie-line Bias Control Strategy Based Load-Frequency Controllers

A. Conventional LFC Controllers

Let us now consider an Integral controller with the gain K_{Ii}, which can be inserted in the i^{th} control-area as one of the conventional controllers. Based on the tie-line bias control strategy, its input is ACE_i and the corresponding output is the control signal $U_i(s)$ as shown below:

$$U_i(s) = \frac{K_{Ii}}{s} ACE_i(s) = \frac{K_{Ii}}{s} \left(\Delta P_{tie,i}(s) + B_i . \Delta F_i(s) \right). \tag{7}$$

The gain constant of the above controller, K_{Ii}, must be defined to satisfy both conditions of the systematically dynamic response: the fast transient restoration and the low overshoot. According to some researches (Hadi 2010; Kundur 1994; Shayeghi et al. 2009), the implementation of this controller is too slow to stabilize multi-control-area interconnected power networks which comprise non-linear elements. Therefore, it is necessary to improve this controller to achieve the better control performances (Richard 2001).

The second type of conventional controllers applied to deal with the LFC problem is PID controller. It is well known that PID controllers have been widely and effectively used in control systems. Also, they are more useful to be applied in the tie-line bias control strategy for the load-frequency stabilization of the power network (Shashi et al. 2013). Basically, this controller has the similar principle to the integral controller as follows:

$$U_i(s) = K_{Pi}\left(1+\frac{1}{sT_{Ii}}+sT_{Di}\right)ACE_i(s). \tag{8}$$

In (8), K_{pi} denotes the proportional coefficient. Meanwhile, T_{Ii} and T_{Di} are the time constant values of the integral and derivative, respectively. Such three factors strongly affect the quality of a control system (Hamed et al. 2013). Hence, it is highly necessary to consider the tuning methods of these factors in control systems applying PID controllers. In this work, we employ the Ziegler-Nichols method (Hamed et al. 2013) to tune these coefficients by its dominant advantages. Applying this method, first, we set the integral and derivative gains to the zero values, then, the proportional gain is tuned to reach a value at which the control system output will fluctuate. In the second step, the derivative gain will be defined with the tuned proportional gain above to make sure the transient performance. In the last step, the integral gain will be finally fixed with the other factors chosen above to ensure the steady state characteristic of the control system. Because the derivative action is too sensitive to reach the steady state, a PI (*proportional-integral*) controller can be used as a substitution of the PID controller in the control system. The obtained results by applying the PI load-frequency controllers will also be mentioned in this work.

B. Intelligent LFC Controller

Based on the aforementioned analyses, conventional regulators can be replaced with the fuzzy logic controllers due to their outstanding advantages. In principle, a FL inference consists of three processes as described below (Timothy 2010; Bimal 2002):

(a) the suitable membership functions (MFs) are designed to convert a set of crisp values into fuzzy logic domain,
(b) a fuzzy logic rule base should be determined to process and evaluate control rules, and
(c) a defuzzification process is implemented to convert a set of fuzzy logic values into the corresponding crisp set that can be used to make the control signal for the system.

Following three above processes, a PD-type FL architecture applied to the control-area #*i* is illustrated in Fig. 3. As shown, each FL architecture uses two inputs: $ace_i(t)$ and $dace_i(t)$ relating to the $ACE_i(t)$ signal and its derivative, $dACE_i(t)$, as follows:

$$ace_i(t) = K_{e,i}.ACE_i(t) = K_{e,i}.\left(\Delta P_{tie,i}(t) + B_i\Delta f_i(t)\right) \tag{9}$$

$$\begin{aligned} dace_i(t) &= K_{de,i}.\frac{d}{dt}ACE_i(t) \\ &= K_{de,i}.\frac{d}{dt}\left(\Delta P_{tie,i}(t) + B_i\Delta f_i(t)\right) \end{aligned} \tag{10}$$

where, $K_{e,i}$ and $K_{de,i}$ denote the scaling factors corresponding to ACE_i and its derivative $dACE_i$. The output of the proposed controller is $u_i(t)$, relating to the control signal of the i^{th} control-area, by the proportional factor Ku_i. It is found that such an FL architecture can be considered as an input/output static nonlinear mapping, and thus the principle of such FL controller can be written as follows:

$$u_i(t) = K_1.ace_i(t) + K_2.\frac{d}{dt}ace_i(t) \tag{11}$$

where, K_1 and K_2 are internal-nonlinear coefficients of the FL inference. From (9), (10) and (11), it is clear to infer the following equation:

$$\begin{aligned} U_i(t) &= K_{u,i}.u_i(t) \\ &= K_{u,i}\left[K_1.K_{e,i}.ACE_i(t) + K_2.K_{de,i}.\frac{d}{dt}ACE_i(t)\right] \end{aligned} \qquad (12)$$

hence,

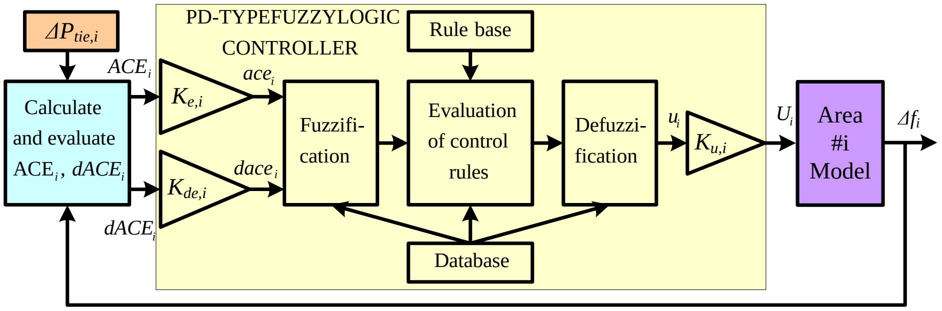


Fig. 3. PD-type FL controller architecture for the *i*th area

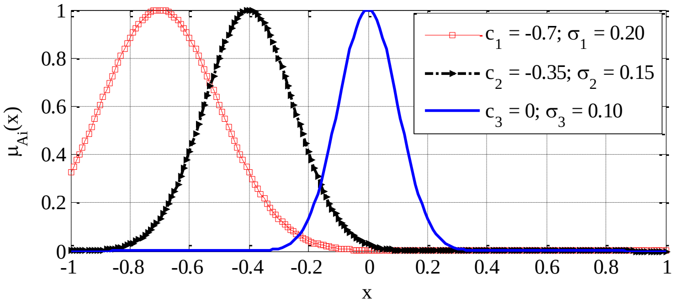


Fig. 4. Gaussian membership function shapes

$$U_i(t) = K_{P,i}^{FL_1}.ACE_i(t) + K_{D,i}^{FL_1}.\frac{d}{dt}ACE_i(t) \qquad (13)$$

where $K_{P,i}^{FL_1} = K_1.K_{u,i}.K_{e,i}$ and $K_{D,i}^{FL_1} = K_2.K_{u,i}.K_{de,i}$ denote respectively two factors which are highly similar to the proportional and derivative coefficients of a PD regulator. Therefore, it can be said that the type of such FL controller is dependent on the PD principle (PD-based FL controller).

Basically, there have been plenty of shapes of MFs can be employed. Also, many methods of defuzzification process are able to be applied in control practice employing FL controllers. In the context of this paper, Gaussian MFs are used for all of two inputs and one output of the proposed PD-type FL controller. In principle, each Gaussian MF, $\mu_{\mathrm{Ai}}(x)$, is mathematically formulated as follows:

$$\mu_{Ai}(x) = \exp\left(-\frac{(x-c_i)^2}{2\sigma_i^2}\right) \qquad (14)$$

where c_i denotes the MF center, while σ_i is the width of the MF #*i*. Fig. 4 shows several cases of the Gaussian MFs with different values of such two parameters. In this study, seven logic levels are used for each Gaussian MF of two inputs and one output of the proposed PD-type FL controller.

Table 1 shows the meanings and values of these logic levels applied to this work. In addition, Table 2 describes an appropriate rule base applied for the proposed PD-type FL controllers using the Mamdani architecture. There are a total of 49 rules used for such controller. Each of these rules is able to be written as: “IF the first input *ace*$_i$(*t*) is **e** and the second input d*ace*$_i$(*t*) is **de** THEN the output *u*$_i$(*t*) is **u**”. For example, the last rule (corresponding to the last row and the last column of Table 2) is: "IF $ace_i(t)$ is **BP** and the second input $dace_i(t)$ is **BP** THEN the output $u_i(t)$ is **BP**". According to the composition rule theory of an FL reasoning, each given rule base can be used to perform a meaningful control action in accordance with a specific condition of the variables. Such a composition rule, employed for the FL inference to generate the output control signal, should be chosen properly enough to achieve the desired control quality. For this study, the MAX-MIN (maximum-minimum) composition is selected since it is the most common and efficient composition for the FL inference. According to such composition rule, the output MF is calculated by using a MIN mechanism. In contrast, a MAX mechanism will be used to calculate the output of the fuzzy model. In the following section, the effectiveness of the proposed LFC methodology using the PD-type FLCs will be demonstrated through simulation processes using MATLAB/Simulink package.

Table 1. Linguistic terms for two inputs as well as one output of the proposed PD-type FL controller

Linguistic variable	**Meaning**	c_i	σ_i
BN	Big Negative	-1	0.1414
MN	Medium Negative	-2/3	
SN	Small Negative	-1/3	
ZO	Zero	0	
SP	Small Positive	1/3	
MP	Medium Positive	2/3	
BP	Big Positive	1	

Table 2. The rule base of the proposed FL inference

dace(t)	***ace(t)***						
	BN	**MN**	**SN**	**ZO**	**SP**	**MP**	**BP**
BN	BN	BN	BN	MN	SN	SN	ZO
MN	BN	MN	MN	MN	SN	ZO	SP
SN	BN	MN	SN	SN	ZO	SP	MP
ZO	BN	MN	SN	ZO	SP	MP	BP
SP	MN	SN	ZO	SP	SP	MP	BP
MP	SN	ZO	SP	MP	MP	MP	BP
BP	ZO	SP	SP	MP	BP	BP	BP

IV. Numerical Simulation

In this section, to implement the numerical simulation processes based on the tie-line bias control strategy corresponding to the Fig. 2 illustrated earlier, four simulation cases of load-frequency controllers are considered, including I, PI, PID, and PD-type FL regulator. In order to evaluate and compare the effectiveness of such four controllers when dealing with the LFC problem, a typical condition of load changes, which is given as a vector $D=[2(\%)\ 1(\%)\ 1.2(\%)\ 1.5(\%)\ 1(\%)]^T$, will be fed to all simulation cases. By using MATLAB software version 2013a, simulation results have been obtained as plotted in Figs. 5-10 as well as indicated in Tables 3-5. First, the frequency deviations of the 1st and 5th areas are described in Fig. 5, corresponding to the application of three conventional regulators (i.e., I, PI, and PID).

Meanwhile, Fig. 6 shows the transient oscillations of the frequency deviations for all control areas using the proposed intelligent PD-type FLCs. Next, Fig. 7 plots the tie-line power deviations of the 2nd and 3rd areas resulting from four categories of the LFC controllers. In order to compare the dynamic responses of different controllers, Fig. 8 (a) illustrates the frequency deviations for only the first area. Also, after calculating the frequency deviation errors of the above controllers, the corresponding error curves can be obtained as represented in Fig. 8 (b). As shown, the frequency change error between I and PID controllers is the smallest, whereas the bias of I and PD-type FL controllers is the largest. Furthermore, to demonstrate numerically the obtained results, Tables 3-5 represent the comparison for all cases. An acceptable frequency tolerance of 0.01% is given to calculate the settling times of the transient oscillations. From these tables, both the overshoot (maximum peak) and settling time of the proposed FL controllers are the best control performances. Finally, Figs. 9 and 10 present the comparison of the frequency deviation, in percentage, corresponding to Tables 3 and 4. It is found that both comparison indices of the proposed intelligent PD-type FLCs with the conventional controllers are much smaller than 100%. As a result, it is able to validate clearly the outperformance and robustness of the PD-type FL control architecture when solving the LFC problem.

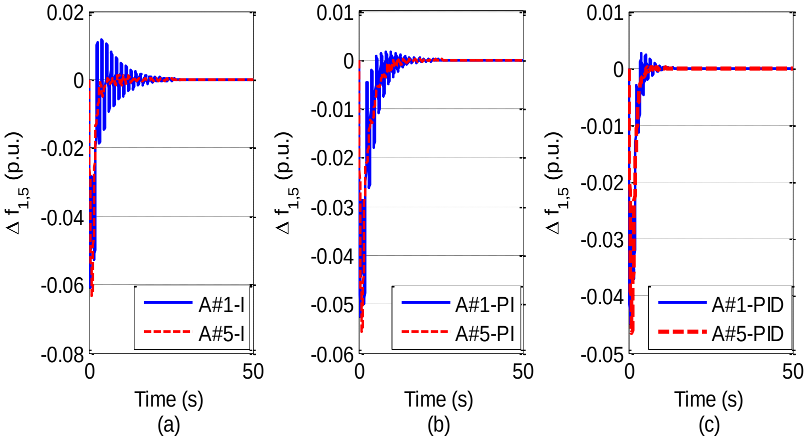


Fig. 5. Transient oscillations of the frequency deviations in the area #1 and area #5 using three conventional LFC regulators

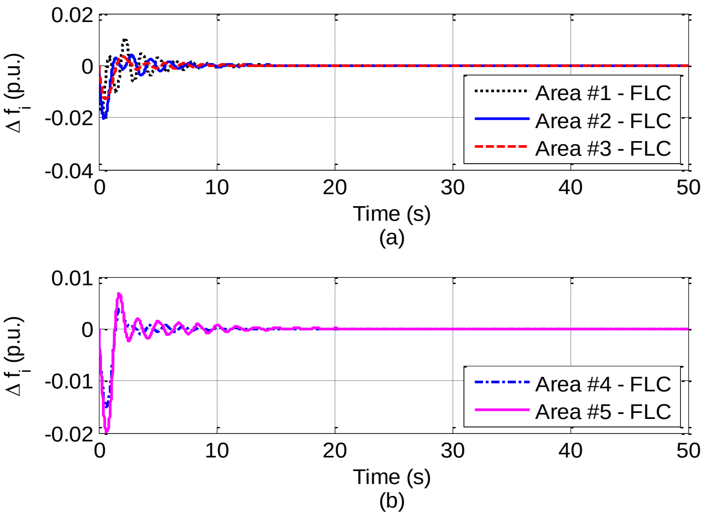


Fig. 6. Frequency deviations in all five control areas using intelligent FL controllers

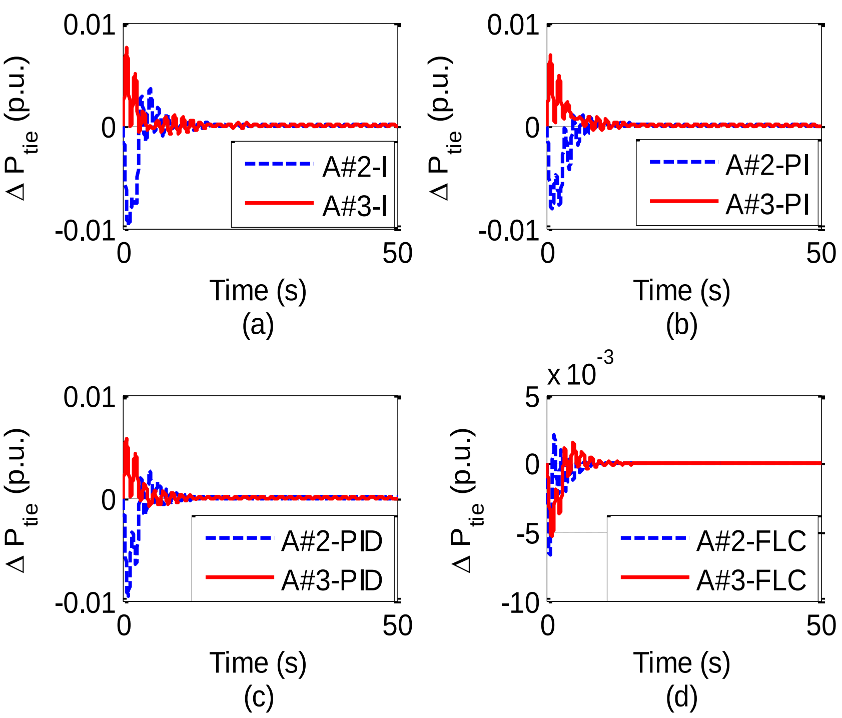


Fig. 7. Transient oscillations of the tie-line power biases in the second and third area using different controllers

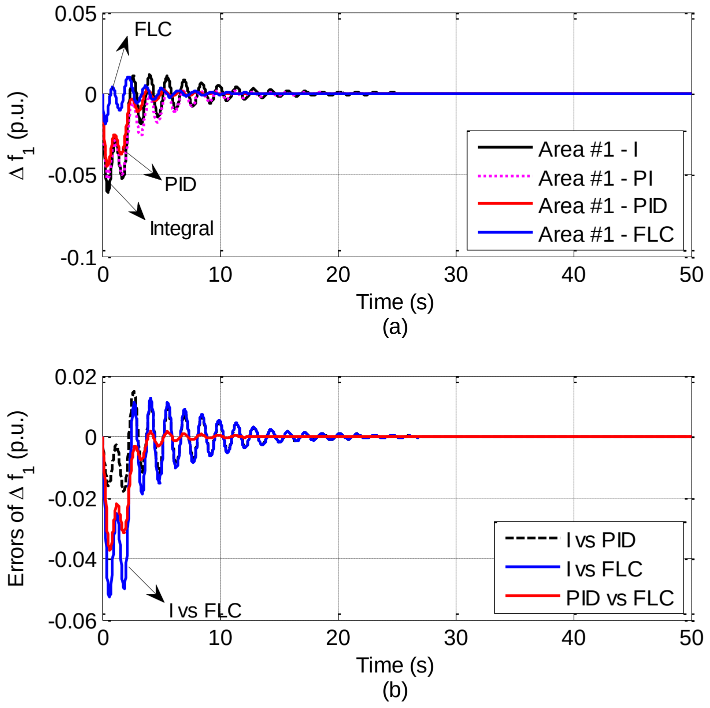


Fig. 8. A comparison of the frequency deviations in the first area using different LFC controllers

Table 3. Maximum peaks, in *p.u.*, for all control-areas using different LFC controllers

Type of controller	**Control-area #1**	**Control-area #2**	**Control-area #3**	**Control-area #4**	**Control-area #5**
I	-0.0606	-0.0612	-0.0632	-0.0640	-0.0632
PI	-0.0526	-0.0529	-0.0557	-0.0562	-0.0557
PID	-0.0447	-0.0472	-0.0469	-0.0472	-0.0465
FLC	-0.0183	-0.0205	-0.0130	-0.0149	-0.0199

Table 4. Settling times, in *second*, for all control-areas using different LFC controllers with $\varepsilon_f = 0.01\%$

Type of controller	**Control-area #1**	**Control-area #2**	**Control-area #3**	**Control-area #4**	**Control-area #5**
I	33.4343	27.8620	34.0926	41.4941	34.0926
PI	25.2580	22.7616	24.5867	30.3569	24.7540
PID	11.8003	17.8729	18.7391	13.2268	10.9479
FLC	10.1979	14.2259	15.9634	10.7732	8.6405

Table 5. Absolute values of maximum peaks of the tie-line power flow deviations, in *p.u.*, for all control-areas using different LFC controllers

Type of controller	**Control-area #1**	**Control-area #2**	**Control-area #3**	**Control-area #4**	**Control-area #5**
I	0.0157	0.0097	0.0076	0.0080	0.0076
PI	0.0142	0.0081	0.0068	0.0072	0.0068
PID	0.0121	0.0076	0.0058	0.0065	0.0065
FLC	0.0083	0.0049	0.0026	0.0021	0.0061

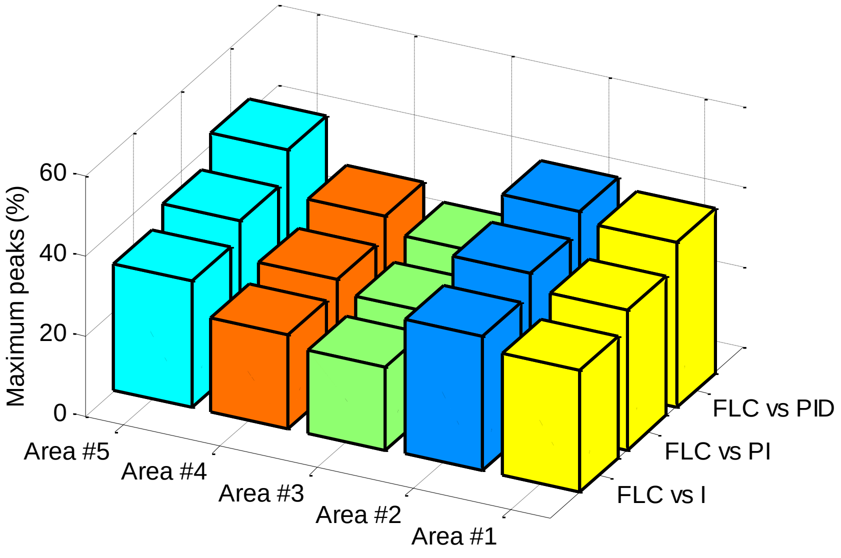


Fig. 9. A comparison (%) of the maximum peaks of the frequency deviations for all areas using different LFC controllers

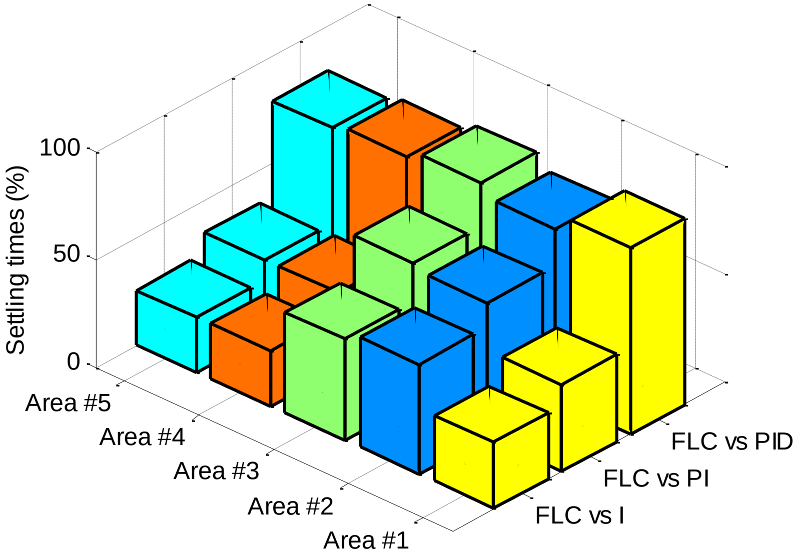


Fig. 10. A comparison (%) of the settling times of the frequency deviations for all areas using different LFC controllers with an acceptable tolerance of 0.01%

V. Conclusions

In this paper, the investigation of different load-frequency controllers, focusing on the intelligent FL control methodology, has been conducted to deal with the LFC problem of a multi-control-area interconnected power network. First, a typical type of five-control-area interconnected non-reheat thermal power systems has been mathematically modeled. Subsequently, the principle and design of two categories of load-frequency controllers including the conventional and intelligent regulators are discussed. Thereafter, various simulations have also been performed to verify the quality of such two types of controllers. Given the desired tolerance of the frequency deviations, intelligent controllers using PD-based FL architecture have achieved the better control characteristics, e.g., smaller overshoots and shorter settling times, in comparison with the conventional controllers. These promising results will further promote the application of the intelligent control methodologies based on the FL technique in order to address efficiently the LFC problem in a practical interconnected power system. For future work, the other modern technique such as Artificial Neural Network (ANN) should be investigated to integrate with the proposed FL control architecture in order to further improve its control qualification. Such an ANN architecture can be used to optimize the parameters of an FL inference, such as the rule base and scaling factors. Moreover, the practical-complicated power systems, e.g., Sichuan’s power network, should be considered in order to further enhance the real application of the proposed control methodology. This means that such a practical electric power grid needs to be modeled more exactly, considering adequate nonlinearities and uncertainties. These characteristics will make the proposed FL-based control architecture more completely and practically.

Appendix

Parameters for five-area interconnected thermal power system model

$T_{g,1} = 0.08$, $T_{g,2} = 0.12$, $T_{g,3} = T_{g,4} = T_{g,5} = 0.1$
$T_{t,1} = 0.28$, $T_{t,2} = 0.32$, $T_{t,3} = T_{t,4} = T_{t,5} = 0.30$
$K_{p,1} = 120$, $K_{p,2} = 100$, $K_{p,3} = K_{p,4} = K_{p,5} = 110$
$T_{p,1} = 22$, $T_{p,2} = 20$, $T_{p,3} = T_{p,4} = T_{p,5} = 18$
$T_{ij} = 0.071$

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