A Comparative Study on Load-Frequency Controllers of a Five-Area Interconnected Power System

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ABSTRACT

The crucial objectives of load-frequency control (LFC) to a multi-area interconnected power system are to maintain the system frequency at a nominal value (50 Hz or 60 Hz) and the tie-line power flows at predetermined values. Based on tie-line bias control strategy, conventional regulators, such as I, PI and PID, were initially used for solving the LFC problem. Due to the complexity, nonlinearity and uncertainty of a multi-area power system in practice, the conventional regulators may not obtain the control performances good enough to bring the network back to the steady state as soon as possible. Meanwhile, intelligent controllers, such as fuzzy logic (FL)-based controllers, are able to completely replace these conventional counterparts. The superiority of the FL-based LFC controllers over the conventional ones for a typical case study of five-area interconnected power grids is validated in this paper through numerical simulations implemented in Matlab/Simulink package. It should be apparent from this comparative study that the LFC controller based on FL technique is a feasible selection in dealing with the LFC problem of a multi-area power network.

Keywords: LFC, Five-Area Interconnected Power System, Conventional Regulator, Intelligent Controller, FL

I. INTRODUCTION

Together with voltage, frequency is a highly important parameter in power system operation and control. The frequency of an electric power grid is a systematic parameter, which is required to be a constant value at any point of the network. The nominal value of the electric power network frequency is 50Hz for most countries in the world, except in the US and Western of Japan the network frequency is 60Hz. It is an undeniable fact that the network frequency changes over time depending on load characteristic which is always varying in an electric power grid. Unacceptable system frequency deviations from the nominal value affect a lot of devices, causing unstable and uneconomic operation of an electric power grid [1-3]. Therefore, it is necessary to establish robust load frequency control (LFC) strategies to control the automatic generation in an interconnected power system [1]. In general, the main roles of these control strategies are to maintain the frequency and tie-line power to ensure the optimal and economical generation in the power network.

Based on the tie-line bias control principle, two types of LFC controllers have been applied, namely conventional and intelligent controllers. At first, the conventional controllers based on the integral (I), proportional-integral (PI), or proportional-integral-derivative (PID) regulators are used successfully to reduce the frequency and tie-line power deviations. However, by applying these controllers, main control

performances are very poor, such as high overshoots and long settling times which strongly affect the operation and stability of the system [2], [4]. To overcome these drawbacks, intelligent controllers using modern control techniques, e.g., fuzzy logic (FL) have been investigating heavily in recent years. By using the FL controllers, the above control performances are significantly improved in order to achieve the desired control performances [4-5].

In this paper, different controllers, namely I, PI, PID, and FL are successfully investigated and compared to demonstrate the effectiveness of the tie-line bias control strategy used in the load frequency control problem. A five-area interconnected thermal power system using non-reheat turbines is mathematically built to implement the above controllers. Via the evaluation of simulation results obtained by using Matlab/simulink software, FL controllers are selected to be a more ideal regulator of this control problem.

In the next section of this paper, we introduce the analysis of a five-area interconnected power system controlled by the tie-line bias control strategy. The following sections present the application of different controllers, namely conventional and intelligent controllers, based on the tie-line bias control scheme. The numerical simulation results and discussions will also be given in the last two sections of this paper to evaluate and choose the most effective controller to stabilize the frequency in an electric power grid.

II. MATHEMATICAL MODEL OF A FIVE-AREA INTERCONNECTED POWER SYSTEM

Establishing a mathematical model of a control system is the first step in designing a control strategy for any plant. In fact, this procedure normally includes several sub-steps, such as identification, mathematical approximation and optimization. This is an important step in order to ensure the accuracy and efficiency of the control system designing.

Practical interconnected electric power grids are highly complicated and it is impossible to create a mathematical model for all power networks. In this paper, a five-area interconnected power system is selected as a typical case study. Figure 1 (a) shows a power system including five areas interconnected through tie-lines. Here, each area or control-area is assumed to be connected with all other areas, so that the tie-line power flows can be easily exchanged among power stations. It is generally supposed that each control-area includes four main elements, i.e. a governor, a turbine, a generator and load. They are presented in Figure 1(b) for the ith control-area. The transfer functions in Laplace domain for these components are given in Table 1 [1, 2, 10].

Table 1: Transfer functions of each basic component of a control-area

Governor	Turbine	Generator-load
$G_{gi}(s)$ $= \dfrac{1}{s.T_{gi}+1}$	$G_{turbine} \dfrac{1}{s.T_{ti}+1}_i$	$G_{\frac{K_{pi}}{s.T_{Pi}+1}}P$

To describe the control plant for the whole system, the following state-space model can be used:

$$\dot{X} = A.X + B.U + F.D \qquad (1)$$

where, $X^T = [\Delta f_i \ \Delta P_{Gi} \ \Delta P_{Vi} \ \Delta P_{tie,i}]$, $i = 1,2,3,4,5$ is the static variable, $U^T = [\Delta P_{C1} \ \Delta P_{C2} \ \Delta P_{C3} \Delta P_{C4} \Delta P_{C5}]$ is the control variation, and $D^T = [\Delta P_{D1} \ \Delta P_{D2} \ \Delta P_{D3} \Delta P_{D4} \Delta P_{D5}]$ is a vector of the load changes. Here, the deviation of the tie-line power of the ith control-area is calculated as follows:

$$\Delta P_{tie,i}(s) = \frac{2\pi}{s} \sum_{\substack{j=1 \\ j \neq i}}^{5} T_{ij}^0 \big(\Delta F_i(s) - \Delta F_j(s) \big)$$

$$(2)$$

where T_{ij}^0 and $\Delta F_i(s)$ are the synchronizing factor of the tie-line and the deviation of the frequency of the ith control-area in the Laplace domain, respectively.

According to the tie-line bias control strategy, the input of the frequency controller is [1, 6-11]

$$ACE_i(s) = \Delta P_{tie,i}(s) + B_i.\Delta F_i(s).$$
(3)

Using the above control signal, $ACE_i(s)$, each control-area might need only one regulator for both goals: elimination of the network frequency deviation and maintenance of the power flow exchange in the tie-lines.

(a)

(b)
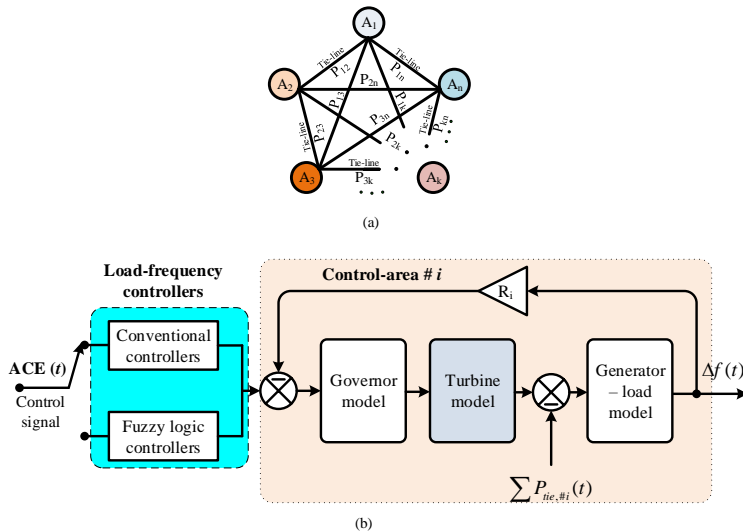
Figure 1. Interconnected power system model for LFC problem

(a) Multi-control-area model

(b) Main elements of a control-area

III.DIFFERENT LOAD-FREQUENCY CONTROLLERS

3.1. Conventional controllers

Generally, the PID (Proportional – Integral – Derivative) regulator is a type of conventional controllers suitable for many control problems. The principle of a PID regulator applied to the LFC is presented below:

$$u_i(t) = K_{pi}.ACE_i(t) + K_{Ii}\int_0^t ACE_i(\tau)d\tau + K_{Di}\frac{d}{dt}ACE_i(t)$$

$$= K_{pi}\left(ACE_i(t) + \frac{1}{T_{Ii}}\int_0^t ACE_i(\tau)d\tau + T_{Di}\frac{d}{dt}ACE_i(t)\right),$$

$$U_i(s) = K_{Pi}\left(1 + \frac{1}{sT_{Ii}} + sT_{Di}\right)ACE_i(s) \quad (4)$$

where, K_{pi}, K_{Ii}, K_{di}, T_{Ii}, and T_{di} are proportional, integral, derivative gain factors, integral time, and derivative time constants, respectively.

Applying the conventional PID regulator, it is necessary to find an appropriate tuning method for three factors: K_{pi}, K_{Ii} and K_{di}. In this paper, the Ziegler-Nichols method to tune these coefficients has been employed. By applying this method, first, the integral and derivative gains are set to be zero, then, the proportional gain is tuned to reach the value at which the output of the system begins fluctuating. 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. Due to the sensitivity of the derivative factor, in many control systems, a PID regulator can be replaced with a PI one and the control performances are quite good enough.

3.2 Fuzzy logic controllers

The interconnected power system is actually characterized by a number of nonlinearities and uncertainties, making the design of an LFC controller highly challenging. Besides, the LFC controllers applying the conventional regulators as mentioned earlier may not be able to obtain the good control quality as required. In this context, an intelligent control strategy using FL controllers should be selected.
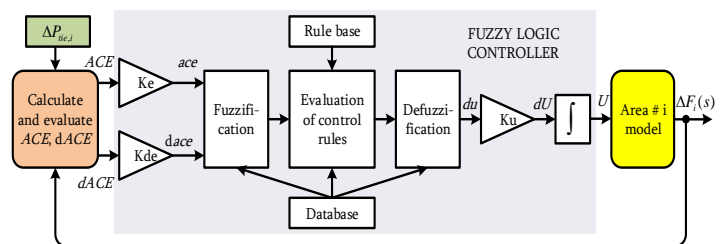
Figure 2: Principle diagram of a FL-based FLC controller
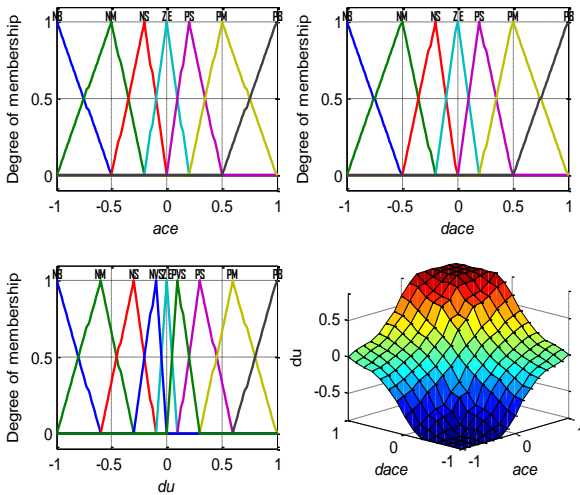
Figure 3: Degree of membership functions and the 3D surface of the proposed FL controller

Let us consider a FL controller which is used for the ith control area in the given power system as shown in Figure 2. Based on the tie-line bias control scheme, there are a total of five FL controllers used in our control system. For each FL controller, as depicted in Figure 2, it has been fed by two input signals, *ace* and the acceleration of *ace*, *dace*, relating to *ACE* and the derivative of *ACE* as follows:

$$ace_i(t) = \frac{1}{Ke_i}ACE_i(t) = \frac{1}{Ke_i}\left(\Delta P_{tie,i}(t) + B_i\Delta f_i(t)\right)$$

$$(5) dace_i(t) = \frac{1}{Kde_i}\frac{d}{dt}ACE_i(t) = \frac{1}{Kde_i}\frac{d}{dt}\left(\Delta P_{tie,i}(t) + B_i\Delta f_i(t)\right) \quad (6)$$

where Ke_i and Kde_i are the scaling coefficients corresponding to *ACE* and the derivative of *ACE*. The output of the given controller is *du* relating to the control signal of the *i*th area, ΔP_{ref_i}, by the proportional factor Ku_i and the summation (or integral) of *dU* (see Figure 2). In general, each FL controller is an input/output static nonlinear mapping and thus the principle of this FL controller can be written as follows

$$du_i(t) = K_1.ace(t) + K_2.dace(t)$$
$$u_i(t) = \int du_i(t)dt = K_1\int ace(t)dt + K_2.ace(t) \quad (7)$$

where K_1 and K_2 are gain coefficients. From (5) - (7), it is clear the following equations can be deduced:

$$U_i(t) = Ku_i.u(t) = Ku_i\left[\frac{K_1}{Ke_i}\int ACE_i(t)dt + \frac{K_2}{Kde_i}.ACE_i(t)\right] \quad (8)$$

and,

$$U_i(t) = K_P.ACE_i(t) + K_I.\int ACE_i(t)\,dt. \quad (9)$$

The equation (9) reveals that the working principle of the FL-based FLC controller is based on the PI regulator. Hence, it is reasonable to define this type of FL controller as a PI-FL controller.

Basically, there are three processes of a PI-FL controller: fuzzification, evaluation of control rule base, and defuzzification, as plotted in Figure 2. For the control rule base of the above FL controller, a 49-rule base is used in the present work. This rule base designed is based on the understanding of the control system in order to minimize the frequency and tie-line power flow changes. A full rule base is illustrated in Table 1 with seven MFs for two inputs *ace(t)* and d*ace(t)* and nine MFs for the output *du(t)*.

Table 1: Rule base for the proposed FL controller

d*ace(t)*	*ace(t)*						
	NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NM	NS	NVS	ZE
NM	NB	NB	NM	NS	NVS	ZE	PVS
NS	NB	NM	NS	NVS	ZE	PVS	PS
ZE	NM	NS	NVS	ZE	PVS	PS	PM
PS	NS	NVS	ZE	PVS	PS	PM	PB
PM	NVS	ZE	PVS	PS	PM	PB	PB
PB	ZE	PVS	PS	PM	PB	PB	PB

NB – Negative Big, NVS-Negative Very Small, NM – Negative, NS-Negative Small, ZE – Zero, PVS-Positive Very Small, PS-Positive Small, PM-Positive Medium, PB-Positive Big

In this design, the MAX-MIN composition is used in which each output, MF, is resulted by a MIN operator.

Meanwhile, a MAX operator has been used for the corresponding FL output. Also, this operation will be illustrated in Figure 3 as the 3D membership surface. To verify the effectiveness of this control strategy, the next section will give the simulation processes and results obtained using Matlab/Simulink package.

IV. NUMERICAL SIMULATION RESULTS

In this section, to implement the simulation of the power system based on the tie-line bias control strategy corresponding to the Figure 3 illustrated earlier, four simulation cases are considered, namely I, PI, PID, and FL controller. In order to evaluate and compare different LFC controllers, a condition of load changes is fed to all simulation cases

$$D^T = [\Delta P_{D1} \ \Delta P_{D2} \ \Delta P_{D3} \Delta P_{D4} \Delta P_{D5}]$$
$$= [2(\%)1(\%)1.2(\%)1.5(\%)1(\%)] \quad (9)$$

where ΔP_{Di} is the load change in the area ith. Our control objective is to regulate the state vector $X_1^T = [\Delta f_i \ \Delta P_{tie,i}]$ which needs to be converged toward the zero-steady state $X_0^T = [00]$ with the best performance characteristics, such as small overshoots and short settling times. Simulation results performed in Matlab/Simulink environment version 2015a, have been obtained as plotted in Figures 4 – 9.
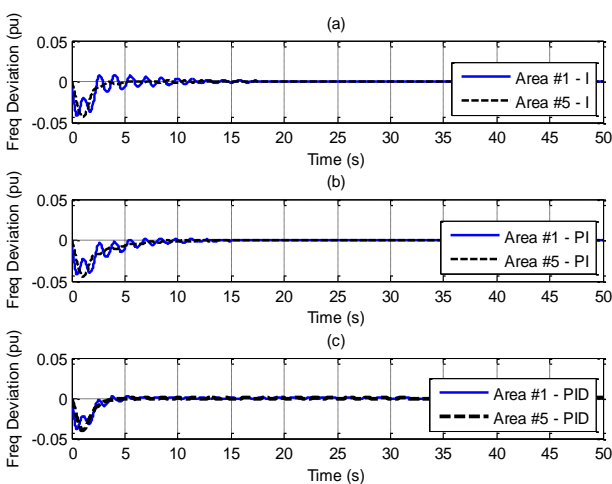
Figure 4. Frequency deviations of the first and the fifth area using conventional regulators
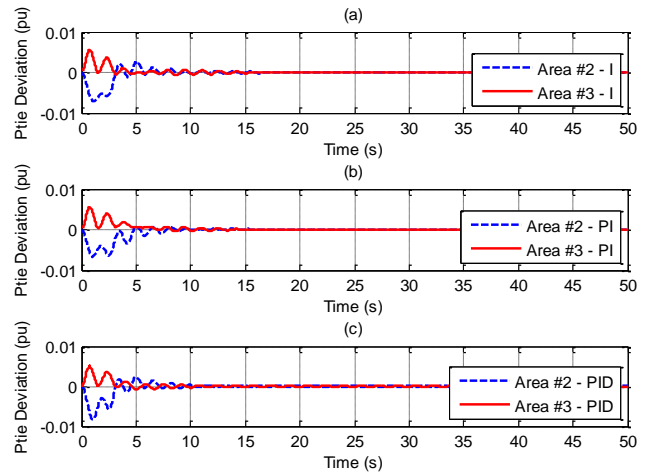
Figure 5. Tie-line power deviations of the 2nd and 3rd area
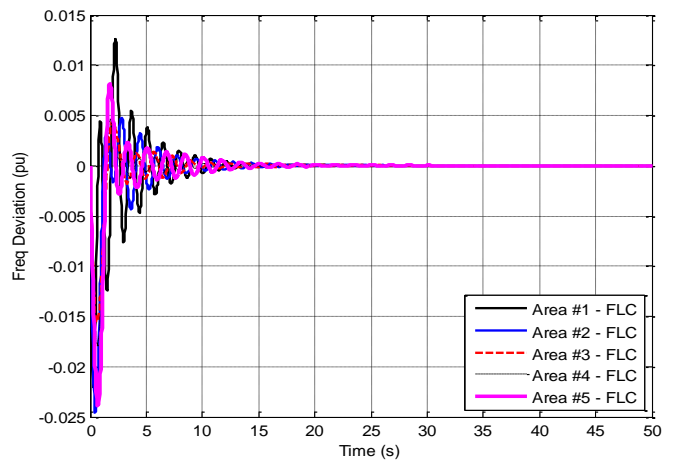
Figure 6. Frequency deviations of five areas using FL controllers

Figure 4 illustrates the frequency deviations of the 1st and 5th areas, corresponding to the application of I, PI, and PID controllers in the given control system. Figure 5(a), 5(b), and 5(c) show the tie-line power deviations of the 2nd and 3rd areas, for three cases: I, PI, and PID controller, respectively. Figure 6 depicts the response of frequency deviations for the control case using FL controller, in which all control – areas are plotted. Figure 7 presents the comparison of the different controllers used above. Figure 7(a) indicates the response of frequency deviation only for the first area. Also, by calculating the frequency deviation errors of the above controllers, Figure 7(b) plots the corresponding error curves. As shown in this figure,

the frequency change error between I-PID controllers is the smallest, whereas the counterpart of I-FL controllers is the largest. Furthermore, to demonstrate numerically the obtained results, Table 2 and Table 3 represent the comparison for all cases. From these two tables, it is clear both the overshoot and settling time of the FL controller are much better than the those of the conventional controllers. These results lead to the removal of the worst case using the integral controller, and the selection of the most effective case using the FL controller for the control system under this study.

TABLE 2: THE COMPARISON OF THE FIRST OVERSHOOT, IN *PU*

CONT-ROLLER	AREA # 1	AREA # 2	AREA # 3	AREA # 4	AREA # 5
I	-0.0418	-0.0422	-0.0436	-0.0441	-0.0436
PI	-0.0421	-0.0423	-0.0446	-0.0450	-0.0445
PID	-0.0389	-0.0410	-0.0408	-0.0410	-0.0404
FL	-0.0220	-0.0246	-0.0156	-0.0179	-0.0239

TABLE 3: THE COMPARISON OF THE SETTLING TIMES, IN *SECOND,* WITH THE GIVEN TOLERANCE OF 0.1%

Controller	AREA # 1	AREA # 2	AREA # 3	AREA # 4	AREA # 5
I	28.3560	26.9654	28.1893	36.5025	28.1893
PI	24.4885	17.5773	23.0834	28.7204	23.1563
PID	16.5271	17.8128	17.5416	11.8289	20.2595
FL	11.7732	14.0725	15.9418	10.5738	10.9078
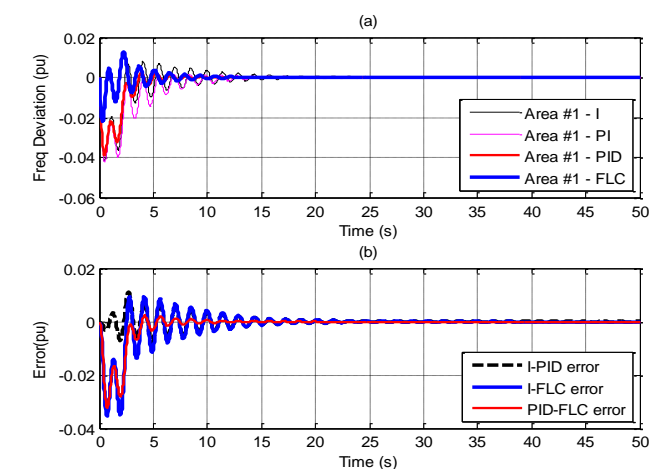
Figure 7. Comparison of the LFC controllers under the present study

V. CONCLUSIONS

This paper investigated a comparative study of different LFC controllers for a typical case of five-area electric power grids. A type of FL controllers has been evaluated in comparison with the conventional counterparts including I, PI and PID regulators. Simulation results and analyses claimed that the FL controller is a perfect choice, achieving better control performances for solving the LFC problem of a multi-area interconnected power system. The difficulties of tuning method selection and/or dealing with the uncertainties and nonlinearities of the network have been able to be efficiently solved when applying the FL-based LFC controllers. Hence, it is feasible to apply this intelligent LFC controller instead of using the conventional counterparts. Future work arising from this study is that it should be necessary to determine an appropriate fuzzy rule base to obtain the desirable control performances for a practically electric power grid.

VI. ACKNOWLEDGMENT

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