

A NOVEL INTEGRATION OF PD-TYPE FUZZY LOGIC CONTROLLERS AND SMES DEVICES TO MAINTAIN THE NETWORK FREQUENCY OF A LARGE-SCALE POWER SYSTEM

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Abstract. A modern electric power plant is typically considered to be a large-scale system. Due to continual and random occurrence of load changes, maintenance of network frequency (or load frequency control LFC) at its nominal value is one of the most crucial control problems in order to ensure the stability and reliability of such an electric power grid. This study investigates a new efficient integration of fuzzy logic controllers based on PD principle and superconducting magnetic energy storage (SMES) devices in an effort to protect the system frequency from the load variations. It is well known that the PD-based fuzzy logic controllers, when applied to an LFC strategy, are capable of damping quickly the oscillations of both the system frequency and tie-line power deviations. In addition, the load disturbances can be compensated if the network is applying the SMES devices. Therefore, the integration between them might become an efficiently feasible solution for the LFC issue. The superiority of the proposed control methodology over conventional regulators is verified through a number of numerical simulations which will be implemented in this study for a five-area electric power grid model.

Keywords. Large-scale power system, LFC, fuzzy logic controller, SMES devices, integrated control strategy.

1. INTRODUCTION

It is well known that an interconnected electric power grid has been generally considered to be a large-scale system which needs an efficiently overall control strategy in order to ensure the stable and reliable operation [1, 2, 3, 4, 5]. Such an interconnected power network usually works under constantly changing conditions of loads, which are dependent only on users, leading to a mismatch between real power and load demand, and thus creating the network frequency deviation from its nominal value. In addition to this phenomenon, tie-line power bias might be automatically generated since it is directly proportional to the network frequency deviation. Both dynamic oscillations of the system frequency and tie-line power flow must be damped in an efficient strategy to restore the normal operation of the electric power grid. Load frequency control (LFC) strategy to rapidly extinguish these dynamic deviations to satisfy acceptable tolerances has been carried out as a necessary part of automatic generation control (AGC) for a power system. If such an interconnected electric

power grid is working under an efficient LFC methodology, its important control features can be successfully guaranteed [3, 6, 7, 8, 9, 10, 11, 12].

Each practical power plant normally contains a number of generating stations called control-areas. These areas are interconnected via transmission lines which are usually defined as tie-lines for power exchange. As a typical example of modern large-scale electric power systems, a five-area network model is chosen under study for this paper. The model is mathematically established first and then it is applied to test the feasibility of the LFC schemes. An efficient solution to the LFC problem applying intelligent controllers based on fuzzy logic technique is also proposed. This control strategy is dependent upon tie-line bias regulation, which was presented in [1, 3, 8, 11, 12]. One of the most important points when applying this control technique is that the tie-line power flow and system frequency deviations must be combined in a technical term called area control error (ACE). These ACE signals are considered to be the inputs of the LFC controllers and they must be driven to zero as rapidly as possible [11, 13, 14, 15, 16]. In this study, the PD (proportional-derivative)-based fuzzy logic controllers are chosen in dealing with the LFC issue. Therefore, both ACE and its derivative are fully used as the input signals in order to achieve the better main control characteristics, such as the smaller overshoots and the shorter settling times, compared with those of the conventional controllers using PI (proportional-plus-integral) regulators.

In this paper, superconducting magnetic energy storage (SMES) devices, which have been considered to design power system stabilizers, are also investigated to solve the problem of LFC [17, 18, 19, 20, 21, 22, 23]. It was found that these SMES units using thyristor-converters and superconducting coil are able to compensate for the sudden large load disturbances, such as the start and/or stop of big industrial factories. This is because their inductors can absorb or release active power in accordance with the decrease or increase of the loads in an electric power grid [12]. Therefore, such SMES units can be used in conjunction with efficient controllers to maintain the network frequency against load variations. The combination of these devices and PD-based fuzzy logic controllers when dealing with the LFC problem is one of the novel contributions of this study. In the following section of the present paper, the principle and model of an SMES unit will be discussed in detail. Then the third section mentions the modeling of a multi-area interconnected power system and particularly focuses on a five-area power network model as a typical case study. Load frequency controllers, including conventional PI and PD-based fuzzy logic regulators, will be described specifically in the fourth section of this paper. Finally, simulation results as well as conclusions will also be presented in the last two sections to verify the effectiveness of the proposed control strategy for a feasible solution of the LFC proposition.

2. MODEL OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE-SMES

There seems to be no compelling reason to argue that an SMES unit is one of the most efficient devices for purpose of energy storage. Such an SMES unit can be considered to be a power system stabilizer since it is able to compensate for load variation, including sudden load changes. This puts forward the view that the SMES devices are quite able to be used in designing a robust LFC strategy.

Although there are generally three types of the SMES units, it is evident that SMES

devices using thyristor converters might be suitably employed for the LFC. This is because they mainly regulate active power flow between AC and DC sides; thus they are able to directly impact on the network frequency, which is highly significant in the LFC problem. The illustration of a thyristor-based SMES unit is shown in Figure 1. In addition to a three-phase transformer, a six-pulse or twelve-pulse converter should be used in order to convert AC power flow into the DC counterpart. In Figure 1, a 12-pulse bridge AC/DC thyristor controlled converter is applied for such an SMES unit. In principle, such a 12-pulse AC/DC bridge converter contains two 6-pulse AC/DC converters in series (see Figure 1). This thyristor-based converter can typically act as a rectifier or an inverter depending upon the values of the firing angles α_i , which are chosen by an electronic control system for the converter. In general, a DC voltage considered to be the output of this converter is theoretically the sum of two DC output voltages of two 6-pulse thyristor-based converters presented in Figure 1, and it should be given as

$$\begin{aligned} E_{d,i} &= U_{d1} + U_{d2} \\ &= V_{d0} \cos \alpha + V'_{d0} \cos \alpha' \end{aligned} \quad (1)$$

where V_{d0} and V'_{d0} , α and α' denote the ideal no-load DC voltages and firing angles of converter R_1 and R_2 , respectively. Assuming that such two 6-pulse AC/DC thyristor-based converters are completely symmetrical, the DC output of the 12-pulse converter can be calculated as follows [12]:

$$E_{d,i} = 2V_{d0,i} \cos \alpha \text{ with } \begin{cases} E_{d,i} > 0 & \text{if } \alpha < \frac{\pi}{2} \text{ in rectifying mode} \\ E_{d,i} < 0 & \text{if } \alpha > \frac{\pi}{2} \text{ in inverting mode.} \end{cases} \quad (2)$$

In (2), $E_{d,i}$, $2V_{d0,i}$ and α are DC output voltage (in volt), ideal no-load DC voltage (in volt) and firing angle (in degree) of the thyristor-based converter. One of the most important parts of an SMES device is a superconducting coil. In principle, applying such an inductor can assist the SMES device in absorbing power into or releasing from this unit. These two processes correspond to the charging or discharging of the coil, relating to the rectifier mode or inverter mode of the thyristor converter. In principle, there is a relation between the current and voltage of the superconducting coil as follows:

$$L_{d,i} = \frac{1}{L_{d,i}} \int_{t_0}^t E_{d,i} d\tau + I_{d0,i} \quad (3)$$

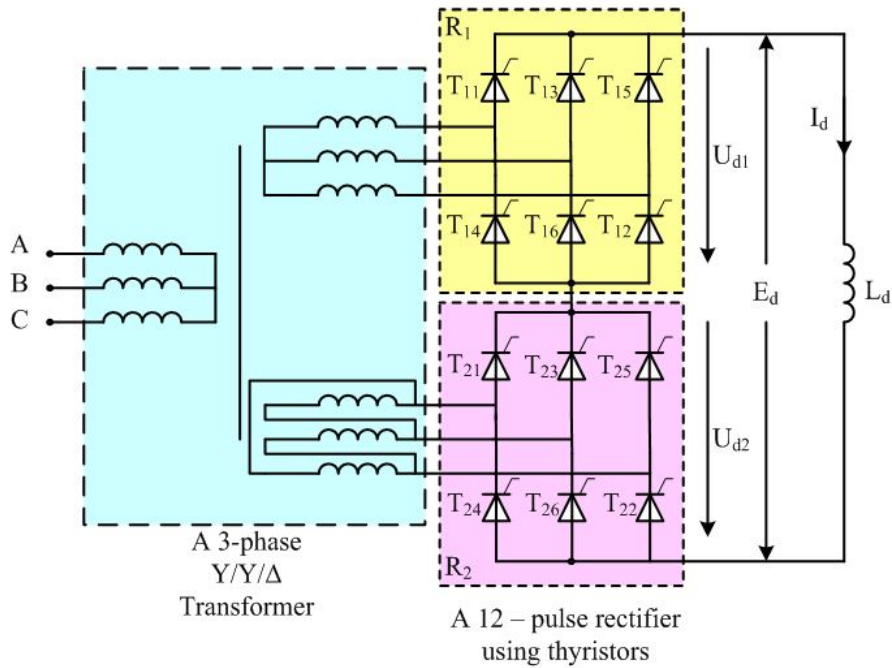
where $I_{d0,i}$ is the initial DC current through the coil. The real power value through the SMES can be computed as:

$$P_{d,i} = E_{d,i} I_{d,i}. \quad (4)$$

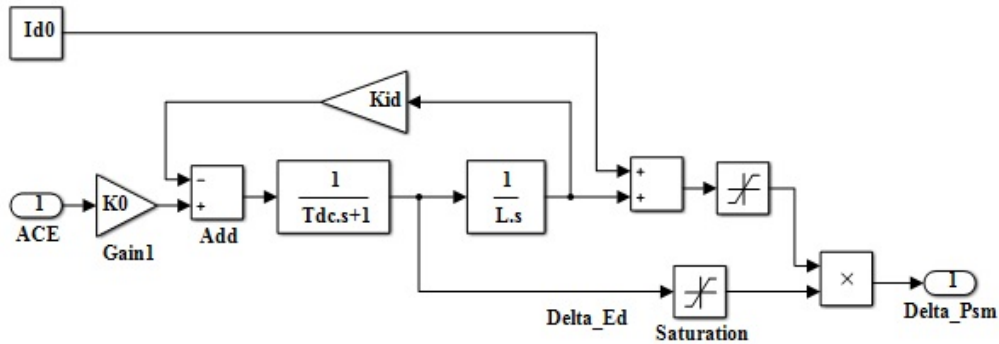
The energy which is stored in the coil should be calculated below:

$$W_{d,i} = \int_{t_0}^t P_{d,i} d\tau + W_{d0,i}. \quad (5)$$

In terms of using the SMES as an efficient part of the LFC strategy, it is necessary to mathematically model such an SMES device. According to the tie-line bias control idea,



(a) Principle block diagram



(b) SMES model built in MATLAB/Simulink platform for the LFC problem

Figure 1. Model of an SMES device using thyristor-based converters

ACE signals must be collected, and then they are taken to both the LFC regulator and the SMES. It means that each generating power should be equipped with an LFC controller and an SMES. The control idea is that the load changes can be compensated by charging or discharging of the inductor, thus the DC current $I_{d,i}$ should become a controlled quantity. According to [22], the increment of DC output voltage $E_{d,i}$ can be computed as:

$$\Delta E_{d,i}(s) = \frac{1}{1 + sT_{d0,i}} (K_{0,i}ACE_i(s) - K_{I_{d,i}} \cdot \Delta I_{d,i}(s)). \quad (6)$$

Taking Laplace transform for equation (3), using a differential computation, the incre-

ment of the DC current through the inductor is:

$$\Delta I_{d,i}(s) = \frac{1}{s.L_{d,i}}.\Delta E_{d,i}(s), \quad (7)$$

where $K_{0,i}$ and $K_{Id,i}$ are constant factors of the SMES device. From (6) and (7), the mathematical model of this SMES built in MATLAB/Simulink platform is illustrated in Figure 1(b). The effectiveness of the SMES units for conducting the LFC problem will be presented in the following sections.

3. MULTI-AREA INTERCONNECTED POWER SYSTEM MODEL

There seems to be a consensus that modern electric power grids, treated as typical examples of large-scale systems, have highly complicated and various structures. In the present study, a typical example under scrutiny is a model of five-area interconnected power network. The fact is that there are also several structures regarding this model as shown in Figure 2. The available evidence seems to suggest that we might only need to choose a particular structure to verify the feasibility of the proposed control method. The others can be conducted in a same manner. From this point of view, the last structure presented in Figure 2(d) is selected in this study. As shown, the fifth control-area is supposed to be interconnected with the other ones for the power exchange. Assuming that the type of thermal power plant is under this study, each generation area or control-area from Figure 2(d) normally consists of three main parts in series: governor, non-reheat turbine and generator-load units (see Figure 3). When solving the LFC problem, the transfer functions of these units for the area i can be found in [4, 5]. It is straightforward to establish the model of the area i in Laplace domain as follows:

$$\Delta F_i(s) = \frac{1}{M_i.s + D_i} [\Delta P_{T,i}(s) - \Delta P_{D,i}(s) - \Delta P_{tie,i}(s)], \quad (8)$$

$$\Delta P_{T,i}(s) = \frac{1}{T_{T,i}.s + 1} \Delta P_{G,i}(s), \quad (9)$$

$$\Delta P_{G,i}.s = \frac{1}{T_{G,i}.s + 1} \left[U_i(s) - \frac{1}{R_i} \Delta F_i(s) \right], \quad (10)$$

$$\Delta P_{tie,i}(s) = \begin{cases} \frac{2\pi}{s} \sum_{j=1, j \neq i}^5 T_{ij} [\Delta F_i(s) - \Delta F_j(s)] & \text{if there is tie-line } i - j \\ 0, & \text{otherwise.} \end{cases} \quad (11)$$

The meaning of the above variables can be found in [17, 3]. A combination of the network frequency and tie-line power deviations can be executed through the following term:

$$ACE_i(s) = \Delta P_{tie,i}(s) + B_i.\Delta F_i(s) \quad (12)$$

where B_i is a frequency bias factor. Taking the signal ACE_i into the input signal of every LFC controller, it must be driven to zero according to the tie-line bias control method. There are also a number of LFC controllers which are able to use this signal for the control purpose satisfying acceptable control quality. The following section presents the discussion of several typical LFC controllers.

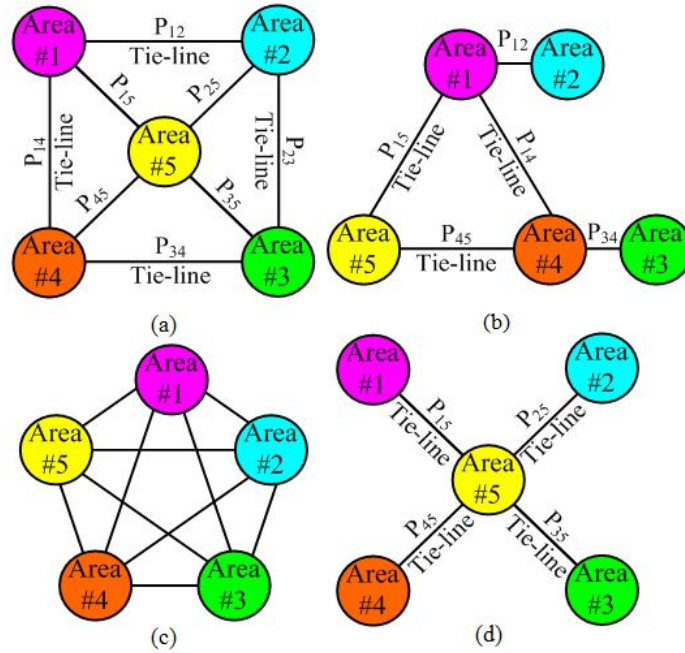


Figure 2. Simple models of five-area interconnected power systems

4. DESIGN OF REGULATORS FOR LFC

4.1. Conventional LFC controllers

In this section, the discussion will point to a number of conventional regulators used for the LFC issue. The fact is that three conventional regulators, including Integral, Proportional-Integral (PI) and Proportional-Integral-Derivative (PID), have been employed for this aim. The first regulators (integral) with simple structure and easy tuning are difficult to ensure the high control performances, and thus their application is actually limited [8]. PID regulators can obtain the better control indices, however, due to a large number of tuning coefficients (K_P , K_I and K_D), it seems to be complicated to apply this type of load-frequency controller. In conclusion, the PI regulators should be chosen in the balance of the foregoing conditions. In principle, with the ACE signal used as the input, the control output of a PI regulator, which is taken to the governor, can be computed as follows:

$$\begin{cases} U_i(t) = K_{P,i} \cdot ACE_i(t) + K_{I,i} \int_0^t ACE_i(\tau) d\tau \\ U_i(s) = [K_{P,i} + K_{I,i} \frac{1}{s}] ACE_i(s), \end{cases} \quad (13)$$

where $K_{P,i}$ and $K_{I,i}$ denote the proportional gain and the integral gain of the above PI controller. The efficiency of the above PI regulators in dealing with the LFC problem will be presented in Section 5 of the paper.

4.2. PD-based fuzzy logic controllers

Fuzzy logic - based control strategy has been applied for a large number of control systems, especially for the nonlinear and uncertain control systems [16]. A large-scale power plant

characterized by inherent nonlinearities and uncertainties is appropriate to the application of fuzzy logic controllers. Although there have been numerous studies on this topic, LFC methodology based on fuzzy logic technique is still of great interest to researchers. This paper aims to represent the design of a typical fuzzy logic - based LFC strategy in combination with the SMES devices as mentioned earlier in order to achieve excellent control performances. The proposed fuzzy logic architecture is illustrated in Figure 3, including two inputs (ACE_i and derivative of ACE_i) and one output (U_i). In general, each fuzzy logic inference system contains three parts, i.e., fuzzification, rule base and defuzzification. The fundamental knowledge of a fuzzy logic architecture can be found clearly in [16]. The fuzzy logic model used in this work is called the PD-based fuzzy logic controller. The principle of this fuzzy logic inference system can be deduced from Figure 3 as follows:

$$U_i(t) = K_u \cdot u_i(t) = K_u \left[K_e ACE_i(t) + K_{de} \frac{d}{dt} ACE_i(t) \right]. \quad (14)$$

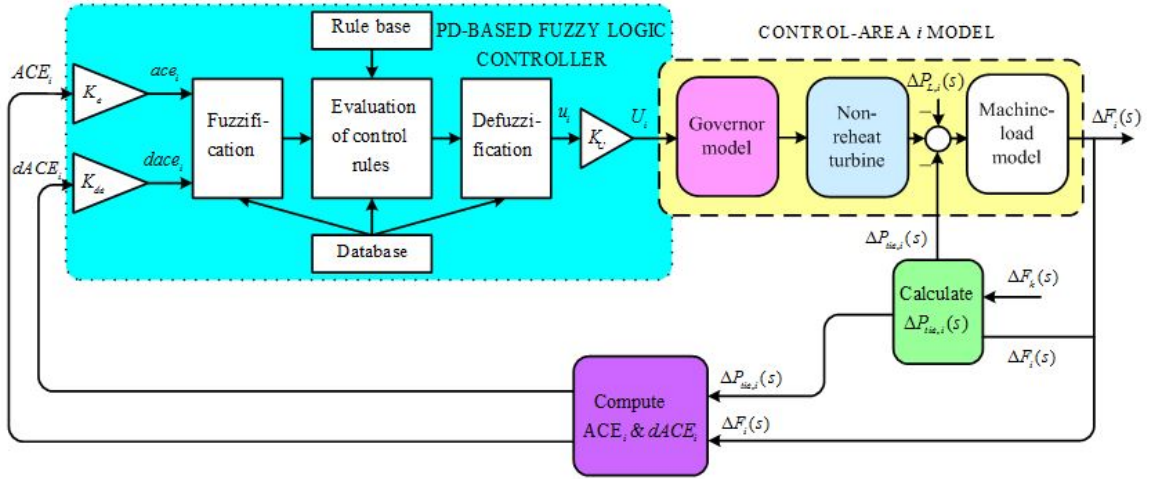


Figure 3. Structure of a PD-based FL controller for the area i

In (14), three factors, K_e , K_{de} and K_u are defined as three tuning factors of the fuzzy logic architecture corresponding to ACE_i , derivative of ACE_i and output signal U_i . From (14), it is straightforward to yield the following:

$$U_i(t) = K_p ACE_i(t) + K_D \frac{d}{dt} ACE_i(t), \quad (15)$$

where $K_p = K_u \cdot K_e$ and $K_D = K_u \cdot K_{de}$. The consensus view seems to be that these two coefficients correspond to two factors of a PD controller, which need to be tuned when designing a regulator based on PD principle. In other words, it might be defined as a PD-like fuzzy logic controller.

To design a fuzzy logic based controller, four steps need to be executed as follows:

Step 1: Determine the number and types of membership functions. In this study, seven membership functions are chosen for each input: $E_k (k = 1, 2, \dots, 7)$ for $ace_i(t)$ and

Table 1. Rule matrix for the PD-based FL controller

$ace_i(t)$	$dace_i(t)$						
	DE_1	DE_2	DE_3	DE_4	DE_5	DE_6	DE_7
E_1	U_1	U_1	U_1	U_2	U_3	U_4	U_5
E_2	U_1	U_1	U_2	U_3	U_4	U_5	U_6
E_3	U_1	U_2	U_3	U_4	U_5	U_6	U_7
E_4	U_2	U_3	U_4	U_5	U_6	U_7	U_8
E_5	U_3	U_4	U_5	U_6	U_7	U_8	U_9
E_6	U_4	U_5	U_6	U_7	U_8	U_9	U_9
E_7	U_5	U_6	U_7	U_8	U_9	U_9	U_9

$DE_l (l = 1, 2, \dots, 7)$ for $dace_i(t)$. All of these membership functions are defined as symmetrical triangular functions. In addition, nine Gaussian curve membership functions are selected for the output of the proposed PD-type fuzzy logic model, including U_1, U_2, \dots, U_9 (see Figure 4).

Step 2: Determine rule base of the fuzzy logic architecture. The rule base is normally defined depending on experience of the experts. We propose a rule base matrix indicated in Table 1 for the PD-like fuzzy logic model based on genetic algorithm (presented in [17, 11]). Because of the continuous and random load change, in order to ensure high quality of the load-frequency control system, it is necessary to use a sufficient number of membership functions. It means that the input signals as well as the output signal need to be divided into small parts to improve the control performances of the system. Normally, the number of membership functions when applying PD-like fuzzy logic architecture is from three to ten ones. In this work, as presented in Step 1, seven membership functions are chosen for each input ($ace_i(t)$ and $dace_i(t)$): E_1, E_2, \dots, E_7 for $ace_i(t)$ and DE_1, DE_2, \dots, DE_7 for $dace_i(t)$. Besides, in order to enhance control capability for the load-frequency regulator presented in this study, we selected nine membership functions for the output signal: U_1, U_2, \dots, U_9 . Using these membership functions for the fuzzy logic reasoning system, it is highly reliable to make sure that the output signal ($\Delta f(t), ACE(t)$) can be driven to zero as quickly as possible. Some explanations in “if-then” form might be drawn from Table 1 as follows:

- (i) if $ace_i(t)$ and $dace_i(t)$ are equal to zeros or very near to zeros, then the current state of output should be remained;
- (ii) if $ace_i(t)$ is not zero however it might be slightly changing, then it is necessary to maintain the current control state;
- (iii) if $ace_i(t)$ is varying significantly, then we need modify the control signal based on the magnitude and sign of $ace_i(t)$ and $dace_i(t)$ to force $ace_i(t)$ towards zero.

Step 3: Choose the method to defuzzification process. In this study, max-MIN rule is selected for this aim since this rule might be of popularity and high efficiency.

Step 4: Compute the scaling factors of this fuzzy logic model. As mentioned earlier, three scaling factors, including K_e, K_{de} and K_u might need to be efficiently tuned in order to obtain the control performances with high quality. For this study, we have used “try-and-error” method to the determination of these three factors.

The above four steps to design a LFC strategy will be implemented in combination with the application of the SMES devices (presented in Section 2). The efficiency of the proposed control methodology will be demonstrated in the following section.

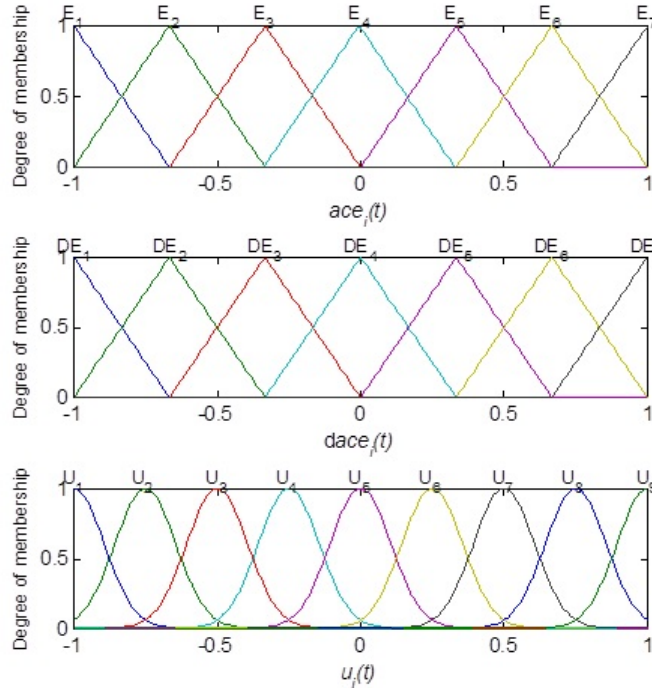


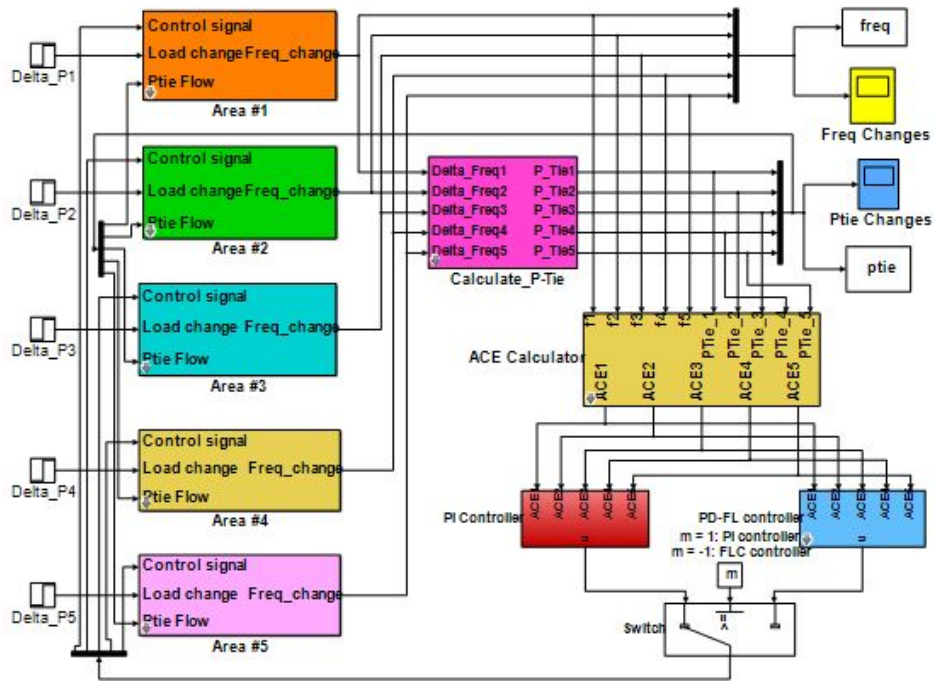
Figure 4. Illustration of membership functions for two inputs and one output of the proposed fuzzy logic architecture

5. NUMERICAL SIMULATIONS AND DISCUSSIONS

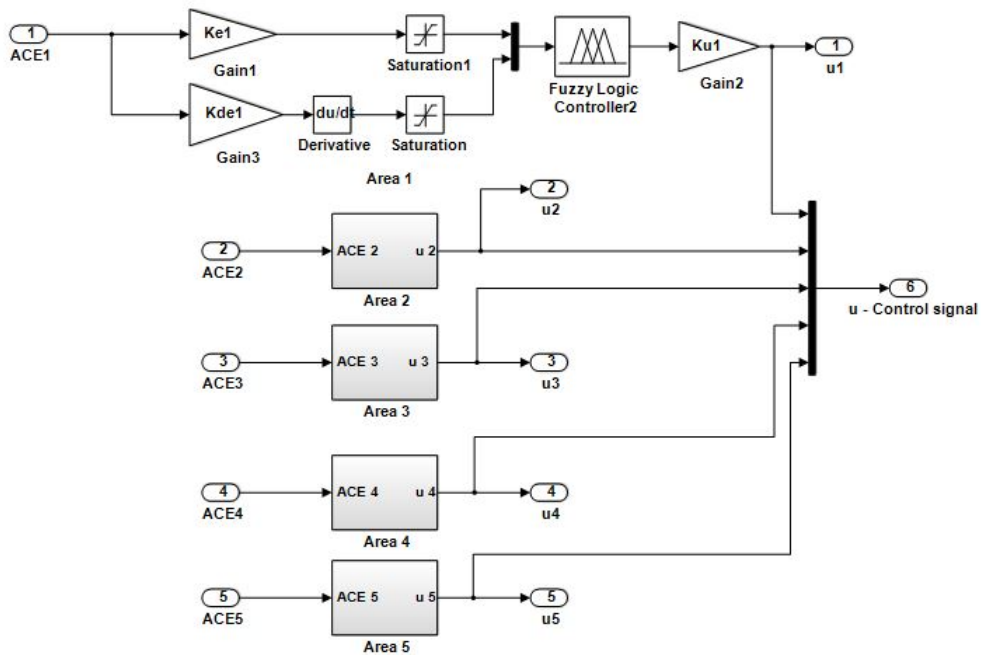
In this section, numerical simulations will be implemented to verify the effectiveness of the proposed controllers as well as the SMES devices to solve the LFC problem. The overall simulation model is built in MATLAB/Simulink package as shown in Figure 5 for the case study mentioned earlier (see Figure 2(d)).

Since loads in a power system can vary randomly at any generating station, load-frequency controllers have to respond efficiently enough to restore the steady state of the network as rapidly as possible. In this paper, two cases of load variations are to be considered as follows:

- (i) Case 1: Let load variation only appear randomly in the most important generating station (area 5) as shown in Figure 6(a). In this case, the step-load will increase at instants of 0(sec), 5(sec) and 10(sec) with the corresponding magnitudes of 0.005(p.u.), 0.01(p.u.) and 0.02(p.u.). Such step-load will decrease at instants of 15(sec) and 20(sec) to the amplitudes of 0.01(p.u.) and 0.05(p.u.), respectively. It would be consistent with an actual condition of daily load in a power plant.



(a) Simulation model with subsystems



(b) Details of the subsystem “PD-FL controller”

Figure 5. Simulation model using different controllers built in MATLAB/Simulink platform

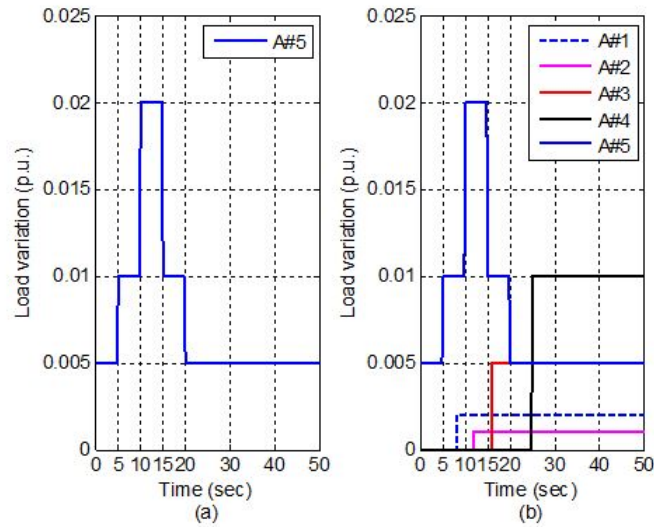


Figure 6. Two load changes applied for simulation purpose

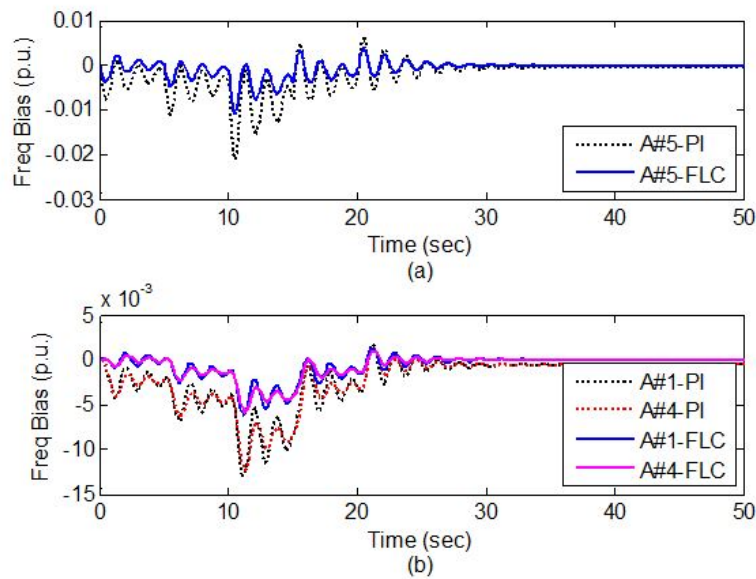


Figure 7. Frequency deviations in the areas #1, #4 and #5 in the first simulation case

- (ii) Case 2: Let load variations occur at all generating areas in the power system model built earlier as shown in Figure 6(b). Load in the area #5 is the same of the first case, meanwhile loads in the other areas are embedded at different instants and amplitudes.

In the above two simulation cases, the SMES units will also be applied to validate their performances. Simulation results obtained are illustrated in Figures 7-10 as well as Table 2. The following discussions will demonstrate the dominant performances of the controllers studied in this work.

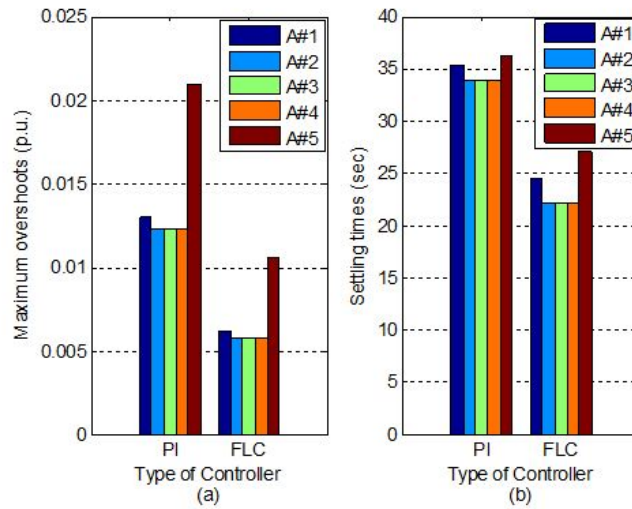


Figure 8. A comparison of maximum overshoots (absolute values) and settling times for all areas in the first simulation case

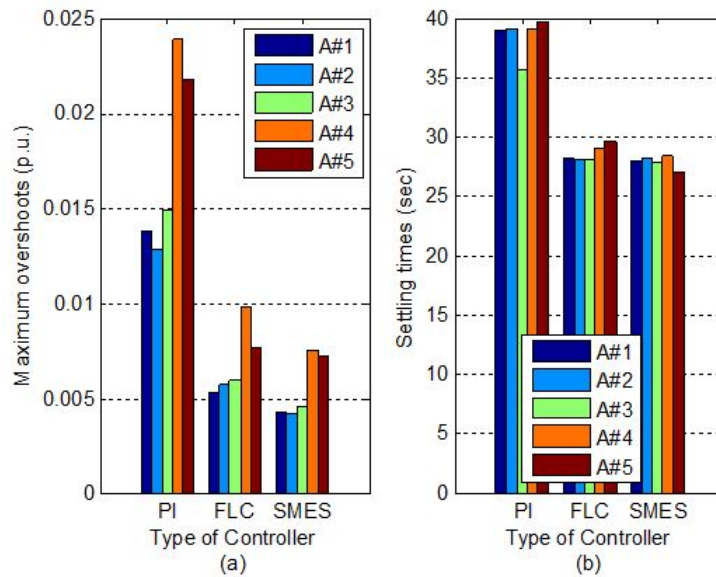


Figure 9. A comparison of (a) maximum overshoots (absolute values) and (b) settling times for all areas in the second simulation case

5.1. Capability of PD-based fuzzy logic controllers

In the first simulation case, Figure 7 describes the response of frequency deviations in several areas using PI and PD-based fuzzy logic controllers. To illustrate numerical results, Figure 8 shows a comparison of maximum overshoots (absolute values) and settling times for all areas with a desired frequency tolerance of 0.05%. From these results, it is clear to draw the following conclusions:

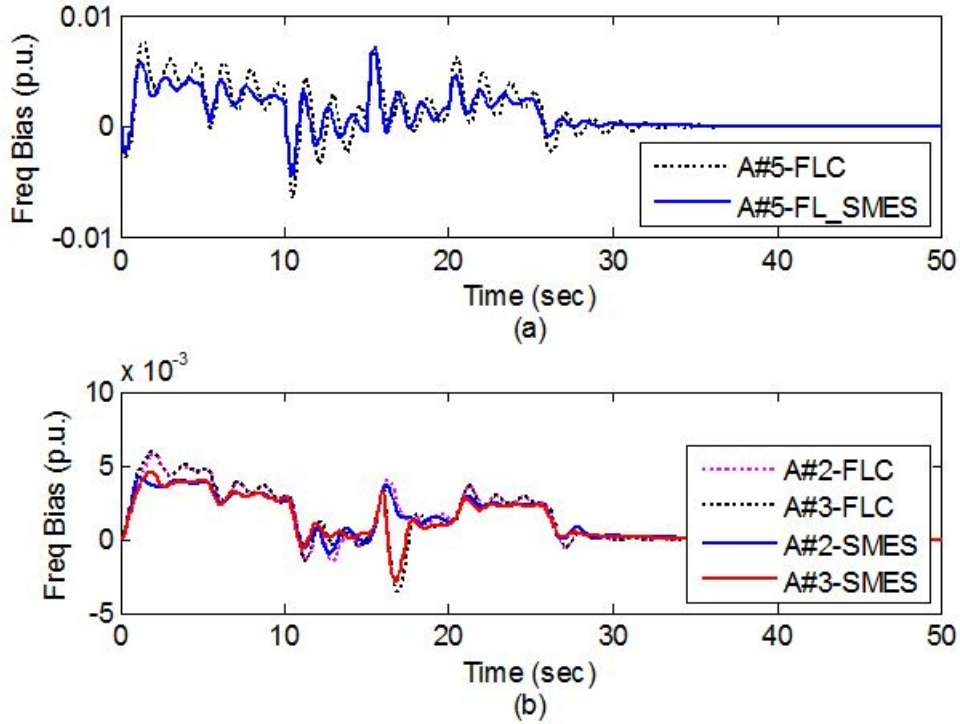


Figure 10. Frequency deviations in three areas 2, 3 and 5 in the second simulation case

- (1) The maximum overshoots as well as the settling times of PD-based fuzzy logic controllers are much smaller than PI regulators. As a result, the control performances of the proposed controllers are much better than those of the conventional PI regulators for conducting the maintenance of the network frequency against the load disturbances.
- (2) Since load change only appears in the fifth area, the frequency of this station will be affected with the biggest deviation (the highest overshoot and the longest settling time). It means that the control indexes in this area are at the worst.

Table 2. A comparison of maximum overshoots (absolute values) of tie-line power deviations, in p.u., for all of areas in both simulation cases

Area	Case 1			Case 2		
	PI	PD-FL	FL-SMES	PI	PD-FL	FL-SMES
Area 1	0.0048	0.0028	0.0021	0.0035	0.0019	0.0015
Area 2	0.0049	0.0029	0.0022	0.0051	0.0030	0.0024
Area 3	0.0049	0.0029	0.0020	0.0051	0.0033	0.0024
Area 4	0.0049	0.0029	0.0023	0.0053	0.0033	0.0028
Area 5	0.0195	0.0114	0.0090	0.0189	0.0114	0.0087

Considering the second simulation case, the results obtained are shown in Figure 9 and Table 2. It is very similar to the first simulation case to assert that the proposed fuzzy

logic controllers have been achieved the better control performances compared with the conventional PI regulators.

5.2. Effectiveness of the SMES devices

In order to verify the performance of the SMES devices, Figure 9, Figure 10 and Table 2 represent simulation results obtained when using PD-based fuzzy logic controllers with and without SMES units. Figure 9 illustrates a comparison of maximum overshoots and settling times of frequency biases for all areas in the second simulation case. Meanwhile, Figure 10 shows the response of frequency changes in the areas 2, 3 and 5 only for controllers based on fuzzy logic with and without the SMES units. Also, Table 2 presents the tie-line power flow deviations for all of areas in two simulation cases using different controllers. From these results, it is confirmed that the combination of the fuzzy logic architecture and the SMES devices can obtain the outstanding control performances compared with the other two control methods when maintaining the system frequency after occurrence of load disturbances in an electric power plant. Thus, it is the demonstration for the feasibility of the proposed control methodology.

6. CONCLUSIONS

This work concentrates on solving the LFC problem in a multi-area interconnected power plant, which has been considered to be a typical example of large-scale systems. A particular model of five-area power networks has been designed as a case study of the practically complicated electric grids. Furthermore, SMES devices and load-frequency controllers based on tie-line bias control scheme are investigated in order to stabilize the network frequency as well as the tie-line power flow against load variations. From this study, it is well known the following conclusions can be drawn.

- (1) LFC is the core of an automatic generation control, playing an important role to ensure the stability and economy of a practical large-scale interconnected power plant.
- (2) PD-based fuzzy logic controllers can solve efficiently the issue of LFC, achieving the better control performances compared with conventional regulators, such as PI.
- (3) SMES units can be used in combination with efficient controllers to obtain the optimal control properties, such as the lowest overshoots and the smallest settling times.
- (4) Due to the complexity of a large and modern power system in practice, it is necessary to model more exactly such electric grid to deal with LFC problem by applying the improved control strategies as mentioned in this study.

Finally, since loads of a power system, which depend only on customers, can vary randomly and continually over time, they should be measured to create the fully practical database for necessary control schemes. This might be of interest for our work in the future.

APPENDICES

A Nomenclature

i	index of control-area $i, i = 1, 2, \dots, n$
$E_{d,i}$	DC output voltage of the AC/DC thyristor based converter, V
$\Delta E_{d,i}(s)$	increment of $E_{d,i}, V$
$V_{d0,i}$	ideal no-load DC voltage of a 6-pulse AC/DC bridge converter, V
α	firing angle of thyristor, degree
$I_{d,i}$	DC current through the superconducting coil, A
$I_{d0,i}$	initial DC current through the superconducting coil, A
$\Delta I_{d,i}(s)$	increment of the DC current through the superconducting coil, A
$L_{d,i}$	inductance value of the superconducting coil, H
$P_{d,i}$	real DC output power of the superconducting coil, W
$\Delta P_{d,i}$	change of real DC output power of the superconducting coil, W
$W_{d,i}$	stored energy in the coil, J
$W_{d0,i}$	initial stored energy in the coil, J
$T_{dc,i}$	time delay of the converter in the power conditioning unit, s
$K_{0,i}$	gain corresponding to ACE input
$K_{Id,i}$	gain corresponding to $\Delta I_{d,i}$ input
f_i	real network frequency, Hz
f_n	nominal network frequency, $f_n = 50Hz$
$\Delta F_i(s)$	frequency deviation of area $i, p.u.$
$\Delta P_{D,i}(s)$	load variation, $p.u.$
$T_{G,i}$	time constant of governor, sec
$T_{T,i}$	time constant of non-reheat turbine, sec
M_i	generator inertia constant, $p.u.$
D_i	load damping factor, $p.u.MW/Hz$
T_{ij}	tie-line time constant, sec
$P_{tie,i}(s)$	tie-line power flow, $p.u.$
$\Delta P_{tie,i}(s)$	deviation of tie-line power flow, $p.u.$
B_i	frequency bias factor, $MW/p.u.Hz$
R_i	speed regulation, Hz/MW
$\Delta P_{T,i}(s)$	change of output of turbine
$\Delta P_{G,i}(s)$	change of output of governor
$U_i(s)$	control signal to governor

B. Parameters of the five-area electric power system model used for numerical simulations

$$\begin{aligned}
T_{G,1} &= 0.08, \quad T_{G,2} = 0.12, \quad T_{G,3} = T_{G,4} = T_{G,5} = 0.10; \\
T_{T,1} &= T_{T,2} = 0.35, \quad T_{T,3} = T_{T,4} = T_{T,5} = 0.30; \\
K_{P,1} &= 120, \quad K_{P,2} = 98, \quad K_{P,3} = K_{P,4} = K_{P,5} = 105; \\
T_{P,1} &= 18, \quad T_{P,2} = 20, \quad T_{P,3} = T_{P,4} = T_{P,5} = 15, \quad T_{ij} = \frac{1}{\sqrt{2}}.
\end{aligned}$$

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