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Application of fuzzy logic for load frequency control of hydroelectrical power plants

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Abstract

The quality of generated electricity in power systems is dependent on the system output, which has to be of constant frequency and must maintain the scheduled power and voltage. Therefore, load frequency control, LFC, is very important for power systems. However, the LFC problem in hydroelectrical power systems has received little attention by researchers so far. In this study, a conventional proportional integral (PI) controller and a fuzzy gain scheduled proportional integral (FGPI) controller have been compared for applying to a single area and a two area hydroelectric power plant, considering that Turkey has several hydro power sources. The comparison study indicated that the proposed FGPI controller has better performance than the conventional PI controller. The study results were compared by simulation.

Keywords: Power systems; Load frequency control; Hydroelectric power plants; Conventional PI controller; Fuzzy gain scheduled PI controller

1. Introduction

Nowadays, electricity generation is very important because of its increasing necessity and enhanced environmental awareness such as reducing pollutant emissions. Since electricity is not stored but consumers expect to get it, its generation must depend on consumption. Electrical power systems are continuously growing in size and complexity with increasing interconnections. Also, their dynamic behaviour depends on disturbances and on changes in the operating point. Since they consist of many generating units and many loads and also their total power demands vary continuously throughout a day, controlling them is very difficult [1]. In interconnected large power systems, variations in frequency can lead to serious large scale stability problems. Load characteristics, unexpected changes in power demand and faults also affect the stability [2]. Additionally, because of suddenly changing consumer demands or some troubleshooting in generating units or network, the system frequency may show some oscillations or corruptions. However, these oscillations have to be limited to certain values. Otherwise, due to these excessive oscillations, some loads have to be extracted from the network, and therefore, producers suffer from the damage. However, continuously tracking load fluctuations definitely causes wear and tear on governor equipments, shortens their lifetime and might require replacing them, which can be very costly [3]. Today, people try to use economical, clean and renewable energy because of global warming. Therefore, output errors of the plant have to be determined and reduced to quite minimum values in short times by using a load frequency controller [4]. For these reasons, advanced control techniques usage must be inevitable in such systems.

Load frequency control (LFC) is one of the major requirements in providing reliable and quality operation in multi-area power systems [2]. Therefore, designing load frequency controllers has received great attention of researchers in recent years, and many control strategies have been developed [5].

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LFC is to regulate a signal called area control error (ACE), which accounts for errors in the interconnection frequency (Δf) as well as errors in the interchange power with neighboring areas over tie lines, i.e. the tie line power error (ΔPtie). Conventional LFC uses a feedback signal that is based on the integral (I) of the ACE or is based on the ACE and its integral (proportional integral, or PI) type controller. These feedback signals are used to maneuver the turbine governor set points of the generators so that the generated power follows the load fluctuations [3].

The ACE for the ith area is defined as

$$\mathrm{ACE} = \Delta P_{\mathrm{tie}} + B_i \Delta f \tag{1}$$

where $\Delta P_{\mathrm{tie}} = P_{\mathrm{tie,actual}} - P_{\mathrm{tie,scheduled}}$ and B_i is the frequency bias factor. This control philosophy is widely used in all power systems, generally for simulation models [6]. The origin of the models was proposed by Refs. [7–9]. In the same manner, the state space and discrete power models have been used [9–11]. In the literature, the proportional integral (PI) controller was used for the proposed control strategy, which is still widely used nowadays in industry. A linear model is written by linearizing the differential equations describing the dynamic performance of the power system around an operating point [12–16].

Additionally, several new controllers such as intelligent controllers and adaptive controllers have been applied for LFC. The neural network is an important technology, which provides good results in LFC in power systems [17–20]. In addition, some researchers have used fuzzy logic controllers for this purpose [21–25]. However, in all these studies, controllers had been applied to a thermal electrical power system, not to a hydroelectrical power system. For the latter system, very few studies have been realized in the literature [6,26].

Considering these situations and Turkey's plentiful hydropower sources, in this study, a two area hydroelectrical power plant was used to apply load frequency control of the power plant. For this reason, a comparison was performed between a conventional PI controller and a FGPI controller. Also, This paper presents a novel load frequency controller manipulated by a fuzzy logic system whose rules are designed to reduce wear and tear of the equipments.

2. Background of hydroelectric power plants in turkey

As a clean and renewable energy, hydropower electrical energy is obtained by converting the potential energy of the water to kinetic energy. Hydroelectricity, or hydroelectric power, is a form of hydropower (i.e. the use of energy released by water falling, flowing downhill, moving tidally, or moving in some other way) to produce electricity. Specifically, the kinetic energy of the moving water is converted to electrical energy by a water turbine driving a generator.

Hydroelectrical energy is the most important renewable energy resource in Turkey. Hydroelectric power stations provide about 40% of the electricity production in the country presently and has a history of about 100 years. The first electricity production in the country started in Tarsus in 1902 with a hydroelectric power station of 60 kW power. In 1923, the total installed capacity of 38 electrical power stations was 33 MW, and their energy production potential was approximately 45 million kWh per year. Of this total, only 0.1 MW was produced by hydroelectric power stations. The population of Turkey in the same year was about 14 million, and electricity consumption per capita was 3.3 kWh per year. In 1953, while the total installed power reached 500 MW, the hydroelectric power accounted for only 6% of this amount, i.e., 30 MW. Between 1953 and 1963, the capacity of hydroelectrical power reached 478 MW, and with the newly established power stations, the hydroelectrical power capacity showed an increase of about 16 times in 10 years. In 1963, the share of the hydroelectric power in the total installed power reached 35% with 1381 MW. In the following years, the amount of electrical consumption per capita has continuously increased and reached 1417 kWh per capita per year in 1999 [27]. By the end of 2010, the total installed electrical power of Turkey is estimated to be 35,587 MW. Of this amount, 22,974 MW will be generated from thermal power systems and 12,578 MW will be gengerated from hydroelectrical power systems. As for total electric energy generation of the country, it will be 140,580 GWh, which will be obtained from 75% thermal and 25% hydroelectrical power systems [28]. The technical hydroelectric energy potential in Turkey is estimated as 216 billion kWh. The economical hydroelectric potential is the total hydroelectric energy from a river basin that can be technically developed and is economically justifiable. In other words, the economical hydroelectric energy potential shows the hydraulic resources with economic feasibility. The economical hydroelectric energy potential of Turkey is about 125 billion kWh. The share of Turkey in the world gross hydroelectric energy potential is about 1% and its economical potential makes 15% of the European economical hydroelectric energy potential [27]. Important river basins that have a hydraulic production potential above 5 TWh are the Euphrates (38.1 TWh), Tigris (16.8 TWh), East Black Sea (11.4 TWh), Coruh (10.5 TWh), Seyhan (7.3 TWh), Kizilirmak (6.8 TWh), Yesilirmak (5.6 TWh), East Mediterranean Sea (5.3 TWh) and Antalya (5.2 TWh) [29]. Given the information mentioned above, it is understood that hydroelectrical power systems control is very important for Turkey.

3. The proposed hydroelectrical power system models

3.1. General overwiev of a power systems

Naturally, electrical power systems have complex and multi-variable structures. Also, they consist of many different control blocks. Most of them are non-linear and/or non-minimum phase systems [21]. Power systems are divided into control areas connected by tie lines. All generators are supposed to constitute a coherent group in each control area. From the experiments on the power systems, it can be seen that each area needs its system frequency and tie line power flow to be controlled [30] in order to give service of good quality to consumers of electrical energy. The frequency control is accomplished by two different control actions in interconnected two area power systems: the primary speed control and supplementary or secondary speed control actions. The primary speed control makes the initial gross readjustment of the frequency. By its actions, the various generators in the control area track a load variation and share it in proportion to their capacities. The speed of the response is limited only by the natural time lags of the turbine and the system itself. Depending upon the turbine type, the primary loop typically responds within 2–20 s. The supplementary speed control takes over the fine adjustment of the frequency by resetting the frequency error to zero through an integral action. The relationship between the speed and load can be adjusted by changing a load reference set point input. In practice, the adjustment of the load reference set point is accomplished by operating the speed changer motor. The output of each unit at a given system frequency can be varied only by changing its load reference, which, in effect, moves the speed droop characteristic up and down. This control is considerably slower and goes into action only when the primary speed control has done its job. Response times may be of the order of 1 min. The speed governing system is used to adjust the frequency. An isochronous governor adjusts the turbine valve/gate to bring the frequency back to the nominal or scheduled value. An isochronous governor works satisfactorily when a generator is supplying an isolated load or when only one generator in a multi-generator system is required to respond to the load changes. For power and load sharing among generators connected to the system, speed regulation or droop characteristics must be provided. The speed droop or regulation characteristic may be obtained by adding a steady state feedback loop around the integrator.

3.2. Hydroelectrical power system model used

The proposed uncontrolled single area hydroelectrical power system is shown in Fig. 1, which was designed under the Matlab 6.5-Simulink software package program [31] where T_w is the water inertia time constant, T_m is the machine starting time constant (s), D is the load damping coefficient, In_1 is the power system input and Out_1 is the power system output.

Also, the proposed two area hydroelectrical power system model, which was designed under the Matlab 6.5-Simulink software package program is shown in Fig. 2.

In these schemes, first a conventional PI controller and then a FGPI controller were applied to the systems for comparison. Both power systems were assumed to be identical. The parameters of the power systems are given in Table 1.

In the systems, the power balance equation for the ith area is written as

$$P_{tie} + P_{gi} - Pl_i(f) = H_i \frac{df_{sys}}{dt} \quad (2)$$

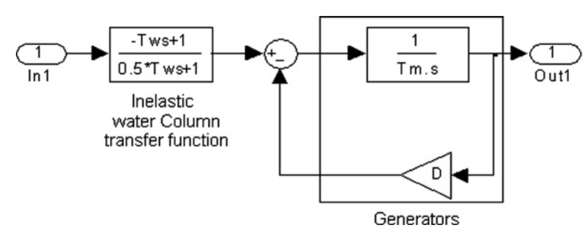

Fig. 1. A single area hydroelectrical power system used in this study.

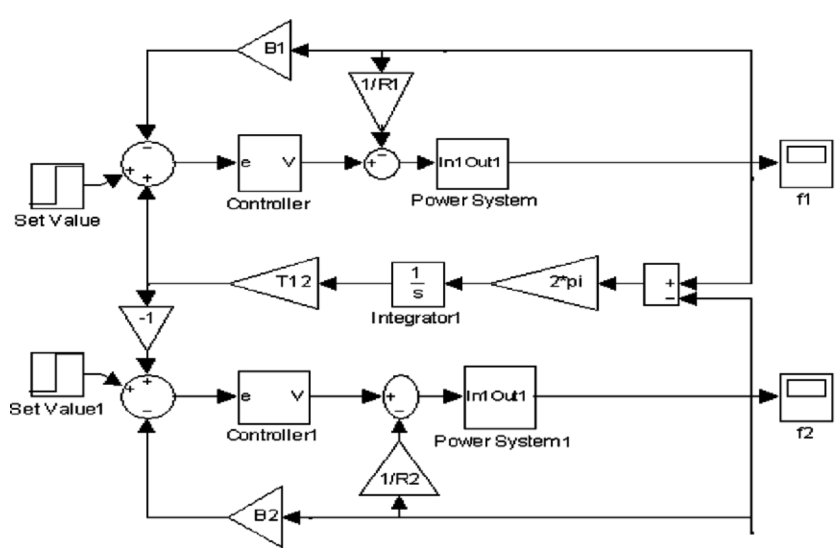

Fig. 2. Two area power system with controllers [10].

Table 1
Parameters of the proposed two area hydroelectrical power system

Names	Abbreviations	Values
Frequency bias factor in area-*i*th	B_i (pu MW/Hz)	1
Regulation constant in area-*i*th	R_i (Hz/pu MW)	2.4
T_{12}	Synchronizing coefficient	0.0707
a_{12}	Synchronizing power coefficient	−1
f_i	Nominal system frequency (Hz)	50
T_w	Water inertia time constant (s)	2
T_m	Machine starting time constant (s)	8
D	Load damping coefficient	1

where P_{tie} is the tie line power flow; P_{gi} is the actual total area generation; $Pl_i(f)$ is the total area load, which is a function of frequency; H_i is the total generator inertia of the ith area, f_{sys} is the nominal system frequency and $H_i \frac{df_{sys}}{dt}$ is the accelerating or deaccelerating power of each area [6].

4. Control methods for the power plants

4.1. Conventional PI controller

Instead of the FGPI controllers in Fig. 2, a conventional PI controller was designed under the Matlab 6.5-Simulink programme and then applied to the sytems at the beginning. Gain values of the PI controllers (K_p and K_i) were obtained according to the system response curve method, and after that, they were optimized using the software. By taking the ACE as the system output, the control vector for a conventional PI controller can be given as

$$\begin{aligned} u_i &= -K_p \mathrm{ACE}_i - \int K_i(\mathrm{ACE}_i)\,dt \\ &= -K_p(\Delta P_{tie,i} + b_i \Delta f_i) - \int K_i(\Delta P_{tie,i} + b_i \Delta f_i)\,dt \end{aligned} \quad (3)$$

In power systems, the conventional PI controllers generally have large overshoots and long settling times. Also, the optimizing time for the control parameters is very long [32]. In this study, the optimized PI gains were taken as $K_P = 1.7$, $K_I = 0.25$ for both the two area power system and the single area power system.

4.2. Fuzzy logic controller

Fuzzy set theory and fuzzy logic establish the rules of a non-linear mapping [33]. The use of fuzzy sets provides a basis for a systematic way for application of uncertain and indefinite models [34]. Fuzzy control is based on a logical system called fuzzy logic. It is much closer in spirit to human thinking and natural language than classical logical systems [35]. Nowadays, fuzzy logic is used in almost all sectors of industry and science. One of them is power plant control. According to many researchers, there are some reasons for the present popularity of fuzzy logic control. First of all, fuzzy logic can be easily applied for most applications in industry. Besides, it can deal with intrinsic uncertainties by changing controller parameters. Finally, it is appropriate for rapid applications. Therefore, a fuzzy logic system (see Fig. 3) has been applied to industrial systems as a controller. Human experts prepare linguistic descriptions as fuzzy rules. These rules are obtained based on experiments of the process' step response, error signal and its time derivative [36].

The expert knowledge is usually in the form of:

IF (input1 is big) and/or (input2 is small) ... (input N is medium) THEN

(output1 is negative big) and (output2 is positive small) ... (output M is zero).

Basically, fuzzy rules provide a convenient way for expressing control policy and domain knowledge. Furthermore, several linguistic variables might be involved in the antecedents (before then) and the conclusions (after then) of these rules. A fuzzy logic system mainly consists of three steps: fuzzification, fuzzy inference and defuzzification. In the fuzzification step, the real variables are translated into linguistic variables by using fuzzy set theory. In the fuzzy inference step, 'If–Then' rules that define the system behavior are evaluated. The defuzzification step translates the linguistic result obtained from the fuzzy inference into a real value by using the rule base provided [37].

4.3. The proposed FGPI controller

Since the calculated gain values of a conventional controller are constant throughout the operation, the controller suffers from some difficulty to adapt to changing system parameters. For this reason, some advanced controllers that vary their gain parameters throughout the operation must be preferred. Therefore, the system can be controlled much better as compared with the control of classic con-

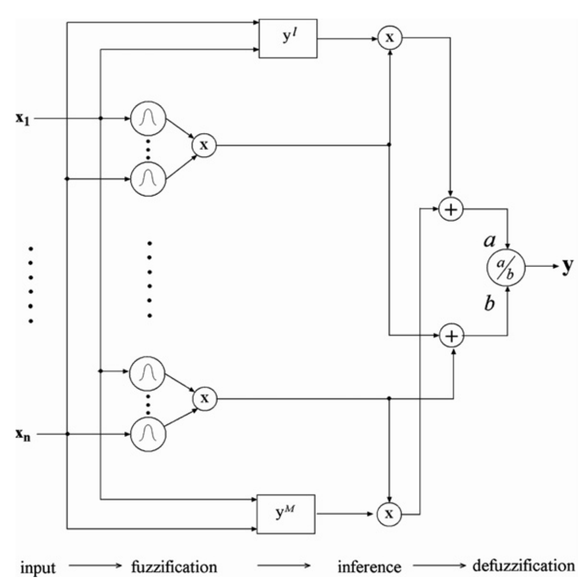

Fig. 3. A simple fuzzy logic system.

trollers [38]. FGPI controllers were designed based on this principle.

In a FGPI controller, the parameters of the conventional PI controller are modified with a fuzzy logic controller. In this study, a FGPI controller is proposed to regulate the outputs of two area and single area hydroelectrical power plants, since it is a suitable technique for non-linear and time variant systems. This technique is used to adjust the gains of the PI controller according to disturbances in the systems outputs. The inference mechanism and the membership functions (MFs) for the proposed FGPI controllers have seven levels. The MFs were chosen to be triangular for obtaining fast response from the system. The ranges of the x axis were determined experimentally. For the controller, the number of rules was taken as 49. The rules of the MFs were formed based on error, e, and its derivative, de. If e is significantly bigger than the set value and de is increased rapidly, then the output of the controller, u, is to be big. Therefore, the output of the system goes to the set value. The appropriate rules for $K_i$and K_p are given in Table 2. The membership functions of these controllers are given in Fig. 4.

Table 2
Rules of K_i and K_p gains of the proposed FGPI controllers

e	de						
	NB	NO	NK	S	PK	PO	PB
NB	PB	PB	PB	PO	PO	PK	S
NO	PB	PO	PO	PO	PK	S	NK
NK	PB	PO	PK	PK	*S*	NK	NO
S	PO	PO	PK	S	NK	NO	NO
PK	PO	PK	S	NK	NK	NO	NB
PO	PK	S	NK	NO	NO	NO	NB
PB	S	NK	NO	NO	NB	NB	NB

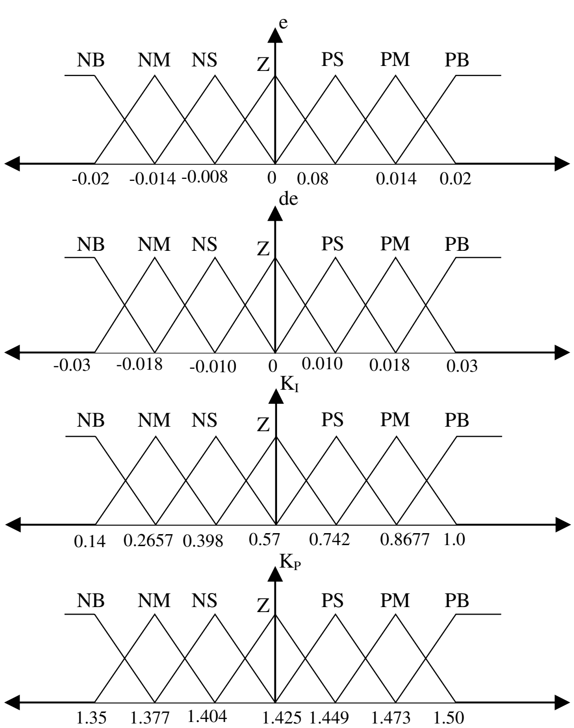

Fig. 4. Membership functions of the FGPI controller.

In the figure, the MFs were named NB (negative big), NM (negative medium), NS (negative smal), *Z* (Zero), PS (pozitive smal), PM (pozitive medium) and PB (pozitive big). Also, e and de are, respectively, the system error and the derivative system error, while K_p and K_i are the proportional and integral gains, which are set by the fuzzy logic controller. The rules of the K_p and K_i were taken to be the same for both FGPI controllers, whereas their intervals of the x axis are different.

5. Simulation results and evaluations

As mentioned in Section 2, currently 40% of the total generated electrical energy in Turkey is obtained from hydroelectrical power systems. Therefore, their control process has become very important for the country. Also, via good controlling them, the economical life of their equipments can be increased and both generation and

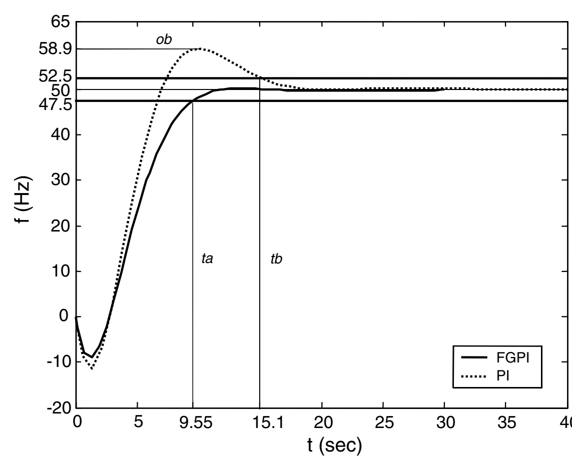

Fig. 5. Output frequencies of the single area power system.

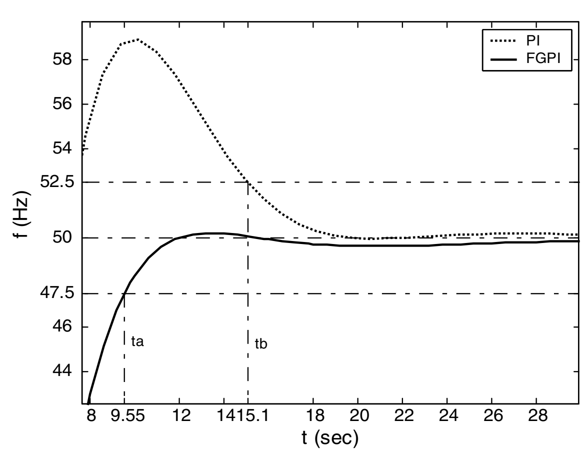

Fig. 6. Zoomed output frequencies of the single area power system.

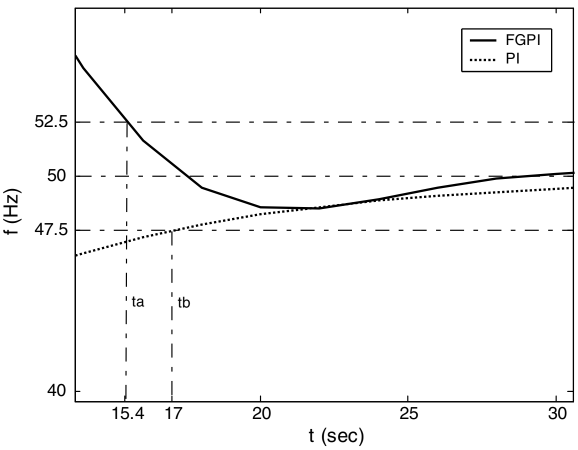

Fig. 7. Output frequencies of the two area power system.

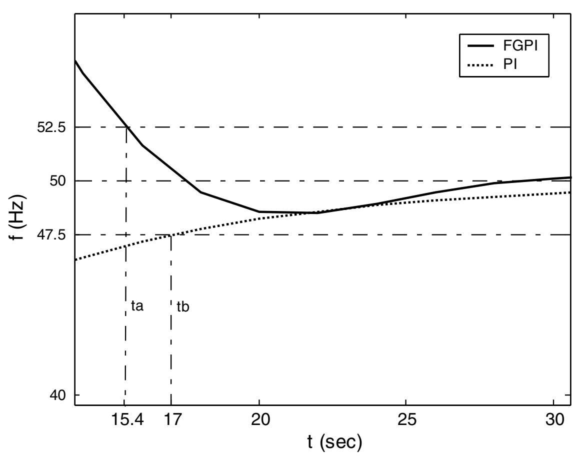

Fig. 8. Zoomed output frequencies of the two area power system.

operation costs can be reduced. This will directly influence the consumer budget positively.

Hence, in this study, single area and two area hydroelectrical power systems and two different controllers, a conventional PI and a FGPI, were designed under the Matlab 6.5-Simulink program for comparison of their load frequency control. Simulation results obtained from the systems are depicted in Figs. 5–8 and Table 3. Output frequencies of the systems were taken as 50 Hz as shown in the same figures. The system outputs were compared in a 2.5% band. t_a and t_b in the figures are the settling times for the FGPI and the conventional PI controller, respectively. Also, o_b is the overshoot of the FGPI controllers. For the single area power plant, as can be observed from the figures, the settling time and overshoots with the proposed FGPI controller are much shorter than those with the conventional PI controller. From Table 3, it is shown that the settling time of the conventional PI controller is 64% longer than that of the proposed FGPI controller. Also, the output of the system has no overshoot with the proposed controller, whereas the conventional PI controller caused a 37% overshoot for the same system. As for the two area hydroelectric power plant, for the conventional PI controllers, there are no overshoot values, since

Table 3
Output values of both systems

	Controllers	FGPI	PI
Single area power system results	Overshoot values (%)	$o_b = -$	$o_b = 37$
	Settling times (s)	$t_a = 9.58$	$t_b = 15$
Two area power system results	Overshoot values (%)	$o_b = 22$	$o_b = -$
	Settling times (s)	$t_a = 15.4$	$t_b = 17$

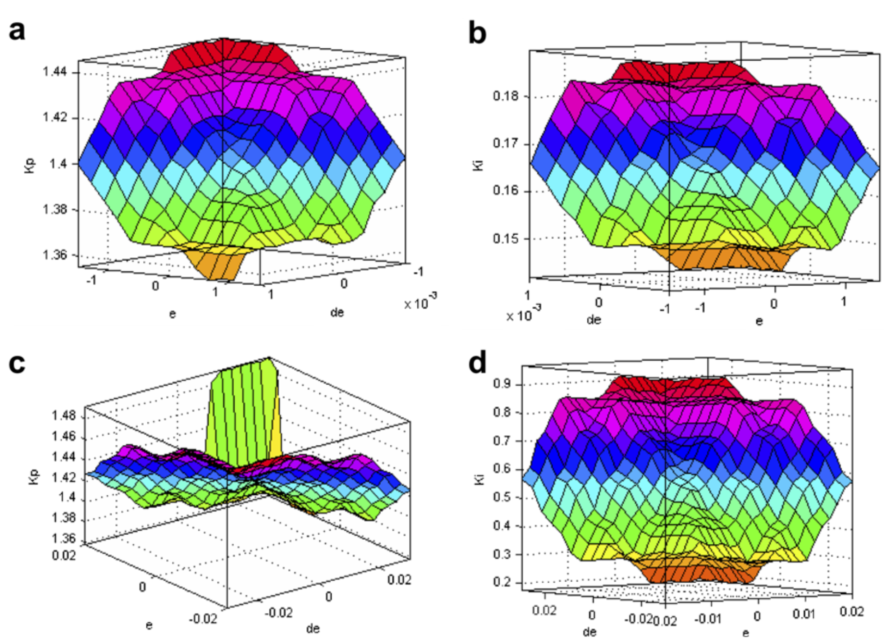

Fig. 9. The variation of e and de with respect to K_i and K_p: (a–b) surface viewers for two area power system and (c–d) surface viewers for single area power system.

it did not exceed the set value of 50 Hz. However, the overshoot values of the FGPI controllers is 22%. As for the settling times, the FGPI controller has about 10% faster response from the conventional PI controller. Their settling times are 15.4 and 17 s, respectively. It is extracted from the results that the proposed FGPI controller has considerably better performances than the other controller for both power systems. When the hydroelectric power capacity of Turkey is considered, the improvement of the power system is very important for the country.

The variation of e and de with respect to K_i and K_p are given in Fig. 9 where a and b indicate the relationship between e, de and K_i/K_p in three dimensions for the two area power plant, while c and d show the relationship between e, de and K_i/K_p in three dimensions for the single area power plant.

6. Conclusions

In this paper, a comparative study was presented using a fuzzy gain scheduling proportional and integral controller, FGPI, and a conventional proportional and integral controller, PI. Both controllers were applied to a single area and a two area hydroelectrical power plant, since Turkey has plenty of hydrological resources. Therefore, it was aimed to contribute to the economy of the country via improving the power systems. For this reason, both controllers and the power systems were designed with the Matlab 6.5-Simulink programme package. For comparison purposes, the parameters of the systems were not changed during the simulations for both controllers.

The simulation results suggest that the FGPI controller has considerably better performances than the conventional PI controller for both power systems, whereas the latter controller has a relatively better overshoot value than that of the former for only the two area power plant. As is known, reduced settling time in power systems significantly reduces generating cost, providing economical benefits to both the management and the consumer. Also, corrosions of the machines used in the system can be prevented by lowered overshoot of the system outputs. Therefore, the machines and power plants are to be longer lived. Hence, the FGPI controllers can be proposed to control such power systems. Thanks to using modern control methods, the productivity of the power system can be augmented. Also, the economical life of their equipments can be increased. In addition, reduced prices of electricity generation cost may supply some advantages to the consumers. The most important thing is that fossil fuels usage can be reduced by means of using hydroelectrical power systems. Therefore, environmental pollution and CO_2 emissions values can also be reduced. In conclusion, because of all the reasons above mentioned, the proposed FGPI controller can be recommended as an advanced controller for providing load frequency control in such single area and two area hydroelectrical power plants.

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