The Investigation of Fuzzy Logic-PI Based Load Frequency Control of Keban HEPP

Beyda Taşar*[*], *Hasan Güler* [**], *Mehmet Özdemir*[**]

[*]Mechatronics Engineering Department, Engineering Faculty, Firat University, Elazig, Turkey (Tel: 0424 237 00 00 (6354); e-mail: btasar@firat.edu.tr).
[**]Electrical and Electronics Engineering Department, Technology Faculty, Firat University, Elazig, Turkey

Abstract: The Keban Hydroelectric Power Plant (HEPP) consists of eight synchronous generators, all of which are interconnected to the power system. In this study, we examine the frequency changes and stability of the Plant with respect to a possible load change in the power system. It is important to keep the frequency constant while the power systems are fulfilling the requested power. Thus, in order to keep the system frequency stable in the event of a possible change in power request, a Fuzzy-logic based proportional-integral (FPI) controller, which can maintain its stability even in the event of system parameter changes, is proposed in this study. The design of this system was performed in Matlab/Simulink Software, and the performance results were compared with the results achieved through a traditional proportional-integral (PI) controller. To simulate the system, we constructed a model of the Keban Hydroelectric Power Plant based on the catalog values.

Keywords: frequency stability, fuzzy logic controller, proportional ıntegration control hydroelectric power plant, Keban Hydroelectric Power Plant

1. INTRODUCTION

The Keban HEPP is a combined rock fill and concrete gravity hydroelectric dam operated by the State Hydraulic Works (DSİ), located in the Elazig Province of Turkey. The dam is 1,097 meters long, and its crest is 207 meters above the level of the river-bed (848 meters above sea-level).

Keban plant is a HEPP which connects to the interconnected power system. Its eight water turbines and generators are capable of producing 1,330 MW. The first four generators produce 157 kW each, and the second four generators produce 165 kW each (Laurent, 2011). Keban HEPP is the world's eighteenth-tallest dam (Ertunç, 1999; Hanmandlu and Goyal, 2008).

Frequency is an important criterion for evaluating the quality and efficiency with which electric power systems supply electrical power. A good quality power system must provide constant frequency and active power balance. The consumers want continuous, stable, quality and reliable energy. If active power balance is provided upon detection of instantaneous changes in power output, then frequency control can also be provided (Hanmandlu and Goyal, 2008, Paish, 2002, Özbay and Gençoğlu, 2010). It is essential to remain frequency constant in response to load changes and power-sharing between generation units while developing and growing the interconnected systems (Laurent, 2011; Ertunç, 1999; Hanmandlu and Goyal, 2008; Paish, 2002).

The operating stability of a power system at fixed frequency is valid only in the case of power balance. The total active power generated in the system must be equal to the sum of active loads, losses and the power flowing out of the system via the connection lines. When this balance is disrupted, the system frequency starts to change (Laurent, 2011; Ertunç, 1999; Hanmandlu and Goyal, 2008). While too much generation Increases the system frequency, too little generation decreases it.

If load changes occur at any of the generation units, all generation units will be affected. If the system has load-frequency control, the system is designed to attain the desired steady state as soon as possible. Load-frequency control brings the system to the desired reference value by making the necessary adjustments without disturbing the system in the case of sudden load changes (Demirören, 2004; Kundur, 1993; Parlak, 2002; Yılmaz, 1997). The system frequency is held constant in spite of load changes by applying the first speed control. In the first speed control or control loop, also known as primary control, while the generated and consumed power levels are equalized, the frequency changes depending on the slope of R. The used speed governor (regulator) determines the R coefficient. The method also known as secondary speed control, in addition to first speed control, corrects the frequency changes that occur because of characteristics of the speed governor and provides shared power increases in the each area of the power systems (Demirören, 2004; Kundur, 1993; Parlak, 2002; Yılmaz, 1997; Özdemirci, 2002). Frequency control involves controlling not only generation and frequency, but also the amount of generation in each area and the connections with other areas while maintaining a prescribed power sharing ratio (Demirören, 2004; Kundur, 1993; Parlak, 2002; Yılmaz, 1997; Özdemirci , 2002).

Many control techniques have been used for secondary load frequency control. Contrary to the traditional PI control, the fuzzy logic control method has been widely used in nonlinear, complex and uncertain, high order and time-delay systems such as engineering problems, robotics, renewable energy, signal processing, power electronics and power system modeling (Özbay and Gençoğlu, 2010;Salhi and Daubabi, 2009; Hassan et al, 2008). Indulkar and Raj (1995) initially designed a fuzzy logic controller to solve the load frequency control problem in a four area interconnected power system (Chamg and Fu, 1997). (Ghoshal, 2003) proposed a method in which a self-adjusting, fast acting fuzzy gain scheduling scheme for conventional integral gain connected three equal power system areas. The responses of the fuzzy logic controllers were compared with those of a traditional integral controller.

To decide proportional and integral gains according to the ACE controller and their changes, (Juang and Lu, 2006) proposed a fuzzy-PI controller. Determination of the rule table is extremely important for power systems. (Denna et al., 1999 and Saravuth et al., 2006) used the tabu search algorithm for the automatic definition of fuzzy logic controller rules. (Sinha et al., 2010) proposed a genetic algorithm (GA) tuned fuzzy controller for automatic generation control (AGC) in three area power systems. Fuzzy logic controllers have been designed (Hemeida, 2010) for not only HEPP, but also thermal power systems. (Çam 2004, 2005) designed a fuzzy controller for a two area interconnected thermal power system. Also (Juang and Lu, 2005) proposed a GA based fuzzy gain scheduling system for a two-area thermal power system. They (Ghoshal, 2005) used GA to determine the optimal integral and PID gains. (Sudha et al. 2012) proposed the generation of optimal fuzzy rules based on fuzzy C for a two-area reheat thermal power system using clustering for decentralized load frequency control (LFC). (Hossein et al., 2007) proposed and designed a multi-stage fuzzy controller in a structured power system.

In this study, the mathematical model and simulation of the eight-area Keban HEPP were built up by first speed, secondary PI, and Fuzzy Logic PI speed control techniques. The changes of interconnected system frequency and amount of generation in the case of changing power demand (increase or decrease) from the system were investigated. The Keban HEPP system model was designed according to real Keban HEPP technical data. The proposed FPI method described in the literature for load-frequency control is applied to a real system, Keban HEPP, and the accuracy and efficiency of the proposed method are shown.

2. SIMULATION MODELLING OF POWER SYSTEM

The block diagram of a one area hydraulic power system is given in Fig. 1. As can be seen in the diagram, a hydraulic power system consists of five main units (Demirören, 2004; Kundur, 1993; Parlak, 2002; Yılmaz, 1997; Özdemirci, 2002). These are the hydraulic turbine, generator, revolution speed governor, load and controller.

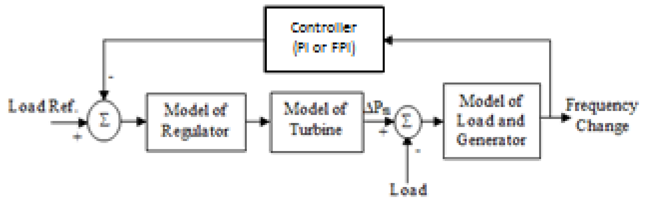

Fig. 1. Block diagram of a one area power system.

2.1. Model and Transfer Function of Hydraulic Turbine

The basic elements of a hydraulic power plant are shown in Fig. 2. The run of the hydraulic turbine is affected by factors such as the inertia of the water column feeding the turbine, compressibility of water, and the elasticity of the pipe at the spillway (Demirören, 2004; Kundur, 1993; Parlak, 2002; Yılmaz, 1997; Özdemirci, 2002). In the stability studies for hydraulic turbine and water column expression, the following assumptions are made:

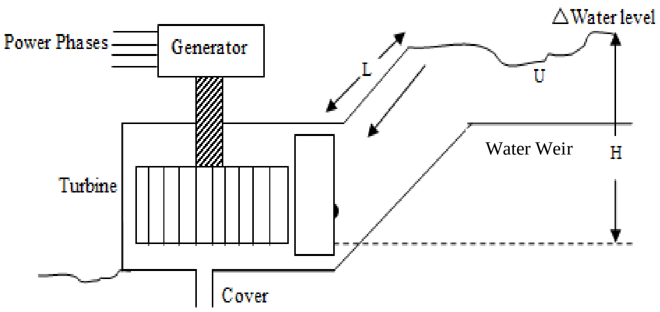

Fig. 2. Basic elements of hydraulic power plant.

- Hydraulic resistance is ignored.
- The spillway pipe is not elastic so the water is not compressed.
- Water speed is directly proportional to the opening cover and the square root of net hydraulic head.
- The output turbine power is proportional to the head and volumetric flow.

The water speed at the spillway for a small place of change near the operating point is

$$\Delta U = \frac{\partial U}{\partial H}\Delta H + \frac{\partial U}{\partial G}\Delta G \quad (1)$$

Where U is water speed; G is the position of the turbine cover plate, and H is hydraulic head. The mechanical power of the turbine is proportional to the initial continuous-state (steady-state) values and flow.

The changes in speed and the turbine cover plate states are expressed as equation 2.

$$T_{\omega} s\Delta\bar{U} = 2(\Delta\bar{G} - \Delta\bar{U}) \quad (2)$$

$$\Delta\bar{U} = \frac{1}{1+0.5sT_\omega}\Delta\bar{G} \tag{3}$$

$$\frac{\Delta\overline{P_M}}{\Delta\bar{G}} = \frac{1-sT_\omega}{1+0.5sT_\omega} \tag{4}$$

Equation 4 is the transfer function of the hydraulic turbine, where T_ω is $\frac{LU_0}{a_g H_0}$. T_ω is between 0.5 and 4 seconds at full load. Equation 4 is the classical transfer function of a hydraulic turbine. It shows the relationship between a change in the amount of cover and the resulting change in output power for the ideal lossless turbine. It can be stated that the speed of the generator and so the power at system output are adjusted by the speed governor and turbine.

2.2. Model of Generator

In power systems, previously unknown amplitude and load changes that occur at specific intervals cause changes in electrical torque output of the generator. This situation, as can be seen from equation 5, causes a mismatch between the electrical moment and Tm mechanical moment and the change in the rotor speed (Demirören, 2004; Kundur, 1993; Parlak, 2002; Yılmaz, 1997; Taşar, 2009,a).

$$T_m = T_e + M\frac{d\omega}{dt} \tag{5}$$

If the relationship between power and torque can be written:

$$P = \omega_r T \tag{6}$$

$$P = P_0 + \Delta P,\ \ T = T_0 + \Delta T\ ve\ \omega_r = \omega_0 + \Delta\omega_r \tag{7}$$

ω_r is a measurement of rotor speed, and ω_0 is a reference to speed in (7), from equation (7);

$$P = P_0 + \Delta P = (\omega_0 + \Delta\omega_r)T_0 + \Delta T \tag{8}$$

In steady-state, electrical torque and mechanical torque are equal and ω_0 is zero, so equation 9 can be written as below. In this equation, M is the inertia constant:

$$\Delta P_m - \Delta P_e = (\Delta T_m - \Delta T_e) = \frac{\Delta\omega_r}{Ms} \tag{9}$$

The transfer function between speed and power in Simulink is shown in Fig. 3.

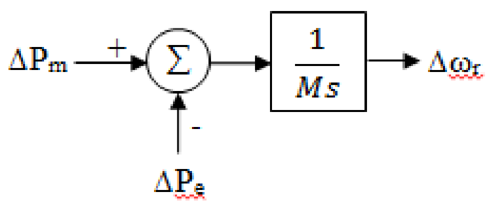

Fig. 3. The transfer function between speed and power.

2.3. Model of Load

The load in the power system is generally a combination of various electrical devices. Electrical power is independent of frequency for resistive loads (purely resistive), such as lighting and thermal loads. Electrical power varies with frequency due to changes in motor speed for fans and pumps (Demirören, 2004; Kundur, 1993;, Parlak, 2002; Yılmaz, 1997; Özdemirci, 2002). Frequency-dependent characteristics of a complex load can be expressed as equation 10:

$$\Delta P_e = \Delta P_L + D\Delta\omega_r \tag{10}$$

If this equation is arranged from equation (9); equation 11 is obtained,

$$\Delta P_m = \Delta P_L + D\Delta\omega_r + Ms\Delta\omega \tag{11}$$

where D is the damping constant. The first part of the equation explains insensitivity to frequency of load change, while the second part of it explains sensitivity to frequency of load change. A reduced model of the load is shown Fig. 4:

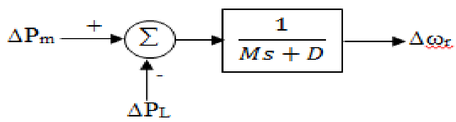

Fig. 4. Reduced model of the load.

2.4. Model of Speed Regulator

Rotation speed regulators which decrease speed in response to increasing loads are used to provide stable load sharing for two or more production units running in parallel in power systems (Demirören, 2004; Kundur, 1993; Taşar, 2009,b). A block diagram of the speed regulator is shown Fig. 5.

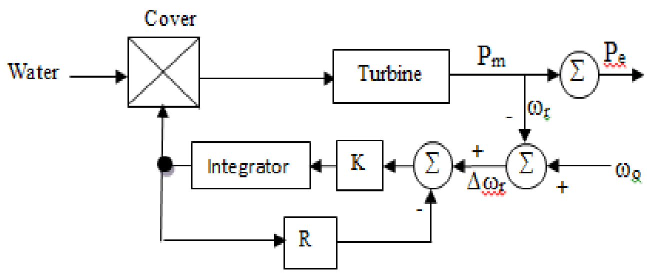

Fig. 5. Block diagram of speed regulator.

$$R = \Delta f/\Delta P \tag{12}$$

$$\Delta f = f - f_0 \tag{13}$$

The ratio of change in output power to change in frequency is equal to R. R is the coefficient for determining deceleration or regulation. A block diagram which shows the relationship between the change of generated power (ΔY) and the change of speed ($\Delta\omega_r$) is given in Fig. 6.

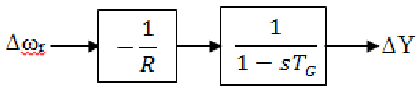

Fig. 6. The transfer function between speed and generated power

2.5. Models of Controller

In the control of load-frequency, the controller structure supporting speed control is used to eliminate frequency deviations in response to load change. In this study, classical PI (proportional-Integrator) and Fuzzy logic-PI were designed and frequency response was analyzed.

3. MODEL OF FUZZY LOGIC BASED POWER SYSTEM STABILIZER

In the literature, a Fuzzy logic based PI controller (FPI) has been proposed to eliminate frequency errors in steady-state response to load change (Özdemirci , 2002; Sağlam, 2007; Küçüksille, 2002; Çam, 2007, Kocaraslan, 2005; Çam, 2002, Chatuverdi et al., 1999). In this study, an FPI controller with two inputs was designed as shown in Fig. 7, and frequency control was implemented by applying the controller to the Keban HEPP power system.

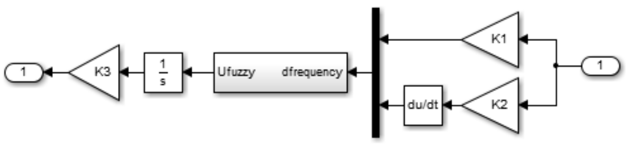

Fig. 7. Matlab model of FPI.

The inputs to the FPI controller are system frequency error (Δf) and a derivative of the frequency error according to time (dΔf/dt) (Chatuverdi et. al. 1995). Positive control signals are applied to the excitation system when the frequency error and its derivative are not zero and deviations in frequency are damped.

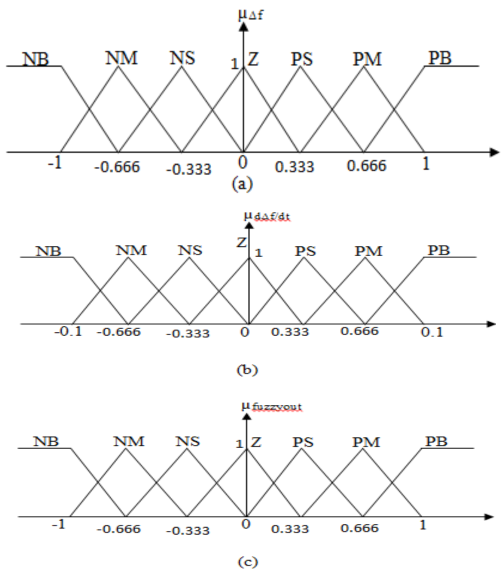

Fig. 8. The membership functions of (a) Δf (b) dΔf/dt (c) the fuzzyout output signal.

The inputs multiplied by K1 and K2 are applied to the FPI controller. The scaling of appropriate K1 and K2 coefficients is important for the proper use of the membership functions. The K3 coefficient is used to scale the output signal of the FPI controller. Thus, the output response can be improved. The limits of Δf and its derivative were set to [-1, 1] and [-0.1, 0.1], respectively. The seven linguistic variables used were Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). The output signal of FPI provided for the Supportive feedback control signal was limited to the range [-1, 1]. These membership functions are defined as triangular functions, since load-frequency control is a rapid application (Çam, Kocaarslan 2004 and Çam 2007). Also, the sensitivity of the controller depends on not only the experts rule, but also the membership functions (Tomsovic, 1999)

The membership functions of the system are in Fig.8. The FPI rules applied to the Keban HEPP can be seen in Table 1.

Table 1. FPI rules applied to Keban HEPP.

	NB	**NO**	**NS**	**S**	**PS**	**PO**	**PB**
NB	NB	NO	NS	NS	NS	NS	S
N0	NO	NO	NS	NS	NS	S	S
NS	NS	NS	NS	NS	S	NS	PO
S	NS	NS	NS	S	PS	PO	PO
PS	NS	NS	S	PS	PS	PK	PS
PO	NS	S	NS	PO	PS	PO	PO
PB	S	PS	PO	PB	PB	PB	PB

The rule table was established according to information provided by the Keban HEPP technical staff. All parameters for the Keban HEPP generator, turbine, and regulator were derived from the same technical personnel. Defuzzy methods are used as a bisector for our fuzzy controller.

4. LOAD- FREQUENCY SIMULATIONS FOR KEBAN HEPP POWER SYSTEM AND NUMERICAL RESULTS

Keban HEPP has eight synchronous generators of which four are 157 MW and the others are 165 MW. The coefficients of Keban HEPP's speed regulator, turbine and generator are given in Table 2.

Table 2. Speed Regulator, Turbine and other parameters of Keban HEPP

Keban HEPP (Unit 1-4)	TR=8 ;TG=0.75; Tw=2; R=0.036; r=0.1
Keban HEPP (Unit 4-8)	TR=8; TG=0.6; Tw=2; R=0.046; r=0.1

The simulation model of the Keban HEPP was implemented by the use of these values in Matlab/Simulink, and the dynamic response of the real system to various load changes was analyzed in simulation.

First, a speed control simulation model of a power system having one generator is given in Fig. 9. This model was obtained taking into consideration the turbine, generator, speed regulator and load transfer functions which have been estimated in the previous title. A Keban HEPP load–frequency control model with eight generators was created based on the single generator system model.

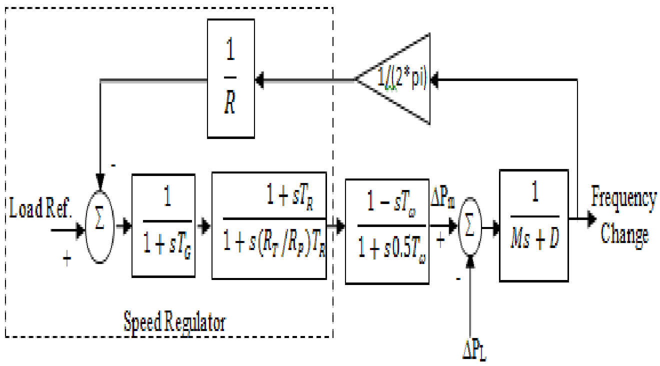

Fig. 9. Simulation model of a power system with one field applied (first speed control method).

The designed first speed controller, PI controller and FPI controller for load-frequency control of the Keban HEPP with 8 generators are given in Figs. 10, 11 and 12, respectively.

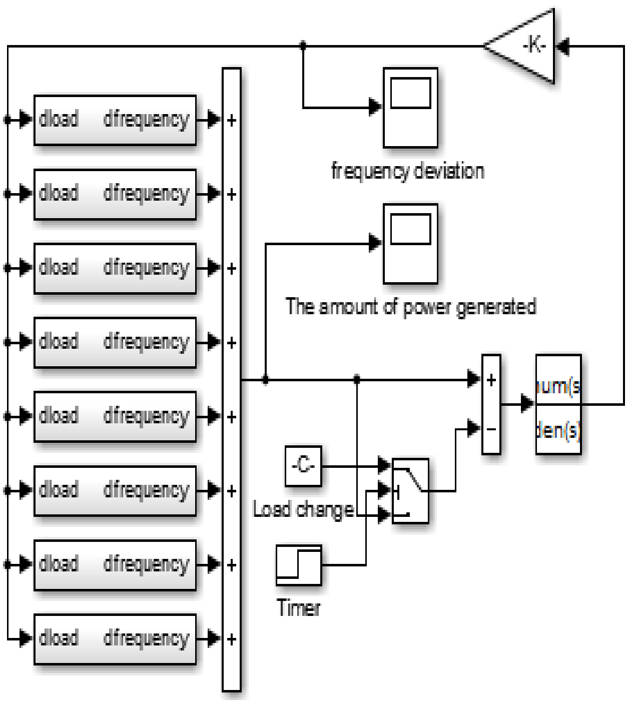

Fig. 10. Simulation of Keban HEPP using first speed control

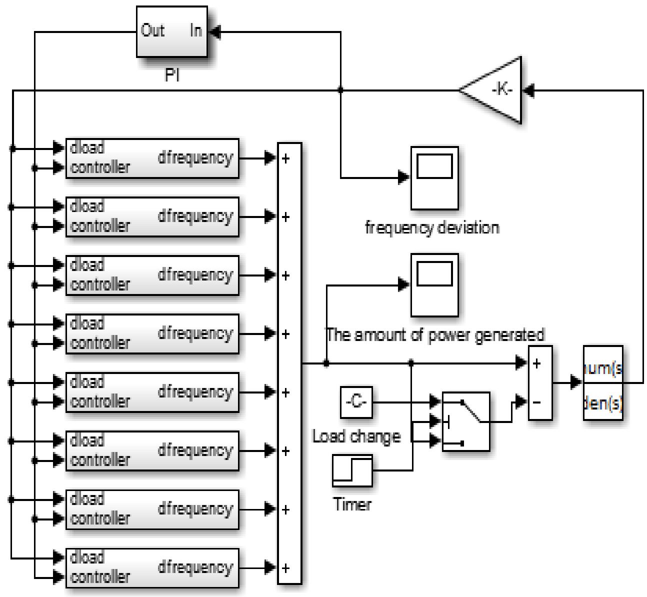

Fig. 11. Simulation of Keban HE***PP*** using PI controller.

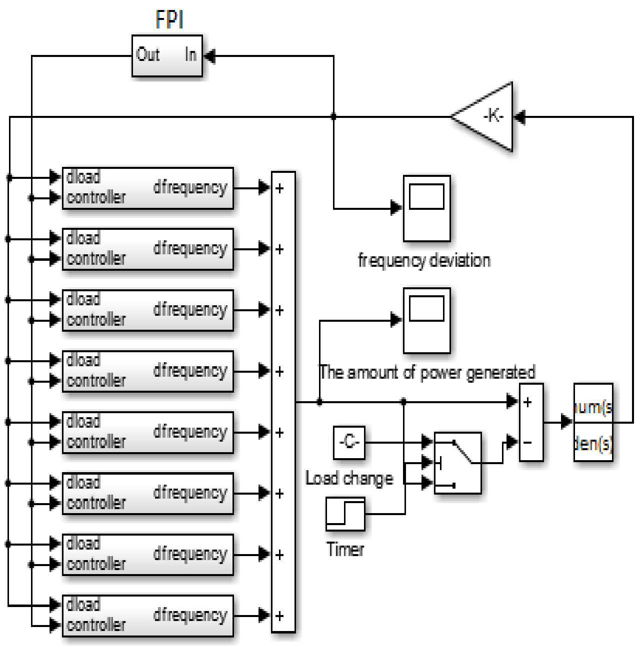

Fig.12. Simulation of Keban HEPP using FPI controller.

Multiple cases of load change, frequency deviations and changes in the generated power amount were graphically and mathematically analyzed for the loads given in Table 3. The loads were added to the system in simulations after 10 seconds.

Table 3. Characteristics of the loads acting on the system

Load Disturbance 1:	%10 load increase (1419 MW)
Load Disturbance 2:	%10 load decrease (1161 MW)
Load Disturbance 3:	%15 load decrease (1130.5 MW)

System frequency deviation and the amount of power generation deviation in the case of load change are shown in Figures 13 through 18.

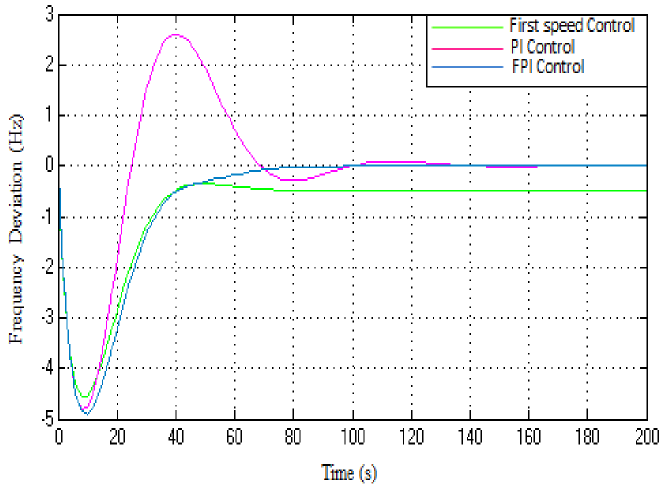

Fig. 13. System frequency deviation in response to 10% load increase.

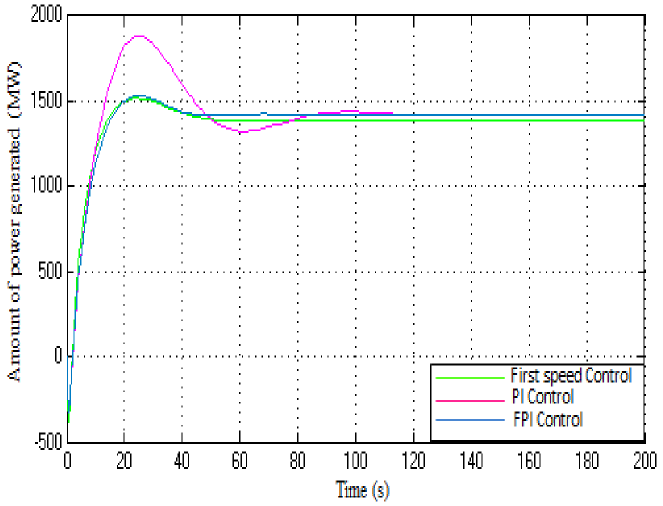

Fig. 14. Amount of power generation deviation in response to 10% load increase.

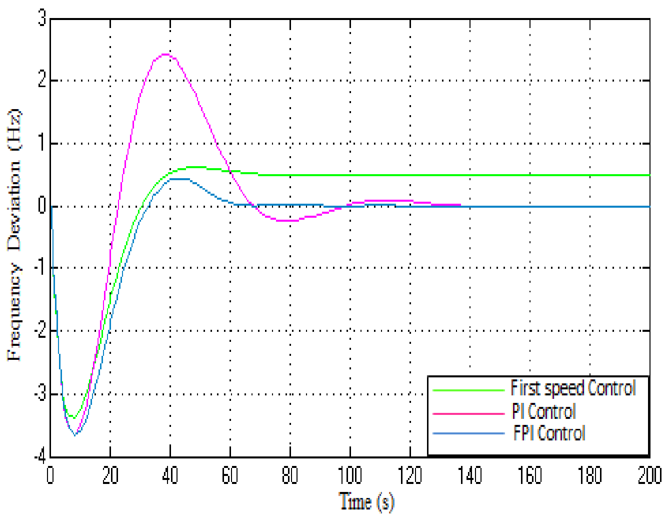

Fig. 15. System frequency deviation in response to 10% load decrease.

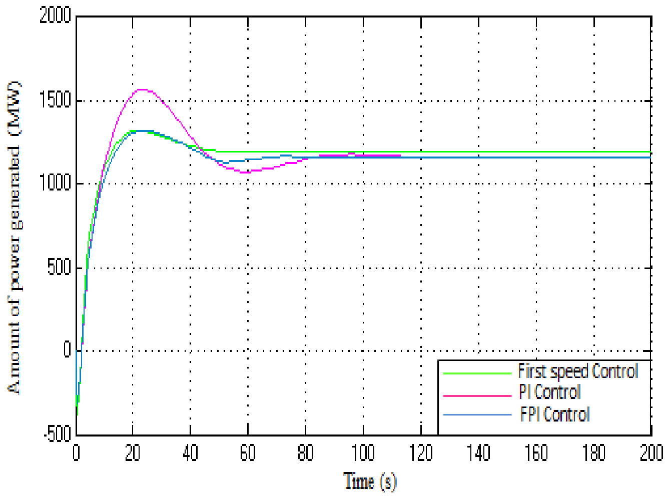

Fig. 16. Amount of power generation deviation in response to 10% load decrease.

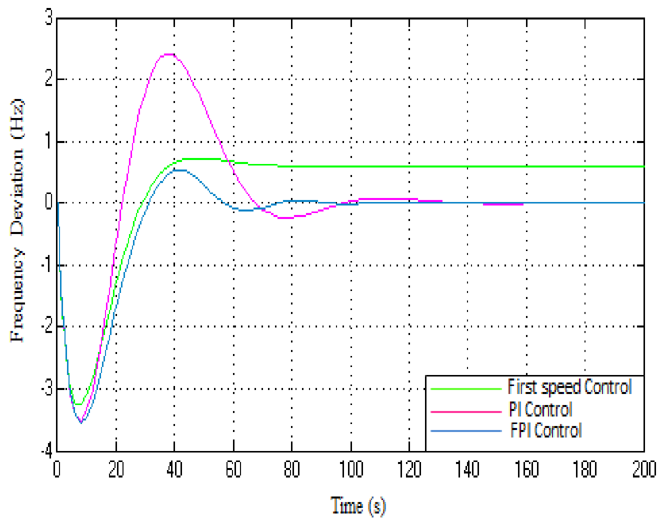

Fig. 17. System frequency deviation in response to 15% load decrease.

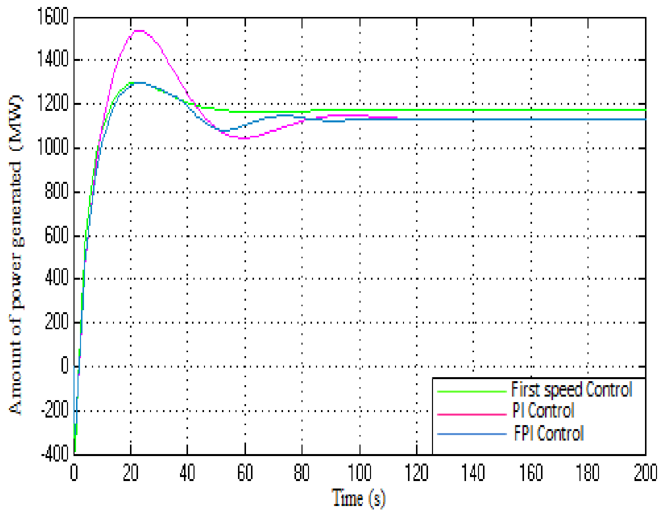

Fig. 18. Amount of power generation deviation in response to 15% load decrease.

It can be seen from the graphical and mathematical analyzes given in Tables 4-9 that when the load increases, the access time to reach the system's steady-state is prolonged, and the maximum exceeding (Overshooting) amplitude increases. In the case of a full load, FPI exhibited much better stability performance, smaller maximum overshooting and shorter settling time for reaching steady-state than did the classical PI controller. Based on the simulation results, we conclude that the FPI controller allowed the Keban HEPP to reach the desired frequency of 50 Hz in a much shorter time with less oscillation.

The essential function of a feedback control system is to reduce the error, e(t), between any variable and its demanded value to zero as quickly as possible. Therefore, the Integral of Absolute Error (IAE) performance criterion used to measure the quality of system response must take into account the variation of e over the whole range of time (RESEEDS 2003).

The value of output size of the absolute integral $J = \int_0^{tsimulation} |\Delta f|\, dt$ is given in Tables 4-13 according to IAE performance criteria for interpretation of the results obtained from the analyzes

Table 4. The numerical results of overshoot of frequency deviation.

Cases	Overshoot of Frequency Deviation (Hz)		
	First Speed Control	PI	FPI
%10 load increases	3.7013 e-4	1.3903	0.00037
%10 load decreases	0.5446	1.1976	0.2293
%15 load decreases	0.728	2.405	0.542

Table 5. The numerical results of overshoot of power generated

Cases	Overshoot of Power Generated (MW)		
	First Speed Control	PI	FPI
%10 load increases	1456.5	1671	1456.51
%10 load decreases	1254	1354.2	1258.1
%15 load decreases	1296	1532	1295

Table 6. The numerical results of IAE criteria for frequency deviation.

Cases	IAE Criteria For Frequency Deviation		
	First Speed Control	PI	FPI
%10 load increases	0.4791	0.7523	0.2875
%10 load decreases	0.3219	0.7528	0.1300
%15 load decreases	0.4318	0.7632	0.1325

Table 7. The amount of power generated in steady state.

Cases	The amount of power generated in steady state (MW)		
	First Speed Control	PI	FPI
%10 load increases	1386.2	1419.1	1419
%10 load decreases	1198	1161	1161
%15 load decreases	1172	1130.4	1130.5

Table 8. Steady state frequency error.

Cases	Steady state frequency error (Hz)		
	First Speed Control	PI	FPI
%10 load increases	-0.4857	0.0019	0
%10 load decreases	0.4857	0.0014	0
%15 load decreases	0.6004	0.0015	0

Table 9. Steady state generated power error.

Cases	Steady state generated power error (MW)		
	First Speed Control	PI	FPI
%10 load increases	-32.8	0.1	0
%10 load decreases	37	0	0
%15 load decreases	41.5	0.1	0

Table 10. Rise time

Cases	Rise time (s)	
	PI	FPI
%10 load increases	24.899	83.15
%10 load decreases	19.144	31.383
%15 load decreases	22.15	32.195

Table 11. Peak time**.**

Cases	Peak time (s)	
	PI	FPI
%10 load increases	40	86.95
%10 load decreases	38.002	43.272
%15 load decreases	38.005	42.002

Table 12. Steady state time.

Cases	Steady state time (s)	
	PI	FPI
%10 load increases	134.79	102.05
%10 load decreases	132.9	87.05
%15 load decreases	132.98	99.02

Table 13. Coefficients of PI and FPI controllers.

Cases	FPI coefficients			PI coefficients
	K1	K2	K3	KI
%10 load increases	1.5	1.5	3	1.5
%10 load decreases	2	1.5	3	1.5
%15 load decreases	1	0.4	3	1.5

The numerical results of the simulations are given in Tables 4-12 so we can interpret the graphical results more clearly and accurately. The numerical results are interpreted as follows:

- The FPI controller allowed the Keban HEPP to reach the desired steady-state in a short time in the case of sudden load change. It is observed that the supportive system without a controller did not meet the requirement of frequency deviation being zero, and the amount of generated power did not meet demand. In the first speed controller system, steady-state frequency errors for %10 load increase, 10% load decrease, and 15% load increase were -0.4857, 0.4857 and 0.6004 Hz, respectively. In the PI controller system, steady-state frequency errors for %10 load increase, 10% load decrease, and 15% load increase were 0.0019, 0.0014 and 0.0015 Hz, respectively. In the FPI controller system, steady-state frequency errors are zero for %10 load increase, 10% load decrease, and 15% load increase.
- In the first speed controller system, steady-state generated power errors for %10 load increase, 10% load decrease and 15% load increase were 32.8, 37 and 41.5 MW, respectively. In the PI controller system, steady-state generated power errors for %10 load increase, 10% load decrease and 15% load increase were 0.1, 0 and 0.1 MW respectively. In the FPI controller system, steady-state generated power errors are zero for all disturbance.
- The maximum overshoots in frequency deviation in response to a 15% load decrease were 0.542 for FPI controller, 2.405 for the classical PI controller, and 0.728 for the supportive system without a controller. The oscillation magnitude and time to reach the desired frequency were significantly reduced in the FPI controller.
- The steady state times in response to a 15% load decrease were 132.98 sec. for FPI controller, 99.02 sec. for the classical PI controller. For the 10% load decrease The steady state times were 132.9 sec. for FPI controller, 87.05 sec for the classical PI controller. Finally for the 10% load increase the steady state times were 134.79 sec. for FPI controller, 102.95 sec for the classical PI controller. The steady time to reach the desired frequency was significantly reduced in the FPI controller. Numerical results were show that stability robustness of FPI is better than PI controller.
- The rise times in response to a 15% load decrease were 32.195 sec. for FPI controller, 22.15 sec. for the classical PI controller. The peak times in response to a 15% load decrease were 42.002 sec. for FPI controller, 38.005 sec. for the classical PI controller. Peak time response of PI controller transient response is faster than FPI controllers for the all disturbances value. But maximum overshoot value and oscillation response of FPI controller is the highest for all the alter disturbance. In the power system; oscillation is an important criterion for the controller design. Peak time must be short with minimum frequency oscillation and minimum overshoot value.
- Çam and Kocaarslan (2002) used the FPI controller for a one area power system. The observed frequency overshoot value and setting time were respectively 0.0201 Hz and 10 sec for 0.01p.u disturbances.
- Çam and Kocaarslan (2004, 2005) used the FPI controller for a one area power system. The observed frequency overshoot value and setting time were respectively 0.027 Hz and 4.26 sec for 0.01p.u disturbances. They used a 5% band of step change loads in their other studies. Also, Çam et. al. (2007) used FPI and standard PI controllers for a two area power system

separately and compared their performance. The observed overshoot value and setting time were respectively 22% and 15.4 sec for 0.01p.u disturbances with the FPI controller. The observed overshoot value and setting time were respectively 37% and 15 sec for 0.01p.u disturbances with the PI controller. In this study, we obtained with the FPI controller 0.0037Hz frequency overshoot and 72.8 second setting time for 10% load (0.1 pu) increases for an eight area power system. The results are supportive of each other.

- Researchers used IAE criteria in their load frequency control studies to compare the result accuracy range using a methodology similar to this study. S. Ramesh et. al. (2010) used an FPI controller for a one area power system and they obtained 0.168 for a 30% disturbance and 0.056 for a %10 disturbance. Tushir et al. (2012) used an FPI controller for a two area power system, and they obtained 0.0053 IAE value for a %30 disturbance. In this study, we used an FPI controller to obtain 0.2875 for a 10% load increase disturbance, 0.13 for a 10% load decrease disturbance, and 0.1325 for a 15% load decrease disturbance for Keban HEPP with eight areas..

- The obtained result in this simulation concludes that the FPI controller exhibits relatively good performance and fast settling time. The conventional integral controller does not yield adequate control performance.

5. CONCLUSION

In this article, a novel alternative controller for load frequency control for power plants which are designed as interconnected systems similar to the Keban HEPP was proposed.

In this study, frequency deviation control for the Keban HEPP was implemented by using the first speed controller, the supportive classical PI controller, and the FPI controller. The frequency deviations for three different loads were analyzed. We observed that the first speed controller did not reached nominal frequency for any load changes. However, the supportive classical PI controller reached nominal frequency and satisfied the requirement of frequency deviation being zero. The FPI controller was designed to shorten the time to reach steady-state frequency. The designed FPI controller reached steady-state frequency in a short amount of time and provided a smaller oscillation amplitude and shorter oscillation time. The proposed FPI controller is a robust controller and was easily adapted to different load values. FPI controllers give effective results for power system frequency control. Contrary to the traditional control which is mostly based on a linearized mathematical model, the FPI control approach solves the problem based on experience and knowledge about the system.

This study is important for literature with respect to using the Keban HEPP's technical data. The proposed FPI method in the literature for load-frequency control is applied to a simulation of a real system (the Keban HEPP), and the accuracy and efficiency of the proposed method are shown.

ABBREVIATIONS AND ACRONYMS

Δf : Frequency Deviation
ΔP_L : Load Change
$\Delta \omega_r$: Angular Velocity of Change
D : Damping Factor
R : Coefficient of Regulation
M : Inertia Constant
T_ω : Turbine time delay constant
TR : Temporary Compensation Delay
TG : (1/K*R) Speed Regulator Time Delay Constant
Te : Electrical Momentum
Tm : Mechanical Momentum
Pe : Electrical Power
Pm : Mechanical Power
PI : Proportional Integration Control

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