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Adıgüzel Hydroelectric Power Plant's Modelling and Load-Frequency Control by Fuzzy Logic Controller

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ABSTRACT
In this study, to realize the load-frequency control according to different loading statuses, modelling of dynamic behaviour of the Adıgüzel Hydroelectric Power Plant (HEPP) was made by using the Matlab/Simulink program. By establishing the dynamic model of 36MVA synchronous generator and other components in the system in a manner reflecting its behaviour in the real system, performance of classical controller and self-adjusting fuzzy logic controller in electro-hydraulic governor circuit was examined according to different load statuses. During the simulation works carried out when both control systems closely watched in the fuzzy logic control system according to different loads the frequency of load and the number of frequency have been observed to be stable in short period of time and allowed tolerance limits.
***Keywords*: ** Fuzzy logic controller, Hydroelectric power plant, Load frequency control

I. INTRODUCTION

Since the industrial revolution, mechanization has rapidly increased and alongside with it so has need for electricity. Because fossil fuel operating power plants have met most of the energy needs a rapid decline in energy resources has become a hot issue of the world. Besides this problem, the issue exacerbates, for the reason that a large amount of electric power cannot be stored. The solution to the problem is both producing sufficient quantity to meet the demand of the electricity when needed and produce much higher yields .We have been compelled to find and use renewable energy sources [1]. Changes in the current supply and demand, the request for economic production, increased environmental responsibility, the necessity of having a fixed or a close value of a network frequency to ensure the provision of adequate operation conditions, all these reveal how important the concept of control in power systems is [2].

The Adıgüzel HEPP on Büyük Menderes River Basin constructed by General Directorate of State Hydraulic Works of Turkey was aimed to produce energy, to irrigation and to prevent floods. The Adıgüzel HEPP is a 140 meter rock fill dam. It creates a reservoir with a storage capacity of 1100 million m3. HEPP of 2x36 MVA has a capacity to provide an annual energy production of 280 million kWh. Each generator is three phase and 50Hz, the generators' terminal voltage is 13.8 kV phase to phase.

Many studies on this subject have been carried out because of the importance of load frequency and the competence of current system's rapid response to these problems. In their study Venkatraman and colleagues, have designed fuzzy logic controller using two different membership functions, including type-I and type-II in a two-area thermal power generation system, and made a comparison with the traditional PI controller [3]. Similarly, Panda and his colleagues suggested a type-II fuzzy logic controller for the stability of a power system with a single area power system connected to an infinite bus and multi-area power system [4]. Zenk and his colleagues have proposed a PI controller based on fuzzy logic to improve the load frequency control in a two area power system [5]. In a study conducted by Vijayaraghav and Sanavullah, they have proposed a hierarchical fuzzy controller for ensuring the stability of power system and the damping of low-frequency oscillation [6]. Taşar and his colleagues studied the Keban HEPP model's response and stability in case of a possible change in the power system load by using Matlab/Simulink software.

By designing (FPI) fuzzy logic-based proportional-integral controller in the electro-hydraulic governor circuit they compared it with traditional proportional-integral controller (PI) [7]. In their study, Naicker and Sekhar made analysis of various disturbance factors in network performance for the automatic generation control (AGC) in multi-area interconnected systems for fuzzy approach and traditional PI controller [8]. Jain and his friends studied the dynamic performance of the load frequency control creating a three area interconnected power system by Matlab/Simulink software. PI controller, designed on the basis of fuzzy logic, showed data such as the settlement time in the system frequency and exceeding in the simulation results. [9]. Kouba and his colleagues studied the effects PID controller with fuzzy logic base on the load frequency control. By creating a model of 9 units in three area production system in simulation they made analysis of transient response of the load change in their areas [10]. With the rapid growth of renewable energy sources Sindhu and Deepthi developed control strategies using fuzzy logic controller in order to minimize deviations in system frequency [11]. By using genetic algorithm-fuzzy system (GAF) in their study, Chaturvedi and his friends designed polar fuzzy controller (PFC) in order to bring the power and frequency in the transmission lines to nominal value if a disturbance effect occurs on the load in any part [12].

In this study, Adıgüzel HEPP's dynamic behavior of the model was created and according to various loading conditions the performance of classical and fuzzy logic controller was studied. When the analysis results are looked through, ripples of frequency and the load is minimized between 2-4 seconds becoming stable in such a short time.

II. DESIGN OF PID AND FUZZY LOGIC CONTROLLER

With the speed-frequency and excitation current-voltage relationship arising from the structure of synchronous generators in mind the two control loops were developed.

(i) Frequency control
(ii) Excitation control

In the interconnected power system, load-frequency control (LFC) and automatic voltage regulator (AVR) equipment is installed for each generator. Considering small changes in load demand, controllers are adjusted to protect frequency and voltage amplitude within the specified limits. Small changes in the active power depend primarily on the rotor angle and frequency. The reactive power basically depends on the amplitude of the voltage. Excitation system's time constant is much smaller than the first movement of the actuator of time constant and the transient disturbance is faster [13].

A properly designed and operated power system must meet the following basic requirements.

(i) The system must be able to meet the constantly active and reactive power demand.
(ii) The system should provide energy with the least cost and least ecological damage.
(iii) The frequency which determines the quality of the energy production system, voltage level reliability and value must be in compliance with the standards.

To meet these requirements, controllers on power system components are available. Generating system is composed of controllers of actuator system and excitation system. Actuator system controls are related to speed regulation and energy system variables. Excitation control supplies the regulation of the generator output voltage and reactive power output [2]. The detailly described approach determines the overall control structure of the power system. To achieve practical and effective solutions for power system control problems it is divided into smaller subgroups as can be seen in Fig. 1.

2.1. PID CONTROLLER

In today's industry, the PID controller is the most widely used type of controller. It was used in the dynamic model of hydroelectric power generation system and its performance was studied. Within the most general terms, PID controller's equation is given in the equation 1.

$$u(t) = K\left(e(t) + \frac{1}{T_I}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}\right) \quad (1)$$

Because the power systems are nonlinear, load frequency control performed by the PI is not fast enough to respond to adaptation to any load change in network and the stable frequency error cannot be reduced to zero. Moreover, as the number of the areas increase it gets more difficult to get hold of the frequency control [1]. Therefore, the PID controller was preferred instead of the PI controller, and theperformance of the controller was compared with fuzzy logic controller (FLC).

As the changes that can occur in the load on the power system cannot be predicted certain values, such as time domain criterion, settling time ,time to rise, exceed in desired frequency response cannot be known for sure. However, the controller coefficients to minimize the frequency error in the search parameters are the intended object to achieve. When PID controller coefficients are available a PID Controller block of Matlab/Simulink blocks that automatically adjusts the PID gains is used. The block diagram representation of PID controller model we use in hydroelectric power generation system is given in Fig. 1.

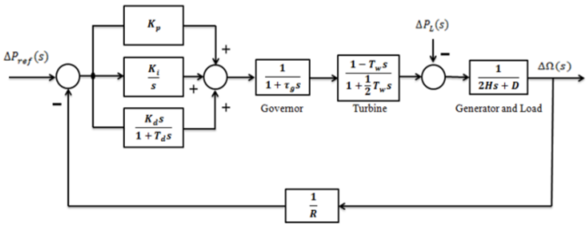

Fig. 1.PID control block diagram of hydroelectric power generation system.

Table 1 you are given PID coefficient gains according to the different load cases for the controller of the load-frequency of PID controller in governor circuit, reference mechanical power (pu), the position of adjusting the wings that the governor controls and output power values at the system . The gain coefficients used in this study ranging from (K_P, K_I, K_D) 0,1 pu to 1,0 pu were determined for each installation.

Table 1. PID Gain coefficients

P_{mek}	*Gate*	P_{elk}	K_P	K_I	K_D
0,1	0,0965	3,1825	0,00558537	0,00000080	8,5467000568
0,2	0,1930	6,7897	0,01124169	0,00000331	8,4482199936
0,3	0,2896	10,4070	0,25623287	0,01780566	-2,4179942742
0,4	0,3861	14,0375	0,71591296	0,04657833	-3,2007578307
0,5	0,4826	17,6865	0,88054668	0,06950864	-3,0580565336
0,6	0,5791	21,3600	1,07148533	0,09612619	-2,5605848591
0,7	0,6756	25,0640	1,21479695	0,14046803	-0,8917655191
0,8	0,7721	28,8000	1,46073222	0,18331606	0
0,9	0,8687	32,5800	1,99686681	0,14315631	-1,2251305837
1,0	0,9652	36,4000	1,26943876	0,18692192	0

2.2. FUZZY LOGIC CONTROLLER

In a fuzzy system, fuzzy inference engine uses fuzzy sets and the rule base rather than math equations. Two sources of information should be taken in consideration first one being values observed and measured and the other being the views of experts.This means in addition to the digital database there is a verbal rule base. Expert opinion is useful for modelling of the unknown uncertainty in the system [14]. In Fig. 2 a design of three input variables Sugeno fuzzy inference block diagram is given.

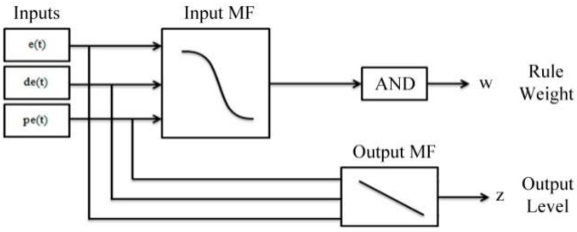

Fig. 2. Sugeno rule operates

The FLC, based on Sugeno fuzzy inference system, was designed to improve the work performance of the power generation system and to achieve the desired power quality. The first of the three input signals to the controller; The error signal e(t), the second; changes according to the time of the error signal de(t)/dt, third; calculated as per-unit pe(t) value of HEPP output power drawn from the bus. The output signal of the controller is u(t) the control signal which controls servomotors in order to set the desired the degree of setting a wingspan. An output value for each rule is obtained as is equation2.

$$u(t) = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \qquad (2)$$

Here, N; the number of rules, W; rule weight, Z; the output level.

As Sugeno type FLC's output consists of real numbers, it is not a matter of question to mark

input signal as membership function. Output variable consists of 27 real numbers and they range from -0,2234 to 1,2246. 27 rule table of the designed controller can be seen in Table 2.Simulation of the synchronous generator, technical data of the electro-hydraulic governor and power transformers are given in Table 3, Table 4 and Table 5.

Table 2. The Membership functions for FLC

Power measured [pe(t)]	*Error [e(t)]*								
	N			**S**			**P**		
	Change in error [de(t)/dt]								
	N	**S**	**P**	**N**	**S**	**P**	**N**	**S**	**P**
PK	-0,2234	-0,1676	-0,1141	-0,0527	0	0,05562	0,1142	0,16638	0,2239
PO	0,27376	0,33451	0,38746	0,44521	0,5	0,55561	0,6174	0,66475	0,7234
PB	0,77835	0,8313	0,88975	0,9438	1	1,05568	1,1142	1,16455	1,2246

The error signal e(t) of FLC's input variables and linguistic variables of the changes in the signal on the error de(t)/dt are negative (N), zero (S) and positive (P).

Table 3. Generator Parameters [15]

Type		A.C. synchronous generator, vertical shaft
Rotor type		Salient pole
Nominal power		36 MVA
Rated power factor		0.85
Rated frequency		50 Hz
Rated voltage		13.8 kV
Rated current		1506 A
Rated speed		300 rpm
Runaway speed		630 rpm
Stator winding resistance		0.0141 Ω
Rotor winding resistance		0.0857 Ω
Rotor pole pairs		10
Stator winding connection		Star
Reactance based on rated load and rated voltage (pu)	X_d	0.992
	X_d'	0.295
	X_d''	0.183
	X_Q	0.687
	X_Q''	0.186
	X_l	0.184
Time constants	T_{do}'	7.133 s.
	T_d'	2.123 s.
	T_a	0.177 s.

Table 4. Hydraulic Turbine and Governor [15]

Type		Vertical shaft Francis
	Max.	132.80 m.
Effective head	Nor.	116.00 m.
	Min.	84.30 m.
Output at normal head		31.375 kW
Discharge at normal head		30 m^3/s
Revolving speed		300 rpm
Water starting time (T_W)		1.4047 s
Permanent droop		0.05
Servo gain (K_a)		3.3
Servo time constant (T_a)		0.07 s

Table 5. Three Phase Transformer Parameters [15]

Nominal Power		36 MVA
Rated frequency		50 Hz
Winding 1 parameters (ABC terminals)	Connection	D11
	Rated voltage	13.8 kV
	Rated current	1506 A
	Resistance	0.0178 Ω
	Inductance	0.00174 H
Winding 2 parameters (abc terminals)	Rated voltage	154 kV
	Rated current	135 A
	Resistance	1.5056 Ω
	Inductance	0.2172 H

Linguistic variables of the power signal pe(t) which is drawn from bus as the third input variable are positive small (PK), positive medium (PO) and positive big (PB). In Fuzzy inference system, the triangle type membership is used and while creating rule base 'and' operator of the logical operations is used.

III. ADIGÜZEL HEPP'S SIMULATION AND LOAD-FREQUENCY CONTROL

Simulation block diagram of the power generation system of Adıgüzel HEPP is given in Fig.3. Power generation system consists of hydraulic turbine, excitation regulator, salient pole synchronous generator, power transformer, load, watt meter, frequency meter and buses. System output is connected to three AC loads, two of which are put through automatically by the cutters in the time specified. With the help of an oscilloscope showing electrical parameters and magnitude size of consumers' system output power, system frequency, the terminal voltage and load current signal analysis were performed. Sub-simulation block diagram of servo-motors, hydraulic turbines, PID and FLC can be seen in Fig. 4.

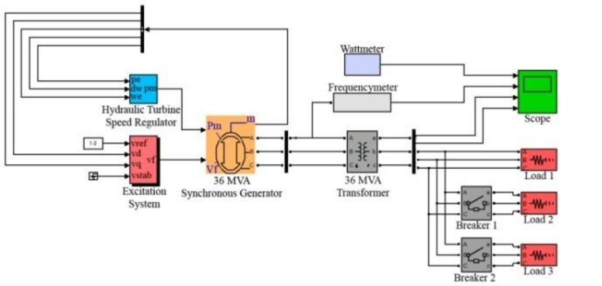

Fig. 3. Simulation block diagrams of HEPP components

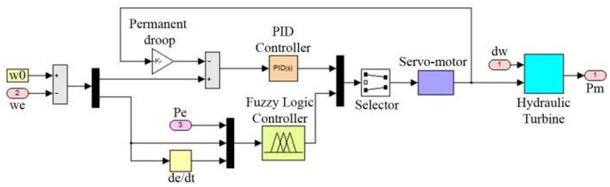

Fig. 4. FLC and PID controller in Matlab/Simulink

IV. SIMULATION RESULTS AND DISCUSSION

Electro-hydraulic governor in Adıgüzel HEPP was examined, PID and FLC were designed to improve system's response time to voltage and frequency changes and to minimize oscillations occurring in the system as soon as possible, and finally simulation studies were performed. When no controller is used in turbine electro-hydraulic governor circuit, the electrical changes in output size of the system were obtained as a result of the simulation processed. Electrical quantities were measured as the signals of consumer power (watts), the system frequency (Hz), the terminal voltage (volts) and load current (amps).

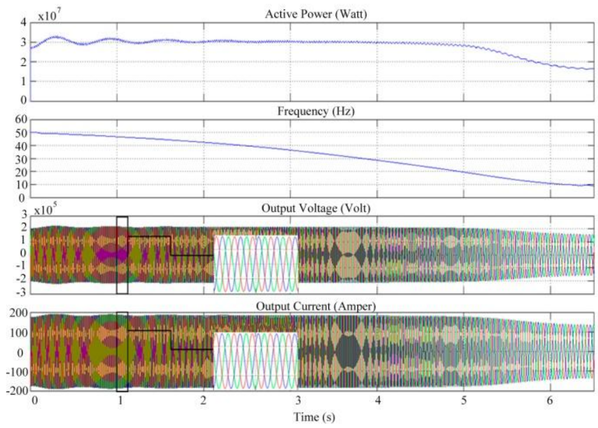

Fig. 5. Change in electrical output magnitudes without controller

As system frequency in permitted tolerance limits was not realized and after about 5 seconds, synchronous generator did not meet the demanded power it was seen that system started to collapse after 5 seconds, when the power generation system in Fig. 5 whose the graphics were fed with 30,6MW (1.0 pu). Likewise voltage, current and frequency decreased to the minimum value. The result of this analysis reads as running an uncontrolled power generation system is not possible both in terms of business and use of clean energy by consumers. It is clear that the quality of the power generated in an uncontrolled system is out of question and will cost huge financial losses to customers.

As it is illustrated in Fig. 4 the sub simulation of block diagram of hydraulic turbine and governor, the speed control of hydraulic turbine is done by PID controller. When synchronous generator was loaded with 1.0 pu consumer load, its dynamic behavior was examined. The coefficients gathered are given in Table 1. In addition, the electrical output size in the simulations were conducted for 120 seconds simulation and power generation system was seen to reach a steady state, and as the simulation results are shown as a 0-5 second section in the graph . This also applies for other graphic simulations that will be carried out.

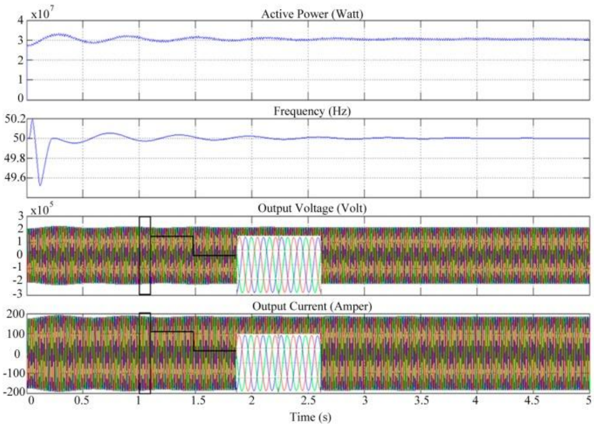

Fig. 6. Change in electrical output magnitudes when loaded with HEPP 30,6MW (1.0 pu)

In the chart of Fig. 6 nominal load of synchronous generator is rated of 1.0 pu, the system frequency is within the desired tolerance limits, effective terminal voltage is measured as$V_{et} = 151{,}7\ kV$ ($V_{max} = 214{,}5\ kV$) and effective load current is measured as $I_{et} = 130{,}8\ A$ ($I_{max} = 185\ A$).In the chart of Fig. 6 nominal load of synchronous generator is rated of 1.0 pu, the system frequency is within the desired tolerance limits, effective terminal voltage is measured as$V_{et} = 151{,}7\ kV$ ($V_{max} = 214{,}5\ kV$) and effective load current is measured as $I_{et} = 130{,}8\ A$ ($I_{max} = 185\ A$).

When performing the power generation system simulation with FLC, the firstly synchronous generator was fed with a load of $12MW$ ($0.4pu$). When the simulation was in progress, in addition to the existing load, with the activation of breaker_1 in Fig. 4 after 5 seconds, another load of $6MW$ ($0.2pu$) was added in total charge of the system load reached to approximately $18MW(0.6pu)$. In addition to this load breaker_2 was activated in the circuit in the 10th second and a load of $12MW$ ($0.4pu$) was also added. After 10 seconds of simulation the total load of the system reached to$30{,}6MW$ ($1.0pu$). The simulation continued for 120 seconds and the system appeared to be fully determined.

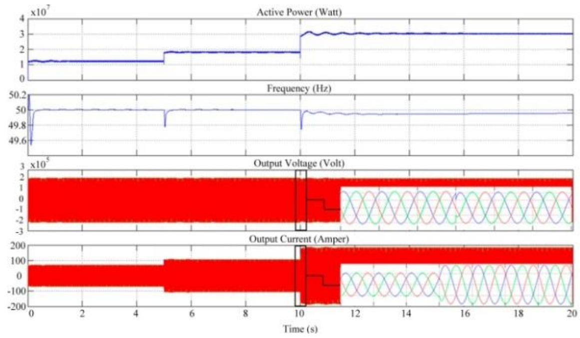

Fig. 7. Changes in the size of the electrical output according to various loading conditions of HEPP

In addition to the simulation studies, the response of FLC and PID controller on the synchronous speed can be seen in Fig. 8. According to results of simulation of synchronous generator under the load of 1.0 the PID controller reached to a stable condition after 35 seconds and the FLC's system seemed to minimize oscillations in 3-4 seconds.

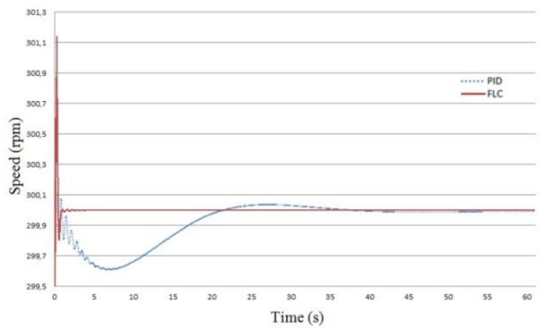

Fig. 8. The response of FLC and PID controllers to the synchronous speed

V. CONCLUSION

To achieve better results from electro-hydraulic governor in load-frequency control, two different controllers such as PID and FLC controllers which perform better than the current controllers were designed. The performance of controllers was studied as the synchronous generator went under different loading conditions and the graphics were made. According to the results of simulation analyses, FLC improved the response time as the load and frequency changed in the system and minimized the oscillations sooner than PID controller did.

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