Comparison of Conventional and Modern Controllers for a Gas Turbine Power Plant

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ABSTRACT

Nowadays, many thermal power plants are established for the generation of electrical energy. In this study, the design of a Gas Turbine Power Plant is analyzed in Ambarlı, Turkey. Then, conventional and modern control techniques are applied for comparison. These controllers are conventional proportional and integral (PI), particle swarm optimization based proportional-integral (PSO-PI) and fuzzy gain scheduled proportional-integral (FGPI). The results show that, the performance of the proposed FGPI is better than the conventional controllers on settling time and overshoot of power outputs.

Keywords: Thermal Power Plant, FGPI, Fuzzy Controller, PI Controller, Particle Swarm Optimization

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Introduction

The generation of electrical energy has gained more importance with the increasing demand and environmental awareness in recent years. Nowadays, a considerable part of the energy generation is provided by fossil fuel based thermal power plants. However, the coal combustion gases can harm the environment and human health. One of the main reasons for these situations, is the change in the parameters of the gas turbine during the generation of energy. The simplest evidence of this is the contamination of the boiler and heating pipe surfaces of the thermal power plant that has been occured throughout the years by coal-burning [1].

Combined cycle power plants (CCPP) has been proposed in [2]. In this study, the effects of inlet fogging and optimization on performance is considered by energy analysis. Moreover, it is indicated that one of the best methods to reduce CO_2 emissions is decreasing the energy losses.

In addition to [1], the control systems play important role due to natural expectations of consumers and the necessity of generation of electricity. Thus, the importance of the control systems in energy generations are rised drastically as shown in [3]. In recent study, energy optimization is performed by using varies optimization algorithm to minimize the CO_2 values and raise the efficiency of the power plant in [4]. In this study, NSGA-II (Non-dominated Sort Genetic Algorithm-II) is applied to get the final solutions in the multi-objective optimization of the CCPP. In [5], Genetic Algorithm and Artificial Bee Colony Optimization are applied for environmental economic load dispatch. Thus, it provides a great advantage for cost reduction and NO_x emission as a result.

Modern optimization and control techniques are applied with the optimized set values and their effects on the active power-frequency control are analyzed in Ambarlı, Turkey in [6]. In the same study, 6 different controller types are performed; PI, PSO-PI, Artificial Bee Colony based Proportional-Integral (ABC-PI), Proportional-Integral-Derivative (PID), Particle Swarm Optimization based Proportional Integral-Derivative (PSO-PID) and Artificial Bee Colony based Proportional-Integral –Derivative (ABC-PID). According to the mentioned work, PID controller

optimized with artificial bee colony optimization gives better results when compared to the other controllers. Furthermore, the model of Ankara-Çayırhan Thermal Power Plant is also considered [7]. Two different controller types are performed in the mentioned study which are PSO-PID and FGPI for their effects on overshoot and settling time. If minimum settling time is required, PSO-PID must be employed. On the other hand, FGPI can be utilized if minimum overshoot and soft adaptation are desired.

In [8], linear matrix inequalities are solved by Genetic Algorithm and Particle Swarm Optimization for adaptive sliding mode controller design is presented. The unstable situation in the gas turbine is overcame by this method. In addition to these, Particle Swarm Optimization-based controller is applied to the thermal power plant in [9]. The reason for this is to prove that, the proposed controller provides a better settling time response than the conventional controllers. Furthermore, a gas turbine engine is regulated with the PSO-based PI controller to illustrate the optimal control solution.

A fractional order fuzzy-PID (fuzzy-FOPID) controller is suggested for cycle power plant (CPP) with dynamic particle swarm optimization system [10]. Fuzzy-FOPID offers the best possible results when compared to the other methods in this study.

In our paper, firstly the model of Gas Turbine Power Plant in Ambarlı, Turkey is obtained and the block diagrams of each module are illustrated with different controllers that are conventional PI, PSO-PI and FGPI. Moreover, the responses of the system with respect to these controllers are compared. The two significant parameters for comparison are overshoot and settling time. It is observed that, although PI controller has no overshoot, the settling time is greater than the other controllers. If cost reduction is considered, this can be taken into account. Contrary, FGPI controller has much better settling time when compared to former. Nevertheless, the proposed study showed that modern control techniques are much more proper than the conventional controllers. The parameters of the controllers are determined by the classical methods. Furthermore, FGPI also increases both the performance and service life of the power plant therefore, employment of the these methods is a necessity for the operation of modern power plants.

Basic Mathematical Model for Gas Turbine

One of most popular power generations systems is the natural gas power plant. Here, air is compressed, burned and enlarged in the turbine to obtain power. Operation principle of gas turbine power plants is as follows: the natural gas is passed through the regulation and measuring station (RMS) and reduced to the operation pressure. It is stored or transmitted to the plant for immediate use with a continuous gas cycle. The natural gas passed through the filter station in the power plant field is transferred to the combustion chambers via the emergency stop and regulation valves. The common shaft includes compressor and turbine. In the model, we used two large silo type combustion chambers with a hybrid burner. Combustion technology is of great importance in terms of environmental legislation. The waste NOx generated after combustion, must be below the threshold value (300 mg/Nm3). The required air in the combustion chamber is obtained by open loop and used with air filters.

The whole system consists of a gas turbine compressor, combustion chamber and turbine. In some cases, it only refers as the turbine. Figure 1 shows the simplified model of the gas turbine. When atmospheric air enters the compressor it is compressed and send to the combustion chamber. In the combustion chamber, high-pressure hot gas is burned by fuel injection. Power is obtained by expanding the turbine. Then, a large portion of the power provided by the turbine is used to run the compressor and a small portion is used in auxiliary tools, the remaining portion is the net power obtained from the plant. Simplified gas turbines should provide air standard requirements.

Simplified model,

- The fluid is air, it is assumed as the ideal gas throughout the cycle

- The combustion process is not taken into account, it is assumed that heat is supplied from outside at constant pressure

- The turbine exhaust and compressor suction operations are neglected. The fluid goes out of the turbine under constant pressure is feedbacked into the compressor.

Whereas the power plant is considered as a closed system where the parameters of the system such as turbine and combustion chamber are open loop components. Cycles which depend on assumptions of air standards are defined as ideal air cycles. Besides these assumptions, models have other assumptions such as some of the state changes are considered to be reversible to obtain approximate results.

Figure 1 shows the P-V and T-s graphs of the Brayton cycle, a simple gas turbine. Heat exchanges are made at constant pressure and compression and expansion processes are isotropic. In this graph, the T-s diagram refers to the gas turbine cycle. From the place where entropy increases, it is seen that the constant pressures are separate. What this means is that, the power provided by the compressor is greater than that provided by the turbine. Otherwise, the target cannot be obtained from the turbine.

Turbine power, compressor power, net power and yield are obtained by applying the first law of thermodynamics to the gas turbine cycle. Thus, it is seen that the yield is a function of the pressure ratio. The yield does not depend on the maximum temperature, the change in specific temperatures depends on the yield temperature.

The Brayton and Carnot cycles with the same temperature range and the same entropy changes are shown on the same

T-s diagram in Figure 2. From the graph, it can be seen that the Brayton cycle consists of small Carnot cycles. Thus, the yield of the Carnot cycle is higher than that of Brayton. The simplified gas turbine is based on the Carnot cycle [6, 11].

Speed Regulator

The turbine power is constantly changes by the variation of the load. The imbalance between the generated power and con-sumed powers is considered as a change in the speed of the turbine. If the load is variable, the generation must be variable to keep the frequency constant. This is done through the by the speed regulator. The speed regulator adjusts the amount of gas to the combustion chamber of the gas turbine. This cycle is a closed cycle which continues until the power and speed error are zero. The amount of gas is controlled by the control valve in the gas turbine. The stop valve is a valve that is connected in front of the control valve and is for protection purposes.
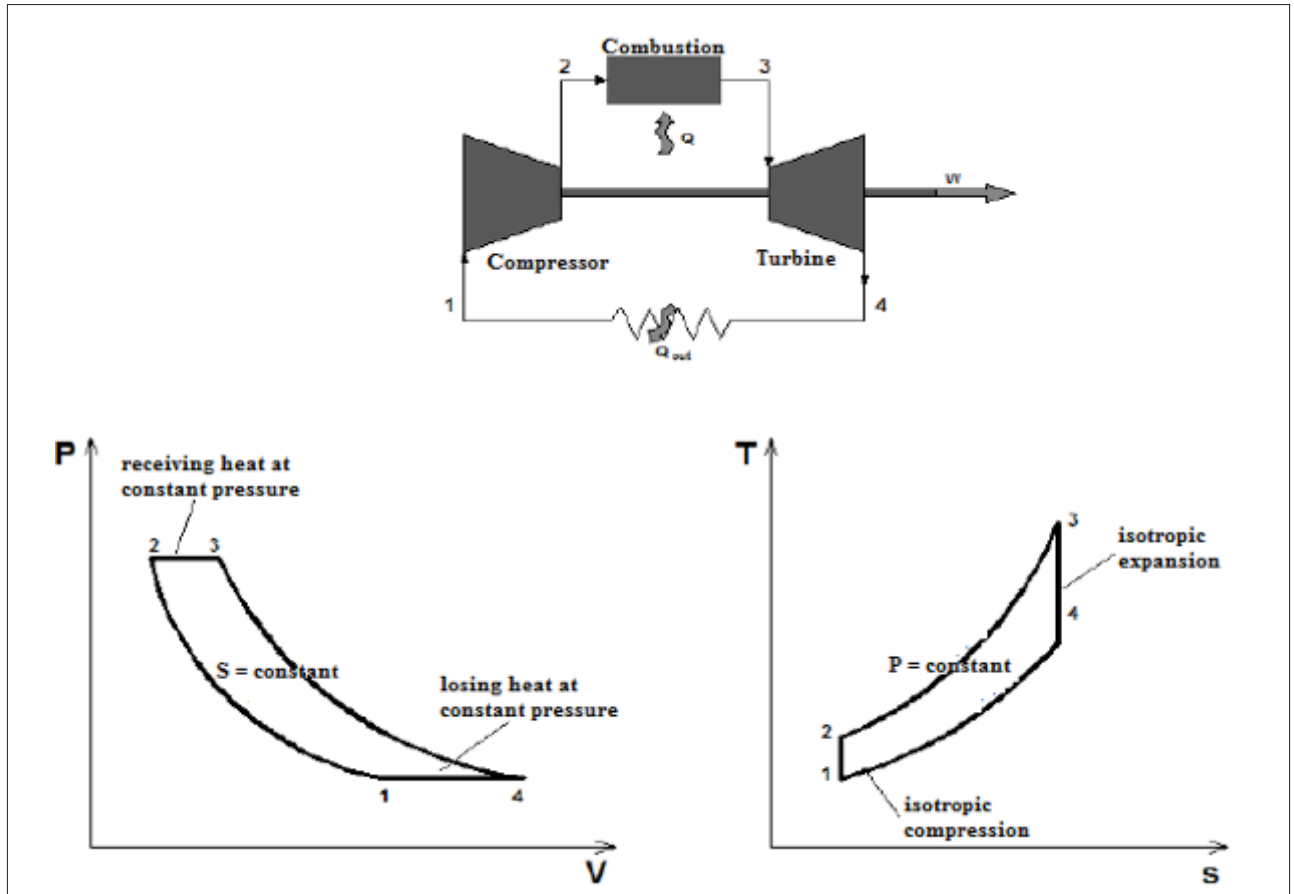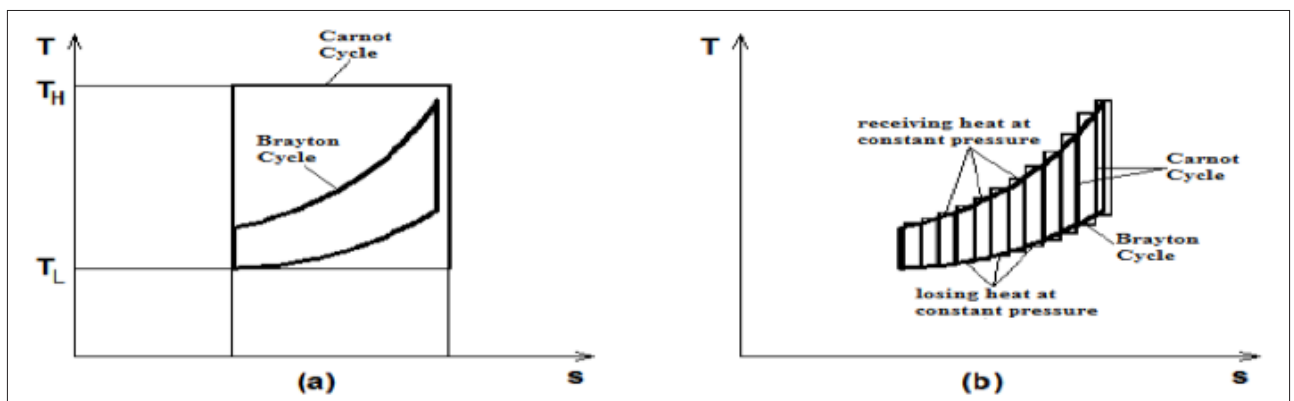

Figure 1. A Simple Gas Turbine Cycle

Figure 2. Comparison between Brayton and Carnot Cycles Efficiencies

Block diagram of a simplified Gas Turbine is illustrated in Figure 3 where speed regulator is first order system.

where

Kd: Speer regulator gain

X: Speed regulator primary time (delay) constant

Y: Speed regulator secondary time (delay) constant

a: Burner gain constant

b: Burner time (delay) constant

T_Y: Combustion chamber time (delay) constant

T_GT: Time (delay) constant depends on turbine dynamic characteristics

Calculated values for related parameters are given in Table 1.

Basic Mathematical Model for the Generator

Generators in power systems are generally considered to be large masses with two opposite moments in Figure 4.

The mechanical moment (T_m) is produced in the turbine and this force has an effect that increases the speed of rotation. In contrast, the electrical moment (T_e) generated by the load causes the speed to be reduced. This happens at a constant speed ($\omega = \omega_0$) when the two moments are equal. The electrical load increases $T_e > T_m$ and the generator slows down. In this case, the generator is accelerated again. Otherwise, the generator is decelerated. In power systems, all these operations are repeated continuously, because the load is not stable. Generator equations are as follows,

$$T_T = I\alpha \tag{1}$$

$$M = I\omega \tag{2}$$

$$P_T = \omega T_T = \omega I\alpha = M\alpha \tag{3}$$

where I is current per phase, α is field flux, ω is angular speed, M is momentum and T_T is total torque.

Initially, it is a single rotating machine and the speed is ω_0 and δ_0 is called as phase angle. Due to the increase of the requested load or mechanical and electrical deterioration, the values T_m and T_e will change. Speed of the machine in case of acceleration is obtained in the following term.

$$\omega = \omega_0 + \alpha t \tag{4}$$

and

$$\Delta\delta = \int (\omega_0 + \alpha t)dt - \int \omega_0 dt = \omega_0 t + \frac{1}{2}\alpha t^2 - \omega_0 t = \frac{1}{2}\alpha t^2 \tag{5}$$

$\Delta\omega$ (frequency deviation) can be identified as,

$$\Delta\omega = \alpha t = \left(\frac{d}{dt}\right)\Delta\delta \tag{6}$$

The relation between phase angle deviation, speed deviation and net acceleration moment is given in equation (7).

$$T_T = I\alpha = I\left(\frac{d}{dt}\right)(\Delta\omega) = I\left(\frac{d^2}{dt^2}\right)(\Delta\delta) \tag{7}$$

Thus, we find the net power

$$P_T = P_m - P_e \tag{8}$$

Table 1. Simplified Gas Turbine Parameter Values[6]

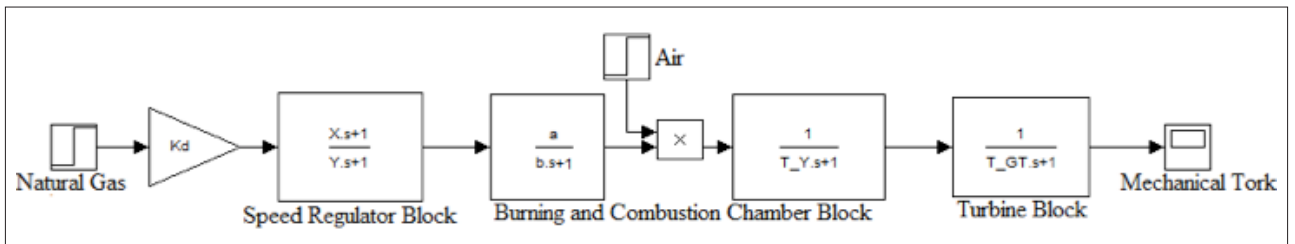| Parameter	K_d	X	Y	a	b	T_Y	T_GT
Value	1	0.65	0.1	1	0.05	0.4	0.1

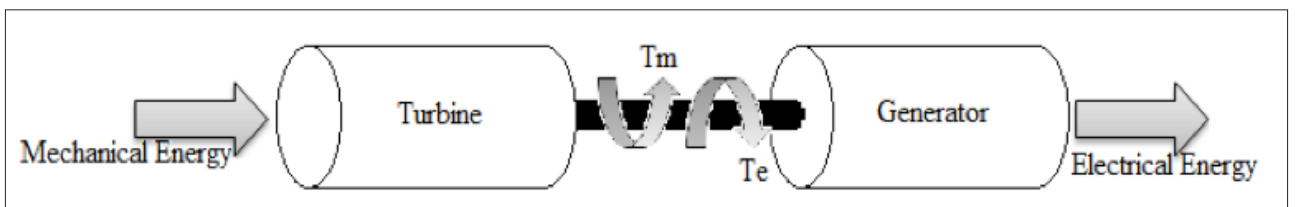**Figure 3.** Simplified Gas Turbine Model

Figure 4. Physical Model of Turbine Generator System

The connection between net power frequency variation is given in equation (9).

$$P_T = \omega_0 I \left(\frac{d\Delta\omega_0}{dt} \right) = M \frac{d\Delta\omega_0}{dt} \tag{9}$$

If equality (9) is written in Laplace form

$$\omega_0 = \frac{1}{Ms} P_T = \frac{1}{Ms} (P_m - P_e) \tag{10}$$

The block diagram of the system obtained from theseequations is shown in Figure 5.

The relation between frequency change $\Delta\omega$ and load change ΔP_L is given in equation (11).

$$\Delta P_e = \Delta P_L + \Delta P_D \rightarrow \Delta P_L = D\Delta\omega \rightarrow D = \frac{\Delta P_L}{\Delta\omega} \tag{11}$$
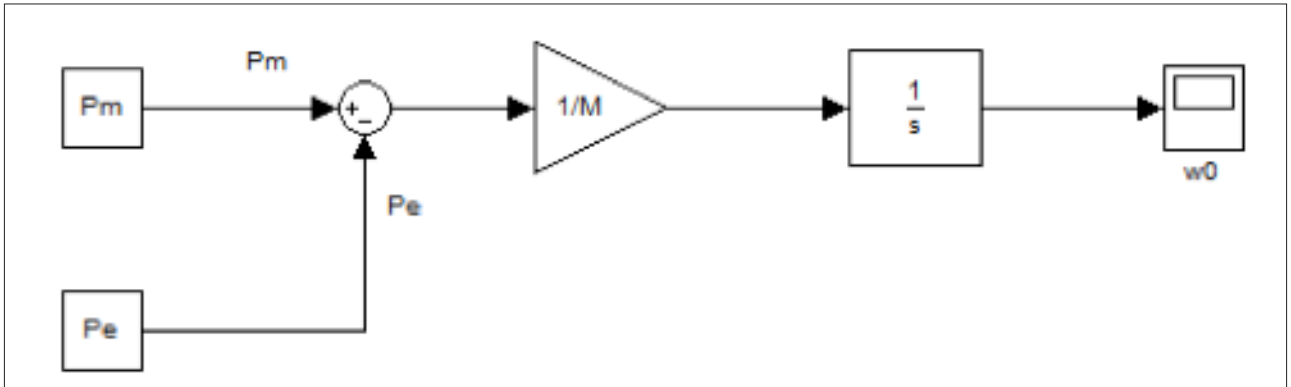

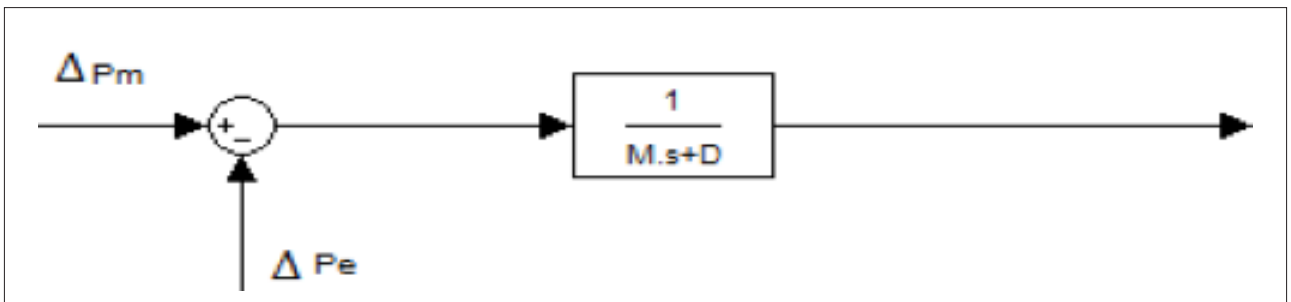**Figure 5.** Simplified Block Diagram of Turbine-Generator System

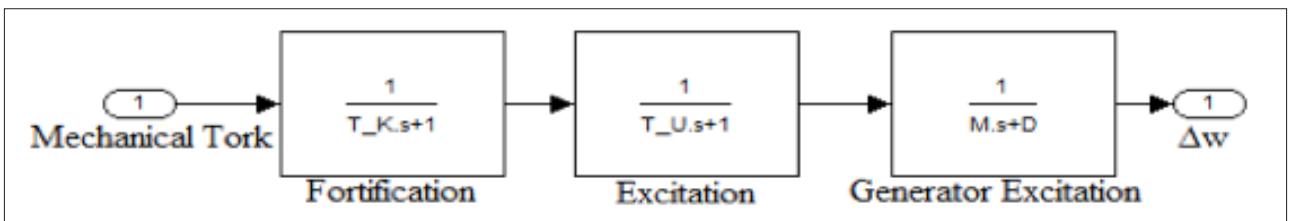**Figure 6.** Block Diagram of the Rotating Mass and Load
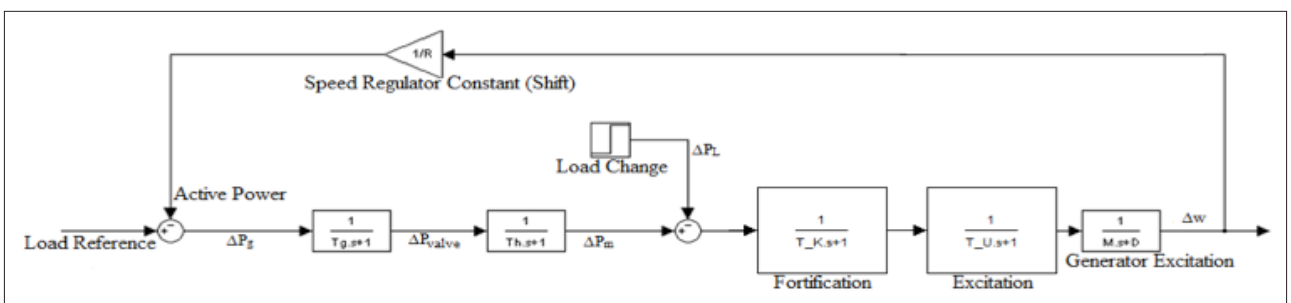

Figure 7. Generator Model

Figure 8. General Model of a Power System

D is the damping constant. It is the percentage of change in frequency which is about 1-2% for the load change. For example, if there is a frequency change of 1% in a load variation of 1%, the damping ratio is obtained from equation (11). The damping factor is D=1/1=1. The load damping model is shown in Figure 6.

If the automatic voltage regulator (AVR) fortification and excitation blocks are added, the diagram becomes as the following in Figure 7.

An overview of the power system can be examined as in Figure 8.

The R value in the figure determines the speed output power characteristics of the production unit. R called as speed regulation constant or shift, shown in equation (12).

$$R = \frac{\Delta\omega}{P_{jn}} = \frac{\Delta f}{P_{jn}} = \frac{f_2 - f_1}{P_{jn}} \tag{12}$$

where

P_{jn}: Nominal active power of the generator unit (MW)

f_2: No load frequency (Hz)

f_1: Frequency in nominal load (Hz)

R: Speed regulation constant or slip (Hz/MW)

$\Delta\omega$: Speed

ΔP: frequency distortion

Thus, the speed regulation constant is added to the system to obtain a simplified generator model in Figure 9.

where

T_K: Fortification time (delay) constant (seconds)

T_U: Excitation time (delay) constant (seconds)

M: Generator time (delay) constant (seconds)

D: Damping Factor

R: Speed regulation constant or slip (Hz/MW)

All values of parameters are given in Table 2.

Table 2: *Simplified Generator Parameter Values[6]*

Controller Methods

The reason for using control systems, the reference value given in the system dynamics parameter changes and depending on the situation defined at the desired level to perform the control criteria.

Conventional PI Controller

The system's response curve method is employed to obtain the best result of the control system in Figure 10 [12].

In a system, there are parameters that affect the settling time of the controller. These are the time constant T_s, dead time delay T_d and system gain. The parameters of the PI controllers according to the system's response curve method are shown in Table 3.

PI controller structure is given in equations [13, 14].

$$K(s) = K_p e(t) + K_i \int_0^t e(t)dt \tag{13}$$

Table 3. PI Controller's Parameter Values[6]

	K_p	T_i
PI	$\dfrac{0.9T_s}{K_s.T_d}$	$3,33T_d$

Table 2. Simplified Generator Parameter Values[6]

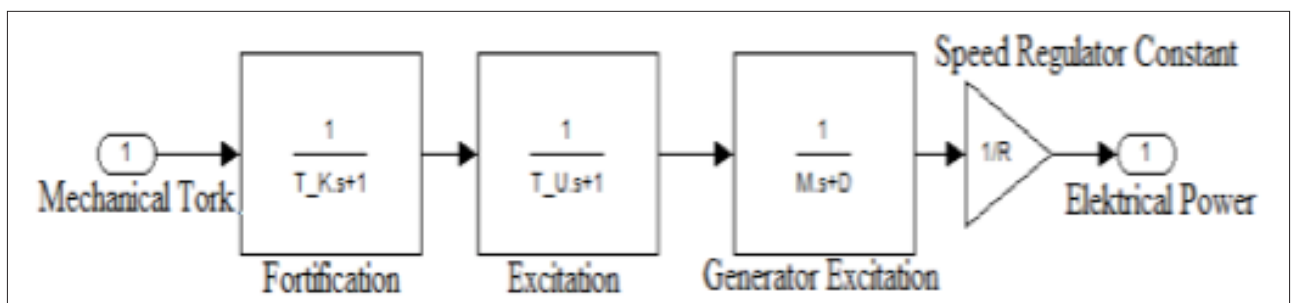| Parameter	T_K	T_U	M	D	R
Value	0,25	1	0,1	1	1

Figure 9. Simplified Generator Model

$$\frac{K_p}{T_i} = K_i \tag{14}$$

K_p is proportional gain coefficient, K_i integral gain coefficient, $e(t)$ is the time error.

PI controller values were obtained by using equation (14) for Gas Turbine.

Result of PI controller parameters are calculated as K_p = 0.680 and K_i = 0.6.

Particle Swarm Optimization Based PI Controller

In literature, particle swarm optimization (PSO) is proposed to find the best results of numerical problems based on the social behavior of bird flocks. In the PSO, each individual or particle travels through the solution space that is identified. Each individual keeps the places it ever visited and best one among them in its mind as well as all the other members of the flock. Then, the total best individual experiences are taken into account and compared to each other in order to reach the global best.

Each individual seeks a solution in the XY coordinate plane in a two-dimensional solution space. The speed of the individual is defined by v_x and v_y (moving along the X and Y axes). Each individual keeps its best value as the best "pbest" value in memory. In addition, each individual keeps the information of the best value, gbest information and pbest information. The position and velocities of each individual are shown in equation (15) and equation (16) as the following term in [13].

$$\vartheta_i^{k+1} = \vartheta_i^k + c_1 rand_1.\left(p_{best_i} - s_i^k\right) + c_2 rand_2.\left(g_{best} - s_i^k\right) \tag{15}$$

$$s_i^{k+1} = s_i^k + \vartheta_i^{k+1} \tag{16}$$

The PSO shows the movement of the search point in a two-dimensional solution space. s^k and ve s^{k+1} shows the current and new individual locations. Moreover, ϑ^k and ϑ^{k+1} shows current and new speeds respectively.

ϑ_{pbest} and ϑ_{gbest}, p_{best} and g_{best} shows the speeds according to their location. Changes in the individual position of these vectors are shown in Figure 11.

The equation (17), (18) which are kept within a certain limit for the damping and oscillation at certain points of the speed, are shown [14].

$$V^{max} = (x^{max} - x^{min})(\%10 - \%20) \tag{17}$$

$$V^{min} = -V^{max} \tag{18}$$

It is kept between certain values by using the coefficients of the particles

$$\vartheta_i^{k+1} = X.[\vartheta_i^k + c_1 rand_1.\left(p_{best_i} - s_i^k\right) + c_2 rand_2.\left(g_{best} - s_i^k\right)] \tag{19}$$

X is the constraint coefficient that is given in equation (20).

$$X = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|}, \varphi = c_1 + c_2 , \varphi > 4 \tag{20}$$

Through the restriction coefficient, individuals will be collected at a single point in the future. Figure 12 shows the particle swarm optimization algorithm scheme [15].

The optimization software is designed to approach the fitness function which indeed is the sum of absolute values of errors to zero.

In the simulation stage, the speed ranges of the individuals are determined as in equation (17) and equation (18). In order to compensate local and global search performances, the X coefficient of equation (19) and equation (20) is used. For simulation, the number of individuals is 5 and the number of iterations is 20. The sum of the absolute values of the error function is used as the target function. The goal of optimization is to find the most appropriate PI gain values. Figure 13 shows a block diagram of the control of particle swarming

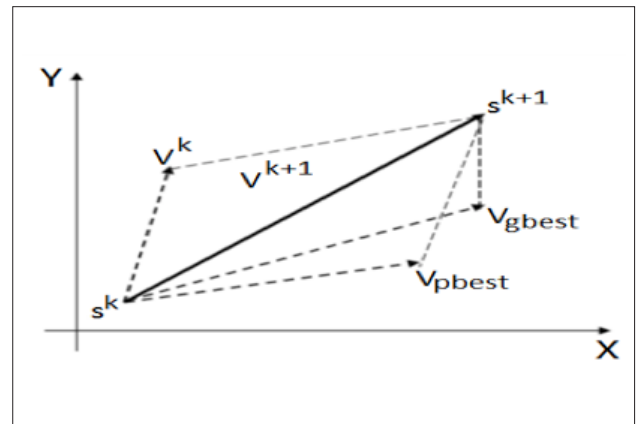As the result of optimization K_p and K_i are found 0.5880, 0.7156.

Figure 10. Response Curve

Figure 11. Particles Movement

The Proposed FGPI Controller

An alternative to Boolean algebra, fuzzy logic system is more suitable for human thought. In particular, it provides great convenience in complex and uncertain control systems.

Fuzzy gain scheduling proportional and integral (FGPI) control generated in the system for each entry and output. Seven membership function has been created. The membership functions created are expressed as follows; NB (Negative Large), NO (Negative Medium), NK (Negative Small), S (Zero), PK (Positive Small), PO (Positive Medium), PB (Positive Large). All membership are chosen as trimf (triangle membership function) because of the more sensitive control range. The value ranges of

all membership functions are arranged in sensitive intervals according to the response of the system to the control response. Fuzzy logic rules and membership functions for determining PI control gain ranges are obtained according to the unit step response of the system.

The fuzzy logic control algorithm is the most important factor in the errors and derivative of errors. To operate a control system at the desired level, the range of the error and the derivative of the error must be adjusted precisely. The variance of the error and derivation of error for the gas turbine is shown in Figure 14 [7].
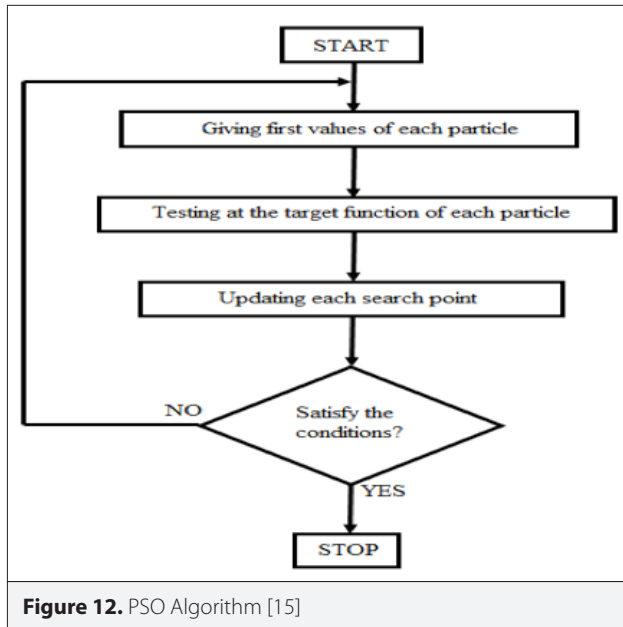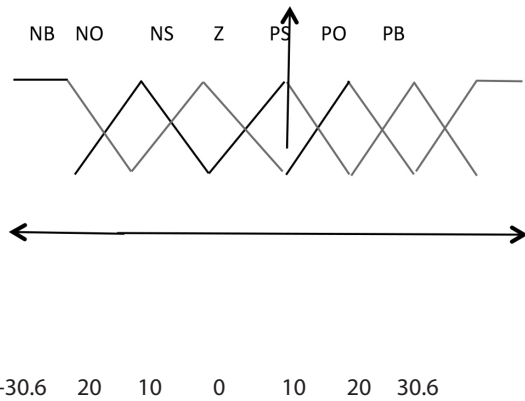

Figure 12. PSO Algorithm [15]
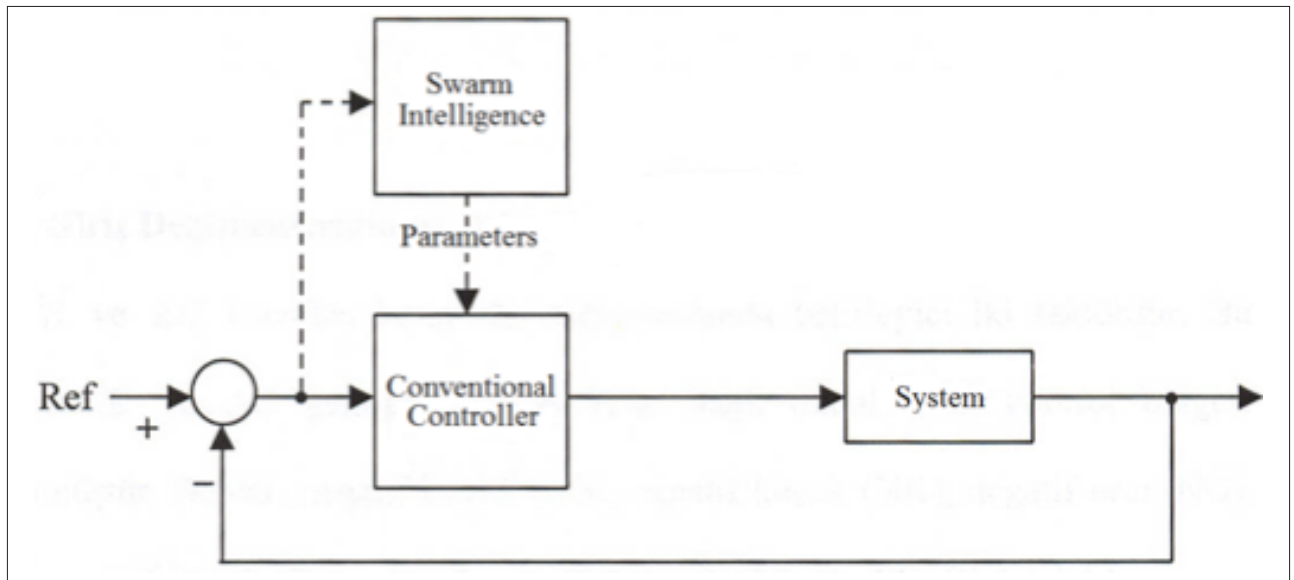

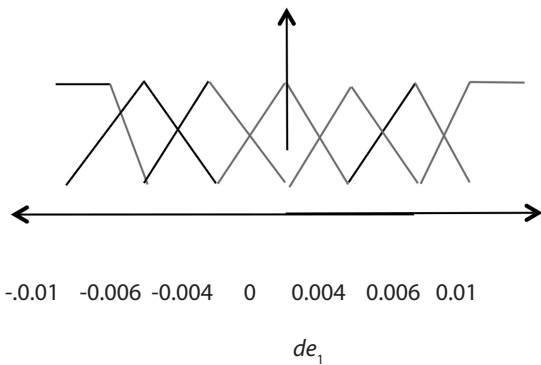NB   NO   NS   Z   PS   PO   PB

-30.6   20   10   0   10   20   30.6

(a)

e_1

NB   NO   NS   Z   PS   PO   PB

Figure 13. Block Diagram of Particle Swarm Optimization

-.0.01   -0.006 -0.004   0   0.004 0.006 0.01

de_1

(b)

Figure 14. a, b. Ranges of Input Variables. Error (a), Derivation of Error (b)

Here, e_1 expresses the error value of the system. The error values are set to -30.6 to 30.6. de_1 represents the derivative of the error which varies from -0.01 to 0.01.

Proposed control system gain values K_p and K_i regulate the Gas Turbine by the selected PI parameters of the controller. The control gain ranges are also precisely arranged. The defuzzification rules of this system are given in Table 4 and Table 5.
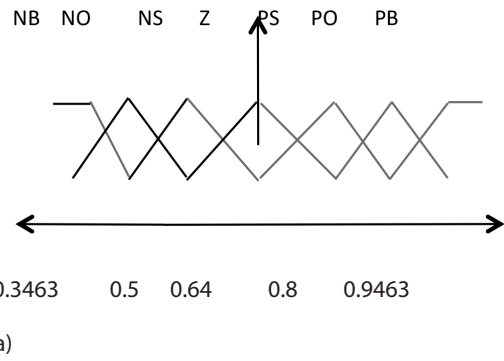
The membership functions for fuzzification of the output values of the gas turbine are shown in Figure 15.a and 15.b.

NB   NO   NS   Z   PS   PO   PB

0.3463   0.5   0.64   0.8   0.9463

(a)

NB   NO   NS   Z   PS   PO   PB

0.4   0.5   0.55 0.75   0.95   1.1

(b)

Figure 15. a, b. Ranges of Output Variables

a) K_p b) K_i

K_p range of the designed Gas Turbine is [0.3463 0.9463] where K_i are designed as [0.4 1.1].

Simulation and Results

In this study, the design of PI, PSO-PI and FGPI controllers are employed. These controllers are applied into the Gas Turbine Power Plant which reduced the mathematical model. The set values of the power plant are used to in the comparison of the results. Response curves obtained from all proposed controllers are shown in Figure 16. The set value is 1 MW and the period is 200 second as a square wave which is suitable to compare the results.

If we focus on the graph, Figure 17 and Figure 18 will be obtained.

The overshoot and settling time are presemnted in Table 6. One can see that, there is no overshoot in Conventional PI controller, the power overshoots of FGPI and PSO controllers are %0.1

Table 4: Rules of K_p parameters for power output [7]

de e	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PB	PB	PM	PM
NM	PM	PM	PM	PM	PM	PS	PS
NS	PS	PS	PS	PS	PS	Z	Z
Z	Z	Z	Z	Z	Z	NS	NS
PS	NS	NS	NS	NS	NS	NM	NM
PM	NM	NM	NM	NM	NM	NM	NB
PB	NB	NB	NB	NB	NB	NB	NB

Table 5: Rules of K_i parameters for power output [7]

de e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NB	NM	NM
NM	NM	NM	NM	NM	NM	NS	NS
NS	NS	NS	NS	NS	NS	Z	Z
Z	Z	Z	Z	Z	Z	PS	PS
PS	PS	PS	PS	PS	PS	PM	PM
PM	PM	PM	PM	PM	PM	PM	PB
PB	PB	PB	PB	PB	PB	PB	PB

Table 6. System performance

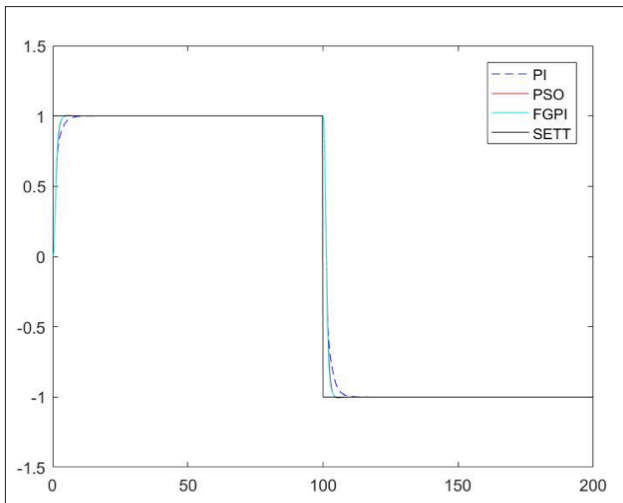|	Overshoot (%)	Settling Time (s)
PI	-	16
PSO-PI	0.2	10
FGPI	0.1	8

Figure 16. Power Output with All Controllers

and % 0.2 respectively. However, if the settling times for power output are taken into account, it will be realized that FGPI controller is less than both PI and PSO-PI controllers. According to the Figures and Table, FGPI controller is better than Conventional PI controller as well as PSO-PI controller. Since the settling time is extremely minimum to the reference signal in the Gas Turbine Power Plant.

Conclusion

In this paper, the model of Gas Turbine Power Plant in Ambarlı, Turkey is analyzed. The controller gain parameters employed in this system are obtained by conventional methods. Afterwards, three controllers namely conventional PI, PSO-PI and FGPI are proposed and compared to each other. In this comparison, minimization of the settling time is desired and it is seen that FGPI is the best among the others. Moreover, conventional PI and PSO-PI parameters reduce the performance and efficiency of
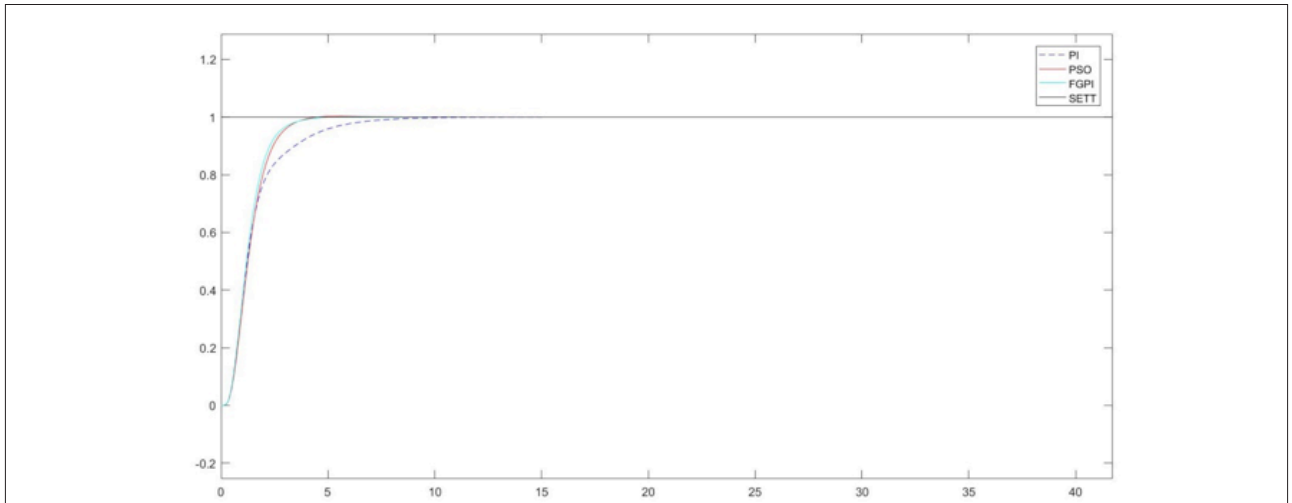

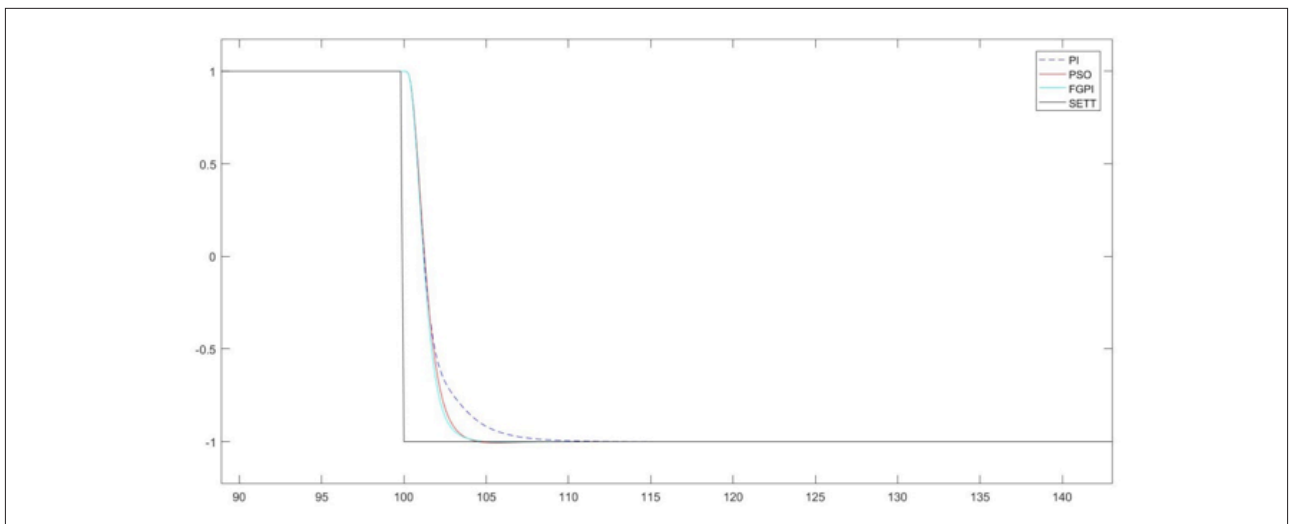
Figure 17. Rise Time Output

Figure 18. Fall Time Output

the plant throughout in its service life. Consequently, it is observed that, FGPI controller achieved satisfactory performance in Gas Turbines.

Peer-review: Externally peer-reviewed.

Conflict of Interest: The authors have no conflicts of interest to declare.

Financial Disclosure: The authors declared that the study has received no financial support.

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