A Hybrid PSO_Fuzzy_PID Controller for Gas Turbine Speed Control

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Abstract

In this paper, a hybrid PSO_Fuzzy_PID controller is designed for speed control of a gas turbine. The aim of the controller is to maintain the turbine speed and the exhaust temperature in a desired interval during startup and operating condition. Here, different parts of the fuzzy controller such as fuzzification, rule base, inference engine, defuzzification, and particle swarm optimization (PSO) algorithm are presented. computer simulations of the controller and gas turbine based on Matlab / simulink simulation platform are performed to investigate the effectiveness of the proposed algorithm. The performance of the proposed algorithm is evaluated during startup and operating condition of the gas turbine. Simulation results well show that the response of the PSO_Fuzzy_PID controller is effectively improved compared with other controllers. The characteristics of the step response such as rise time, settling time and overshoot are considerably decreased, and the value of the steady state error is minimized.

Keywords: *Gas Turbine, Fuzzy Control, Speed Control, PSO algorithm*

1. Introduction

Nowadays power generation by means of gas turbine power plants is playing a major role worldwide [1]. Wide spread application of a gas turbine in electricity generation and the dynamic nature of this system has doubled the necessity of its accurate modeling and variables control. Also exact identification of the parameters of the system, and temperature and speed control are important issues.. Nonlinear controllers, such as sliding mode controller presented in [2]. In [3], a genetic algorithm based multipurpose controller was presented for gas turbine. In [4], an optimized LQR controller was suggested. In [5], a particle swarm optimization (PSO) algorithm was used in optimizing the PID controller parameters for the exhaust temperature control of a gas turbine system. In [6], the mathematical model of an exhaust temperature control of micro turbines was discussed. In [7], an H_∞ robust controller have been designed for a gas turbine to control speed and exhaust gas temperature simultaneously. In [8], the non-linear mathematical model of a gas turbine was simulated in Matlab/Simulink using the Park transformation. a PID fuzzy controller was designed to the speed control of gas turbine generator sets, and the simulation results of this model were significantly acceptable. In [9], a neural fuzzy network control was proposed for nonlinear models, a speed control scheme for a single shaft gas turbine was suggested and simulated in Matlab/Simulink. The results showed that by tuning the fuzzy neural network controller, the performance of the system can be achieved in a wide range of operating conditions compared to the fuzzy logic controller and fuzzy PID controller. It indicated that the controller has adaptive ability and robustness. In [10], a neural-fuzzy controller was presented to control the gas turbine. This controller was comprised of two inputs (speed and mechanical power); an output (fuel), while a neural network was designed to tune the gains of fuzzy logic controller based on the operating condition of the biomass-based power plants. The simulation results showed that by tuning fuzzy logic controllers, optimal time domain performance of the system can be achieved in a wide range of operating condition compared to fixed parameter fuzzy logic controllers and PID controllers. Various mathematical and thermodynamic models have been proposed for a gas turbine. Among the various models, the Rowen models [11] are simple and practical [7]. The other models are more precise but have not been chosen quite often for control purposes due to nonlinearity or complexity [7].

The purpose of this paper is to design a PSO_Fuzzy_PID controller to control the speed of the gas turbine. The results is compared with responses of the other controllers for the same turbine model. The paper is sectioned as follows: in Section 2, the dynamic modeling of the gas turbine is presented. In Section 3, the algorithms of applying fuzzy logic and PSO in gas turbine speed control are discussed. In the fourth section, the results of the designed controller during startup and operating condition of the gas turbine are well illustrated, and finally, in Section 5, the conclusion is presented.

2. Gas Turbine Modeling

Gas turbines are generally comprised of compressor, combustion chamber, and turbine, where the gas pressure (usually air) is initially increased in compressor (in multi-stage compressors up to 12 times) and the pressured gas is heated in combustion chamber then. Afterwards, the gas is injected with high pressure and temperature to the turbine and the thermal energy of the gas is converted in to mechanical energy. The general view of gas turbine is illustrated in Figure 1.

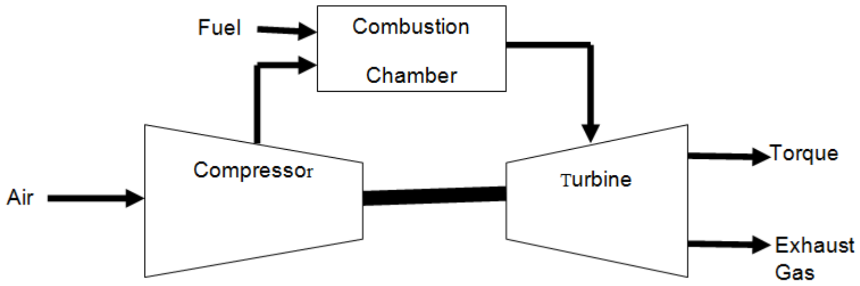

Figure 1. General Schematic of a Gas Turbine

One of the limitations should be considered in turbines is the fact that the turbine speed should not overstep a certain level since the frequency of the generated power is directly related to the turbine speed. The exhaust temperature should also be limited because of the physical and economical consideration. In order to have a correct and normal function, different protection and control systems are applied in gas turbine plants. These systems control different parameters such as turbine input/output temperature, shaft speed, shaft vibration rate, flame condition, the amount of cooling airflow, etc, among of which, some parameters are more significant. Each parameter's variation should stay in a permitted range. An alarm is initially activated if the amount of a parameter exceeds the permitted level. The turbine might damage if the problem is not overcome. Therefore, the turbine is compulsively out of service.

Gas turbines usually possess the following five controllers:

1. **Start controller:** This controller is in charge of system start and turbine speed increase, which is accomplished in open-loop form through several stages and steps.
2. **Speed controller:** This controller removes the start controller out of service in the speeds close to the nominal speed and is in charge of increasing the turbine speed at the end of starting stage and accurately regulating the speed before the unit synchronization and close the generator breaker.
3. **Load controller:** The turbine control is transferred automatically from the speed controller to the load controller after generator breaker closing and unit synchronization. The load controller is in charge of turbine load increase and decrease to reach the determined unit load level.
4. **Turbine's maximum temperature limit controller:** This controller is the turbine temperature limiter. The controller is responsible to prevent the turbine overloading if the temperature exceeds the maximum turbine's tolerable temperature threshold.
5. **Turbine's mechanical load limit controller:** this controller limits the mechanical load of the turbine and prevents turbine to reach the maximum tolerable torque.

The output signals of the above-mentioned controllers enter to a MIN gate block, in which, it is determined which controller is active and controls the turbine operation. During the unit operation, all above controllers are active all together while the one with lower sending signal actually controls the turbine.

In this paper, Rowen model has been used. In this model, the low value selector (LVS) system inputs are three output signals obtained from speed, temperature, and acceleration control systems. Here, the acceleration should not exceed 0.01 pu/sec.

The dynamic model of gas turbine and its control systems is illustrated in Figure 2. Two functions exist in model structure. The first one, *f1*, calculates the exhaust temperature in terms of the turbine speed, *N*, and the fuel flow, *WF*. The second one, *f2*, calculates the generated turbine torque in terms of *N* and *WF*. Here, *a*, *b* and *c* are the fuel system transfer function coefficient, *TF1* is fuel system time constant, *KF* is fuel system feedback. In this model, a first order system with time constant (*TCD*) is allocated for the compressor and a pure delay (*ECR* and *ETD*) is considered for the combustion reaction time and the exhaust system transport. The values of the applied variables and constants are expressed in appendix.

3. PSO_Fuzzy_PID Controller Application for Gas Turbine Speed Control

In this paper, fuzzy, PSO, and PID controllers are designed to control the gas turbine speed and operate in parallel in the hybrid controller. The hybrid PSO_Fuzzy_PID controller is shown in Figure 3.

3.1. Fuzzy Logic Structure

The basic structure of a fuzzy logic controller is illustrated in Figure 4. A fuzzy logic controller commonly consists of four sections including: fuzzification, inference engine, rule bases, and defuzzification. A rule base is made up of series of IF-THEN rules corresponding to the fuzzy inputs and leading to the fuzzy outputs. The rules can be developed using knowledge from experts or operators in the field, as well as historical experience.

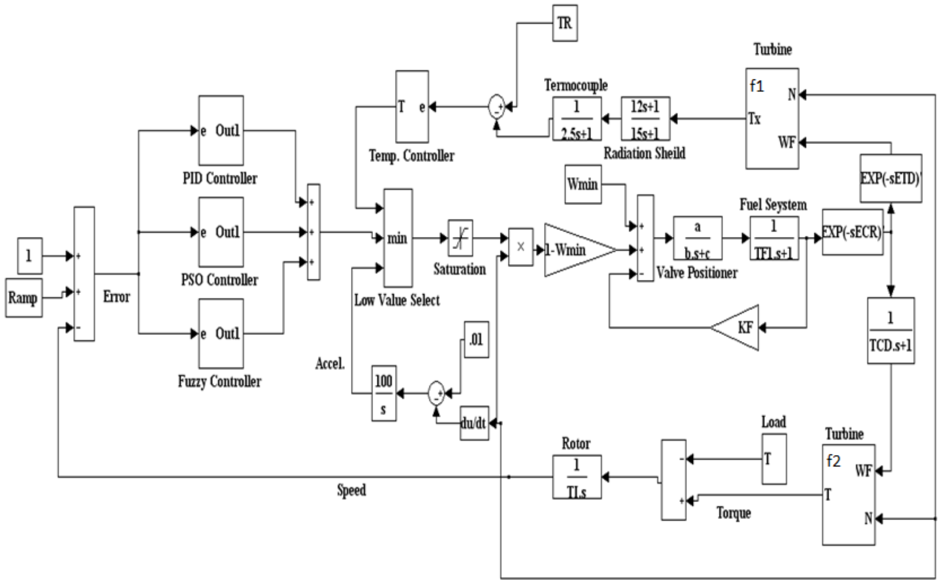

Figure 2. Dynamic Model of Gas Turbine and its Control Systems

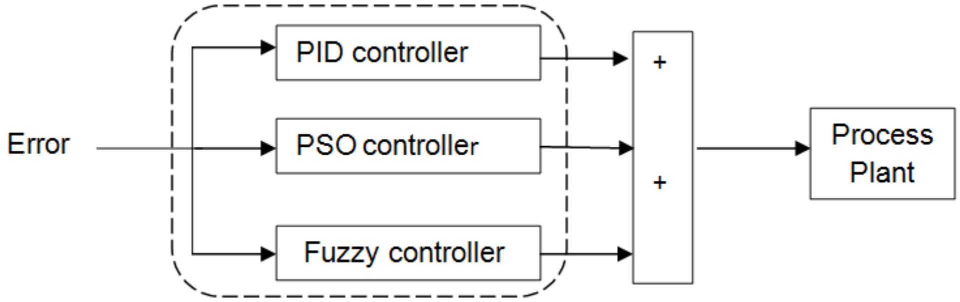

Figure 3. Hybrid PSO_Fuzzy_PID Controller

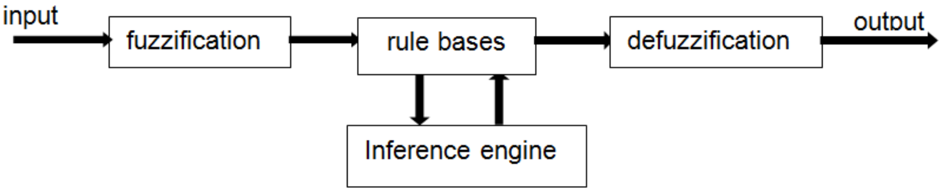

Figure 4. Fuzzy Logic Controller Structure

To design the fuzzy controller some variable which can represent the dynamic performance of the system should be chosen to be fed as the inputs [10]. In this paper, the fuzzy logic controller has two inputs and one output. The inputs are turbine speed deviation (e) and its derivative (Δe) and the output is the change in controller position. The number of linguistic terms for each linguistic variable is selected as seven (Negative Big=NB, Negative Mean=NM, Negative Small=NS, Positive Small=PS, Positive Mean=PM, Positive Big=PB). The inference mechanism is based on Mamdani technique. In this design, the minimum is applied for data AND operator, maximum for OR operator, minimum for implication operator, maximum for aggregation operator, and finally centroid technique for defuzzification. The membership functions for inputs variations are Gaussian and they are considered triangular for the controller output variations. The membership function of inputs and the output variations are shown in Figure 5 and Figure 6, respectively. In this system, 49 fuzzy rules are defined for startup and operating condition of gas turbine. The rule table for speed controller is shown in Table 1.

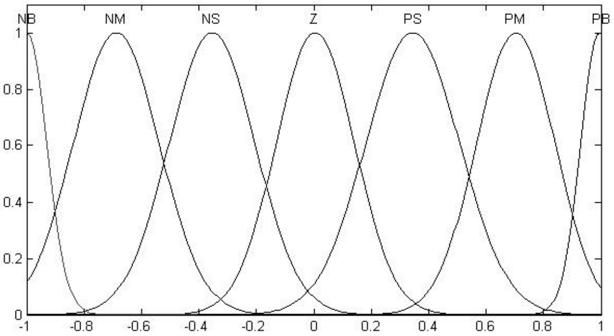

Figure 5. Membership Functions for Inputs

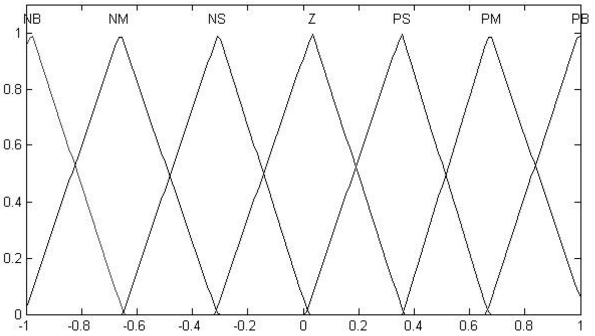

Figure 6. Membership Functions for Output

Table 1. Control Rules

		Δe(t)						
		NB	*NM*	*NS*	*Z*	*PS*	*PM*	*PB*
e(t)	*NB*	NB	NB	NB	NM	NM	NS	Z
	NM	NB	NB	NM	NM	NS	Z	PS
	NS	NB	NM	NS	NS	Z	PS	PM
	Z	NM	NM	NS	Z	PS	PM	PM
	PS	NM	NS	Z	PS	PS	PM	PB
	PM	NS	Z	PS	PM	PM	PB	PB
	PB	Z	PS	PM	PM	PB	PB	PB

3.2. PSO Algorithm

The principle of PSO is to simulate a collective behavior used to show the motion of birds and fish. PSO has simulated the birds' motion along two directions. The position of each individual (representative) is represented by *x y* vectors and *Vx* (velocity on x-axis) and *Vy* (velocity on y-axis) express the velocity. Although in PSO, each member has an adaptive speed (location change) due to which moves in search space, each one has a memory, in other words, it remembers the best position it has reached in the search space. Therefore, each member moves on two directions. 1- Towards the best position they have met, 2- Towards the best position the best member has met in neighborhood.

According to the issues mentioned above, the position of each member is determined via its own speed and position. The velocity and position of each particle is modified according to Eq.1 and Eq.2, respectively [12]:

$$V_i^{K+1} = WV_i^{K+1} + C_1 rand_1 \times (pbest_i - S_i^K) - C_2 rand_2 \times (gbest - S_i^K \qquad (1)$$

$$S_i^{K+1} = S_i^K + V_i^{K+1} \qquad (2)$$

Where ,

V_i^K =current velocity of particle i at iteration k

V_i^{K+1}: new velocity of particle i at next iteration k+1

S_i^K: current position of particle i at interation k

S_i^{K+1}: new position of particle i at next iteration k+1

C_1 and C_2: adjustable cognitive and social acceleration constants

$rand_1, rand_2$: random number between 0 and 1

$pbest_i$: personal best of particle i

gbest: global best of the population

The following weighting function is usually utilized in Eq.1.

$$W = W_{max} - \frac{W_{max} - W_{min}}{iter_{max}} \times iter \qquad (3)$$

Where,

W: inertia weight

W_{max}: initial inertia weight

W_{min}: final inertia weight

$iter_{max}$: maximum number of iterations

iter: current iteration

The algorithmic steps involved in PSO algorithm are as follows:

1. Initialize the population – positions and velocities
2. Evaluate the desired optimization fitness function of the individual particle (pbest)

3. Keep track of the individuals highest fitness (gbest)
4. Modify velocities based on pbest and gbest position
5. Update the particles velocities and positions according to Eq.1 and Eq.2.
6. Repeat steps 3-6 until the stopping criterion of maximum generations is met.

In this paper, the PSO algorithm is used to calculate the optimum values (K_p, K_i, and K_d) of PSO controller. The performance indices, mean squared error (MSE), integral of time multiplied by absolute error (ITAE), and integral of time multiplied by square error (ITSE), defined as follows (Eq.4-Eq.6) are usually applied for optimum controller tuning.

$$\text{ITSE} = \int_0^\infty t\, e^2(t)\, dt \tag{4}$$

$$\text{ITAE} = \int_0^\infty t\, |e(t)|\, dt \tag{5}$$

$$\text{MSE} = \frac{1}{t}\int_0^t (e(t))^2\, dt \tag{6}$$

In this paper, the optimum values of PSO controller are calculated based on all the three performance indices and the best response is selected as PSO controller from overshoot, settle time, and rise time viewpoint. The parameters applied in this simulation are as follows:

$n = 20$ (number of particle)
$W_{max} = 0.9$
$W_{min} = 0.4$
$iter_{max} = 200$
$C_1 = 1.4$
$C_2 = 1.4$

4. Simulation Results Analysis

In this section, the performance of the controller designed for startup and operating condition is evaluated. Five controllers, PSO, Fuzzy, PID, Fuzzy_PID, PSO_Fuzzy_PID, are designed for gas turbine model and the results are compared in order to evaluate the performance of the controllers. The simulation results well showed that the performances of the controllers are almost similar during startup. Therefore, here, just the results of the PSO_Fuzzy_PID controller are presented. In operating condition, the results of controllers differ. All simulations are carried out in Matlab/Simulink.

4.1. Startup

The simulation results of gas turbine control system during startup using PSO_Fuzzy_PID are shown in Figures 7-8. Figure 7 shows the speed variations during startup. The ratio of rotor speed change to reach to the nominal speed is due to the operation of low value selector (LVS), which changes from accelerator control loop to rotor speed control and reaches to the favorite point.

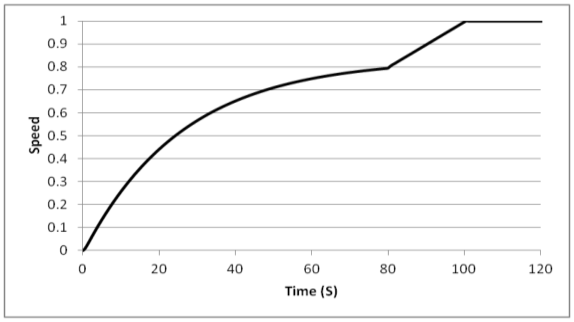

Figure 7. Speed Variations during Startup

Figure 8 shows the temperature variations of exhaust gas. The temperature reaches to 412℉ steady state temperature after passing the transient state. The temperature increase amount in transient state does not exceed the protective thresholds and consequently the turbine does not get out of the operation mode in starting stage and does not show trips.

4.1.1. Speed Tracking During Startup, Figure 9 shows the operation and the performance of the controller in tracking the speed variations during startup. In this simulation, the turbine speed changed from 200 sec with 1% unit base slope to evaluate the system performance. This figure shows the modest ability of this controller in speed tracking. In this figure, the speed tracking is in a way that no overshoot is seen in system response and an appropriate tracking is obtained.

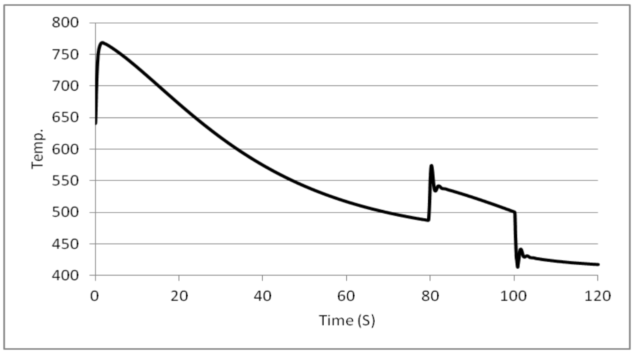

Figure 8. Temperature Variations in Turbine's Chimney

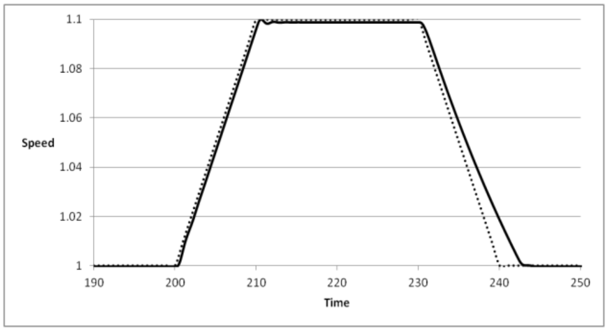

Figure 9. Speed Variations Tracking During Startup

4.2. Operating Condition

To investigate the performance of the designed controller under different operating condition, the operating condition of the system has been changed. The load variation rate is considered 0.3 of the base unit in step form. The load variations curve is shown in Figure 10.

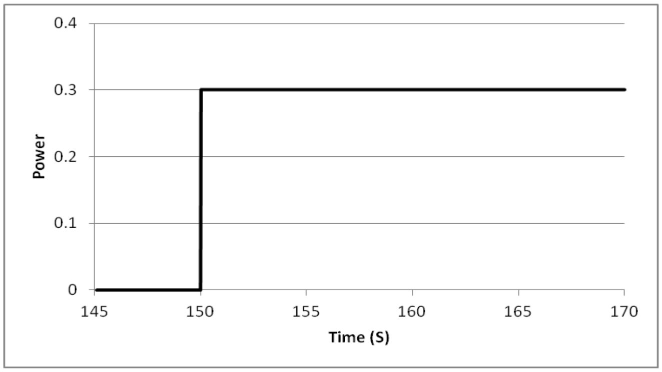

Figure 10. Load Variations in Operating Condition

Figure 11 shows the operation of the five controllers in power controlling against the load variations. As shown in this figure, it is obvious that the controllers have reached to the favorite value and show a proper response. Here, the PSO_Fuzzy_PID controller shows the optimum response.

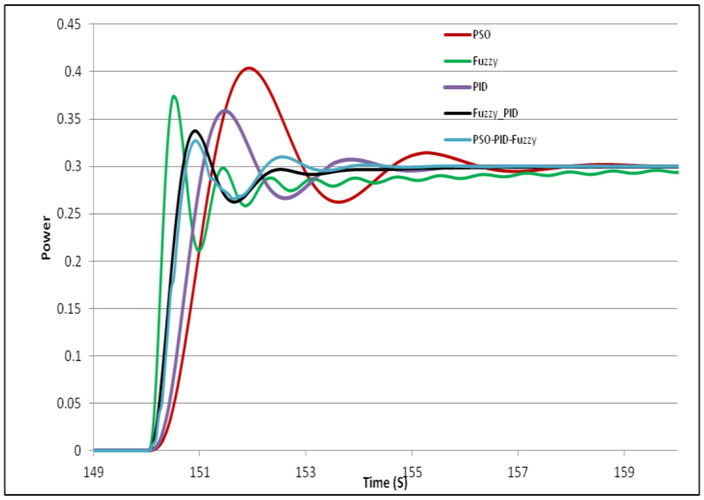

Figure 11. Produced Power of Gas Turbine

In Table 2, the simulation results of several controllers in this state are illustrated. The overshoot rate of the PSO_Fuzzy_PID controller is 8.87%, which is the least among all controllers. The maximum overshoot, 34.5%, is of PSO controller. PSO_Fuzzy_PID controller shows the minimum settling time 3.87 sec. the maximum settling time is 11 sec. and belongs to Fuzzy controller. The performance indices values of controllers are well shown in Table 2. This table depicts that the PSO_Fuzzy_PID controller shows the minimum error value among all controllers.

Table 2. Simulation Results

	ITAE	ITSE	MSE	%Speed Error	Overshoot	Settling Time	Rise Time
PSO	536.9573	100.7593	0.01708	1.005	34.5028	8.04	0.82
Fuzzy	571.3392	101.1843	0.01710	1.669	24.6596	11.043	0.216
PID	542.5325	100.8700	0.01709	1.189	19.3934	5.65	0.694
Fuzzy_PID	539.2664	100.7206	0.01708	0.985	12.4376	4.04	0.4
PSO_Fuzzy_PID	523.4590	100.5233	0.01701	0.601	8.8681	3.87	0.45

In Figure 12, the speed variations of controllers caused by load variations are shown. It is obvious that the PSO_Fuzzy_PID controller has the best response. The steady state percentage of the speed error is illustrated in Table 2. The minimum steady state error percentage is 0.6% and the maximum is 1.67%.

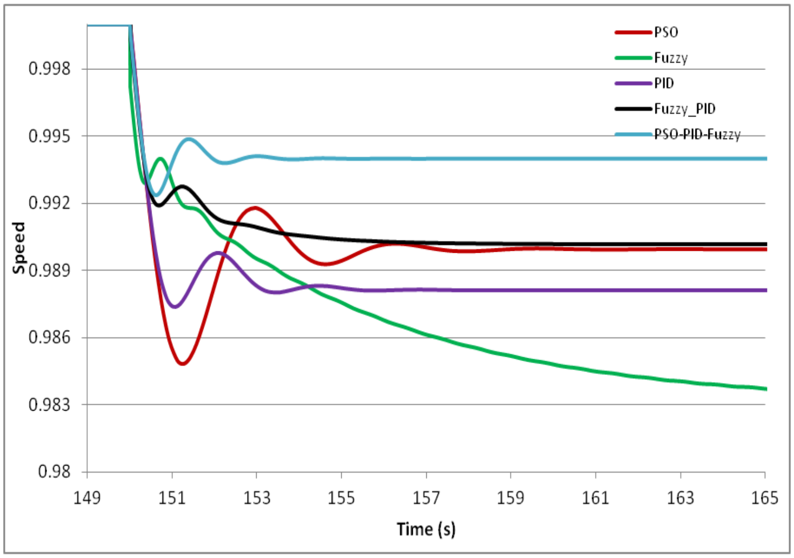

Figure 12. Turbine Speed

The simulation results and the comparisons show that the PSO_Fuzzy_PID controller has a considerable advantage in compare with other controller in load tracking and speed control. The overshot and settling time values are considerably decreased in this controller.

5. Conclusion

In this paper, a PSO_Fuzzy_PID controller is designed to control the gas turbine speed. In the proposed model, PID, Fuzzy, and PSO controllers operate in parallel. In this paper, seven linguistic states are selected for each variable and the triangular membership function is applied to these variables. In this controller, 49 rules are defined to control the gas turbine in starting and operating condition. PSO algorithm is applied to calculate the optimum controller values and performance indices are considered as target functions to tune them. In this paper, the performance of the designed controller is presented for startup and operating condition. The simulation results show that the PSO_Fuzzy_PID controller has the minimum overshootand minimum settling time values and the speed steady state error value is tiny. The results comparison depicts that the PSO_Fuzzy_PID controller shows more efficient response in compare with other investigated controllers.

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Appendix

The values of the applied variables and constants are expressed in Table I.

Table I. Dynamic Model Parameters

Parameters	Value
W	16.7
X	0.6
Y	1
Z	1
MAX	1.5
MIN	-0.1
A	1
B	0.05
C	1
Wmin	0.23
TF1	0.4
KF	0
ECR	0.01
ETD	0.04
TCD	0.2
TR	950
Tt	450
f1	Tx=TR-700*(1-WF)+550*(1-N)
f2	1.3*(WF-0.23)+0.5*(1-N)
TI	15.64