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Simple Cycle Gas Turbine Dynamic Analysis Using Fuzzy Gain Scheduled PID Controller

Mohamed Iqbal Mohamed Mustafa

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Abstract

Heavy Duty Gas Turbines (HDGT) which ensure clean and efficient electrical power generation in grid-connected operation experiences load disturbances on regular basis. Proportional plus Integral plus Derivative (PID) controller has been introduced to simple cycle gas turbines rated from 18.2 to 106.7 MW. In addition, Fuzzy gain scheduled PID controller has been proposed and their dynamic behavior is analyzed. The simulation results in terms of time-domain parameters and error criteria reveal that the fuzzy gain scheduled PID controller yield better response during dynamic and steady-state period. Further, the stability of gas turbine is analyzed from the dynamic performance of various state variables, viz., fuel demand (Wd), valve positioner signal (Vp), fuel supply (Wf2), turbine torque developed (F2), and actual torque (Tt) which are also being analyzed in this paper. Analysis of the dynamic response also ensures that the fuzzy tuned PID controller is a suitable controller to be implemented with the latest derivative speedtronic governor control system of the HDGT power plants.

Keywords

Fuzzy gain scheduled PID controller

Heavy duty gas turbine

Simple cycle operation

Speedtronic governor

Dynamic analysis

1 Introduction

Gas turbines are extensively used in power industries for the last 40 years. Advanced gas turbine technology, efficient energy conversion, and flexibility of using multiple fuels are the special features of HDGT [1]. Gas turbine useful for simple cycle operation consists of a compressor, combustion chamber, and a turbine. The stability of such a system is affected when it is subjected to severe load disturbances. As the gas turbine installations are increased, the analysis of gas turbine dynamics also becomes most important [2]. Many researches are being carried out globally to identify the simulation model for the gas turbines [2,3,4]. Among all the models, SPEEDTRONIC Mark IV developed for General Electric gas turbines has become popular for analyzing the dynamic response [5, 6]. Literature review on Speedtronic Governor based gas turbine models reveal that it can be used in either droop governor mode or isochronous governor mode [6, 7]. Because of droop characteristics of the governor, steady-state response of the HDGT plants become poor and hence requires a secondary controller to improve the response [7, 8]. A case study of 84 biomass gasifier power plants in Tamilnadu, India also reveals that the efficient controllers are needed to improve the stability behavior [9, 10].

Since the Proportional–Integral–Derivative (PID) Controllers are versatile, highly reliable, and easy to operate, they are commonly used in control industries [11, 12]. Initially, PID controllers are implemented in a simplified gas turbine model with the gains tuned by conventional methods [13]. It is also possible to embed the soft computing control in the recent governor control mechanisms [13]. Hence fuzzy logic technique is introduced for tuning PID gain parameters. Since the dynamic performance of an engine can be analyzed based on engine speed, the step response of gas turbine has been analyzed based on turbine speed (N) against the step load disturbance.

As the turbine installations are increasing drastically, it is mandatory to analyze the turbine stability [14, 15]. Therefore, the state variables, namely, speed deviation (e), fuel demand (Wd), valve positioner signal (Vp), fuel supply (Wf), turbine torque developed (F2), actual torque (T), and turbine speed (N) have been identified and their behavior is analyzed using MATLAB. On comparing the dynamic responses for a load disturbance, an adaptive controller for stable operation of gas turbine in grid-connected operation is identified.

2 Modeling of Gas Turbine

The dynamic simulation model of Speedtronic Governor based HDGT plants consists of three limiters for controlling the turbine speed, turbine acceleration and exhaust temperature. Even though the speed governor can work as droop governor or isochronous governor, droop mode was found as a suitable model for interconnected network [7]. Speed governor controls the turbine speed based on the speed deviation signal, *e*, which is the difference between the desired speed and original speed (*N*). Based on the speed deviation, *e*, the speed governor decides the fuel demand, Wd in order to keep the system stable. Fuel demand signal, Wd as the function of speed deviation, *e* is expressed in Eq. (1).

$$\mathrm{Wd}\left(s\right)=\frac{W\left(Xs+1\right)}{Ys+Z}.e\left(s\right)$$

(1)

Based on the fuel demand signal, Wd, the fuel supply signal, Wf2 is generated by the valve positioning mechanism and fuel system actuator. Valve positioning mechanism decides the valve position, Vp, which gives the fuel supply signal, Wf2, the output of fuel system actuator. Based on the Input–Output signals, the valve positioner and fuel system of gas turbine can be expressed as given in Eqs. (2) and (3), respectively.

$$\mathrm{Vp}\left(s\right)=\frac{a}{bs+c}.\mathrm{Wd}\left(s\right)$$

(2)

$$\mathrm{Wf2}\left(s\right)=\frac{1}{1+sT}.\mathrm{Vp}\left(s\right)$$

(3)

Gas turbine torque, F2 is determined by the fuel supply level, Wf2, and the turbine speed, *N*. It is expressed as shown in Eq. (4). Turbine torque will bring down the speed error to zero. The step load disturbance, T_L of 1 p.u. magnitude is applied and the actual torque (Tt) which is the difference between the developed torque (F2) and the load torque (T_L) has been obtained. It is then converted into turbine speed, *N* by the rotor dynamics block as shown in Eq. (5). The gas turbine rotor time constant, *T*1 ranges from 12.2 to 25.2 [6].

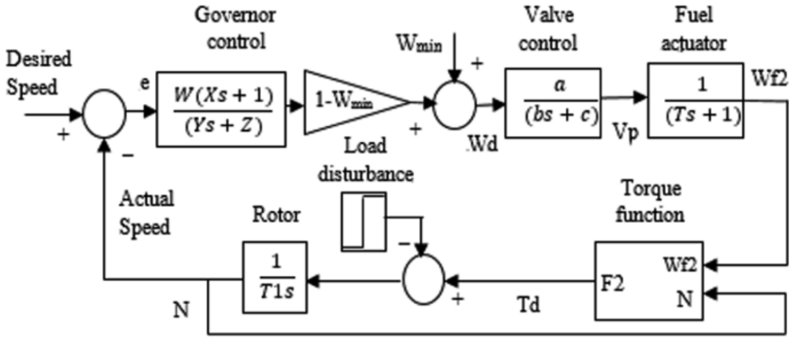
$$\mathrm{F2}=1.3\left(\mathrm{Wf2}-0.23\right)+0.5\left(1-N\right)$$

(4)

$$N\left(s\right)=\frac{1}{T1s}.\mathrm{Tt}\left(s\right).$$

(5)

Fig. 1



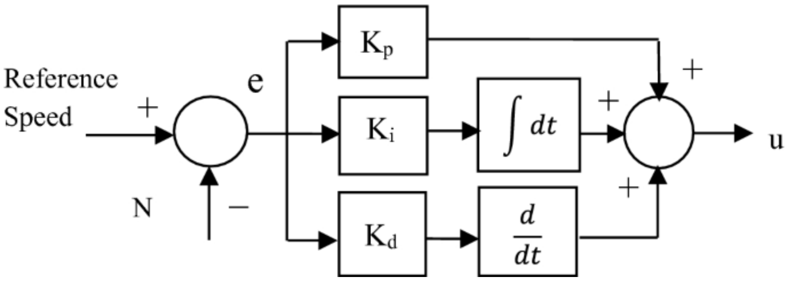
Simulation model of HDGT plant

The acceleration limiter takes the control action only during startup time and the influence of the same during normal operating condition is negligible. Similarly, the temperature control loop will work, if the limit of exhaust temperature is exceeded. Since the acceleration and temperature limiter does not influence much during normal operation, these limiters are eliminated and simplified the transfer function model [6, 13]. The simplified model consisting of the dominant speed control loop with all the above dynamic variables is shown in Fig. 1. It is used for analyzing the dynamic responses of all the state variables of the HDGT plants.

3 Development of PID Controller

PID Controller has been widely used in many process control industries since it was introduced in the market by 1939 [11, 12]. PID controller as shown in Fig. 2, delivers the control signal, $u(t)$, based on the PID controller gains, namely, Proportional (K_p), Integral (K_i), and Derivative (K_d) gains as shown in Eq. (6).

Fig. 2



Structure of PID controller

$$u\left(t\right)=K_pe\left(t\right)+K_i\int_0^t e\left(t\right)\mathrm{d}t+K_d\frac{\mathrm{d}e\left(t\right)}{\mathrm{d}t}$$

(6)

In this paper, two tuning procedures, viz., conventional and fuzzy tuning methods are used for developing PID controllers. Initially, PID controllers are tuned by ZN and Performance index methods. Fuzzy logic technique has also been used for tuning the gains of the PID controllers as detailed below.

3.1 Fixed Gain PID Control

Even though there are many algorithms available to tune the PID controller gains, Ziegler–Nichols (ZN) method has been found to be the standard and most widely used procedure [16,17,18]. In this paper, the tuning rules of ZN method as mentioned in Table 1 has been applied for PID tuning. Values of PID parameters have been arrived using the gain (K_u) and time (T_u) when the system response oscillates with constant magnitude.

Table 1 PID gain tuning by ZN method

Performance index method is another tuning procedure used to determine the values of PID parameters of HDGT [19, 20]. Integral of error terms namely squared error (J_{ISE}), squared error multiplied with time (J_{ITSE}), and absolute error multiplied with time (J_{ITAE}) as given in Eqs. (7), (8), and (9) are considered as performance indices criteria for tuning purpose.

$$J_{\mathrm{ISE}} = \int e^2 \mathrm{d}t$$

(7)

$$J_{\mathrm{ITSE}} = \int (e^2) t \mathrm{d}t$$

(8)

$$J_{\mathrm{ITAE}} = \int |e| \, t \mathrm{d}t$$

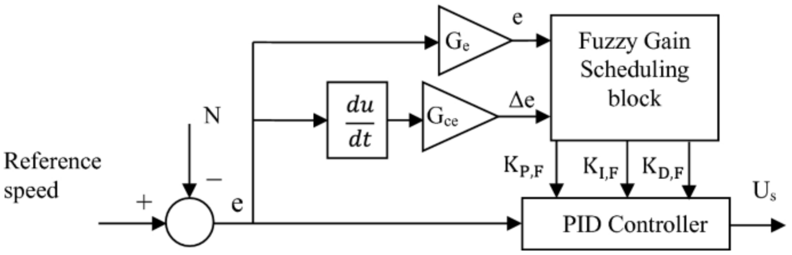
(9)

By this procedure, the gain parameters are obtained by adjusting the gains until the slope becomes minimum in performance index plot [20]. The PID controllers with the PID gains tuned by these fixed gain PID tuning procedures are implemented in MATLAB and the dynamic behavior is compared as shown in Sect. 5.

3.2 Fuzzy Gain Scheduled PID Control

Since, the control mechanism should be more adaptive for the dynamic system; self-tuning methods are evolved to keep track of the system dynamics [21,22,23,24,25]. In this paper, fuzzy sugeno model-based gain scheduling PID controller is presented and their dynamic performances are analyzed in detail. L. A. Zadeh proposed fuzzy set theory in 1965 [26]. The gas turbine speed deviation, $'e'$ and the change in speed deviation signal, $'\Delta e'$ are the driving inputs for fuzzy gain scheduling block and the control signal $U_s(t)$ is used as the output signal as shown in Fig. 3.

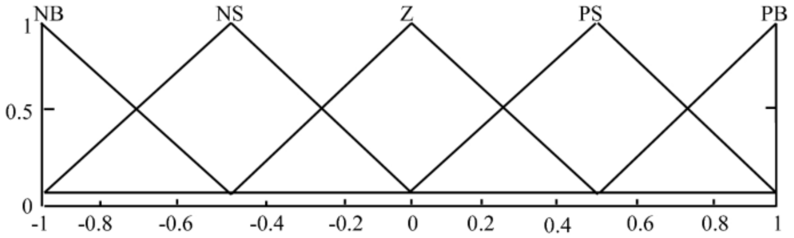
Fig. 3



Structure of fuzzy gain scheduled PID controller

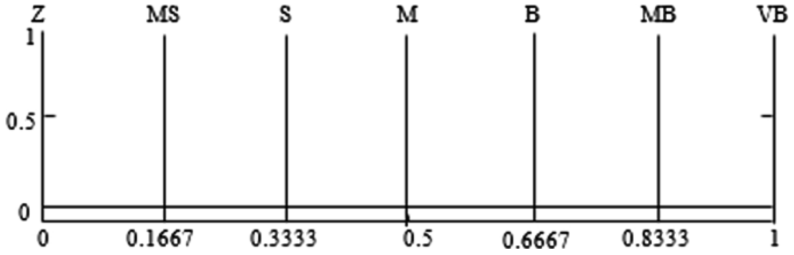
In this paper, Sugeno fuzzy model has been considered with triangular membership function (MF) for input signals and constant membership function for output signal as shown in Figs. 4 and 5, respectively. Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB) are selected as the linguistic variables for the input signal. On the other hand, the linguistic variables, namely, Very Big (VB), Medium Big (MB), Big (B), Medium (M), Small (S), Medium Small (MS), and Zero (Z) are chosen for the output signals. Table 2 shows the fuzzy rules using these linguistic variables.

Fig. 4



Triangular MF for the input signals of fuzzy PID controller

Fig. 5



Constant MF for the output signals of fuzzy PID controller

Table 2 Rules for Fuzzy PID controller

The rule base is formulated using IF-THEN rules. Development of fuzzy gain scheduled PID controller involves three stages, viz., fuzzification, evaluation of rules and defuzzification. During fuzzification stage, the error and error rate are converted from crisp value to fuzzy value. Based on these values, the antecedent of fuzzy rules is obtained by selecting 'PROD' as fuzzy operator. During second stage, the output of each fuzzy rule is obtained using 'MIN' as implication operator. Then the fuzzy output of all rules is combined by choosing 'MAX' as aggregation operator. Finally, the combined fuzzy output is converted into crisp value by selecting WTAVER as defuzzification method. Finally, the PID gains are derived from the product of $K_{P,F}$, $K_{I,F}$, $K_{D,F}$ and the PID gains. The output signal of F-PID controller, $U_s\left(t\right)$ is expressed in terms of self-tuned PID gains as given in Eq. (10). Then the F-PID controller is implemented with the Simulink model of 5001M HDGT and the step response is obtained as shown in Sect. 5.

$$U_s\left(t\right) = K_{P,S}e\left(t\right) + K_{I,S}\int e\left(t\right)\mathrm{d}t + K_{D,S}\frac{\mathrm{d}e\left(t\right)}{\mathrm{d}t}$$

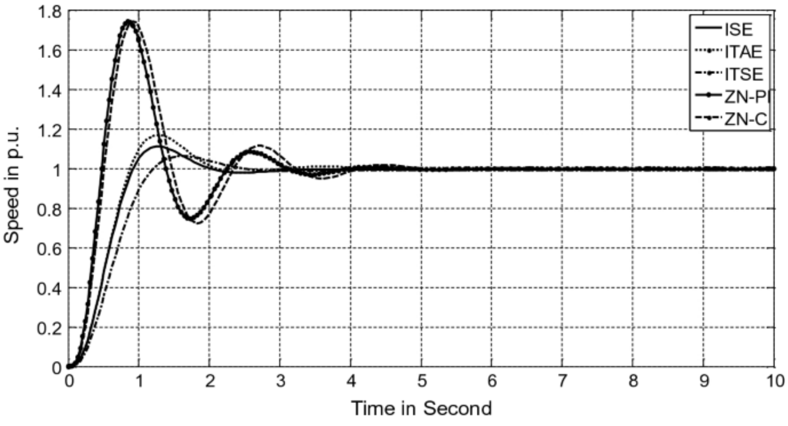
(10)

4 Simulation Results and Discussion

MATLAB/Simulink model of HDGT is implemented with conventionally and fuzzy-based PID controllers and the responses are compared to identify an adaptive controller for gas turbine. Gas turbine model is simulated for 1.0 p.u. step load variation applied at *t* = 1.0 s. Initially, the PID controller gains of 5001M HDGT model are tuned by ZN and Performance index methods and the gain parameters are shown in Table 3. Based on the droop characteristics presented in [27], HDGT model has been simulated for 4 percentage droop with PID controller. In this paper, ZN-C and ZN-PI-based PID controllers have alone been considered for analysis due to poor dynamic response by ZN-SO and ZN-NO methods. Figure 6 compares the step responses by these tuning methods.

Table 3 Controller gains conventional tuning procedures

Fig. 6



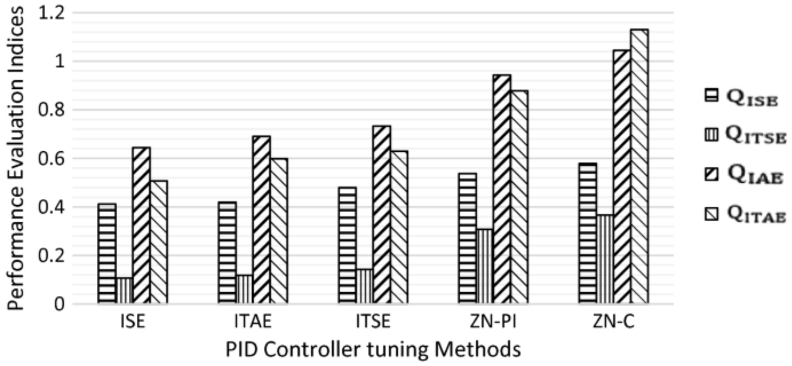
Dynamic performance of HDGT plant with PID controllers

The transient and steady-state parameters are shown in Table 4. Even though the steady-state deviation (Ess) is almost zero by all the rules, maximum overshoot (Mp), rise time (Tr) and settling time (Ts) of ZN-PI based controller are lesser comparing to ZN-C method. Further, it is also noted that the ISE based PID performs better during steady-state period. Moreover, the overall comparison of these methods indicates that ISE improved both the steady-state as well as transient behavior.

Table 4 Time domain parameters with PID controllers

It would be appropriate to conclude the time-domain performance using performance index terms. Therefore, the integral of error terms, namely, square of error (Q_{ISE}), square of error multiplied with time (Q_{ITSE}), absolute of error (Q_{IAE}) and absolute of error multiplied with time (Q_{ITAE}) as shown in Eqs. (11)–(14), respectively, have been obtained and shown in Fig. 7.

Fig. 7



Performance evaluation indices of 5001M with PID controllers

$$Q_{\mathrm{ISE}} = \int e^2 \mathrm{d}t$$

(11)

$$Q_{\mathrm{ITSE}} = \int (e^2) t\mathrm{d}t$$

(12)

$$Q_{\mathrm{IAE}} = \int |e|\, \mathrm{d}t$$

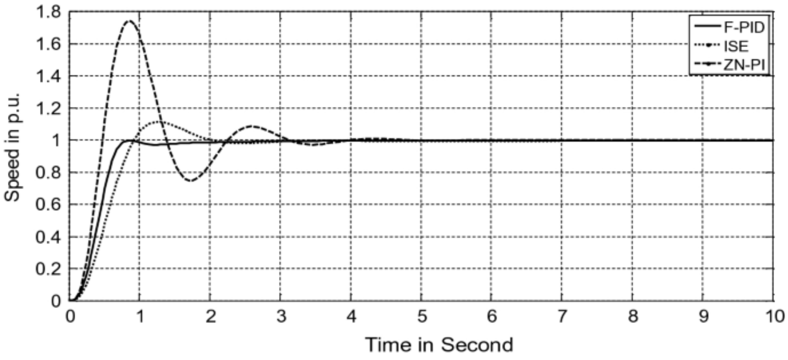
(13)

$$Q_{\mathrm{ITAE}} = \int |e|\, t\mathrm{d}t$$

(14)

It is clear that ZN-PI method yields better performance among ZN methods. On comparing this with performance index methods, PID controller tuned by ISE gives improved dynamic and steady-state responses. Then the fuzzy tuned PID controller is developed as explained in Sect. 3 and the responses are compared as shown in Fig. 8. The values of Mp, Tr, Ts, and Ess are shown in Table 5. It is understood from Mp, Ts, and Ess that the fuzzy tuned PID has improved the overall performance. For validation, the error indicates are also obtained during simulation and presented in Fig. 9. The values of Q_{ISE}, Q_{ITSE}, Q_{IAE}, and Q_{ITAE} for Fuzzy gain scheduled PID controller are found to be very less and witnessed for the optimal behavior.

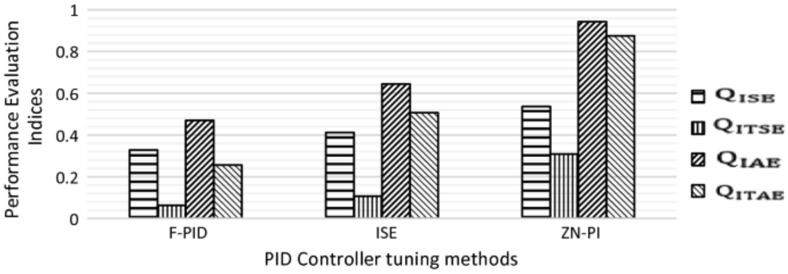
Fig. 8



Comparison of step responses of HDGT plant

Table 5 Time-domain parameters with F-PID, ISE and ZN-PI tuned controllers

Fig. 9

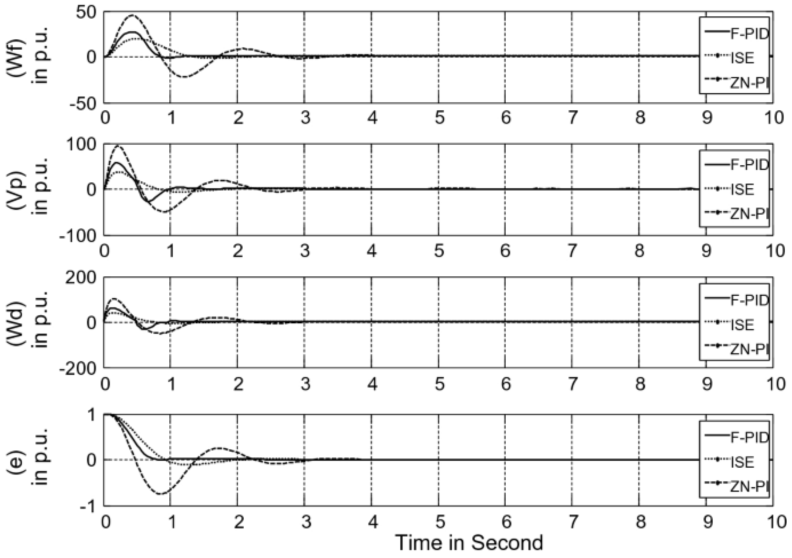


Comparison of performance evaluation indices

For ensuring the stability of turbine during load disturbance, the dynamic behavior of error (e), fuel demand (Wd), valve positioner (Vp), and the fuel supply signal ($\mathrm{Wf2}$) with ZN-PI, ISE and fuzzy-based

PID are obtained as given in Fig. 10. The dynamic simulation results show that the fuel demand, valve position, and fuel supply signals with F-PID reacted faster compared ISE and ZN-PI methods. It is also noticed that these responses reach their equilibrium point when the error signal approaches zero.

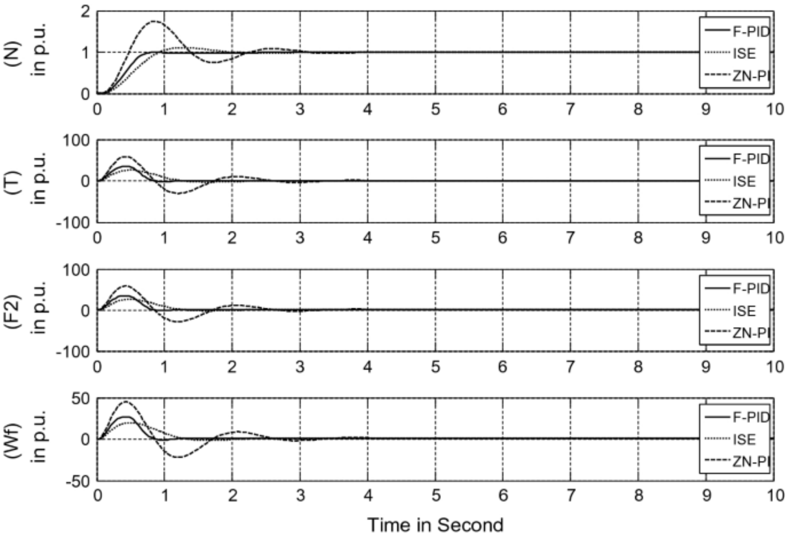
Fig. 10



Dynamic response of e, Wd, Vp and Wf2 with different controllers

Based on the load disturbance and hence the fuel demand signal, the torque is generated by turbine torque function. As presented in the Simulink model of HDGT in Sect. 3, the rotor dynamics with the rotor time constant, T1 is responsible for generating speed signal, *N*. Figure 11 shows the dynamic responses of $\mathrm{Wf2}$, Tt and N of 5001M model with based on the fuel supply signal, $\mathrm{Wf2}$. Here again, the F-PID controller response is noticed as faster than other methods. It is also identified that the torque developed by the HDGT, Tt reaches its normal value. Hence, the actual torque (*T*) required for the given load disturbance reduces the speed deviation signal to 0.0 p.u. and then settles at its equilibrium point 0.0. per unit. The actual speed (N) of HDGT plant reaches the desired speed of 1.0 p.u.

Fig. 11



Dynamic response of Wf2, Tt, T, and N with different Controllers

With respect to all the dynamic responses of state variables, F-PID reacts faster during dynamic and steady-state period. The time-domain parameters and error indices also witness that fuzzy logic technique based PID improves both the transient and steady-state performances. In addition, the response of the state variables also indicates that the HDGT plant can be more stable with fuzzy tuned PID controller. Hence the Fuzzy gain scheduled PID controller is found to be an adaptive PID controller for HDGT plant in interconnected operation.

5 Conclusion

HDGT plants with droop governor require an effective secondary controller to improve the steady-state and dynamic behavior. Modeling of gas turbine and control using fixed gain and Fuzzy logic tuned PID controllers have been presented in this paper. Simulation results of 5001M HDGT model based on time-domain parameters and performance indices prove that F-PID tuned PID can perform better under load disturbances. Further, the reliable operation of HDGT has also been ensured by analyzing the behavior of state variables during uncertainties. The dynamic responses show that fuzzy gain scheduled PID controller responds faster for the load disturbances and hence provides stable operation irrespective of the turbine speed variation and rotor time constant. Therefore, the fuzzy logic-based PID controller is considered to be the adaptive controller for grid-interactive gas turbine plants.

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Author information

Authors and Affiliations

Department of Electrical and Electronics Engineering, PSG Institute of Technology and Applied Research, Coimbatore, Tamil Nadu, India
Mohamed Iqbal Mohamed Mustafa

Corresponding author

Correspondence to Mohamed Iqbal Mohamed Mustafa .

Editor information

Editors and Affiliations

Department of Electronics and Communication Engineering, Jaypee University of Information Technology, Waknaghat, Himachal Pradesh, India
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