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Small and large signal modeling of heavy duty gas turbine plant for load frequency control

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ABSTRACT

In this paper, the transfer function model of heavy duty gas turbine has been developed for doing load frequency control studies. Based on the large signal model of Rowen, small signal model has been developed. This model is much suitable for doing Automatic Generation Control. Proportional integral and derivative secondary controller has been developed for both the small and large signal models to improve the system response. Ziegler Nichols' method, Simulated Annealing and Fuzzy Gain Scheduling have been used for tuning the secondary controller. Ziegler Nichols' method is used as conventional tuning, whereas Simulated Annealing is a search based tuning and Fuzzy Gain Scheduling is adaptive. It is found that Simulated Annealing tuned Proportional Integral Derivative Controller yields better response than other two controllers in both large signal and small signal model of heavy duty gas turbine plant.

Introduction

Gas turbine plants are used in isolated operation and small networks. They are commonly deployed in bio mass plants, offshore installation and oil fields in desert area. The gas turbine plants are highly sensitive to load disturbance. For the efficient and stable operation, effective controllers are required. For the optimal design of controllers, modeling of the system is essential.

Based on investigation and experiments, Rowen has presented the simplified mathematical model of the heavy duty gas turbine plant [1]. Rowen model is validated by conducting tests [2]. Later, the model is used for twin shaft combustion turbine [3], prime movers and energy supply models [4] and micro turbine model [5,6]. Large signal approach is carried out in this modeling. The modeling is used by many researchers in developing the optimal controller for gas turbine plant using Artificial Neural Networks [7], Fuzzy Logic Controller [8], Neuro Fuzzy [9] and Genetic Algorithm [10]. The parallel operation of gas turbine plant is also performed using Rowen's model [11,12].

In Load Frequency Control (LFC), small signal approach is globally followed by the researchers [13]. Since large signal based transfer function model is developed by Rowen, performing LFC on gas turbine is found to be difficult. Appropriate modifications are to be carried out on the large signal model to convert it into small signal model. Modeling combined cycle power plant for simulation of frequency excursion, comparative analysis of gas turbine model and utility experience with gas turbine paved the way for small signal model [14–16].

Researchers have modified the Rowen model and developed the small signal model based on [14–16]. Such a model is used for multi source multi area system in load frequency control applications [17–19]. In those models, fuel control limitation and turbine characteristics are not considered. These effects did not create significant impact in their results due to dominant governor and power system characteristics.

In this paper, large signal model of gas turbine proposed by Rowen is presented. Based on this, small signal model is developed considering all the factors discussed by Rowen. This small signal model is more suitable for doing load frequency study. Both the small and large signal models of gas turbine models are simulated and appropriate secondary Proportional Integral Derivative (PID) controller is designed using Ziegler Nichols' (ZN) method, Simulated Annealing (SA) and Fuzzy Gain Scheduling (FGS). The performance of all the controllers are judged based on performance indices and the best controller is identified.

Section 'Modeling of Gas Turbine Plant' presents the modeling of small and large signal gas turbine model. The different tuning methodologies of PID controller are presented in Section 'Develop ment of Controller'. Section 'Simulation Results and Discussions' explains the simulation and comparative performance analysis of PID controller on gas turbine models. The conclusion is presented in Section 'Conclusion'.

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Modeling of gas turbine plant

The transfer function model of heavy duty gas turbine plant has been developed by Rowen [1]. He has presented the large signal model of the gas turbine plant. The governing equations of each component in gas turbine plants are developed by conducting suitable tests. Speed governor, valve positioner, fuel system, turbine and rotor are the major components of the gas turbine plant.

While doing load frequency control analysis, the large signal model developed by Rowen is not suitable. Small signal model of gas turbine is required to perform load frequency control analysis and design of suitable controllers for the effective performance. This can be obtained by differentiating the large signal model developed by Rowen. The system is assumed to be operating in linear region for converting large signal model to small signal model.

Speed governor

Speed governor is the control device in the gas turbine plant for controlling the speed of the system. It can be either droop or isochronous type. The output of the speed governor is proportional to the error in speed in case of droop governor. The rate of change of output is proportional to the speed error in case of isochronous type. Eq. (1) express the speed governor as modeled by Rowen [1]

$$\mathrm{VCE}(s) = \frac{W(Xs+1)}{Ys+Z}e(s) \tag{1}$$

Based on small signal modeling of speed governor in thermal power plant [13], the speed governor of gas turbine represented in Eq. (1) is modified for small signal and presented in Eq. (2)

$$\Delta\mathrm{VCE}(s) = \left(\Delta P_{\mathrm{ref}}(s) - \frac{1}{R}\Delta f(s)\right)\frac{Xs+1}{Ys+Z} \tag{2}$$

Since 23% of the total fuel is required for the self sustained operation of gas turbine, only 77% of fuel is controllable. This is incorporated in the large signal model as represented in Eq. (3)

$$F_d(s) = (0.77 * \mathrm{VCE}(s)) + 0.23 \tag{3}$$

For small signal model, Eq. (3) is differentiated and presented in Eq. (4)

$$\Delta F_d(s) = 0.77 * \Delta\mathrm{VCE}(s) \tag{4}$$

Valve positioner

The valve positioner of gas turbine in large signal presented in Eq. (5) is differentiated to obtain the small signal model and presented in Eq. (6)

$$e_1(s) = \frac{a}{bs+C}F_d(s) \tag{5}$$

$$\Delta e_1(s) = \frac{a}{bs+C}\Delta F_d(s) \tag{6}$$

Fuel system

Similar to valve positioner, the fuel system of large signal model in Eq. (7) is modeled for small signal and furnished in Eq. (8)

$$F_s(s) = \frac{1}{\tau_f s+1}e_1(s) \tag{7}$$

$$\Delta F_s(s) = \frac{1}{\tau_f s+1}\Delta e_1(s) \tag{8}$$

Turbine dynamics and turbine

By conducting suitable experiments on gas turbine, Rowen has provided the gas turbine dynamic behavior as in Eq. (9). The torque output of the gas turbine is presented in Eq. (10). For stiff system, torque output in Eq. (11) is suitable.

$$W_f(s) = \frac{1}{\tau_{CD}s+1}F_s(s) \tag{9}$$

$$T_d(s) = 1.3(W_f(s) - 0.23) + 0.5(1 - N(s)) \tag{10}$$

$$T_d(s) = 1.3(W_f(s) - 0.23) \text{ for stiff system} \tag{11}$$

To obtain the small signal model of the turbine modeling, Eqs. (9)–(11) are modified and presented in Eqs. (12)–(14)

$$\Delta W_f(s) = \frac{1}{\tau_{CD}s+1}\Delta F_s(s) \tag{12}$$

$$\Delta T_d(s) = 1.3\Delta W_f(s) - 0.5\Delta N(s) \tag{13}$$

$$\Delta T_d(s) = 1.3\Delta W_f \text{ for stiff system} \tag{14}$$

Power system

In large signal model, the toque is converted to speed based on the rotor time constant (τ_1) using Eq. (15)

$$N(s) = (T_d - T_L)\frac{1}{\tau_1(s)} \tag{15}$$

For doing load frequency control analysis, the significant state variable i.e., change in frequency is computed from change in torque as expressed in Eq. (16). The power system modeling is similar to that of thermal power plant [13].

$$\Delta f(s) = (\Delta T_d(s) - \Delta T_L(s))\frac{K_p}{1+T_p s} \tag{16}$$

Based on Eqs. (1), (3), (5), (7), (9)–(11) and (15), the large signal transfer function model of heavy duty gas turbine plant has been developed and presented in Fig. 1.

Based on Eqs. (2), (4), (6), (8), (12)–(14) and (15), the small signal transfer function model of heavy duty gas turbine for load frequency control has been developed and presented in Fig. 2.

The large signal model is majorly used for analyzing the gas turbine operating independently. Developing controllers and control strategy for parallel operation among gas turbine is done using large signal model of gas turbine. In case of interconnected operation of gas turbine with power system, small signal model is preferred. Load frequency control, deregulated operation and control, and design of controllers can be done only through small signal model.

Development of controller

Due to the drooping characteristics of the governor in gas turbine plant, the speed of large signal model and change in frequency of small signal model will not settle at rated speed and zero change in frequency respectively. This drooping characteristic can be overcome by including a secondary PID controller [20] presented in Eqs. (17) and (18) for large and small signal model respectively.

$$u(s) = \left(k_P + \frac{k_I}{s} + k_D s\right)e(s) \tag{17}$$

$$\Delta P_{\mathrm{ref}}(s) = \left(k_P + \frac{k_I}{s} + k_D s\right)\Delta f(s) \tag{18}$$

The PID controller varies the governor input and power reference setting in large signal and small signal model based on error in speed and change in frequency respectively. In this paper, PID

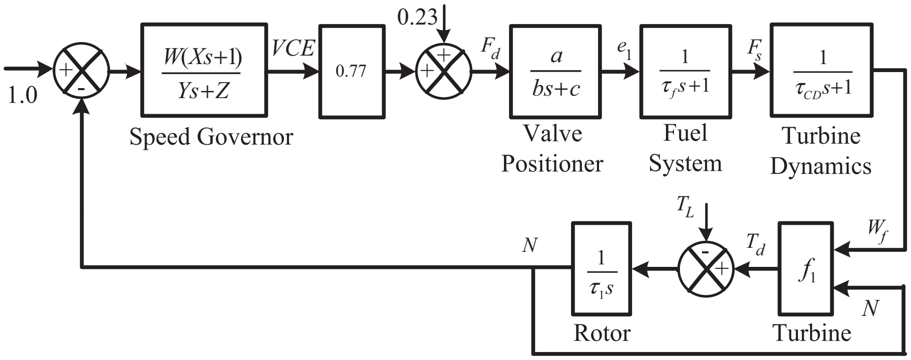

Fig. 1. Transfer function model of gas turbine plant for large signal analysis.

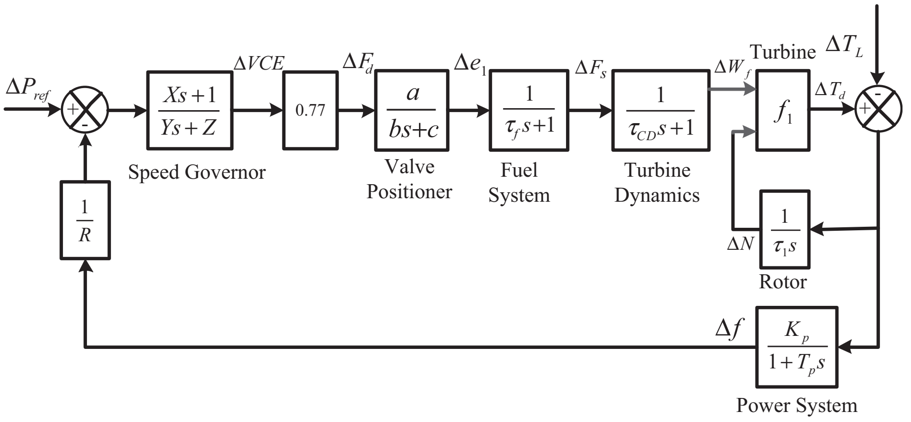

Fig. 2. Transfer function model of gas turbine plant for small signal analysis.

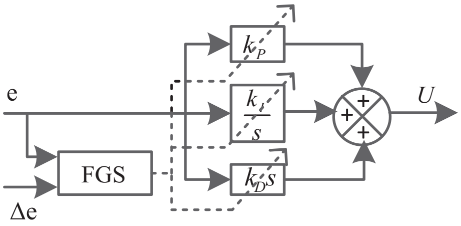

Fig. 3. Fuzzy scheduled PID controller.

Table 1
Fuzzy rules for scheduling PID gain values.

$\Delta e/e$	N			Z			P		
	k_P	k_I	k_D	k_P	k_I	k_D	k_P	k_I	k_D
N	N	N	P	N	N	P	Z	Z	Z
Z	N	N	P	Z	Z	Z	P	P	N
P	Z	Z	Z	P	P	N	P	P	N

Table 2
Gain values of PID controller for gas turbine plant in large signal analysis.

Tuning method	k_P	k_I	k_D
ZN tuned PID	15.5478	0.2633	3.127
SA tuned PID	3.2999	2.5538	2.0235

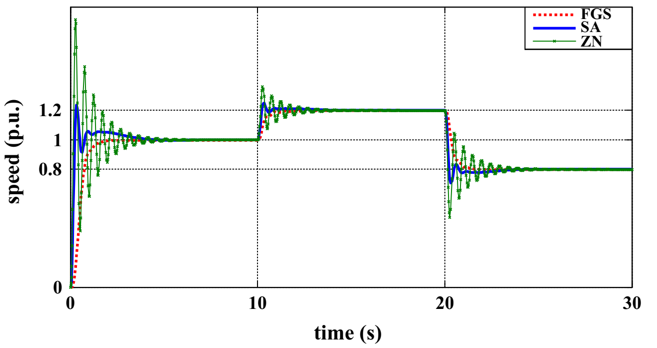

Fig. 4. Large signal comparison analysis of gas turbine plant controlled by ZN, SA and FGS tuned PID controller.

Table 3
Performance analysis of large signal modeled gas turbine plant with different controllers.

Secondary controller	ITAE	ISE	ITSE
FGS PID	5.844	0.2568	1.104
SA tuned PID	3.703	0.1542	0.4843
ZN tuned PID	8.293	0.3551	1.234

controller is tuned using ZN method [21], SA method [22,23] and FGS [24]. ZN is used for bench marking, SA is for optimal search and FGS is for adaptive gain.

SA is used to optimize the PID controller gain values using change in frequency and error in speed as objective function for

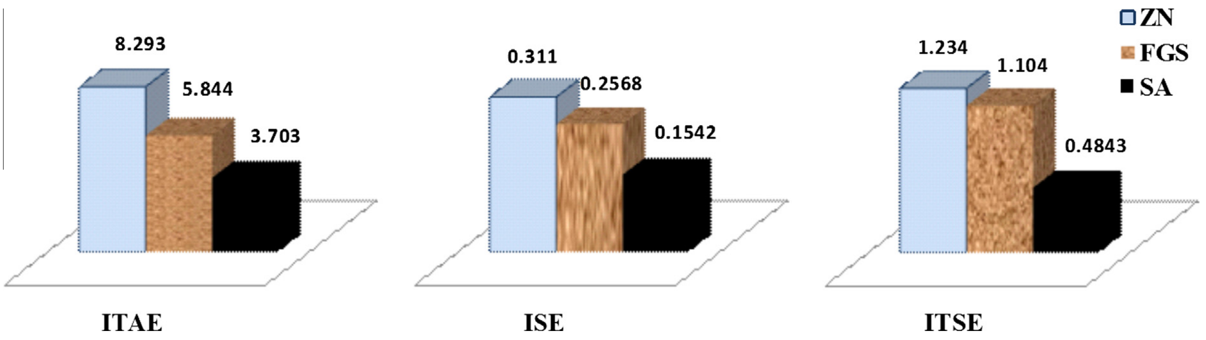

Fig. 5. Performance indices based comparison of large signal modeled gas turbine plant with FGS, SA and ZN controllers.

Table 4
Gain values of PID controller for gas turbine plant in small signal analysis.

Tuning method	k_P	k_I	k_D
ZN method	0.5365	0.4645	0.0992
SA method	1.2012	5.4730	1.0090

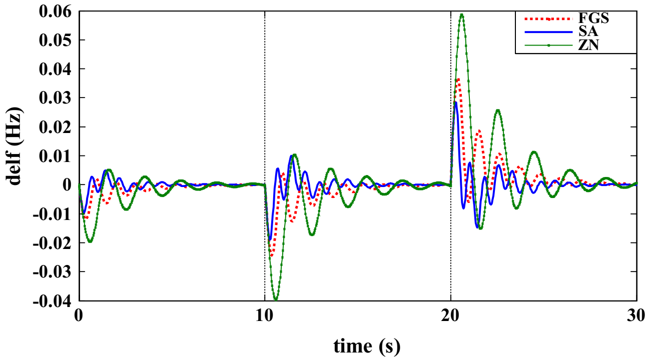

Fig. 6. Small signal comparison analysis of gas turbine plant controlled by ZN, SA and FGS tuned PID controller.

Table 5
Performance analysis of small signal modeled gas turbine plant with different controllers.

Secondary controller	ITAE	ISE	ITSE
FGS PID	1.305	0.0012	0.0191
SA tuned PID	0.8177	0.0005	0.0081
ZN tuned PID	2.888	0.0042	0.0701

small signal and large signal model respectively. The variables to be optimized are 3. In Simulated Annealing, search space is explored based on temperature. Initially the temperature is chosen to be 100 and decrements slowly in the search space with every 10% setting to its new equilibrium state with more number of states on following with Boltzmann probability distribution. The stopping criteria based on error minimization is, best function value equals the current function value.

In FGS, error in speed and change in error in speed are used as the inputs for large signal whereas, change in frequency and derivative of change in frequency are used as inputs in small signal model. Both inputs and output are of three trapezoidal membership functions. The Input range for error and change in error are $[-1\ 1]$ and $[-3\ 3]$ whereas for output is $[-3\ 3]$. The range is applicable for all the controller gains. For small signal modeling, the outputs of FGS are scaled by 0.3, 0.2 and 0.05 for k_P, k_I and k_D respectively. The structure of FGS and the rules are furnished in Fig. 3 and Table 1.

Simulation results and discussions

The transfer function model of large signal heavy duty gas turbine plant shown in Fig. 1 has been developed in MATLAB Simulink. To overcome the drooping characteristics of the speed governor, a secondary PID controller is included as explained in Section 3. The PID controller gain values tuned using ZN and SA methods are furnished in Table 2. The ZN, SA and FGS tuned PID controller are incorporated to the gas turbine plant and simulated with a unit step load disturbance at zero time with speed reference as 1.0 p.u. Later, the speed reference is changed to 1.2 p.u. at 10 s and to 0.8 p.u. at 20 s. The response of the system with different controllers is furnished in Fig. 4.

The comparison response clearly shows that, all the three controllers remove the offset. To identify the optimal controller, the performance indices [25] like Integral Time Absolute Error (ITAE), Integral Square Error (ISE) and Integral Time Squared Error (ITSE) are calculated using Eqs. (19), (20) and (21) respectively. The calculated ITAE, ISE and ITSE are furnished in Table 3 and as bar chart in Fig. 5.

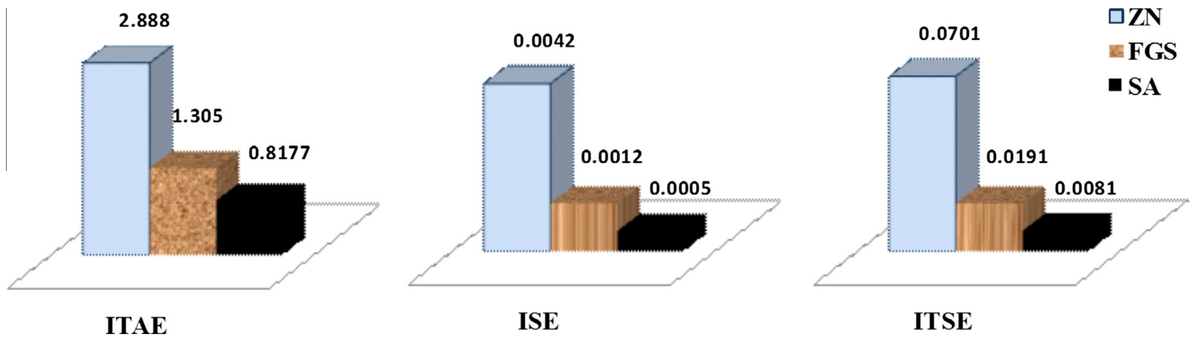

Fig. 7. Performance indices based comparison of small signal modeled gas turbine plant with ZN, SA and FGS controllers.

$$\mathrm{ITAE} = \int |e| t \, dt \tag{19}$$

$$\mathrm{ISE} = \int e^2 \, dt \tag{20}$$

$$\mathrm{ITSE} = \int e^2 t \, dt \tag{21}$$

The comparison based on Table 3 and Fig. 5 show that SA tuned PID controller follows the change in speed reference much better than ZN and FGS tuned PID controller.

The small signal analysis model of heavy duty gas turbine plant presented in Fig. 2 is developed in MATLAB Simulink with PID controller tuned using ZN, SA and FGS. The ZN and SA tuned values of PID controller are furnished in Table 4. The system is simulated for 1% step load increase, 2% step load increase and 3% step load decrease at 0 s, 10 s and 20 s respectively. The simulated response is presented in Fig. 6. To identify the better controller, the performance indices are measured using Eqs. (19)–(21). For comparison, the measured values are tabulated in Table 5 and presented as bar chart in Fig. 7.

From the performance indices, it is evident that SA tuned PID controller is more suitable for heavy duty gas turbine plant under large and small signal analysis.

Conclusion

The transfer function model of heavy duty gas turbine plant for small signal analysis is derived from the large signal model. The response of the system is improved with the help of secondary PID controller. Using ZN, SA and FGS, the PID controller gain values are tuned. The large signal model is tested with the changes in the speed reference. The small signal model is tested for load variations with different magnitude at different time. The performances of the different PID controllers are tested for these disturbances using performances indices ISE, ITSE and ITAE. On comparing the performance indices of PID controllers in the small and large signal modeled gas turbine plant based, it is found that SA tuned PID controller provides better response than ZN and FGS tuned PID controller.

Appendix A

s	laplace operator
VCE	governor output (p.u.)
e	error in speed (p.u.)
W, X, Y, Z	speed governor constants; $X = 0$; $Y = 0.05$; $Z = 1$; $W = K_D = 1/\mathrm{droop}$
K_D	governor gain 2–10%
e_1	valve positioner output (p.u.)
a, b, c	valve positioner constants; $a = 1$; $b = 0.05$; $c = 1$
F_s	fuel system output (p.u.)
τ_f	fuel system time constant; 0.4
W_f	gas turbine dynamic characteristics
τ_{CD}	compressor discharge volume time constant; 0.1
T_d	turbine torque (p.u.)
N	turbine rotor speed (p.u.)
T_L	load torque (p.u.)
u	PID controller output
τ_1	turbine rotor time constant; 15.1
Δf	change in system frequency (p.u.)
K_p, T_p	power system constants; 100, 20
ΔP_{ref}	change in power reference setting (p.u.)
R	governor droop setting (Hz/p.u. MW)
k_P, k_I, k_D	proportional, integral and derivative controller gain respectively

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