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

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A B S T R A C T

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