International Journal Of Engineering Research And Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 20, Issue 6 (June, 2024), PP. 73-78

Enhancing Load-Frequency Control System of Gas Turbine Using Non-linear Design Technique Based PID Controller

Amabikutol Emmanuel Jonathan
[1]*Department of Electrical and Electronic Engineering*
Federal University Otuoke
Otuoke, Nigeria

ABSTRACT *The significance of efficient control system for load-frequency conditioning in gas is that it makes sure that both quality and reliable transient response are achieved. This paper presents the design of a load-frequency control (LFC) system for enhancing response performance of a gas turbine. The model dynamic of a simple-cycle, single shaft heavy duty gas turbine operating at nominal conditions for speed/load-frequency control was obtained. A proportional integral and derivative (PID) compensator was designed using a nonlinear model of the MATLAB/Simulink. The PID was integrated with the Simulink model of a gas turbine. Simulations were conducted for unit step speed with the initial analogue compensator, and then with the designed PID compensator. The results showed that both compensators were able to achieve the design specification. The PID was then improved by adding a low pass filter to the derivative component. Simulation was then performed with the improved PID, and the result showed that the overshoot level was significantly reduced. This indicated an improvement in the transient response performance and hence better stability in nominal speed/load-frequency operating condition*

Date of Submission: 12-06-2024 Date of Acceptance: 24-06-2024

I. INTRODUCTION

Gas turbines are widely used as power generating engines because they are flexible and have low investment cost. They are one of the most important sources of power generation for nations with natural gas resources [1]. Manufacturing of efficient, reliable and durable gas turbines requires dynamic modeling and simulation. According to [2] the traditional role of the gas turbine as fast response unit, ideal for improving primary control response of the power system, has been to a certain extent lost, due to relatively high constraints in ramping up and down the power output during the normal operation. Also, accurate modeling of power components is required for power system stability [2]. A simplified model presented by Rowen [3] has been used frequently for the study of gas turbine.

The stability study of a gas turbine is basically performed on basis of three control loops: load-frequency control, temperature control and acceleration control. The acceleration control is concerned with the control of the acceleration rate of the gas turbine during the acceleration to operating speed. The acceleration control output is restricted by the minimum fuel limit to maintain flame. The speed control takes care of the speed of the gas turbine at operating speed when the turbine is not synchronized to the power system or is selected by the operator to perform frequency control in a multi-machine interconnected system. The speed control is restricted by the minimum fuel limit. The load control functions in normal parallel operation to observe a base or a peak load limit based on temperature control. Load is controlled by changing the speed/load set point. The exhaust temperature control controls fuel so as to provide a controlled temperature increase or decrease and an upper limit for normal operation. The average value of the thermocouples sorted highest to lowest is the exhaust temperature feedback.

The control loop mainly active when the gas turbine is operating at nominal conditions is the load-frequency control (LFC). The input to this control is the speed/load set-point. The control section is restricted by the minimum fuel limit. The speed control or LFC is also the most important aspect during stability study. The dynamics of the parts of the gas turbine that are essentials in analysing the transient characteristics of a load-frequency control in gas turbine are considered in this paper.

A simplified mathematical model of a heavy-duty single-shaft gas turbine was presented by [3]. In order to include features that were not in the previous work, [2] presented a mathematical model of the same gas turbine with characteristics and features that affect the application of this kind of gas turbine to mechanical drive systems with variable speed in [4]. Yee et al [5,6] carried out a comparative analysis and overview of different existing models of power plant gas turbines. A similar work was carried out by [7]. They carried out a complementary and comparative analysis of different gas turbine models response in terms of their applications and accuracy.

A new control system that uses steam injection as an auxiliary input to improve the transient performance of the single-shaft gas turbine during frequency drops was proposed by [8]. The performance of the proposed control algorithm was investigated under different scenarios and the results showed that the application of steam injection improves the performance of the regular control algorithm significantly, especially near full load condition. Hassan et al [1] carried out a simple procedure for estimating the parameters of Rowen's model for heavy duty gas turbines (HDGTs) in dynamic studies for analysis purposes. The parameters of a 265MW HDGT were derived using Rowen's model and several simulations were performed in MATLAB/Simulink. A study on load frequency control in a single area power system was carried out by [9]. It stated that the goal of a load frequency control was to minimize the transient variations of the power system variables and also to ensure that steady state errors were zero. The objective of the research was to study the reliability the various control techniques of load frequency control through simulations perform in the MATLAB/Simulink environment.

In this paper, the dynamic equations of a single shaft gas turbine are obtained and are modeled using Simulink blocks. A nonlinear proportional integral and derivative (PID) compensator is designed and integrated with a Simulink model of a gas turbine. The aim is to design a control system that will improve the response performance of a gas turbine.

II. MATHEMATICAL MODEL OF GAS TURBINE AND CONTROL SYSTEM DESIGN

Gas turbine has three basic control loops but the loop mainly responsible during nominal operation is the load-frequency control (LFC). This paper is concerned with the model of a gas turbine for LFC. Thus, this section is divided into two subsections as follows.

2.1 Mathematical Model of Gas Turbine

Fuel System

The fuel system of a gas comprises the fuel valve and actuator. The valve positioner regulates the fuel injection into a gas turbine. The valve positioner equation in the form of a transfer function is given as in [3]:

$$V(s) = \frac{a}{bs + c} \tag{1}$$

where a, b, and c are the valve positioner constants.
The transfer function of the fuel system is:

$$F(s) = \frac{1}{T_{fc}s + 1} \tag{2}$$

T_{fc} is the fuel system actuator time constant in seconds.
The block diagram of the fuel system is show in Figure 1.

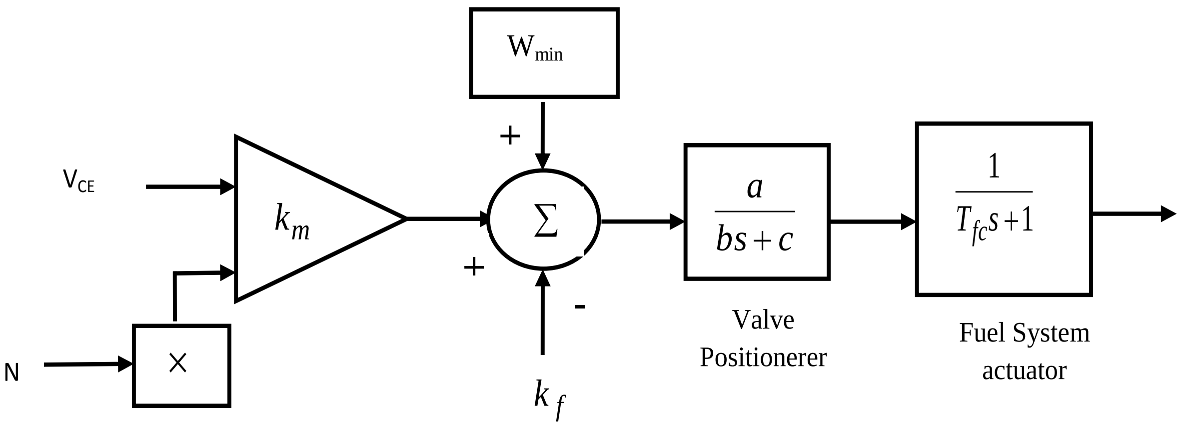

Figure 1: Block representation of the fuel system

The output of the least value gate (LVG) is V_{CE}. It governs the least amount of fuel needed for a given operating point and also an input to the fuel system. N is the turbine speed expressed in per unit (p.u.) and also serves as an input to the fuel system. W_{min} is the minimum amount of fuel flow. k_m is equal to 1-W_{min} and k_f is the fuel system feedback.

Compressor-Turbine System

The time delay combustion of fuel in the combustor is given by:

$$e^{-sT_{CR}} \tag{3}$$

T_{CR} is the combustion reaction time delay constant in seconds.

The hot computation gas expansion is expressed as a transfer function given by:

$$T(s) = \frac{1}{T_{CD}s+1} \tag{4}$$

T_{CD} is the compressor discharge volume time constant in seconds.

The block diagram of compressor-turbine dynamics is shown in Figure 2 and the electric generator connected to gas turbine is driven by mechanical torque given in [3] by:

$$T_m = 1.3*(W_f - 0.23) + C(1-N) \tag{5}$$

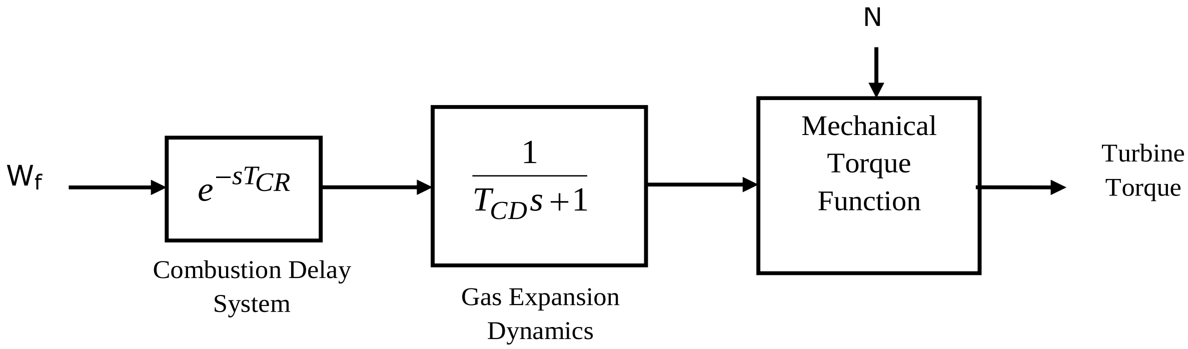

Figure 2: Block representation of compressor-turbine dynamics

The value of C varies between 0.5 and 0.67 [10]. The value of C has been selected as 0.5 here. The constant 0.23 takes care of typical fuel rate characteristics. It rises linearly from zero power state at 23% fuel rate to 100% rated output [11]. W_f is the fuel demand signal in p.u.

The Simulink block of a typical an analogue governor/compensator is shown in Figure 3 for a simple-cycle, single shaft heavy duty gas turbine operating at nominal conditions for speed/load-frequency control.

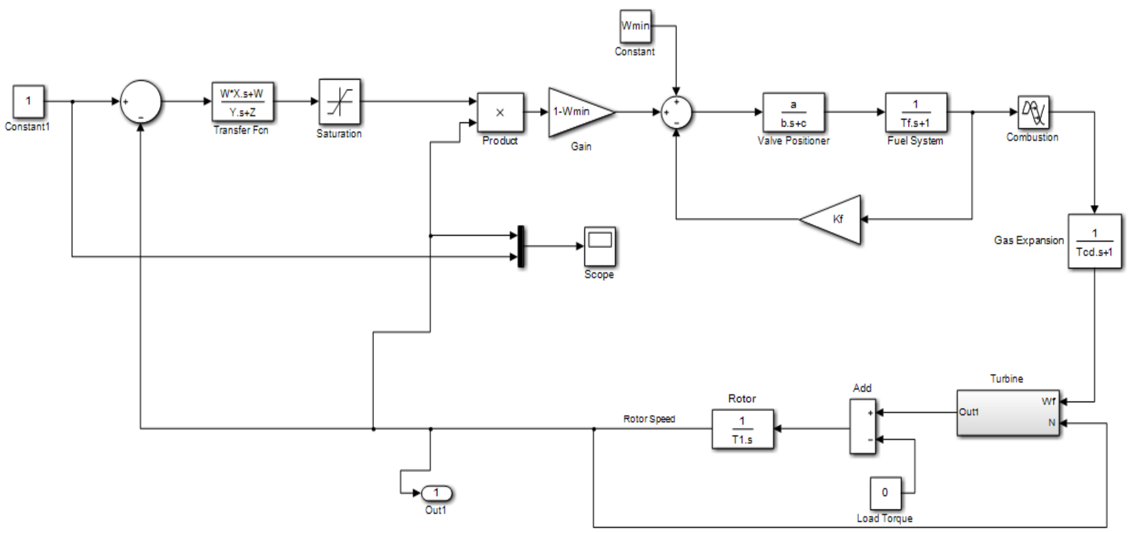

Figure 3: Simulink model of gas turbine for LFC with analogue compensator

The model parameters of [12] are used in this paper and are shown in Table 1 for a typical single-shaft, simple-cycle, heavy duty gas turbine (HDGT) operating at nominal conditions, which integrates an analogue compensator.

Table 1: Model Parameters and Numerical Values [12]

Parameter	**Symbol**	**Unit**	**Values**
Governor speed gain=1/droop	W	p.u.	16.7
Governor lead time constant	X	sec.	0.6
Governor lag time constant	Y	sec.	1.0
Control mode (1=droop, 0= isochronous)	Z	-	1
Upper limit of fuel demand	F_{max}	p.u.	1.5
Lower limit of fuel demand	F_{min}	p.u.	-0.1
Valve positioned	a	-	1
Valve positioned	b	-	-0.1
Valve positioned	c	-	1
Minimum fuel flow	W_{min}	-	0.23
Fuel control time constant	T_{FC}	sec.	0.4
Fuel system feedback	K_{FB}	-	0
Combustion reaction time delay constant	T_{CR}	sec.	0.01
Compressor discharge volume time constant	E_{CD}	sec.	0.2
Turbine inertia constant	T_I	sec.	15.64

2.2 Control System Design

The parameters of a PID controller are usually determined by a selection process called tuning. In the literature, the Ziegler-Nichols methods and its modified version are often used [13][14][15]. In this context, a numerical technique is employed using the optimization toolbox in Simulink. Using the Simulink design optimization toolbox requires that the output of the plant, which in this case is the rotor speed, be constrained to the desired step response based on the specification of the design. The design specification in this case is: 5% overshoot and 20 seconds settling time.

The parameters of the initial compensator [12] as in Table 1 were used first for the simulation and the step response obtained is shown in Figure 4. The Equation of the initial compensator is given by:

$$G_c = \frac{W*X+W}{Ys+Z} \tag{6}$$

Substituting values in Table 1 gives:

$$G_c = \frac{10.02s+16.7}{s+1} \tag{7}$$

The nonlinear optimized PID compensator designed with this approach is given by:

$$C(s) = K_p + K_i\frac{1}{s} + K_d s \tag{8}$$

$$= 120 + \frac{0.000000987}{s} + 21.58s \tag{9}$$

The nonlinear PID controller was further modified by adding a low pass filter to the derivative components and this defined by:

$$C(s) = K_p + K_i\frac{1}{s} + K_d\left(\frac{Ns}{s+N}\right) \tag{10}$$

$$= 120 + \frac{0.000000987}{s} + \frac{215.8s}{s+10} \tag{11}$$

The simulation results for the different compensator are presented in Figures 4, 5, and 6.

III. SIMULATION RESULTS AND DISCUSSION

3.1 Simulation Results

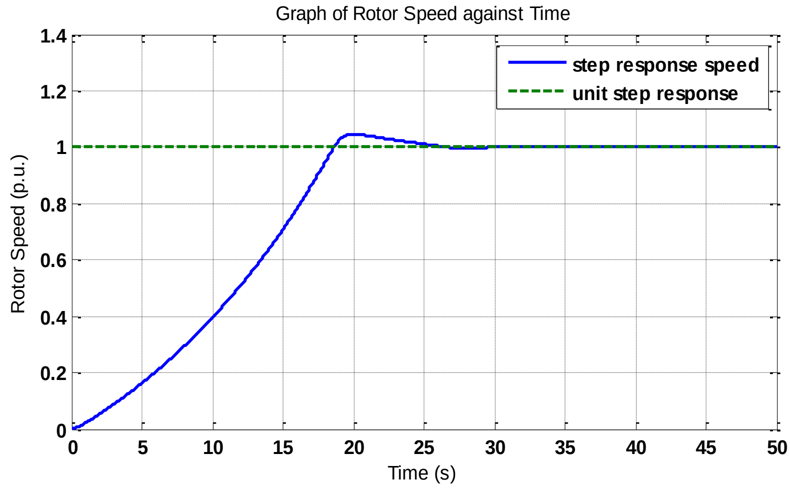

Figure 4: Speed control step response with initial compensator

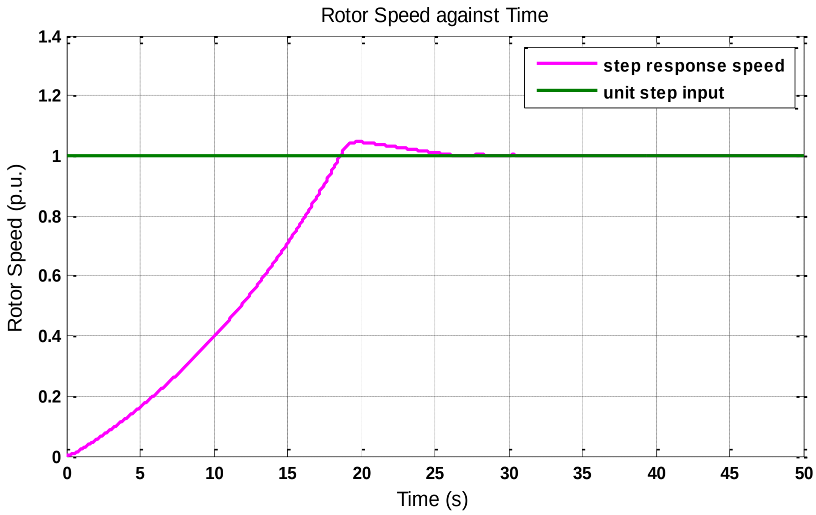

Figure 5: Speed control step response with optimized PID compensator

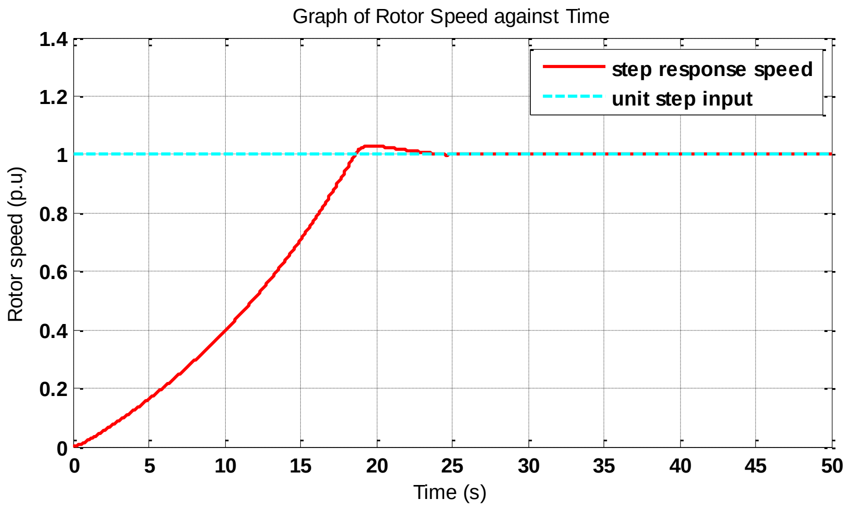

Figure 6: Speed control step response with modified PID compensator

3.2 Discussion

The simulations of the speed control system conducted in Matlab/Simulink environment are presented in Figures 4, 5, and 6. In Figure 4, the simulation result showed a transient response performance of the control system using the initial compensator maintained at the designed specification. In order to test the effectiveness of the designed PID compensator, the rotor speed of gas turbine is measured at nominal conditions and compared to a unit step reference speed (1p.u). The simulation performed as shown in Figure 5 demonstrated that the PID was able to meet the designed specification. In Figure 6, the simulation result for the improved optimized PID compensator showed that the overshoot level of the transient response of the speed control system has been significantly reduced, which indicates improvement. Hence, the stability performance of gas turbine is improved during nominal operation. In all cases a settling time of 20 seconds was achieved.

IV. CONCLUSION

The nonlinearity of the gas turbine model has resulted in using a nonlinear control approach to design an optimized the PID compensator in this paper. The focus of the study was on the design of a controller to enhance the transient response performance of a gas turbine. In order to achieve this, local response performance were imposed on the system by constraining the response output to meet the design specification.

The optimized algorithm of the controller was developed and simulated using the nonlinear block of the MATLAB/Simulink. The effectiveness of the designed controller is shown by the simulations. Hence, a control system that is easily implemented in conventional power system analysis tools for speed/ load-frequency control (LFC) is presented.

This paper only addresses transient performance of LFC in a gas turbine. It is desired to carry out detail analysis of gas turbines in power system by reviewing their dynamic models and improving their control systems in future work.

REFERENCES

[1]. Hassan Moustafa M.A., Emam Shalan H. and Bahgat A.B., Parameter Estimation and Dynamic Simulation Of Gas Turbine Model In Combined Cycle Power Plants Based On Actual Operational Data, Journal of American Science,7(5), pp. 303-310, 2016.

[2]. Sergiu St. Iliescu, Ioana Făgărăşan, Victor Popescu, and Călin Soare, Gas Turbine Modeling for Load-Frequency Control U.P.B. Sci. Bull., Series C, Vol. 70, Issue 4, pp.1-8, 2008,

[3]. Rowen W. I., Simplified mathematical representations of heavy-duty gas turbines, ASME J. Eng. Power, Vol. 105, 983, pp. 865–869, 1983,.

[4]. Rowen W.I., Simplified Mathematical Representations of Single Shaft Gas Turbines in Mechanical Drive Service, Turbo machinery International, pp. 26-32, 1992.

[5]. Yee S. K., Milanovic´ J. V. and Hughes F. M., Overview and Comparative Analysis of Gas Turbine Models for System Stability Studies, IEEE Transactions on Power Systems, vol. 23, no. 1, pp. 108-118, 2008.

[6]. Yee S. K, Milanovic´ J. V. and Hughes F. M., Validated Models for Gas Turbines Based on Thermodynamic Relationships, IEEE Transactions on Power Systems, vol. 26, no. 1, pp. 270-281, 2011.

[7]. Shalan H. E. M. A, Moustafa Hassan M. A., Bahgat A. B.G., Comparative Study on Modeling of Gas Turbines in Combined Cycle Power Plants, Accepted for presentation at 14th MEPCON2010 Conference, Organized by Elec. Power Dept., Cairo University, Egypt, Dec. 2010.

[8]. Saeed Bahrami , Ali Ghaffari and Marcus Thern, Improving the Transient Performance of the Gas Turbine by Steam Injection during Frequency Dips, Energies, 6, 5283-5296, 2013, doi:10.3390/en6105283

[9]. Pranab Patnaik ,Load Frequency Control in a single Area Power System, A Thesis submitted to the Department of Electrical Engineering, National Institute of Technology, Rourka -789008, pp.1-35, 2013,

[10]. BankTavakoli M. R., Vahidi B., and Gawlik W., An Educational Guide to Extract the Parameters of Heavy Duty Gas Turbines Model in Dynamic Studies Based on Operational Data, IEEE Trans. Power Syst., vol. 24, No. 3. August 2009.

[11]. Godswill Ofualagba, The Modeling and Simulation of a Microturbine Generation System, International Journal of Scientific and Engineering Research, vol.2, Issue 2, pp. 1-7, February-2012,

[12]. Hajagos L.M., Berube G.R., Utility experience with gas turbine testing and modeling, Power Engineering Society Winter Meeting, , **Vol. 2**, pages 671-677, 2001.

[13]. Garcia, D., Karimi, A., Longchamp, R. and Dormido, S., PID controller design with constraints on sensitivity functions using loop slope adjustment, in Proceedings of the 2006 American Control Conference, Minneapolis, Minnesota, USA', pp. 268 -273., 2006.

[14]. O'Dwyer, A., Handbook of PI and PID Controller Tuning Rules (3rd edn, Imperial College Press, London, 2009)

[15]. Ogata, K., Modern Control Engineering (fourth edn, Prentice-Hall, Inc. Upper Saddle River, New Jersey, 2002)