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Robust Set-Point Weighted PID Controller Design using Genetic Algorithm for Electric Furnace Temperature Control System

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Abstract: This article explores the methodology to design an efficient controller for electric furnace temperature control system. Because of the presence of significant amount of nonlinearity and time variability, it becomes very difficult to design a suitable controller to control the temperature of the electric furnace system. But in many practical problems, it is of prime importance to maintain a stable temperature profile of the electric furnace. In this paper, the design of Set-Point Weighted Proportional Integral Derivative (SPWPID) controller has been considered and the controller parameters have been optimized using Genetic Algorithm (GA). The performance of the system with this SPWPID controller has been compared with that of the conventional PID controller designed using Ziegler-Nichols, Cohen-Coon, Direct Synthesis and Nelder-Mead method. The result of comparison reveals the superiority of SPWPID controller over the PID controller designed using different methods. For this electric furnace system with SPWPID controller, robustness analysis has been performed and the result clearly indicates the system to be robust. As a further scope of research, fractional order SPWPID controller will be designed in future for this system and it is expected to show more robust and improved performance as compared to the above mentioned controllers.

Keywords : Electric Furnace; Temperature Control; PID, Set-Point Weighted PID (SPWPID); GA.

1. INTRODUCTION

The electric furnace is one variant of the furnaces available today for domestic and commercial use. Its application can be found from household to industries. For producing heat, it uses electricity as the main power source. The design of a controller for this system is a challenging task because of the nonlinearity and time variability present in this system. The controller in an electric furnace system plays an important role as the temperature control of the system is a matter of great importance for maintaining a certain temperature level within the furnace. There are different control strategies available for controlling the temperature of electric furnace system which includes the use of classical methods to soft computing-based methods. In [1], the performance of PID controller using Ziegler-Nichols, Cohen-Coon, Direct Synthesis and Nelder-Mead method for the temperature control of electric furnace system is provided The design of PID controller for temperature control system using Genetic Algorithm has been explained in [2]. Wang *et al.* in their paper [3] discussed the design of fractional order controller using Particle Swarm Optimization for electric furnace temperature control. In [4], for a temperature control system, recurrent neural fuzzy network controller has been designed. Han *et al.* explained temperature control of electric furnace system using fuzzy PID controller [5]. Chang *et al.* discussed single parameter PID controller design for temperature control system is discussed [6]. Decoupling control of electric furnace temperature based on DRNN neural network is provided in [7]. Fei and Hongxing in their paper [8] discussed the temperature control strategy for the electric furnace using adaptive fuzzy technique.

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Among different types of controller, PID controller is widely used for the temperature control of electric furnace system because of its simple structure and easy implementation. Different techniques are opted to provide an overall good performance but a controller is rarely found where it has got the potential to provide a good response in all respects.

This paper provides a novel approach where an SPWPID controller is designed to efficiently control the temperature of the electric furnace system. The controller parameters have been optimized using GA. The performance of the system with the SPWPID controller is then compared with that of the conventional PID controller designed with Ziegler-Nichols, Cohen-Coon, Direct Synthesis and Nelder-Mead method [1].

This paper is organized into six sections. Section 1 gives the introduction of the paper. In section 2, schematic diagram and transfer function of electric furnace system is provided. A brief overview and structure of SPWPID controller is provided in section 3. Section 4 is about the objective function formulation and optimization. Section 5 deals with the simulation diagram, the response of the system with SPWPID controller, root locus, bode and robustness analysis. In section 6 the conclusion part and the future scope of research is highlighted.

2. ELECTRIC FURNACE TEMPERATURE CONTROL SYSTEM

The main components of electric furnace temperature control system are electric furnace, thermocouple and controller. The schematic diagram of the system [1] is depicted in Fig.1.

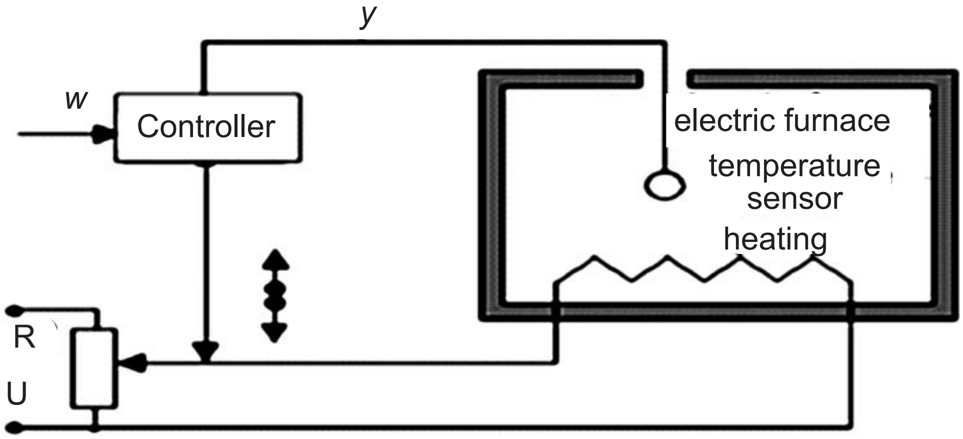

Figure 1: Electric furnace temperature control system

where, *w* is input voltage, U is output voltage from the controller, R is armature resistance and *y* is output voltage from thermocouple.

The transfer function of the electric furnace has been taken from [9] and is given as

$$G_1(s) = \frac{0.15}{s^2 + 1.1s + 0.2} e^{-1.5s} \tag{1}$$

Using first order Pade approximation, the exponential term can be approximated as

$$e^{-1.5s} \approx \frac{1 - 0.75s}{1 + 0.75s} \tag{2}$$

Substituting the approximate value of the exponential term in equation (1), the transfer function of the electric furnace becomes

$$G_P(s) = \frac{-0.1125s + 0.15}{0.75s^3 + 1.825s^2 + 1.25s + 0.2} \tag{3}$$

3. SET-POINT WEIGHTED PID CONTROLLER

The SPWPID controller resembles a 2 DOF controller structure. It has got more flexibility to satisfy the design specifications as different signal paths are present for set-point and process outputs. SPWPID controller can be represented as a PID controller with a PD controller present in the inner loop [10]. The control structure of an SPWPID controller with plant and unity feedback is provided in Fig. 2. Because of such structure, this type of controller is also known as PID-PD controller.

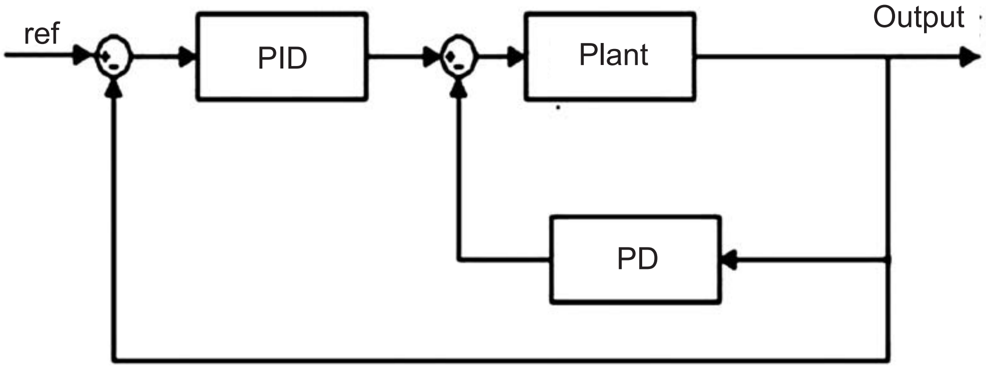

Figure 2: Control Structure of an SPWPID controller

4. OBJECTIVE FUNCTION FORMULATION AND OPTIMIZATION

4.1. Dominant Pole Calculation

In this study, the design specifications have been considered as

$$\text{Damping ratio } (\zeta) \;\leq\; 0.8, \text{ Settling time } (t_s) \text{ 2 sec}$$

$$\text{Gain Margin} \;\geq\; 10 \text{ dB and Phase Margin} \geq 60^\circ$$

From the basics of the control system, it is known that settling time is a function of ζ and ω_n. For 2% tolerance band, using the value of $\zeta = 0.8$ and $t_s = 2$ sec, ω_n is found to be 2.5 rad/sec. Substituting the values of ζ and ω_n in the standard second order characteristics equation $(s^2 + 2\,\zeta w_n s + w_n^2) = 0$, the dominant poles have been found to be at

4.2. System with SPWPID Controller

The characteristics equation of the system with SPWPID controller for unity feedback is given by

$$1 + G_P(s)(G_{PID}(s) + G_{PD}(s)) \;=\; 0 \tag{4}$$

where, k_{p1}, k_i and k_{d1} are the proportional, integral and derivative gain of PID controller and k_{p2} and k_{d2} are the proportional and derivative gain of the PD controller. With the value of controller parameters, the above equation can be written as

$$1+\left(\frac{-0.1125s+0.15}{0.75s^3+1.825s^2+1.25s+0.2}\right)\left((k_{p1}+\frac{k_i}{s}+k_{d1}s)+(k_{p2}+k_{d2}s)\right) \;=\; 0 \tag{4}$$

4.3. Objective Function Formulation

Substituting the value of s_1 in eq. (5), and separating the real (R) and imaginary (I) parts, one obtains

$$R \;=\; 1+0.0543\,k_{p1}-0.0302\,k_i-0.0275\,k_{d1}+0.0543\,k_{p2}-0.0275\,k_{d2} \tag{6}$$

$$I \;=\; -0.0541\,k_{p1}+0.0043\,k_i+0.1896\,k_{d1}-0.0541\,k_{p2}+0.1896\,k_{d1} \tag{7}$$

The objective function 'f' considered for obtaining the value of k_{p1}, k_i, $k_{d1,}$ k_{p2} and k_{d2} has the form

$$f \;=\; |R|^2+|I|^2 \tag{8}$$

4.4. Objective Function Optimization Using GA

For finding the SPWPID controller parameter values, the objective function ‘*f* ’ has been optimized using GA. Number of population, bit size, cross over probability, mutation probability and number of iteration has been taken as 40, 10, 0.8, 0.125 and 25.

The objective function considered over here has five unknowns *i.e.* k_{p1}, k_i, k_{d1}, k_{p2} and k_{d2}. The range of these parameters considered for writing the MATLAB code has been decided after a number of trial runs and provided in Table 1

Table 1
Range of controller parameters considered for writing the MATLAB code

Parameter	K_{p1}	k_i	K_{d1}	K_{p2}	K_{d2}
Lower range	3	0.5	3	0.2	0.65
Upper range	3.5	0.65	3.5	0.5	0.80

After optimizing the objective function within the mentioned range of parameters through GA, the values of controller parameters has been found and given in Table 2.

Table 2
SPWPID controller parameter values obtained using GA

Parameter	K_{p1}	k_i	K_{d1}	K_{p2}	K_{d2}
Value	3.0343	0.6148	3.0175	0.2417	0.6677

5. RESULTS AND DISCUSSION

Unit step signal has been considered as the input signal for this study. The simulation diagram of the system with SPWPID controller is given Fig. 3

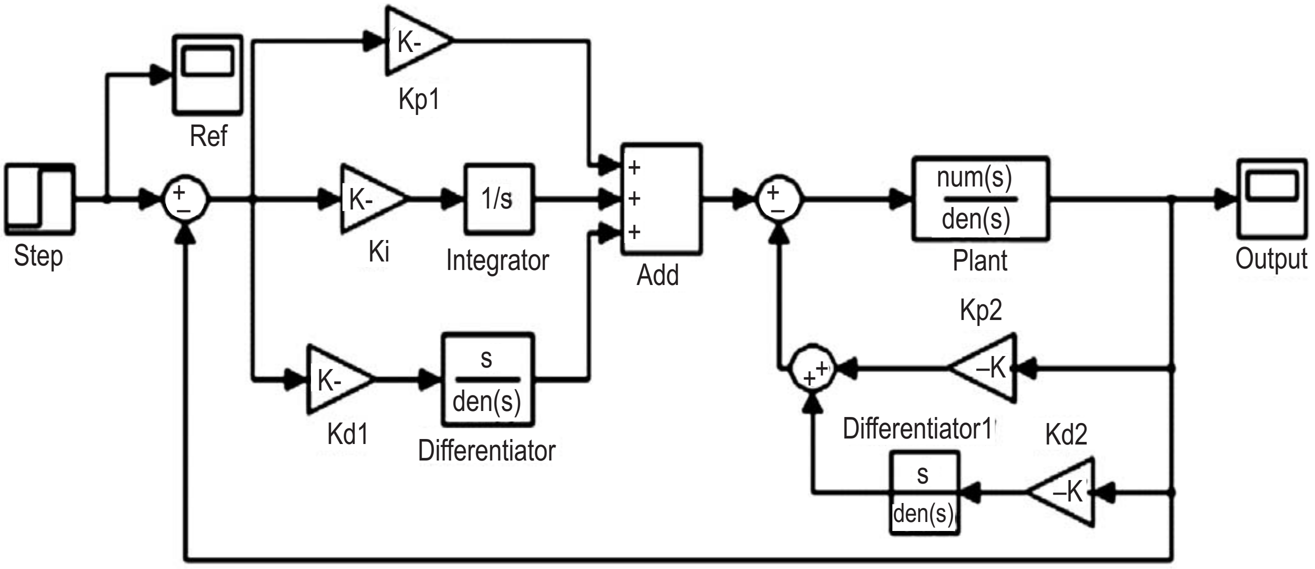

Figure 3: Electric furnace system with SPWPID controller

The simulation is carried out for 25 seconds and the response of simulation with SPWPID controller has been provided in Fig. 4

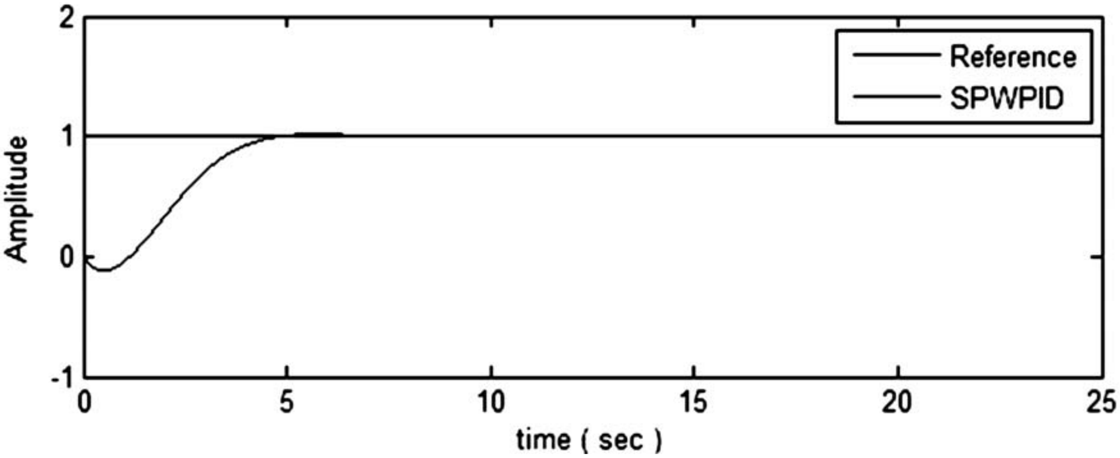

Figure 4: Simulink response of electric furnace system with SPWPID

Maximum overshoot, rise time and settling time for this design is 1.64 %, 2.4 sec and 4.49 sec respectively.

In Fig. 5, the step response of the system with the controller designed with different techniques have been shown which clearly indicates the superiority of the SPWPID controller over the PID controllers designed with Ziegler–Nichols, Cohen-Coon, Direct Synthesis and Nelder-Mead method [1].

The controller parameters and the performance of controllers designed using different techniques for the electric furnace system have been summarized in Table 3.

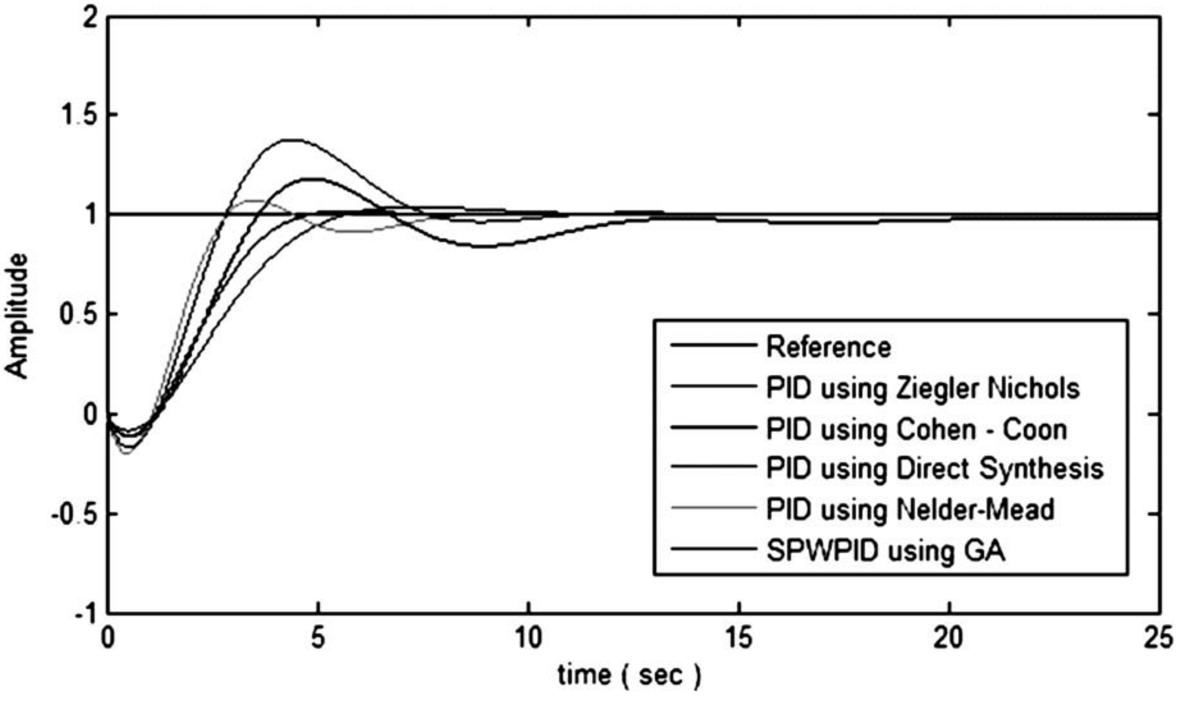

Figure 5: Step response of electric furnace system with the controller designed with different techniques

From the data available in Table 3, it is clear that SPWPID controller provides better performance as compared to conventional PID controller. The transfer function of the electric furnace system with the SPWPID controller is given by

$$G_{CL}(s) = \frac{-0.3395s^3 + 0.1113s^2 + 0.386s + 0.09222}{0.75s^4 + 1.41s^3 + 1.434s^2 + 0.6222s + 0.09222} \tag{7}$$

Table 3

Performance comparison of different Controllers

Method	*PID using Ziegler-Nichols [1]*	*PID using Cohen-Coon [1]*	*PID using Direct Synthesis [1]*	*PID using Nelder-Mead [1]*	*SPWPID using GA*
Parameter/ Performance					
k_{p1}	4.4573	3.9931	2.515	3.7918	3.0343
k_i	1.1430	0.4144	0.4572	0.6324	0.6148
k_{d1}	4.3455	2.6267	2.2864	5.5941	3.0175
k_{p2}	NA	NA	NA	NA	0.2417
k_{d2}	NA	NA	NA	NA	0.6677
Rise time (sec)	1.2927	1.8049	3.0855	1.3115	2.40
Maximum Overshoot (%)	37.3952	17.5964	3.6878	7.0007	1.64
Settling time (sec)	9.9689	20.8248	9.211	7.6578	4.49
IAE, t = 25 sec, t_s = 0.05 sec	66.1566	75.8543	63.8816	46.8696	54.4165
ISE, t = 25 sec, t_s = 0.05 sec	46.9428	47.4828	49.8496	39.0113	44.9191
ITAE, t = 25 sec, t_s = 0.05 sec	165.7948	331.2438	123.7873	79.1089	87.8725
ITSE, t = 25 sec, t_s = 0.05 sec	63.2175	67.7626	62.8954	32.0055	47.6429
Gain margin (dB)	6.81	7.51	11.1	6.71	9.79
Phase margin (degree)	37	45.9	67.6	60.4	62.2
Sensitivity	2.4232	2.1257	1.5307	2.0671	1.6269
Complementary sensitivity	1.6185	1.4427	1.0012	1.2421	1.0009

5.1. Root Locus Analysis

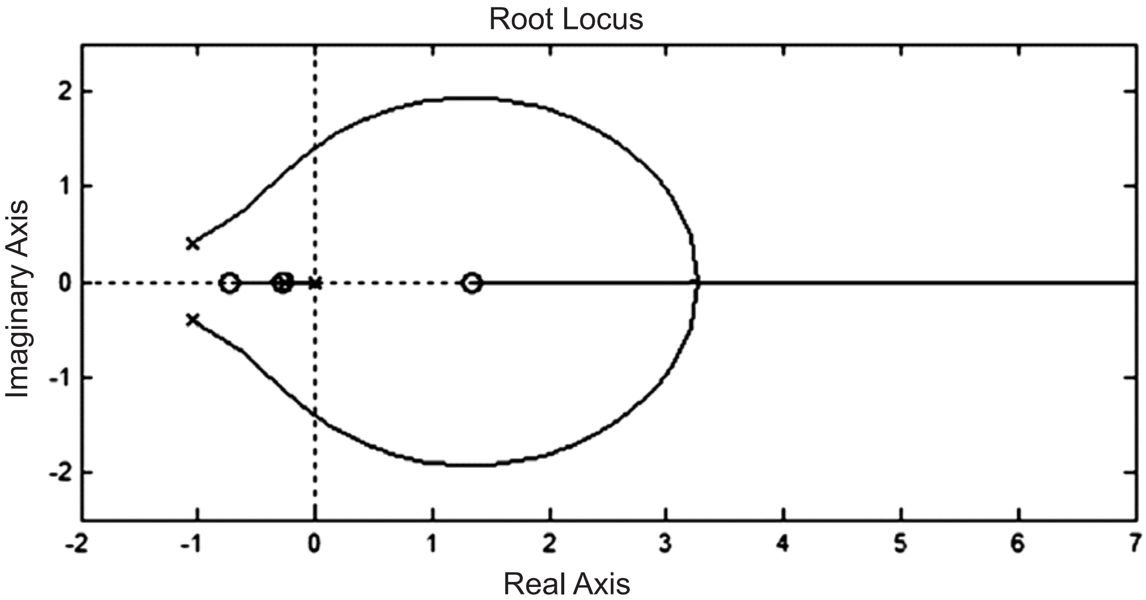

Figure 6: Root locus curve of the electric furnace system with SPWPID controller

The time domain and stabilization behaviors of the control system can be analyzed through Root locus [11]. Fig. 6 depicts the root locus curve for the system with the SPWPID controller. The closed loop poles of the system along with the damping ratios are provided in Table 4. From Table 4, it is clear that all the closed loop poles of the system are lying on the left hand side of *s*-plane and hence guarantee the stability.

Table 4
Closed loop poles and damping ratio of the electric furnace system with SPWPID controller

Closed loop poles	*Damping ratio*
$-0.5829 + 0.7809i$	0.5982
$-0.5829 - 0.7809i$	0.5982
$-0.3574 + 0.0422i$	0.9931
$-0.3574 - 0.0422i$	0.9931

5.2. Bode Analysis

Bode plot allows to gather the information regarding the frequency response of a system [11]. The magnitude and phase plot of the electric furnace system with the SPWPID controller is shown in Fig. 7.

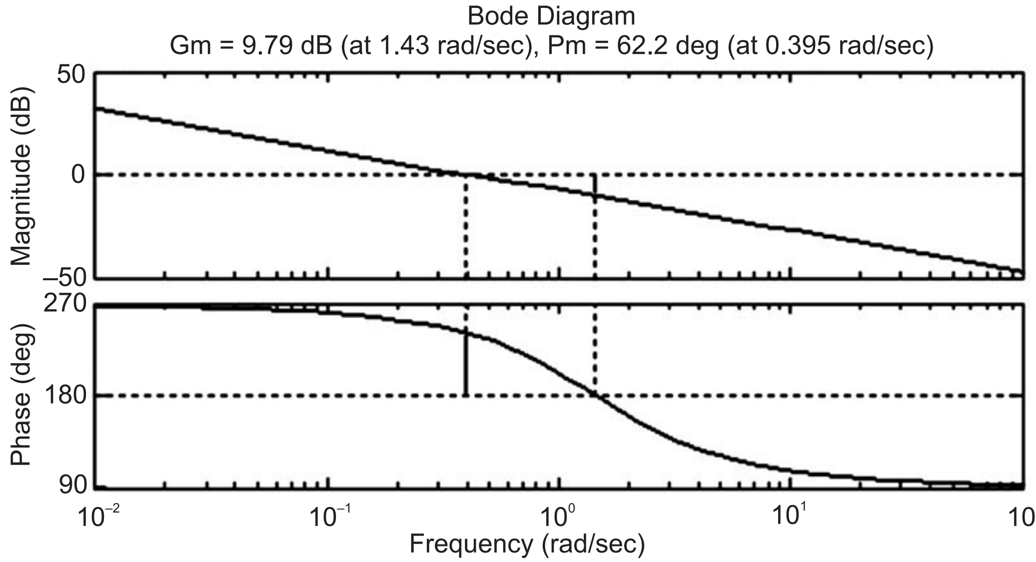

Figure 7: Bode plot of the electric furnace system with SPWPID controller

Table 5
Bode analysis of the electric furnace system with SPWPID controller

Gain margin (dB)	*Phase margin (deg)*	*Delay margin (sec)*	*Closed loop stability*
9.79	62.2	2.75	yes

5.3. Robustness Analysis

If a system can hold its stability in the presence of some noise, disturbance and parameter variation, then the system is said to be robust. A robust system has to satisfy some specific conditions [12]. Sensitivity and complementary sensitivity can be a measure of robustness of a system. Sensitivity ensures output disturbance rejection and complementary sensitivity is a measure of high frequency noise rejection. For a system to be robust, both the sensitivity and complementary sensitivity should be less than or equal to two. For the electric furnace system with SPWPID controller, it has been observed that sensitivity and complementary sensitivity is equal to 1.6269 and 1.0009 respectively which clearly indicates the robustness of the system.

6. CONCLUSION

In this study, a robust SPWPID controller optimized using GA has been designed for electric furnace temperature control system and the performance of the controller has been compared with the conventional PID controller designed using Ziegler-Nichols, Cohen-Coon, Direct Synthesis and Nelder-Mead method. It has been found that SPWPID controller provides better transient response than the PID controllers designed using different techniques. For improving time domain response and robustness, this particular approach of using SPWPID can be extended to the other class of plants. As a further scope of research, fractional order SPWPID controller will be designed for the same plant and the performance will be compared with the performance of this design.

7. REFERENCES

1. V. Sinlapakun and W. Assawinchaichote, "Optimized PID controller design for electric furnace temperature systems with Nelder-Mead Algorithm," *International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON 2015),* pp. 1- 4, 2015.
2. D. Lu, J. X. Wang and J. F. Li, "The Temperature Control of Electric Furnace Based on PID Genetic Algorithm," *Advanced Materials Research,* Vols. 490-495, pp. 828-834, 2012.
3. P. G. Wang, L. Zhang and X. P. Zong, "Particle Swarm Optimization of $PI^{\lambda}D^{\mu}$ Control of Heating Furnace Temperature Control System," *Applied Mechanics and Materials*. Vol. 721, pp. 205-209, 2014.
4. C. F. Juang and J. S. Chen, "A recurrent neural fuzzy network controller for a temperature control system," *The 12th IEEE International Conference Fuzzy Systems, FUZZ '03,* Vol. 1, pp. 408-413, 2003.
5. Y. Han, J. Jinling, C. Guangjian and C. Xizhen, "Temperature control of electric furnace based on fuzzy PID," *International Conference on Electronics and Optoelectronics (ICEOE 2011),* Vol. 3, pp. 41-44, 2011.
6. J. Chang, D. Wang, and T. Li, "The Electric Heating Furnace Temperature Control Based On SPID," pp. 1673–1679, Springer Berlin Heidelberg, Berlin, Heidelberg, 2009.
7. D. Wen, "Decoupling control of electric heating furnace temperature based on DRNN neural network," *International Conference on Electronic Computer Technology (ICECT 2010),* pp. 261-264, 2010.
8. T. Fei and L. Hongxing, "Adaptive fuzzy control for the electric furnace," *IEEE International Conference on Intelligent Computing and Intelligent Systems (ICIS 2009)*, pp. 439-443, 2009.
9. J. Paulusová and M. Dúbravská, "Application of Design of PID Controller for Continuous Systems," *FEI STU,* Slovak Republic.
10. C. C. Chen, H. P. Huang and H. J. Liaw, "Set-Point Weighted PID Controller Tuning for Time-Delayed Unstable Processes," *Industrial and Engineering Chemistry Research,* Vol. 47, No. 18, pp. 6983–6990, 2008.
11. K. Ogata, "Modern Control Engineering," Fourth edition, Prentice-Hall Inc., USA, 2002.
12. A. Ghosh, T. R. Krishnan, P. Tejaswy, A. Mandal , J. K. Pradhan and S. Ranasingh, "Design and implementation of a 2-DOF PID compensation for magnetic levitation systems," *ISA Transactions.* Vol. 53, pp. 1216-1222, 2015.