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Temperature Control of an Electric Furnace with Intuitive Control Methods

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ABSTRACT In our daily life, electric furnaces are frequently used both in our homes and in industry. In electric furnaces, resistance heaters are placed on the upper and lower sides and temperature control is realized by on-off control method. Nevertheless, this method is unstable for applications where highly sensitive thermal control is required. Proportional-Integral-Derivative (PID) control stands out in precision heat treatment with its simplicity and stability. In this study, On-Off, Proportional, Proportional-Integral, and PID control methods were applied to the electric furnace at a reference temperature of 125 °C. The system model and parameters were determined by using the Ziegler-Nichols method. Also, by using the zero-crossing detection technique, the trigger signal and the network frequency were synchronized and the possible noise in the system was minimized. From the test results obtained; the stability and superiority of these control methods were compared. There is permanent error in P control. Thanks to the I component, permanent error in PI and PID control is eliminated. In addition, the best system response was achieved with PID control.

Keywords: On-Off Control, Proportional Integral Derivative Control, Temperature Control

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1. INTRODUCTION

Electric furnaces are widely used in industry and at homes for different purposes. Generally, heating in electric furnaces is carried out with the help of resistors placed on the upper and lower surfaces of furnace. The on-off control is the most basic control technique. However due to the unstable operation of this control method, deviations occur on the desired reference value in heat treatments. PID control method is used frequently in electrical furnaces which require very sensitive heat treatments [1]. In a study [2], the temperature control of an electric furnace by the PID method was performed using a microcontroller. To improve the performance of the PID controller, artificial neural networks or fuzzy logic can be used together [3–6]. Besides, the selection of PID parameters has a significant effect on control performance as presented in [7, 8]. Although there are many studies about oven temperature control in literature, most of these are simulation-based [9–23]. Only a few studies have provided experimental results [24–25]. However, the electronic components of the system and their structures are not given in detail in these articles. Also, synchronized switching was not exploited in these studies to prevent noise on the network. In this study, the suggested system model and PID parameters were obtained by using the Ziegler-Nichols method. Then On-Off, Proportional (P), Proportional-Integral (PI), PID control methods were applied to the electric furnace at 125 °C reference temperature. The stability of these control techniques was compared. Moreover, the trigger signal, and the network frequency were synchronized and the possible noise in the system was minimized by using the zero-crossing detection method.

2. EXPERIMENTAL

The block diagram of the real-time temperature control system is shown in Figure 1. The resistors and sensors are positioned on the upper and lower surfaces of the electric furnace. With the help of the programmed microcontroller, trigger signals were sent to these resistances to heat the furnace. Four intuitive control techniques were performed with the help of return signals from the sensors. Also, the system was eliminated from disturbing effects by synchronizing the network frequency with the trigger signals utilizing the zero-pass detection circuit.

2.1. Zero-Pass Detection Circuit

The electric furnace is heated by two 1500 W resistors, one at the base and the other at the ceiling. The resistances are independently controlled by the trigger signals generated by the microcontroller board at 10 ms increments over 100 ms period. The synchronization between the trigger signal and the network frequency is ensured by the zero-pass detection circuit. The schematic diagram of the zero-crossing circuit is shown in Figure 2 and the printing circuit is shown in Figure 3. The mains voltage is detected by the H11L1 zero crossing detecting circuit circuit. Supply voltage for H11L1 integrated is provided by 12V DC 2 W transformer, 1.5 a bridge diode, LM7805 linear voltage regulator and peripherals [26]. Mains voltage is reduced to 12 VAC by a second transformer and then applied to the integrated circuit via 1 kΩ resistor. The integrated circuit produces a pulse of 5 V amplitude and 500 µs width for every zero crossings.

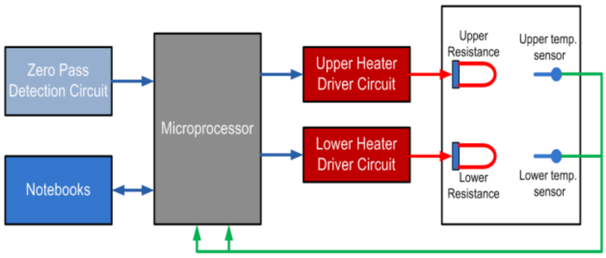

Fig. 1. Block diagram of the system

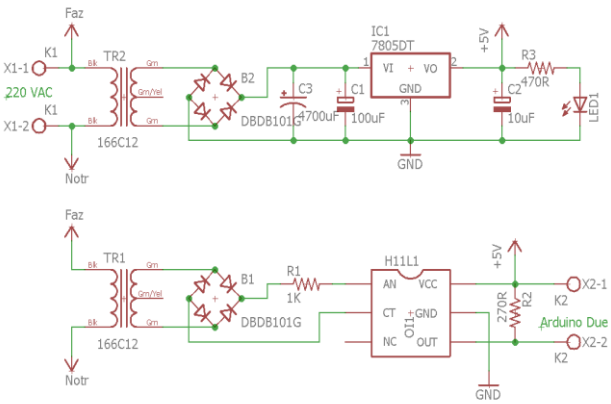

Fig. 2. Schematic diagram of the zero-crossing detection circuit

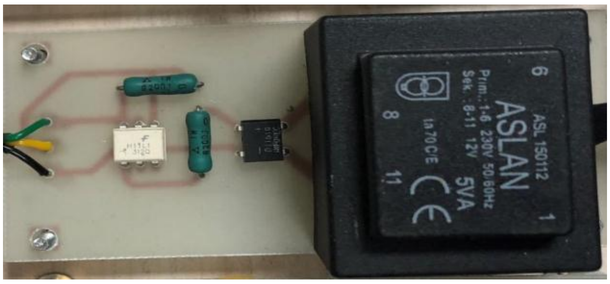

Fig. 3. zero-pass detection circuit established in current study

2.2. Heater Driver Circuit

It adjusts the instantaneous power of the resistors used in heating of the furnace in 101 steps according to triggering signal. The schematic diagram of the driver circuit is shown in Figure 4 and the printed circuit is shown in Figure 5.

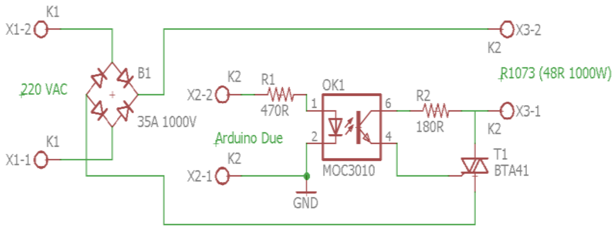

Fig. 4. Schematic diagram of the heater driver circuit

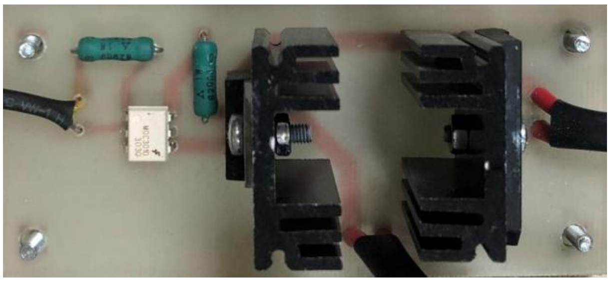

Fig. 5. Heater driver developed in current work

Figure 6 shows the change of voltage at the mains and resistance terminals over time while Figure 7 shows the change in voltage at the load terminals according to the trigger signal. Mains voltage (V_s) is applied to the resistor after it is rectified with a 35 A 1000 V bridge diode with 1.1 V threshold voltage (V_γ). The output of the resistor is connected to the BTA41 triac of 41 A 600 V with 10 mΩ dynamic resistance (R_d) [27]. The trigger signal from the controller board is applied to the BTA41 via the MOC3010 optically isolated triac driver. When the triac conducts, the resistance voltage (V_r) given in Figure 6 is obtained. The voltage $V_r(t)$ is defined by Equation (1) for $V_s(t) > 2V_\gamma$ and calculated by $V_r(5\,ms) = V_{r_{max}} = 305.8$.

$$V_r(t) = \left(V_{s_{max}}|sin100\pi t| - 2V_\gamma\right)(1 - R_d) \quad (1)$$

Here |.| absolute value operation. In Figure 7, the voltage at the resistance terminals is given for the 80% fill rate. In Figure 7, the rectified mains voltage, shows the output of the zero-pass detection circuit, the trigger signal generated by the microcontroller and the voltage at the heater terminals.

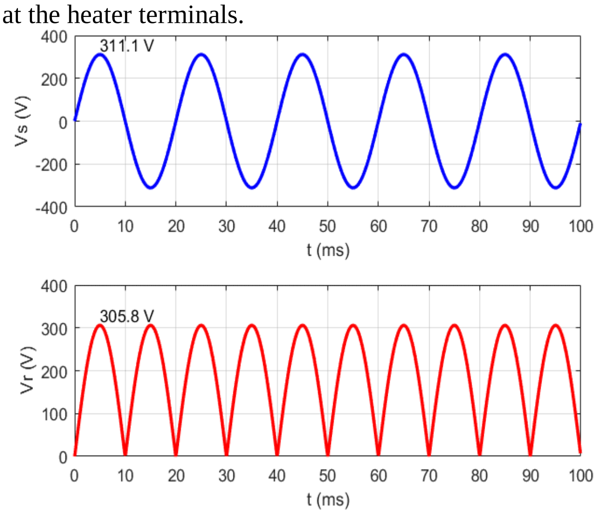

Fig. 6. Variation of voltage at mains and resistance terminals over time

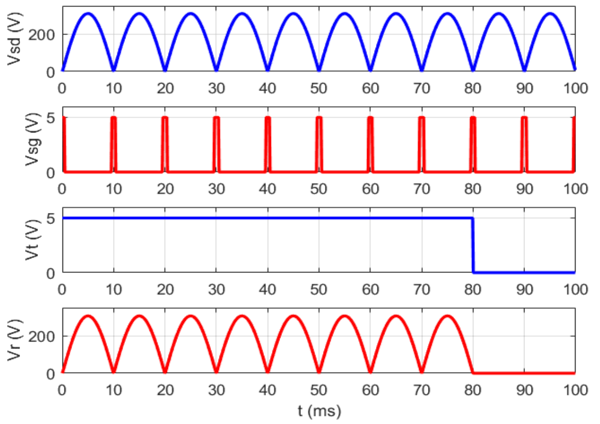

Fig. 7. Variation of voltage at load terminals according to the trigger signal over time

2.3. Modeling of Electric Furnace

Ziegler-Nichols' step response method was used to model the electric furnace. In this method, the step function is applied to the system input, and a curve shown in Figure 8 is obtained. Figure 8 shows the values of the dead time point (*L*), the distance between the tangent point, the dead time (*T*) and the system output value (*K*).

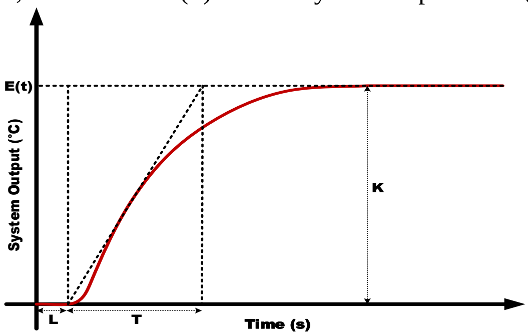

Fig. 8. Ziegler-Nichols step response graph

The output graph obtained by applying a unit step trigger signal to the input of the electric furnace as shown in Figure 9.

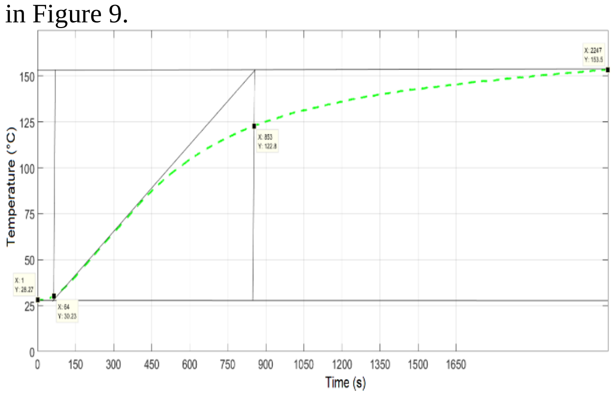

Fig. 9. The output graph obtained by applying a unit step function to the input of the electric furnace

From the graph in Figure 9, one can obtain $K = 153.5$, $T = 789$, and $L = 64$. Using these values, the system model is determined. Equation (2) is used to model the system with the Ziegler-Nichols step response method.

$$G(s) = \frac{K*e^{-Ls}}{Ts+1} \qquad (2)$$

If $K = 153.5$, $T = 789$, and $L = 64$ are replaced in (2), the system model $G(s)$ is obtained as shown in Equation (3).

$$G(s) = \frac{153{,}3*e^{-64s}}{789s+1} \qquad (3)$$

2.4 Determination of PID Parameters

Open-loop Ziegler-Nichols tangent model was used to obtain the system parameters. Table 1 shows the values of $K = 153.5$, $T = 789$ and $L = 64$ obtained from Figure 9.

Table 1. Open loop Ziegler-Nichols tangent model parameters formula

Control Method	K_P	K_I	K_D
Proportional	T/L	-	-
Proportional-Integral	$0.9\times T/L$	$0.3/L$	-
Proportional-Integral-Derivative	$1.2\times T/L$	$1/2\times L$	$0.5\times L$

The values of *K*, *L*, *T* replaced in Table 1 and the calculated system parameters are given in Table 2.

Table 2. The obtained system parameters

Control Method	K_P	K_I	K_D
Proportional	12.320	-	-
Proportional-Integral	11.088	0.0047	-
Proportional-Integral-Derivative	14.780	0.0079	35

When determining system parameters, it is necessary to consider the measurement errors of sensors providing data and measurement devices that we measure and the disturbing errors that affect our system from the outside. System parameters have been calibrated based on the results obtained above. Thus, the most appropriate system parameters for the developed system was obtained. Table 3 shows the calibrated system parameters. Here K_p is the proportional gain factor, K_i is the integral gain coefficient, and K_d is the differential gain constant.

Table 3. The calibrated system parameters

Control Method	K_P	K_I	K_D
Proportional	10	-	-
Proportional-Integral	8	0.002	-
Proportional-Integral-Derivative	10	0.002	35

3. RESULTS

In this study, temperature control was performed by using On-Off, P, PI, and PID controllers at 125 °C reference temperature of an electric furnace. Figure 10 shows the real-time change of temperature signal for four different control techniques and the control signals are given in Figure 11. Figure 11 shows that the On-Off control is not steady state and the panel temperature oscillates around the reference value. There is also a offset error in P control. On the other hand, offset error disappeared in PI and PID. Finally, the best system response was achieved with PID.

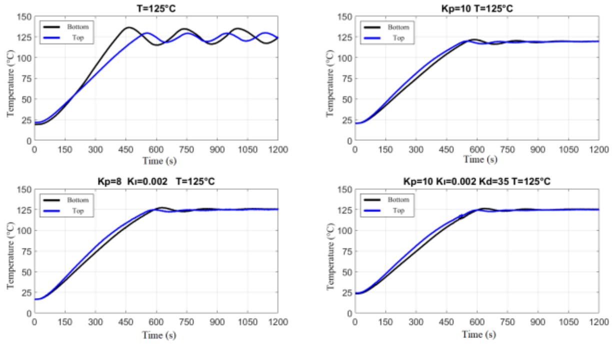

Fig. 10. The real-time change of the panel temperature

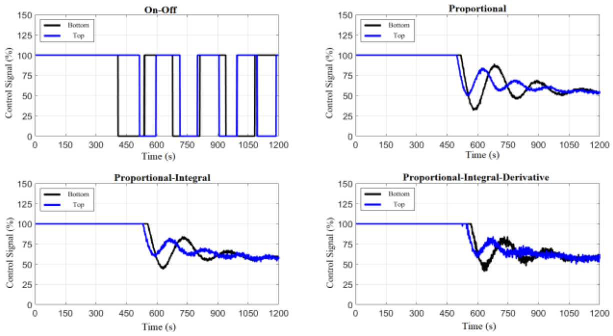

Fig. 11. The change of the control signals with time

The performance values for the lower panel and the top panel of four different control methods are given in Table 4, and Table 5, respectively. Here the time-weighted sum of the absolute value of the error (ITAE) is chosen as the objective function. Obtained results were found to be compared to the results given at [24].

Table 4. Bottom panel measurement results

Performance Criteria	*On-Off*	*P*	*PI*	*PID*
Max. Value (°C)	136.60	121.74	127.50	**126.63**
Overlap (%)	9.28	-	2.00	**1.31**
Settling Time (s)	-	**1,095**	1,127	1,104
Rise Time (s)	**464**	574	627	640
Offset Error (° C)	-	5.7	0.3	**0,2**
ITAE	7.4e+06	9.1e+06	6.5e+06	**6.2e+06**

Table 5. Top panel measurement results

Performance Criteria	*On-Off*	*P*	*PI*	*PID*
Max. Value (°C)	130.03	120.16	126.22	**126.18**
Overlap (%)	4.03	-	0.98	**0.94**
Settling Time (s)	-	1,109	1,144	**1,040**
Rise Time (s)	**555**	556	585	601
Offset Error (°C)	-	4.9	0.4	**0.3**
ITAE	6.6e+06	8.6e+06	5.6e+06	**5.4e+06**

4. CONCLUSION

In this study, the temperature control of an electric furnace was carried out in real-time by using four different control methods. 125 °C was selected as the reference temperature. Using the open-loop Ziegler-Nichols tangent technique, the control parameters were obtained. Real-time graphs of the temperature and control signals are also provided in Figure 10 and Figure 11, respectively. The following conclusions can be drawn from these results and graphs;

It was observed that the temperature oscillated above the determined reference value and did not reach the reference temperature, although it reached the best rise time in on-off control. In the P control method, it was observed that the oscillation of the temperature signal was prevented. However, the steady-state error was found to be very high. PI control technique showed that the oscillation of the temperature signal was eliminated, and the steady-state error was minimized. PID control method was reduced much more the offset error and it was found to provide faster settling time compared to the PI control technique. The results obtained are similar to [24] and according to the ITAE criteria, the best control method for both the top and bottom panels of the electric furnace was found to be PID control.

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