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# Design and development of automatic voltage regulator using Ziegler-Nichols PID for electrical irons testing

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**ABSTRACT**

This research presents an automated voltage regulation system crucial for a power input test of electric irons based on SNI IEC 60335-2-3 clause 11.4. The system is designed with an Arduino-based proportional-integral-derivative (PID) control mechanism to augment voltage stability and meet the standard requirement. The system comprises a microcontroller for PID control, a dimmer as the actuator, and a voltage sensor for error measurement. It utilizes the Ziegler-Nichols (Z-N) oscillation method to determine the PID control parameters. The simulation results identified a third-order transfer function as the best fit for the system, and the optimal PID parameters for the system are $K_p$=60, $K_i$=125, and $K_d$=500. The system was tested under the electric iron's active and non-active conditions. The proposed PID system demonstrated stable responses, effectively regulating the system voltage with minimal overshoot and settling time, and meeting standard requirements even under varying load conditions. It suggests potential applications beyond electric iron testing, promising efficiency improvements in broader household product testing.



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## 1. INTRODUCTION

The Ministry of Industry (MoI) of the Republic of Indonesia has issued regulation No. 17/M-IND/PER/2/2012 [1] as a regulation for the mandatory implementation of Indonesian National Standards (SNI) SNI 60335 -1:2009 [2]. This regulation aims to improve the competitiveness of Indonesian home appliance industries, ensure the quality of such products, and protect users against hazards with high-quality electronic products [1]. The SNI IEC 60335-2-3:2009 clause 11.4 states that the home appliances with heating elements are operated under normal conditions and at 1.06 times the rated input voltage. In addition, home appliances with motors, transformers, and heating elements with an input voltage lower than the rated voltage with a temperature rise over the limits shall be tested repeatedly with an input voltage of 1.06 times the rated voltage [3]. To fulfill this clause requirement during the testing process, we typically supplied home appliances with 1.06 times their rated voltage manually from the voltage source. In this research, we propose a new test technique via automatic voltage regulator (AVR) using Ziegler-Nichols (Z-N) proportional-integral-derivative (PID) control for supplying 1.06 rated voltage into the product.

Numerous research topics focus on AVRs that employ voltage control in synchronous generators and voltage regulators for three-phase applications [4], [5]. However, these AVRs are unsuitable for testing single-phase electric iron. Additionally, their research findings maintain the generator's terminal voltage at its nominal value using control methods such as neural networks, fuzzy logic, and PID control. Another research paper discusses AVR simulation with tuning methods that enhance control signal amplitude and quality factors in DC motor plants [6]–[8]. Still, it lacks a clear explanation of PID control for AVRs or PID applications in testing technology. In this study, a single-phase AVR is designed and proposed using PID control applied to an embedded system to test electric irons.

Designing an AVR is crucial for creating an effective test plan and conducting more controlled tests. The AVR automatically generates stable test voltages as needed, enhancing the efficiency of testing time. This paper proposes a new AVR system for electric iron testing using a Z-N PID-based Arduino approach. The system includes the transfer function of the AVR, allowing it to control and stabilize the input voltage at 1.06 times the rated voltage.

## 2. METHOD

This research employs an experimental method with the following steps. The proposed test system is shown in Figure 1. The input voltage is supplied by a slide transformer (TRIAC), which adjusts the input voltage to 1.06 times the rated voltage [3]. The set point voltage can be entered using a keypad, and the results are displayed on a 16×2 LCD screen on the system [9].

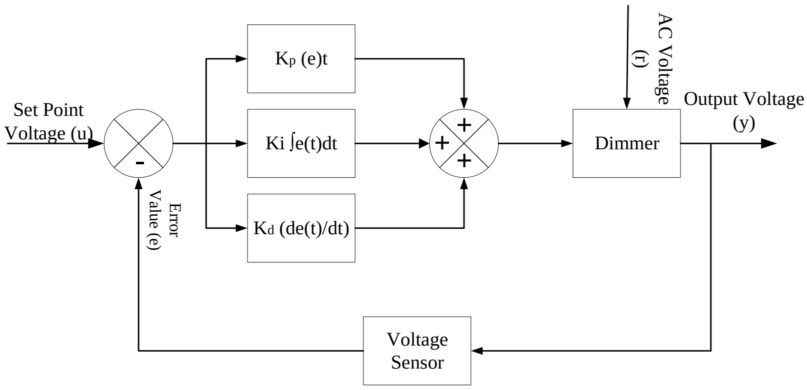



Figure 1. Proposed diagram block AVR system

The (Z-N) PID method is used in controlling the program [10]. Figure 1 shows the block diagram of the AVR system with a PID controller, with the Arduino as an essential part, as it is connected to both the dimmer and the voltage sensor [11]. The PID controller optimizes the set point voltage as input (u), output voltage (*y*), AC voltage as reference input (*r*), and error of the sensor (*e*) [12]. The basic PID in (1) and (2) has input u, output y, the reference input *r*, and *e* value [13], [14].

$K_p$, $K_i$, and $K_d$ are the constants of proportional, integral, and derivative components, respectively [15]. The values of $K_i$ and $K_d$ can be simplified using (3) and (4) [16]. Ti and Td represent the integral time and derivative time in seconds, respectively [17]. The (Z-N) method can be divided into two approaches: the Z-N open-loop method, which uses an S-shaped process reaction curve, and the Z-N closed-loop method, which employs an oscillation curve [12], [18], [19].

$$e = r - y \tag{1}$$

$$u(t) = k_p e(t) + k_i \int_0^t e(t)\,dt + k_d \left(\frac{de(t)}{dt}\right) \tag{2}$$

$$k_i = \frac{k_p}{T_i} \tag{3}$$

$$k_d = \frac{k_p}{T_d} \tag{4}$$

Figure 2 presents the results of the closed-loop method block diagram, where the integral time ($T_i$) is set to infinity and the derivative time ($T_d$) is set to zero [20]. The proportional ($P$) controller increases the proportional gain constant from 0 to the critical or maximum value ($K_{cr}$), resulting in a constant oscillation curve [21]. Figure 2 determines the critical gain ($K_{cr}$) and the critical gain's period ($P_{cr}$). The gain parameters for the Z-N close-loop method are set according to the values specified in Table 1 [12], [15].

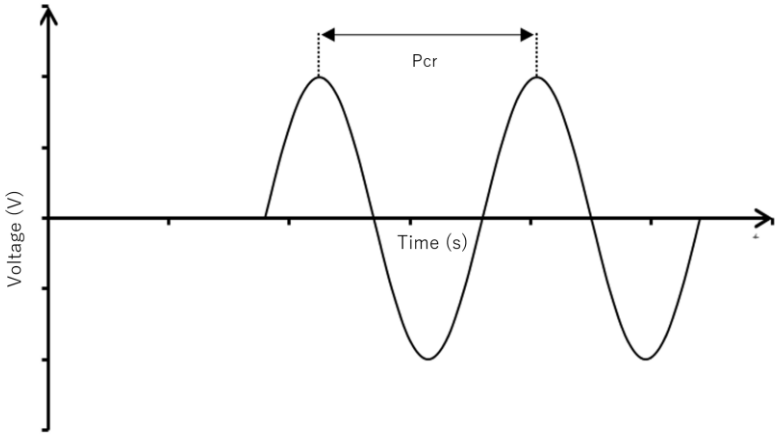



Figure 2. Oscillation curve of Z-N

Table 1. Z-N closed-loop method critical gain

| Controller type | $K_p$ | $K_i$ | $T_d$ |
|---|---|---|---|
| P | 0.5 Kcr | ∞ | 0 |
| I | 0.45 Kcr | 0.83 Pcr | 0 |
| D | 0.6 Kcr | 0.83 Pcr | 0.83 Pcr |

Various software tools have recently been developed to identify single-input single-output (SISO) systems, such as MATLAB's system identification toolbox [22]. Input data from the plant affects the output data in either the time or frequency domain. The input-output system results are utilized to identify the transfer function parameters [23]. Additionally, pole-zero analysis assesses the system's stability [24].

The dimmer is connected to digital pin 2 of the microcontroller to set the output voltage. The microcontroller code calculates the PID controller values to maintain the desired output voltage [11]. The dimmer receives input from single-phase AC voltage, and the TRIAC adjusts the sine wave of the AC voltage to zero using a zero-crossing detector [25]. The zero-crossing detector synchronizes the dimmer, as the input from the mains supply can cause a slight phase shift that may result in anomalies in the output performance [26]. The synchronizing pulse is buffered by a small-signal transistor 547 and connected to the signal output header. The other TRIAC is connected to the electric iron as a load [27].

The voltage sensor uses a simple circuit that consists of a mini transformer and dual op-amp LM358 [28]. The mini transformer acts as a step-down transformer, converting the high-input voltage to a low-voltage output. The transformer's low-voltage output is approximately 2.5 volts [9]. The LM358 and a variable resistor work together to invert the negative AC voltage to a positive value, allowing the microcontroller's analog input to read a voltage close to 5 volts. The voltage at the microcontroller's analog input can be calculated using the equation provided in [23], where $R_1$ is a limiting resistor in the input, and $R_2$ is the value of the variable resistor [27].

## 3. RESULTS AND DISCUSSION

The implementation of in (1)-(3) in microcontroller code is determined by the algorithm in pe. The $\int_0^t e(dt)$ equal to the sum of error value from the voltage sensor and the previous error value. The $\left(\frac{de(t)}{dt}\right)$ equal to delta error of the voltage sensor. All of the data measured and calculated used in float type by microcontroller. This section briefly explains the tuning methods in two subsections: the close-loop analysis by simulation approach and the evaluation of the system using the electric iron.

Algorithm 1. PID algortihm

| Pesudocode |
|---|
| PID=($K_P$*error)+($K_i$*integral error)+($K_d$*derivative error);<br>error=r-y;<br>deltaerror=errorReadNow-errorReadPref;<br>integral=errorReadNow+integral;<br>B=KI*integral;<br>C=KD*deltaErrorRead; |

### 3.1. Closed-loop analysis

This study uses the closed-loop to determine the control gain of the AVR system. The AVR response in the closed-loop system exhibits an oscillatory shape, as illustrated in Figure 3. This curve is used to determine the value of $P_{cr}$ derived from the system's period of 1.6 s, and the $K_{cr}$ is 100. The closed-loop calculations for $K_p$, $K_i$, and $T_d$ are presented in Table 2.

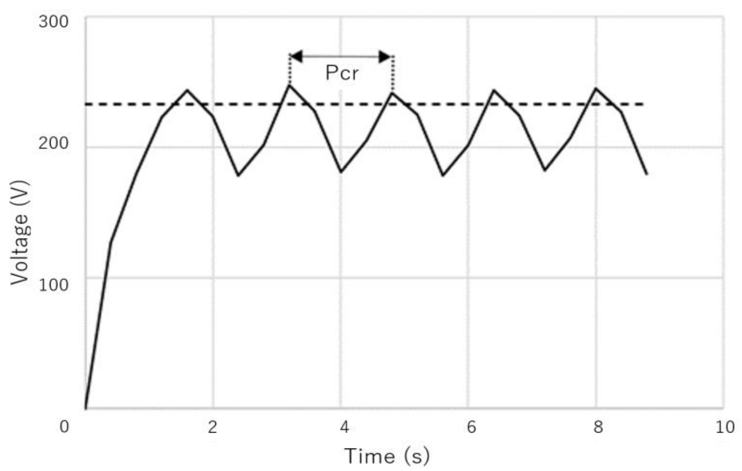



Figure 3. Closed-loop proposed test system oscillation curve

Table 2. Result of Z-N critical gain

| Controller type | $K_p$ | $K_i$ | $T_d$ |
|---|---|---|---|
| P | 50 | ∞ | 0 |
| I | 45 | 1.33 | 0 |
| D | 60 | 1.33 | 1.33 |

The transfer function of the proposed system is simulated in the time domain for the input or output system. This experiment uses three different order systems to simulate the proposed model. Table 3 shows the proposed system's transfer function estimation in continuous time. It uses system identification by MATLAB, which uses data from closed-loop measurements. The transfer function order is obtained from trial and error of different number poles and zeros, for example, 1-pole and 2-zero, to obtain the 2nd order transfer function model.

Table 3. Simulation model approach

| Order | Transfer function model |
|---|---|
| 1st | $\left(\frac{0.344}{s^2 + 7.69e^{-06}}\right)$ |
| 2nd | $\left(\frac{1.521e^{04}s + 1.167}{s^2 + 4.101s + 10.45}\right)$ |
| 3rd | $\left(\frac{1522s - 3.153}{s^3 + 1.168s^2 + 2.363s + 2.76}\right)$ |

Figure 4 illustrates the estimated model output with the best fit and pole-zero plot in different order control systems. The 1st order does not have an S-value in the numerator transfer function, so it does not have a zero position. The zero positions of 2nd and 3rd have the similar location. The 2nd and 3rd order have pole positions on the left side as a stable region. Based on the simulation, the best fits for the 1st, 2nd, and 3rd orders are 3.122, -17.49, and 87.09, respectively. This result shows that the 3rd order transfer function best fits the proposed system. Since it is on the 3rd (high) order system model, there is a potential for system instability due to the feedback loop.

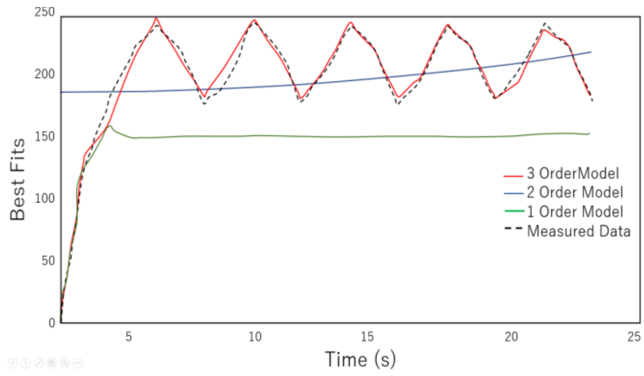



Figure 4. Result of best fit measured data and simulation model

In contrast, Figure 5 shows that the pole of the 1st-order system is located at the same position as the zero, placing it in an unstable region. The real and imaginary poles of the 2nd and 3rd order systems are approximately -2.1±j2.5 and -1.2±j1.5, respectively. The real component of the 2nd-order system is situated further to the left compared to the 3rd-order system, which results in the 3rd-order model having an output more similar to a closed-loop system.

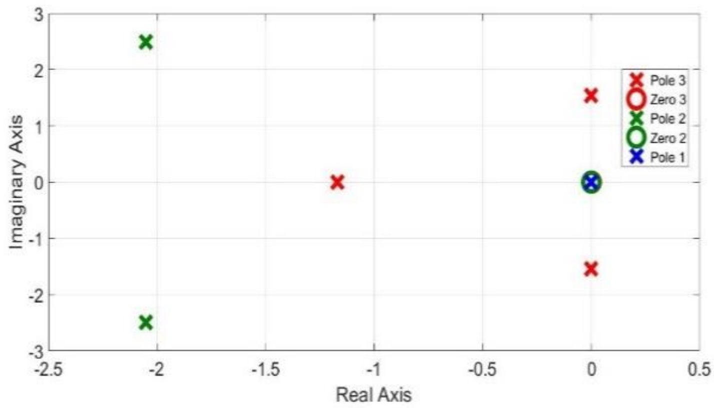
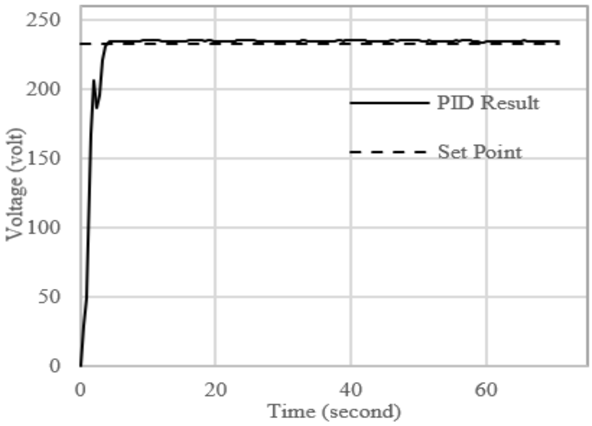
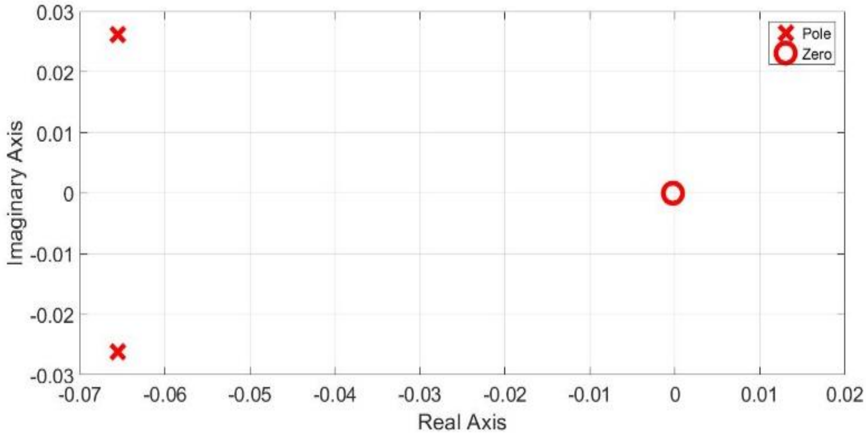



Figure 5. Pole-zero plot of measured data and simulation model

Figure 6(a) shows the PID system's response. The curve shows the system closely tracking the step response curve under steady-state conditions with a set point value of 233 volts. The system response only needs short rise-time ($T_r$) and settling-time ($T_s$) to achieve steady state value. The values of $T_r$ and $T_s$ are 2.24 s and 4.23 s, respectively. The steady-state error data is obtained after $T_s$ is achieved. The undershoot at $T_r$ occurred before the steady state condition; hence, it does not influence the system. The average error ($e$) is 1.0052 volts with a maximum steady-state voltage of 234.52 volts. Furthermore, the system response has an output voltage slightly different from the set point voltage. Figure 6(b) explains the pole-zero plot, indicating a zero at the origin of the real and imaginary axes. The pole has a lower value than the closed-loop result, at -0.065±0.028 J.




(a)




(b)

Figure 6. Electrical iron testing response system with: (a) PID and (b) pole-zero plot

### 3.2. System evaluation

The validation of the PID system with a single electric iron is depicted in Figure 7 under two conditions: with the heating element of the electric iron switched off and switched on. The proposed system is tested using one electric iron and two electric irons in this experiment. With one electric iron, the PID controller successfully maintains the AVR voltage within the set point limits, regardless of whether the heating element is activated or not. During the off-condition, the system stabilizes within 20 s, with a $T_r$ of 9.7 s, a $T_s$ of 16.4 s, and a maximum overshoot ($M_p$) of 234.22 volts. In the on-condition, the system curve has $T_r$ 6 s and $T_r$ 12 s. The curve shows that $M_p$ and maximum undershoot ($m_p$) are 1.5% and 1% off from the set point when the heating element activates. The Mp and mp values also adhere to the standard requirement of staying below 1.06 times the rated input voltage. The average of e is 1.502 volts with a maximum steady-state error of 235.27 volts.

When using two electric irons, the AVR operates within voltage ranges close to the limits stipulated by the standard. Figure 8 shows that the system experiences an off-condition in 8.8 s, with a $T_r$ of 26 s, a $T_s$ of 70.8 s, and an $M_p$ of 234.25 volts. This occurrence is attributed to using two electric irons, which accelerates the system's performance compared to when only one electric iron is used as a load. The simultaneous activation of the heating elements in electric irons no. 1 and no. 2 leads to an increase in the maximum voltage utilized by the proposed system. Nevertheless, it remains compliant with regulations, with a maximum voltage of 234.42 volts.

In this proposed system, the Z-N method can control an AVR and become fully automated to assist in the testing of electric iron. This advancement promises to enhance testing efficiency and simplicity significantly compared to previous methods. This system holds potential for broader applications beyond electric iron testing, including other household product testing.

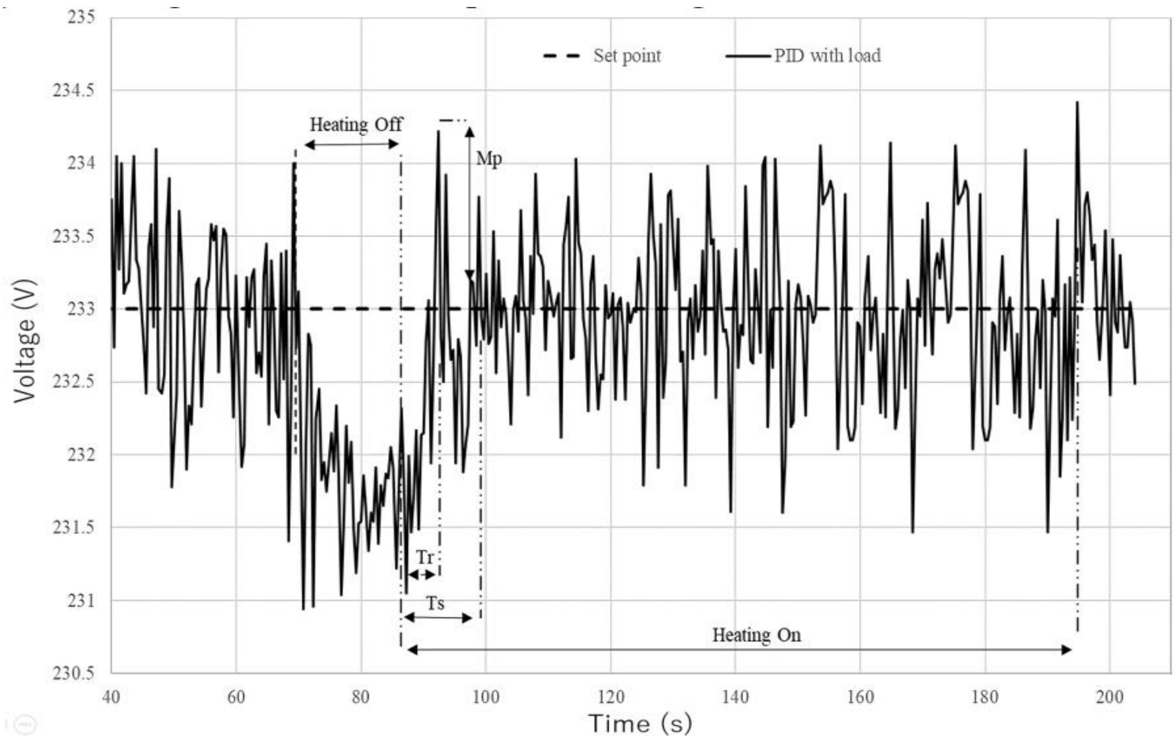



Figure 7. System response uses one electric iron

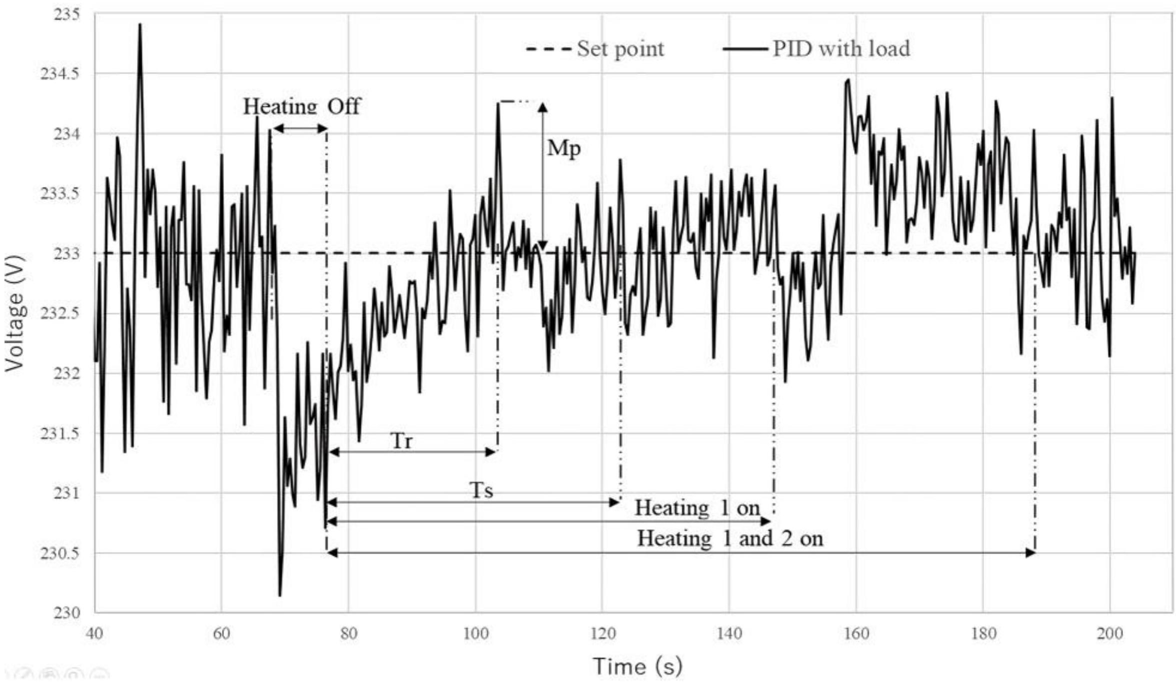



Figure 8. System response uses two electric irons

## 4. CONCLUSION

This research paper proposes a Z-N PID-based controller system designed to regulate the input voltage when testing electric iron. MATLAB's system identification tool identifies the proposed system as a 3rd order transfer function with a best fit of 87.09 for closed-loop conditions. The Z-N PID-controlled system demonstrates superior performance, characterized by its closed-loop s-curve response and minimal values in the pole-zero plot during system identification. Experimental testing is conducted using electric irons to validate the proposed system, demonstrating its efficacy in meeting the input voltage standard requirement by maintaining it within 1.06 times the rated voltage.

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