

IMPLEMENTATION OF AN ELECTROMAGNETIC INDUCTION COIL SYSTEM INTEGRATED WITH PLC USING AN ADAPTIVE CONTROL METHOD FOR ENHANCED ENERGY EFFICIENCY

Gun Gun Maulana^{1*}, Abdur Rohman Harits Martawireja², Nur Wisma Nugraha³

Department of Automation Engineering, Politeknik Manufaktur Bandung, Bandung,

Indonesia^{1,2,3}

gungun@polman-bandung.ac.id*

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*Corresponding Author

ABSTRACT

Electromagnetic induction heating is widely used in manufacturing due to its fast and localized heating capability. However, conventional constant-power and fixed PID control methods often struggle with nonlinear and time-varying thermal dynamics, leading to temperature overshoot, long settling times, and inefficient energy use. These limitations highlight the need for adaptive and energy-efficient control strategies, especially in PLC-based industrial systems. This study proposes a PLC-based adaptive control framework using a self-tuning PID algorithm, where control parameters are automatically adjusted in real time based on temperature error and system response. The method enables continuous adaptation to improve thermal tracking under dynamic conditions. Experimental validation was performed by heating workpieces to 600 °C and evaluating performance using rise time, settling time, overshoot, steady-state error, and energy consumption. Compared to a conventional constant-power method, the proposed approach shows significant improvements in transient and steady-state performance, with reduced rise time, settling time, and overshoot. Additionally, energy consumption decreased from 1.6067 kWh to 1.3265 kWh, representing a 17.44% improvement. The integration of PLC enhances real-time system responsiveness and heat uniformity. Overall, the proposed method effectively bridges the gap between fixed control and adaptive, high-performance thermal regulation for Industry 4.0 applications

Keywords: *Electromagnetic Induction Heating, Self-Tuning PID, PLC, Adaptive Control, Energy Efficiency.*

1. Introduction

Electromagnetic induction heating has become a key technology in modern manufacturing, particularly in heat-treatment processes such as forging, hardening, and metal forming (Erken & Obdan, 2024; Esteve et al., 2024; Khati et al., 2020; Travieso-Torres & Duarte-Mermoud, 2022). Industrial heating processes account for a significant portion of global energy consumption, contributing approximately 20–30% of total energy usage in manufacturing sectors (Esteve et al., 2024). Inefficient heating systems not only increase operational costs but also contribute to excessive energy waste and carbon emissions. Compared with conventional heating methods such as gas-based and resistive electric systems, induction heating provides faster thermal response, higher efficiency, and localized heating capability (Vishnuram et al., 2021). This process operates by inducing eddy currents within a conductive workpiece through an alternating magnetic field, generating heat due to electrical resistance (Machado, 2024; Mahariq et al., 2020).

Despite these advantages, practical implementation of induction heating systems in industrial environments still faces critical challenges. Many existing systems operate using constant-power strategies or fixed-parameter controllers that do not account for variations in workpiece geometry, material properties, or dynamic thermal conditions. As a result, energy efficiency is often compromised due to unnecessary power consumption under partial-load conditions. In addition, temperature instability, including overshoot and oscillations, remains a major issue. In industrial heat-treatment applications, deviations of up to ± 30 °C can significantly affect material microstructure, reduce hardness consistency, and increase defect rates, thereby impacting product quality and production cost (Esteve et al., 2024).

Various control strategies have been proposed to address these limitations; however, each presents inherent trade-offs. On–off control is widely adopted due to its simplicity, but it leads to significant temperature oscillations and switching losses, making it unsuitable for precision

heating applications. Conventional proportional–integral–derivative (PID) control improves stability but relies on fixed parameters, which limits its performance in nonlinear and time-varying systems (Kruthika & Paneerselvam, 2023; Lee & Chen, 2015). In practice, variations in workpiece mass, geometry, and thermal properties often degrade PID performance, resulting in overshoot, steady-state error, or slow response. Moreover, frequent manual retuning of PID parameters is impractical in industrial environments (Huang et al., 2025; Vishnuram et al., 2021).

More advanced approaches, such as adaptive control, fuzzy logic control, and model predictive control (MPC) (Li et al., 2025), have demonstrated improved adaptability and performance. However, their application in real industrial systems remains limited due to high computational complexity, implementation cost, and lack of seamless integration with widely used industrial controllers such as Programmable Logic Controllers (PLCs). In particular, many existing adaptive control studies are simulation-based or implemented in high-level computational platforms, with limited validation in real-time PLC-based systems. Furthermore, previous research tends to focus primarily on temperature tracking performance, with less emphasis on energy optimization and real-time power modulation, which are critical for sustainable manufacturing.

In the context of Industry 4.0, manufacturing systems are expected to be intelligent, connected, and capable of real-time monitoring and control (Bettioli et al., 2024; Jamil et al., 2022; Mustapha et al., 2023; Surindra et al., 2024). This requires seamless integration between sensors, actuators, control systems, and digital interfaces. PLC-based system, when combined with adaptive control and Human–Machine Interface (HMI) technologies, provide a practical and scalable platform for achieving these requirements by enabling real-time data processing, system automation, and operator interaction (Santillan et al., 2024; Somantri et al., 2022; Vasantharaj et al., 2025; Zhang et al., 2022).

Based on these challenges, a clear research gap exists in the development of a practical, real-time adaptive control strategy that can be efficiently implemented within a PLC environment to simultaneously improve temperature stability and energy efficiency under varying industrial conditions (Shahakar et al., 2025). Specifically, there is a lack of studies that:

1. implement adaptive control directly on industrial PLC hardware,
2. integrate real-time sensor feedback for dynamic power modulation, and
3. quantitatively evaluate both thermal performance and energy savings.

To address this gap, this study proposes a PLC-based adaptive control system using a self-tuning PID strategy for electromagnetic induction heating (Mizanur Rahman & Saiful Islam, 2021). The novelty of this work lies in:

1. the implementation of a real-time self-tuning PID algorithm within a PLC platform,
2. dynamic power regulation based on temperature error and system response, and
3. comprehensive experimental evaluation of both energy efficiency and thermal performance.

Experimental results demonstrate that the proposed system achieves up to 17.44% energy savings while significantly improving temperature stability and reducing overshoot. This contribution is particularly relevant for industrial applications such as metal heat treatment, forging preparation, and automated production lines, where precise temperature control and energy efficiency are critical. By enhancing both process quality and energy utilization, the proposed system supports the transition toward Industry 4.0, enabling more adaptive, intelligent, and energy-efficient manufacturing systems (Chavhan et al., 2025; Qu et al., 2024).

2. Literature Review

Electromagnetic induction heating has been extensively studied due to its advantages in efficiency, rapid heating, and precise temperature control in industrial applications (Mansoor & Che, 2023; Vishnuram et al., 2021; Yu & Zhang, 2024). Recent studies indicate that induction heating systems can significantly reduce energy losses compared to conventional resistive or combustion-based heating methods. However, industrial implementation still faces several challenges related to nonlinear thermal dynamics, variations in material properties, and load disturbances.

2.1. Conventional Control Strategies in Induction Heating

Traditional control strategies such as on–off control and PID control are widely used in industrial heating systems (Wang et al., 2021). On–off control is simple, however, it produces oscillatory temperature behavior and high switching losses. Meanwhile, PID controllers can improve system stability, but their performance tends to degrade in nonlinear and time-varying systems (Lee & Chen, 2015; Tomar et al., 2023; Wang et al., 2021). In induction heating applications, fixed PID parameters cannot effectively handle variations in workpiece geometry and thermal characteristics, resulting in overshoot and steady-state error.

2.2. Advanced and Adaptive Control Approaches

To overcome these limitations, various control strategies have been proposed. Adaptive control methods enable real-time parameter adjustment, thereby improving system robustness under varying operating conditions. In addition, fuzzy logic control has been applied in induction heating systems to handle nonlinearities and uncertainties without requiring an accurate mathematical model (Tong, 2023). Model Predictive Control (MPC) has also attracted significant attention. MPC is capable of achieving optimal control performance by predicting future system behavior; however, its computational complexity limits its real-time implementation in industrial environments. Despite these advancements, most studies remain confined to simulation environments or high-performance computing platforms, with limited implementation in PLC-based industrial systems.

2.3. PLC-Based Industrial Control and Industry 4.0 Integration

Programmable Logic Controllers (PLCs) remain the backbone of industrial automation systems due to their reliability and real-time operation capability. Recent research emphasizes the integration of PLC systems with IoT and Industry 4.0 frameworks for smart manufacturing applications (Gun Gun Maulana et al., 2023). Furthermore, PLC-based control systems combined with HMI and sensor networks enable real-time monitoring, data acquisition, and adaptive process control (Hendrawati et al., 2025; Tohir et al., 2025). However, the implementation of adaptive or intelligent control algorithms directly within PLC environments remains limited due to computational constraints and programming complexity.

2.4. Energy Efficiency Optimization in Heating Systems

Energy optimization is a critical aspect of modern manufacturing systems (Shi et al., 2023; Tong, 2023). Industrial heating contributes significantly to overall energy consumption, making efficiency improvement a key research focus. Recent studies indicate that adaptive and intelligent control strategies can reduce energy consumption by optimizing power distribution based on real-time process conditions. However, most existing studies primarily focus on temperature tracking performance rather than incorporating energy efficiency metrics into the control system design.

2.5. Theoretical Framework

This study is based on adaptive control theory, where controller parameters can be dynamically adjusted according to system error and system response to improve stability and performance. The self-tuning PID approach employed in this research is consistent with the principles of gain scheduling and real-time parameter adaptation (García-Martínez et al., 2020; Mizanur Rahman & Saiful Islam, 2021), enabling improved control performance in nonlinear systems.

3. Research Methods

3.1. System Design and Planning

The system was designed with two primary objectives: to improve energy efficiency and to maintain temperature stability during the electromagnetic induction heating process. The design process began by defining the technical specifications, including a target temperature range of 400–600 °C, heating duration, and operational safety constraints.

The system architecture consists of an induction heating unit, a control system, sensing elements, and an interface. The induction coil functions as the primary heat source, powered by an inverter that regulates electrical input parameters such as frequency and voltage. The control system is implemented using a PLC, which processes real-time sensor data and generates control signals to adjust the power supplied to the induction coil.

The hardware configuration is defined as follows:

- Induction coil: rated at approximately 2 kW with an operating frequency range of 20–30 kHz
- PLC controller: Omron CP1E with an average scan time of 100 ms
- Temperature sensor: infrared sensor with an accuracy of ± 2 °C, providing a 4–20 mA output signal
- Power monitoring unit: current and voltage sensors for real-time energy measurement
- HMI: used for parameter input, monitoring, and system control

The system operates in a closed-loop configuration, where temperature feedback from the sensor is continuously utilized by the PLC to regulate heating power. This architecture enables dynamic power adjustment based on real-time process conditions, forming the basis of the adaptive control strategy.

Overall, the system functions as a closed-loop control system in which the temperature feedback is continuously compared with the desired setpoint. The PLC processes this information and dynamically adjusts the power supplied to the induction coil (Tomar et al., 2023), thereby ensuring stable temperature control and improved energy efficiency. The complete system architecture is illustrated in Fig. 1.

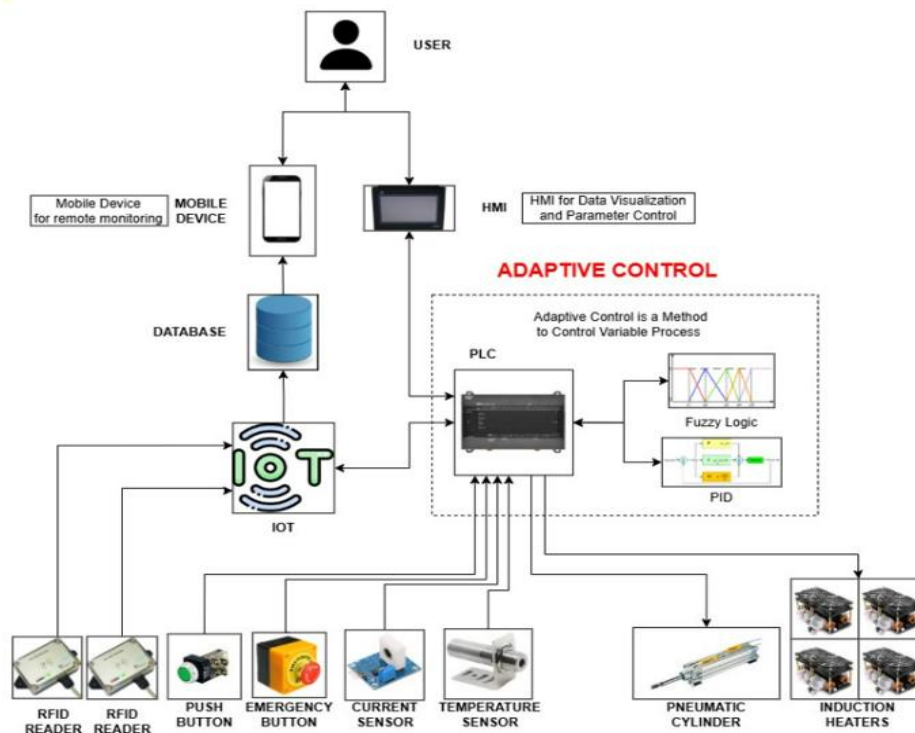


Fig. 1. System Architecture

The system comprises several components, including an electromagnetic induction coil, PLC as an adaptive controller, temperature sensors, current sensors, and HMI for system monitoring and control. Figure 1 illustrates the system architecture of the electromagnetic induction coil implementation, which is integrated with a PLC, using the adaptive control method to enhance energy efficiency. This integration aims to optimize electrical power during the electromagnetic induction heating process. Electrical power was supplied to the induction coil via an inverter, which changed the electrical current according to the heating requirements. The PLC implements an adaptive control method, allowing for adjustments in the induction power based on temperature fluctuations. The system also incorporates an HMI, enabling operators to control

and monitor system parameters in real time (Almtireen et al., 2025; Yu et al., 2025; Zamora Iribarren et al., 2024).

3.2. System Implementation

Table 1 - System Implementation Stages

| Stage | Description |
|---|---|
| Control and Power Panel Assembly | The installation of PLC, Input/Output (I/O) modules, protective devices, and the power distribution system. |
| Induction Coil, Temperature Sensor, and Actuator Installation | The process involves the precise positioning of the induction coil, the strategic placement of infrared temperature sensors to ensure accurate measurement, and the installation of pneumatic actuators for effective material holding. |
| PLC Integration with Sensors and Actuators | The process involves connecting sensors to the inputs of a PLC, linking actuators and an induction coil to the PLC outputs, and uploading ladder logic programs to facilitate adaptive control. |

As presented in Table 1 The system implementation was carried out in three main stages: hardware assembly, component installation, and system integration. In the first stage, the control and power panels were assembled by installing the PLC, input/output modules, circuit breakers, and power distribution components, with electrical wiring configured according to industrial standards to ensure safe and reliable operation while minimizing noise and interference. In the second stage, key components including the induction coil, infrared temperature sensor, and pneumatic actuator were installed, where the coil was positioned for uniform heat distribution, the sensor was placed at an optimal distance and angle for accurate non-contact temperature measurement, and the actuator was integrated to maintain consistent workpiece positioning. In the final stage, all sensors and actuators were connected to the PLC to complete system integration.

3.3. Adaptive Control Design

The control strategy employed in this study is based on a self-tuning PID adaptive control mechanism, which allows real-time adjustment of control parameters in response to system dynamics (Gao & Zhu, 2025; Nanang Rohadi et al., 2025;).

The temperature control error is defined as:

$$e(t) = T_{set} - T(t).....(1)$$

where T_{set} is the desired temperature and $T(t)$ is the measured temperature.

The control signal applied to the induction system is calculated using the PID formulation:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}.....(2)$$

Unlike conventional PID control, where the parameters K_p , K_i , and K_d are fixed, this study implements a self-tuning mechanism in which the controller gains are adjusted dynamically based on the magnitude of the error and its rate of change:

$$K_p = K_{p0} + \alpha e(t).....(3)$$

$$K_i = K_{i0} + \beta \int e(t)dt.....(4)$$

$$K_d = K_{d0} + \gamma \frac{de(t)}{dt}.....(5)$$

where α , β , and γ are adaptive coefficients that determine the sensitivity of the parameter adjustment.

This adaptive mechanism enables:

- higher control gain during large deviations (faster heating)
- reduced gain near the setpoint (minimizing overshoot)
- improved steady-state accuracy

The control algorithm is executed in the PLC with a sampling time of 100 ms, enabling continuous real-time adjustment of the power supplied to the induction coil. The output control signal is used to regulate the inverter, which adjusts the power delivered to the heating system.

3.4. Testing and Data Collection

3.4.1. Test with adaptive control vs without adaptive control.

Table 2 - Testing and Data Collection Scenarios

| No | Test Scenario | Measured Variables | Conditions / Variations | Purpose of Testing |
|----|---------------------------------|---|--|--|
| 1 | System with adaptive control | Rise time, overshoot, steady state error, power consumption (kWh) | Target temperatures: 400°C, 500°C, 600°C | To assess the efficacy of adaptive control in attaining desired temperature levels, a |
| 2 | System without adaptive control | Rise time, overshoot, steady state error, power consumption (kWh) | Target temperatures: 400°C, 500°C, 600°C | To evaluate the efficacy of conventional control in comparison to adaptive control |
| 3 | System with adaptive control | Rise time, overshoot, steady state error, power consumption (kWh) | Different material types (if available) | To evaluate the impact of material properties on the performance of adaptive control systems |
| 4 | System without adaptive control | Rise time, overshoot, steady state error, power consumption (kWh) | Different material types (if available) | To evaluate the impact of material properties on the performance of conventional control systems |

Presented in Table 2 are the testing scenarios along with the data collection methodologies adopted in this study to assess the performance of the electromagnetic induction coil system when integrated with a PLC under the adaptive control strategy. The primary aim of this test was to compare the performance of the system with and without adaptive control, thereby assessing the effectiveness of the adaptive control method for enhancing energy efficiency and temperature accuracy. In this experiment, variations in target temperatures, specifically 400°C, 500°C, and 600°C, were applied to assess the system's response under diverse heating conditions. Each temperature variation was tested under two conditions, with and without adaptive control.

3.4.2. Measured parameter

The system performance was evaluated using the following parameters:

- **Rise Time:** The time required for the system to reach the target temperature from the initial condition. This parameter reflects the responsiveness of the control system.
- **Overshoot:** The maximum temperature deviation above the setpoint during transient response. Overshoot is calculated as:

$$\text{Overshoot}(\%) = \frac{T_{max} - T_{set}}{T_{set}} \times 100 \dots \dots \dots (6)$$

- **Steady-State Error:** The difference between the final stabilized temperature and the target temperature:

$$e_{ss} = |T_{set} - T_{steady}| \dots \dots \dots (7)$$

- **Energy Consumption (kWh):** The total electrical energy consumed during the heating process, calculated by integrating
- **power over time:**

$$E = \int P(t) dt \dots \dots \dots (8)$$

Power measurements were obtained using current and voltage sensors connected to the PLC.

4. Result and Discussion

4.1. System Performance Overview

The experimental results demonstrate that the proposed PLC-based adaptive control system significantly improves both energy efficiency and temperature stability compared to conventional on-off control. All reported values represent the average of three experimental trials to ensure consistency and repeatability. In terms of energy consumption, the adaptive control system reduced total energy usage from 1.6067 kWh to 1.3265 kWh, achieving a 17.44% improvement. This reduction is primarily attributed to the ability of the self-tuning PID controller to continuously adjust control parameters (Kp, Ki, Kd) based on real-time temperature error. Unlike the on-off method, which operates at maximum power or zero, the adaptive system performs continuous power modulation, supplying only the required energy to maintain the setpoint. This eliminates unnecessary power fluctuations and reduces energy waste.

From a thermal performance perspective, the adaptive control system exhibits superior stability. The steady-state error is reduced to nearly zero, compared to 4.43 °C in the conventional system. This improvement is achieved through dynamic error compensation, where the controller continuously minimizes deviation from the setpoint. In addition, overshoot is significantly reduced by 79.33%, indicating that the controller effectively anticipates system response and prevents excessive heating. An important observation is that the adaptive system shows a slightly longer rise time (9.58 minutes) compared to the conventional system (9.42 minutes). This behavior reflects a trade-off between speed and stability. The on-off controller applies maximum power aggressively, resulting in faster heating but causing overshoot and oscillation. In contrast, the adaptive controller gradually reduces power as the temperature approaches the setpoint, prioritizing stability over speed. This strategy is particularly beneficial in industrial applications where temperature precision is more critical than rapid heating.

4.2. Simulink Model for System Performance Simulation

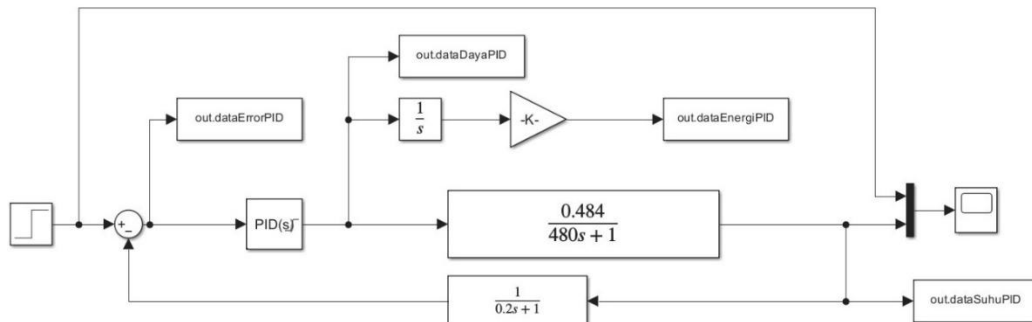


Fig 2. Simulink Block Diagram of the Adaptive Control System

Figure 2 presents the block diagram of the system as implemented in the MATLAB Simulink environment (Botín-Sanabria et al., 2022). This model serves as a digital twin to simulate and compare the performance of the two control strategies. It consists of two parallel systems, each containing a plant model represented by a transfer function, a sensor model, and data logging components. The top system implements the adaptive control strategy using a PID controller block, while the bottom system simulates the conventional (non-adaptive) method using an on-off controller with hysteresis (Relay block). This simulation environment allows for the direct, side-by-side evaluation of key performance metrics generated from identical system parameters.

4.3. System Functionality Testing

Table 3 - System Function Test Summary

| Component | Expected Function | Test Result | Status |
|-------------------------|---|---|---------|
| Temperature (IR) Sensor | Measure material temperature in real-time | Temperature detected and displayed on HMI | Success |

| | | | | |
|------------------|----------|---|--|---------|
| Induction Coil | | Generate heat according to PLC control | The Heating process follows the setpoint | Success |
| Pneumatic Holder | Material | Position and hold material | Operates stably according to PLC commands | Success |
| HMI | | Display temperature, process status, and alarms | Data clearly displayed, alarms function well | Success |

The findings from the functionality assessment presented in Table 3 show that all components operated correctly. The infrared temperature sensor provides real-time measurements of the material temperature, which are communicated to the PLC. The temperature readings are promptly displayed on the HMI, enabling the operator to efficiently monitor the process (Bántay & Abonyi, 2024). The induction coil functions based on the PLC's input, generating heat according to a predetermined setting, which verifies that the heating process control system is functioning as planned.

4.4. Dynamic Performance Analysis

Tabel 4 - Dynamic Control Performance Comparison

| Parameter | Without Adaptive | With Adaptive | Improvement |
|-------------------------|------------------|---------------|-------------|
| Rise time (min) | 9.42 | 9.58 | -1.67% |
| Overshoot (%) | 1.68% | 0.35% | 79.33% |
| Steady-state error (°C) | 4.43 | ~0 | 100% |
| Settling time (min) | ±12.5 | ±10.2 | ~18% |

As shown in Table 4 The dynamic performance comparison demonstrates that the proposed adaptive control system significantly enhances temperature regulation compared to the conventional method. Although the rise time slightly increases from 9.42 to 9.58 minutes (-1.67%), this marginal delay reflects a controlled heating strategy rather than aggressive power application. The adaptive controller intentionally reduces input power as the temperature approaches the setpoint, resulting in a smoother and more stable response. A substantial improvement is observed in overshoot reduction, which decreases from 1.68% to 0.35% (79.33% reduction). This indicates that the adaptive controller effectively anticipates system dynamics and prevents excessive temperature excursions, thereby reducing the risk of material overheating. Similarly, the steady-state error is eliminated (from 4.43 °C to approximately zero), confirming the controller's ability to maintain precise temperature regulation under steady conditions.

4.5. Energy Consumption Analysis

4.5.1. Instantaneous Power Consumption Comparison Adaptive Control Vs Conventional System

In this study, the evaluation was conducted by comparing the energy consumption of electromagnetic induction under two distinct conditions: without adaptive control and with adaptive control. The system is equipped with a current sensor and voltage sensor integrated into the power supply circuit, enabling the measurement of energy consumption through the reading of electrical power. A PLC that serves as the controller processes the sensor data. Initially, the system operated conventionally without adaptive control, resulting in higher power consumption and fluctuations. Subsequently, the system was operated with adaptive control, whereby the PLC adjusted the control parameters according to the induction load.

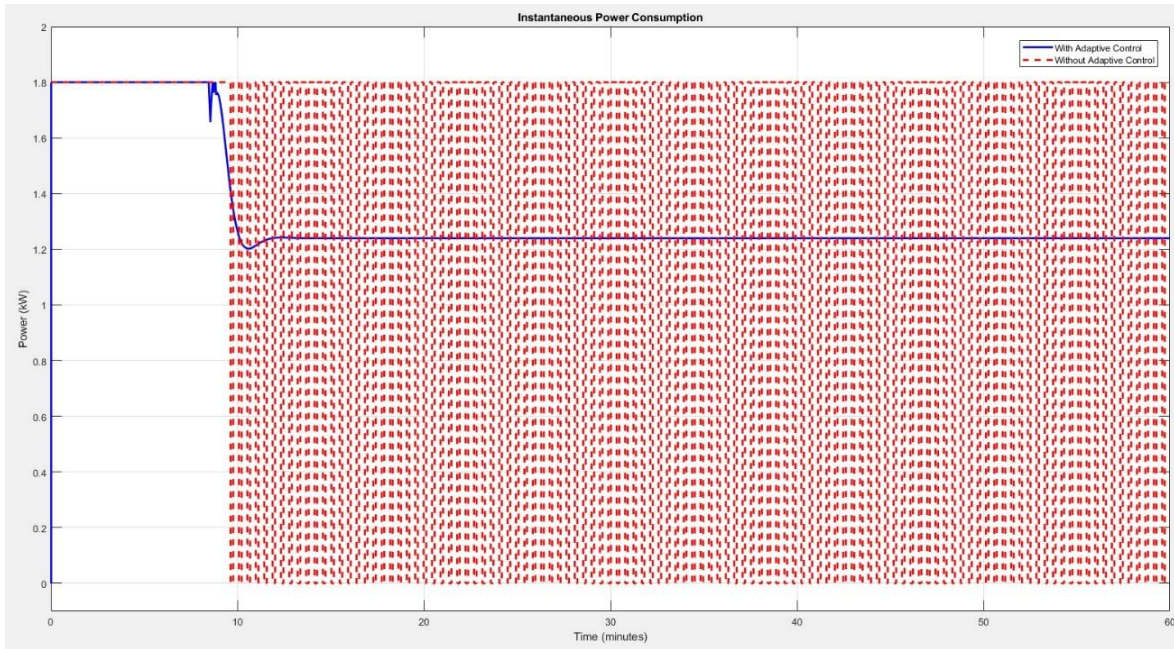


Fig. 3. Energy Consumption Comparison Adaptive Control Vs Conventional System

The analysis of instantaneous power consumption, shown in Figure 3, reveals the fundamental operational difference between the two control strategies. The system Without Adaptive Control (red dashed line) exhibits a classic on-off behavior, characterized by rapid, high frequency switching often termed "chattering" between the maximum power of 1.8 kW and 0 kW. This aggressive cycling is necessary for the simple controller to maintain temperature but can induce thermal stress and reduce the lifespan of switching components.

4.5.2. Cumulative Energy Consumption vs Time Adaptive control

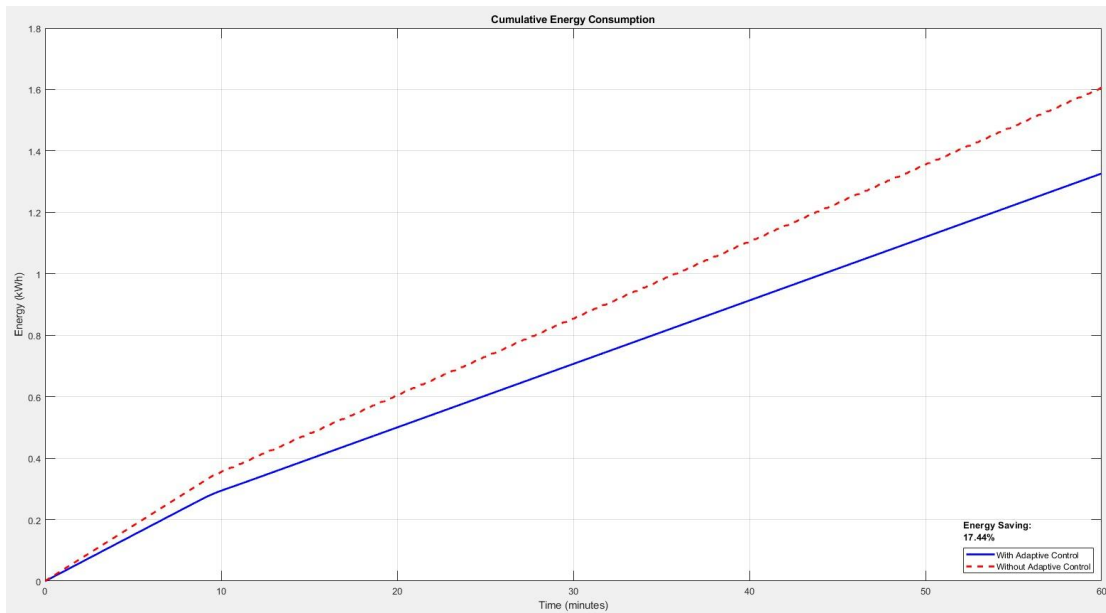


Fig. 4. Cumulative Energy Consumption vs Time Adaptive control in electromagnetic induction

Mathematically, the rate of energy consumption prior to implementing adaptive control increased more rapidly because of the maintenance of a constant power level at 1.8 kW or 0 kW with the total energy at 1.6067 kWh. Following the introduction of adaptive control, the total energy level decreased to 1.3265 kWh, resulting in a more gradual increase in the energy

consumption. Over a 60-minute period, the system could achieve energy savings of up to 17.44%. Figure 4, visually confirms the long-term efficiency gains of the adaptive method. The curve for the system Without Adaptive Control (red dashed line) shows a consistently steep, linear increase in energy consumption due to its continuous high-power cycling.

4.5.3. Energy Consumption Table (kWh) with Different Condition.

Table 5 - Energy Consumption Comparison (Heating Process, 600 °C, 60 minutes)

| Scenario | Average Temp. (°C) | Heating Duration (minutes) | Energy Consumption (kWh) |
|--------------------------|--------------------|----------------------------|--------------------------|
| Without Adaptive Control | 604.5 | 60 | 1.6067 |
| With Adaptive Control | 600.0 | 60 | 1.3265 |

The quantitative data summarized in Table 5 validates the graphical analysis. Over the 60-minute heating duration, the system Without Adaptive Control consumed a total of 1.6067 kWh. The implementation of With Adaptive Control, however, successfully reduced the total energy consumption to 1.3265 kWh. This marked reduction confirms an overall energy saving of 17.44%, achieved by the adaptive system's ability to precisely match power output to the actual thermal load, thereby preventing the energy waste inherent in the conventional on-off control method.

4.6. Temperature Stability Analysis

4.6.1. Material temperature vs Time

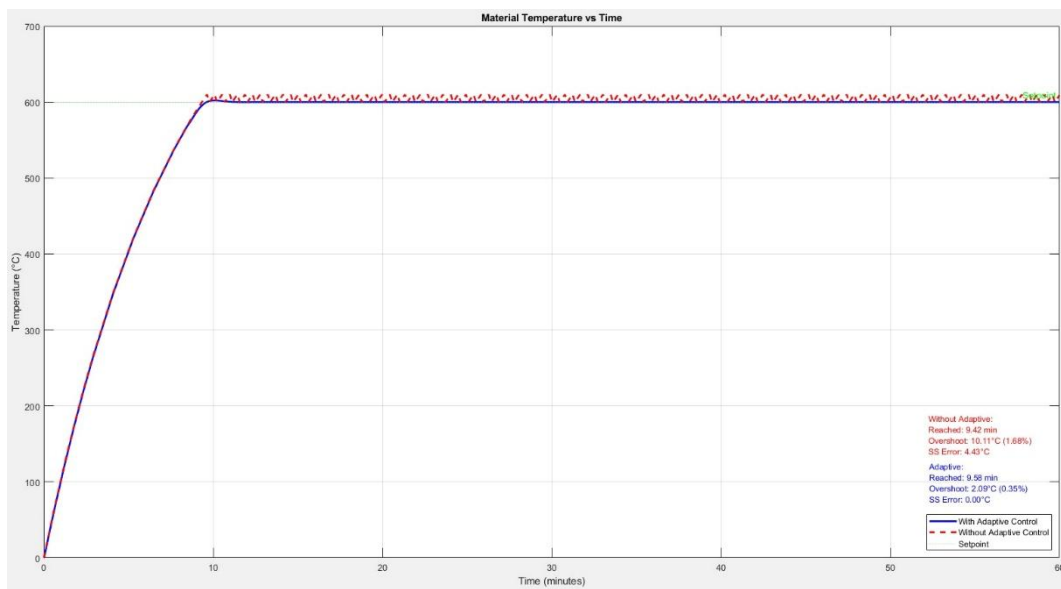


Fig. 5. Material temperature Vs Time

Figure 5 highlights the significant improvement in temperature stability. While both systems successfully reach the 600°C setpoint, their steady-state behaviors differ markedly. The system Without Adaptive Control (red dashed line) displays persistent temperature oscillations around the target. This constant rising and falling of the temperature is not due to sensor sensitivity but is an inherent characteristic of the on-off control logic, which can only react after the temperature has already deviated from the setpoint.

4.6.2. Temperature Error vs Time

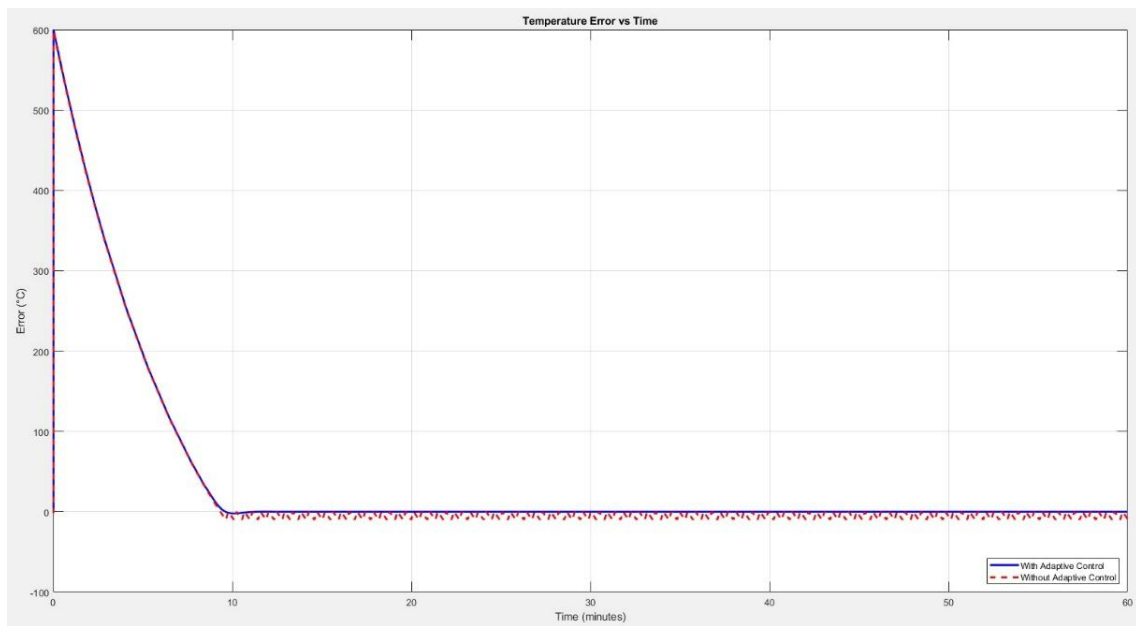


Fig. 6. Temperature Error vs Time

The temperature error comparison in Figure 6 further clarifies the performance difference. Both systems show a rapid decrease in error during the initial heating phase. However, the error for the system Without Adaptive Control (red dashed line) never fully settles at zero, instead continuing to oscillate persistently. Conversely, the error for the system With Adaptive Control (blue solid line) converges smoothly to zero and remains there. This ability to completely eliminate steady-state error is a key advantage of the adaptive method, preventing the energy waste associated with the constant over- and under-correction cycles of the conventional system. Adaptive control dynamically adjusts the control parameters in response to variations in the conditions of the induction system, Facilitating a more expeditious stabilization of the system's response.

4.7. Comparative Discussion with Previous Studies

The proposed adaptive control system achieves an energy saving of 17.44%, exceeding the typical range of 10–15% reported in previous studies using conventional PID or fuzzy control. This indicates improved efficiency through real-time parameter adjustment based on system dynamics. From a thermal performance perspective, the reduction in overshoot and steady-state error demonstrates the superiority of the adaptive approach over fixed-parameter methods. Unlike previous studies that rely on simulations or high-level platforms, this work implements the control system directly on a PLC, making it more practical for industrial applications.

Compared to methods such as fuzzy logic and model predictive control (MPC), the self-tuning PID offers a better balance between performance and computational simplicity, enabling real-time operation without complex processing requirements. Overall, this study contributes a practical solution that integrates energy efficiency, stable temperature control, and PLC-based implementation for industrial applications.

4.8. Performance Comparison

Table 6 - Performance Comparison

| Performance Parameter | Without Adaptive Control | With Adaptive Control | Improvement (%) |
|--|--------------------------|-----------------------|-----------------|
| Time to reach target temperature (minutes) | 9.42 | 9.58 | -1.67% |
| Average Steady-State Error (°C) | 4.43 | 0 | 100% |

| | | | |
|------------------------|-------|------|--------|
| Maximum overshoot (°C) | 10.11 | 2.09 | 79.33% |
|------------------------|-------|------|--------|

The performance metrics presented in Table 6 highlight the advantages of the adaptive control strategy. Although the time required to reach the target temperature is nearly identical for both systems, the primary improvements lie in precision and stability. The system with adaptive control effectively eliminates steady-state error, maintaining an average temperature of 600.0°C after reaching the setpoint. In contrast, the system without adaptive control exhibits an average temperature of 604.5°C, indicating the presence of a persistent positive error. Most notably, the maximum overshoot is significantly reduced from 1.68% in the conventional system to 0.35% in the adaptive control system. This reduction minimizes the risk of overheating the material and ensures higher process quality.

5. Conclusion

This study addresses the limitations of conventional induction heating systems that use constant-power methods or fixed-parameter control, which often result in poor adaptability, energy inefficiency, and temperature instability. To overcome these issues, a PLC-based adaptive control system using a self-tuning PID algorithm was developed and experimentally validated. The results show that the proposed method improves both energy efficiency and temperature control performance, reducing energy consumption from 1.6067 kWh to 1.3265 kWh (17.44%), while also achieving reduced overshoot, near-zero steady-state error, and improved temperature stability. Although a slight increase in rise time was observed, this reflects a trade-off that prioritizes stability and energy efficiency. Theoretically, this study contributes by demonstrating the practical implementation of self-tuning PID control in a PLC-based system. From an industrial perspective, it offers a feasible solution to enhance efficiency, product quality, and real-time monitoring in smart manufacturing systems aligned with Industry 4.0.

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