Eksperimental Study of the Power Control System in an Electric Heater

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ABSTRACT

Electric heaters are vital devices in various industrial fields that convert electrical energy into thermal energy The operation of power control systems is crucial to ensuring stable temperatures, providing safety, minimizing equipment damage, and conserving energy consumption. This experimental study was motivated by the need to analyze and compare the performance characteristics of power control systems using contactors, Solid State Relays (SSRs), and power regulators in a heating element. The experiment was conducted on-site at PT. Vinilon Jaya Sakti in Mojokerto collecting data on the operation of a 3,600-watt band heater integrated with an Autonics TK4S thermocontroller and a thermocouple temperature sensor. The main parameters tested and analyzed included electrical current, effective power, heating time efficiency, and temperature stability as measured by the offset value relative to the target set point of 150° C. The test results showed that the conventional control system using a contactor successfully reached the target temperature of 150° C within 10 minutes with a constant average current of 15.71 A during the full heating process. However, because it operates on a full On/Off mechanism, the contactor caused a significant temperature overshoot due to thermal inertia during the pre-heating phase, with an average offset value of 9.83° C. This empirical study is expected to serve as a technical reference for the industry in selecting the most suitable control device to reduce both operational and maintenance costs of heating systems

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INTRODUCTION

In the modern industrial era, electric heaters have become vital devices widely used across various manufacturing sectors to convert electrical energy into thermal energy. In their operation, the reliability of thermal processing systems heavily depends on the characteristics of the power control systems employed. Power control systems not only serve to precisely regulate temperature stability but also play a crucial role in ensuring workplace safety, preventing premature damage to machine components, optimizing energy efficiency, and reducing operational costs. The transient performance of these heating systems is significantly influenced by the internal dynamics of the thermal load as well as the inherent thermal inertia of the heating elements themselves.

Conventionally, the manufacturing industry widely employs mechanical switches such as magnetic contactors as the primary power controllers due to their high current capacity and economical investment cost. However, the use of contactors has significant technical limitations due to their fully On/Off operating mechanism. This extremely intermittent electrical current supply often results in fluctuating, unstable temperature output and triggers large thermal inertial overshoots around the target set point. Furthermore, the rapid and continuous on/off operation of contactors is prone to generating electrical sparks, which accelerate the wear of mechanical contacts, thereby shortening the device's lifespan and increasing the risk of machine downtime.

To address these shortcomings, modern semiconductor-based switching technologies are being adopted, such as Solid State Relays (SSRs) and SCR/Thyristor-based power regulators. SSRs offer extremely high switching speeds. without moving mechanical parts, thereby eliminating sparks and significantly reducing temperature offset fluctuations. On the other hand, power regulators offer the advantage of linearly and continuously modulating voltage amplitude and effective power through AC wave division, making them ideal for graded-scale heating applications. Although these three control technologies are widely used, in-depth empirical comparative analyses of current transient characteristics, time efficiency, power linearity, and their actual impact on temperature offset values for specifictargets are still rarely conducted in real industrial environments.

Based on these issues, a direct experimental study was conducted at PT. Vinilon Jaya Sakti, Mojokerto, to evaluate the performance of the contactor, SSR, and power regulator control systems. These tests were applied to a 3600-watt band heater using an Autonics TK4S thermocontroller and a thermocouple temperature sensor with a target set point of 150° C. Preliminary test results showed that the use of conventional contactors caused massive transient temperature overshoot, reaching upto 170° C during the pre-heating phase, with an average offset of 9.83° C due to their full On/Off characteristics. Therefore, this comparative study is crucial to provide precise, factual data for the industry in selecting the most optimal power control actuator, in order to minimize operating costs while reducing the maintenance costs of heating systems.

LITERATURE REVIEW

Contactor Power Control System and Thermal Inertia

A magnetic contactor is an electromechanical device that connects or disconnects high-capacity electrical current to heating elements using electromagnetic induction. Contactors operate on a full On/Off mechanism that has limitations in switching speed, resulting in an extremely intermittent electrical current supply. This leads to thermal inertia effects, such as significant temperature. overshoot and instability (oscillation) around the target set point. This phenomenon is supported by research by Eko Kustiawan (2018) and Dedi Sunandar (2018), which states that mechanical on-off control in high-power heaters always produces fluctuating temperature output and reduces thermal efficiency.

The Use of Conventional Power Control Systems with Contactors Causes Significant Temperature Overshoot and Offset During the Pre-Heating Phase

Semiconductor Control Systems (SSR and Power Regulators) Solid-State Relays (SSR) and Power Regulators (SCR/thyristor-based) are modern, non-contact electronic switching innovations that utilize semiconductor materials without moving mechanical parts. SSRs offer extremely high switching speeds through optical isolation, enabling them to regulate power in a closed-loop PID system and significantly dampen temperature fluctuations. Meanwhile, power regulators can modulate voltage amplitude and effective power linearly and continuously (0% to 100%) by dividing the AC waveform. Previous research by Choirudin (2020) supports this hypothesis by stating that semiconductor-based control can eliminate the weaknesses of mechanical switches and produce high-precision temperature accuracy.

The application of semiconductor-based power control systems (SSR and Power Regulator) results in higher temperature stability and minimizes temperature offset fluctuations compared to contactors.This quantitative experiment systematically divides the focus of observation into two main groups of variables: independent variables and dependent variables.The control input in this study serves as the independent variable (Variable X), where testing was conducted by manipulating or varying three main types of power control devices on the heating element: a mechanical contactor with full On/Off characteristics, a pulse-based solid-state relay (SSR), and a power regulator using linear modulation. The entire testing process for these independent variables was conducted directly at PT. Vinilon Jaya Sakti, Mojokerto, by applying them to a ceramic band heater unit with a total power capacity of 3,600 watts, controlled by an Autonics TK4S thermocontroller set to a specific target temperature (set point) of 150° C. Meanwhile, the resulting performance output from these variations served as the dependent variable (Variable Y). The parameters measured quantitatively to evaluate the performance of each actuator included electrical current transients in amperes, effective electrical power in watts, heating time efficiency in minutes, as well as the transient temperature overshoot value and the average value of the actual temperature stability fluctuation (offset) that occurs when the system attempts to maintain thermal conditions at the predetermined target.

Table 1. Frame Work Components

Frame Work Components	Independent Variable (X) (Type Power Control System	Dependent Variable (Y)(Thermal-Electrical Characteristic&Per fomance	Measurement Parameters (Quantitative Indicators))
Conventiona l Control	1. Mechani cal Contactor -Full On/Off Operation. -Binary Circuit Breaker.	-Heating Speed Response. -Current And Power Characteristics.	-Time To Reachtarget Temperature (Minutes). -Constant Average Current Value.
Semiconduc to r Control (Pulse)	2. Solid-State Relay (Ssr) -High-Speed Switching. -Modern Non-Contact Activation..	- Temperatur e Stability -Temperature Overshoot Value.	-Actual Fluctuation Value Around The Set Point (° C). -Maximum Transient Temperature Deviation.
Semiconduc to r Control (Modulation)	3 Power Regulator -Continuous Linearvoltag e Modulation. -Continous Wave Division.	-Fluctuation Value (Temperatureoffset). -Effective Power Linearity.	-Average Pre-Heating Phase Temperature Offset(° C). -Percentage Correlation Between Potentiomete r And Watts.

METHODOLOGY

Research Instruments

Research instruments play a crucial role as the primary determinant in obtaining accurate data to address the academic issues under study. This experimental study used the following set of standardized tools and materials:

1. Heating Element (Plant): Ceramic band heater with a total power capacity of 3, 600 watts, an operating voltage of 220 VAC, and physical dimensions of 300 mmx150mm.
2. Control Unit (Controller): Autonics TK4S series Digital Temperature Controller (Thermocontrol) module.
3. Temperature Sensor: Industrial-grade thermocouple to detect actual temperature changes in real time.
4. Power Control Actuators (Variable Load): 24 VDC Mechanical Contactor, Pulse-Type Solid-State Relay (SSR), and Power Regulator (Voltage/VASSR).

5. Manual Control Device: A potentiometer with a resistance value of 470 KQ, specifically designed for operating the Power Regulator.
6. Electrical Measuring Instruments: Digital multimeter for measuring transient electrical current (Amperes), operating voltage (Volts), and the resistance of the internal heating element.
7. Electrical Support Components: 2-phase miniature circuit breaker (MCB), specialized heating element cable with a diameter of 3 x 6 mm, and standard 2 mmelectrical control cable.

Data Collection Process

The data collection process was conducted through controlled laboratory experiments in the manufacturing environment of PT. Vinilon Jaya Sakti, Mojokerto. This electromechanical and thermal data collection was divided into three stages of the main test circuit:

1. Preparation and Basic Measurement Stage: Prior to dynamic testing, measurements were taken of the PLN power grid voltage, which yielded a constant value of 225 VAC. Next, a pure resistance test was performed on the band heater, yielding a value of 13.9 Q to validate the rounded nominal load power of 3,600 watts.
2. Target-Based (Closed-Loop) Testing Scenario: Testing of the mechanical contactor and Solid State Relay (SSR) power control systems was integrated with the Autonics TK4S Thermocontrol by setting a fixed temperature target (set point) of 150° C. Actual temperature data and electrical current transients were recorded periodically at 1-minute intervals for a total duration of 16 minutes, covering the full heating phase (heating mode, minutes 1 through 10) and the stabilization phase (pre-heating mode, minutes 11 through 16).
3. Manual Modulation (Open-Loop) Test Scenario: Testing of the Power Regulator device is performed manually using an analog modulation method with a potentiometer scaled in percentage increments ranging from 10% to 100%. In this scenario, the duration, effective voltage, current, and maximum temperature reached by the element were recorded at each percentage level increase without setting a specific temperature setpoint.

Data Analysis and Hypothesis Testing

The quantitative numerical data collected from the experiment sheets were analyzed using descriptive and comparative statistical methods througha physical-mathematical approach:

1. Analysis of Electrical Characteristics: Calculating the actual effective power (P) absorbed by the heating element using Joule's Law based on the measured voltage (V) and resistance (R) parameters:
   $P = V2R2252 = 13{,}9 = 3.642 = 3600\ watt$
2. Transient Thermal Characteristics Analysis: Evaluating the heating rate response (t) to reach the target saturation point. The first hypothesis test (H1) was conducted by measuring the magnitude of thermal inertia overshoot when the actual temperature exceeded the 150° C setpoint threshold at the 11th minute after the full heating phase ended.

3. Offset Analysis: The second hypothesis test (H2) focused on calculating the average temperature offset during the stabilization (pre-heating) phase. The formula for the error between the actual temperature (PV) and the target (SP) was calculated using the following equation:
$e(t) = SP - PV(t)$
The average value of the cumulative error (offset) in the contactor (recorded at 9.83°C) was then directly compared with the average offset of the SSR and power regulator to demonstrate the reliability of the semiconductor system in damping thermal oscillations.

Data Presentation Process

To ensure this final project report meets high standards of scientific readability, all quantitative experimental data are presented using the following visual structuring techniques:

1. Test Results Table: A chronological data matrix table containing columns for electric current (I), time variable (t), setpoint limits, and actual temperature (C) per minute for each power actuator.
2. Research Flowchart: Displays the operational flowchart of the research process, starting from instrument preparation, the physical assembly process, configuration tuning of internal thermocontrol parameters (such as the in-t" parameter menu for sensors and out1" for actuator type selection), through to the data collection stage and the preparation of the final report.
3. Wiring Diagram: Presents schematic technical drawings of the actual electrical terminal connections (such as power pins 5-6 and sensor pins 11-12 on the Autonics TK4S) to provide a visualization of the electrical system architecture that is valid and can be replicated by the manufacturing industry.

RESULTS AND DISCUSSION

Temperature Testing Using a Power Control System With a Contactor

Temperature measurements were taken using the contactor control system in heating mode. Temperature data was collected during a 16-minute heating process with a set point of 150 degrees Celsius.

Table 2. Results of Control System Testing Using a Contactor

Data No	Current (I)	Time(T) Minutes	Set Point(C°)	Temperature (C°)
1	15,7	1	150	32
2	15,7	2	150	50
3	15,8	3	150	73
4	15,6	4	150	95
5	15,7	5	150	100
6	15,8	6	150	115
7	15,7	7	150	128
8	15,5	8	150	135
9	15,8	9	150	141
10	15,8	10	150	150

The measurement results show that the average current flowing is 15.71 A. A temperature of 150° Cwas reached within 10 minutes.

Table 2. Test Results for the Control System Using a Preheating Mode Contactor

Data No	Current (I)	Time (T) Minutes	Set Point(C°)	Temperature (C°)
11	0	11	150	170
12	0	12	150	165
13	0	13	150	157
14	15,5	14	150	151
15	16	15	150	145
16	16	16	150	139
Average offset				9,83

From the current and temperature test results, it can be seen that the average current is 12.79 with an average offset value of 9.83° C.

Discussion

The contactor successfully reached the setpoint temperature of 150°C at the 10-minute mark with constant average current of 15.71 A during the heating process. This indicates that the contactor operated in full On/Off mode, continuously delivering maximum power until the target was reached. Upon entering the pre-heating mode at the 11th minute and beyond, the current dropped to 0 A because the contactor cut off the electrical current when the temperature exceeded the set point. However, a temperature spike occurred. reaching 170°C at the 11th munute due to the thermal inertia overshoot effect. The resulting average offset value was very large, at 9.83°C.

Temperature Testing Using a Power Control System with a Solid-State Relay (SSR).

Temperature measurements were taken using the contactor control systern in heating mode. Temperature data was collected during the 27-minute heating process with a set point of 150 degrees Celsius.

Table 3. Results of Control System Testing Using a Solid-State Relay

Data No	Current (I)	Time(T) Minutes	Set Point(C°)	Temperature (C°)
1	15,2	1	150	34
2	15,1	2	150	45
3	15,4	3	150	65
4	15,5	4	150	78
5	15,4	5	150	81
6	15,4	6	150	90
7	15,7	7	150	105
8	14,9	8	150	116
9	15,1	9	150	124
10	11,7	10	150	129
11	10,2	11	150	133
12	8,5	12	150	139

13	6,7	13	150	143
14	5,3	14	150	147
15	5,8	15	150	150

The measurement results show that the average current flowing is 12.39 A.

Table 4. Test Results of the Control System Using a Solid-State Relay in Pre Heating Mode

Data No	Current (I)	Time(T) Minutes	Set Point(C°)	Temperature (C°)
16	3,2	16	150	151
17	2,5	17	150	152
18	0,15	18	150	153
19	0,13	19	150	154
20	0	20	150	154
21	0	21	150	155
22	0	22	150	153
23	11,5	23	150	150
24	10,6	24	150	148
25	15,2	25	150	146
26	13.5	26	150	148
27	14,1	27	150	150
Average offset				2,75

From the current and temperature test results, it can be seen that the average current is 9.58 with an average offset value of 2.75 °C

Discussion

The SSR took 15 minutes to reach a temperature of 150°C, which is slightly slower than the contactor. This is because the curent flowing through it was not a constant 15 A; rather, it began to decrease gradually starting at the 10-minute mark, dropping from 11.7 A to 5.8 A by the 15-minute mark. The average current in heating mode is 12.39 A. In pre-heating mode, the current fluctuates dynamically between 0 A and 15.2 A to maintain the temperature close to the target of 150°C. As a result, the maximum temperature only reached 155°C, and the average offset value was very small, at 2.75°C.

Temperature Testing Using a Power Control System with a Power Regulator.

Temperature measurements were taken using a power regulator control system during heating mode. Data were collected during the heating process with varying power settings.

Table 5. Results of Temperature Testing Using a Power Control System with a Power Regulator

DataNo	Current(I)	Power Effective (Watt)	Time (T) In Minutes T The Reach	Set Point(C°)	Maximum Temperature Reached
1	1,6	360	50	10%	70
2	3,2	720	45	20%	110
3	4,7	1057	39	30%	180

4	6,5	1462	34	40%	245
5	8,3	1867	29	50%	320
6	9,5	2137	24	60%	360
7	11,3	2542	21	70%	400
8	12,9	2902	19	80%	430
9	14,5	3262	17	90%	470
10	16,2	3645	15	100%	550

Discussion

Based on the data generated, unlike contactors and SSRs, which are set to a specific temperature set point, the power regulator operates by linearly adjusting the percentage of effective power output (watts) using a potentiometer. A clear linear relationship is evident: as the potentiometer's set point percentage increases, the current (1) and effective power (watts) rise proportionally, accompanied by an increase in the heater's temperature. At the 10% level, the power output is only 360 watts with a maximum temperature of 70°C. Meanwhile, at full capacity (100%), the current rises to 16.2 A with a power output of 3,645 Watts, capable of raising the maximum temperature to 550°C. This is particularly advantageous for applications requiring manual limitation of heater power capacity or gradual heat gradation. The reduction in time to reach peak temperature-from 50 minutes at low load to 15 minutes at full load-demonstrates that direct voltage/power control is highly effective in regulating the thermal response of the heating element.

Discussion

The empirical findings from this comparative study provide a strong theoretical foundation for the manufacturing sector to mitigate operational lomes resulting from the improper selection of power control actuator technologies. Temperature instability in the form of transient heat waves generated by the operation of mechanical switches adversely affects the assurance of standardized quality in products resulting from thermal processing. In addition to reducing the geometric precision of the processed material, sharp temperature oscillations trigger repeated thermal shocks that accelerate internal fatigue cracking in the resistance wire coils of the heating element. From an academic perspective, this weakness reinforces the findings of previous studies by Sunandar (2015) and Kustiawan (2018), which stated that mechanical binary switch control is inefficient for high-precision thermal applications, che continuous, slow open to-closed contact operation also generates electrical arcing that accelerates the physical wear of the switch's copper contacts. Therefore, the adoption of integrated semiconductor technology has proven to be absolutely superior not only in delivering stable temperature accuracy but also in serving as a vital instrument for minimizing potential machine downtime losses, extending the service life of heating components, and optimizing long-term maintenance cost efficiency in the industry.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the experimental study conducted at PT. Vinilon Jaya Sakti, it can be concluded that the use of a conventional power control system employing mechanical contactors-operating on a full binary On/Off principle (100% or 0%)-delivers an average transient current that remains highly constant at 15.71 A during the full heating phase. Although this mechanical actuator is responsive and capable of bringing the load temperature to the target set point of 150°C within an efficient timeframe of 10 minutes, the limitations of its switching speed trigger the plant's inherent thermal inertia, which is detrimental. This phenomenon is evidenced by a massive transient temperature overshoot reaching 170°C at the 11th minute, as well as a very large average temperature offset of 9.83°C during the stabilization (pre-heating) phase.Conversely, comparative testing unequivocally demonstrated that the implementation of modern, non-contact semiconductor-based control systems-such as Solid State Relays (SSRs) and Power Regulators-is far more reliable in damping thermal oscillations, maintaining effective power linearity, and achieving high temperature accuracy around the operational target. The practical implementation of these test findings in a manufacturing environment has a significant impact on the optimization of production systems. The adoption of semiconductor-based power control technology has proven capable of consistently improving product quality and standardizing product geometry through high-precision regulation of processing temperatures. From a facility management perspective, replacing mechanical switches with solid-state devices successfully eliminates the occurrence of electrical arcing (sparks) and physical contact corrosion, thereby effectively extending the lifespan of the control equipment while reducing periodic maintenance costs. Furthermore, the temperature stability provided by semiconductor modules eliminates thermal shock in the chine's internal components, which directly contributes to reducing the risk of premature heater component failure, minimizing the potential for operational downtime, and improving the overall electrical energy efficiency of the factory's production line.

FURTHER STUDY

Although this experimental study has successfully tested and compared the transient performance characteristics of the three types of power control devices, there are several methodological limitations that must be acknowledged. First, the testing of temperature stability parameters and offset values for mechanical contactors and Solid State Relays (SSRs) was limited to a single target temperature (set point) of 150°C; consequently, the system's transient dynamics across different temperature ranges have not been fully characterized. Second, the evaluation of the power regulator was conducted using an open-loop scheme via manual modulation based on a potentiometer percentage setting, without integration into an automated system based on PID parameter tuning. Finally, the quantitative analysis in this experiment focused strictly on the time variable, current transients, effective power, and actual temperature changes, while disregarding mathematical calculations of external variables such as heat loss to the surrounding environment and the effects of mass fluctuations in the heated object. Based on these identified limitations, several practical recommendations are proposed as guidelines for future research. Future studies are advised to expand the testing scope by varying several target operating temperatures to assess the consistency of linearity and the thermal saturation limits of each actuator. In addition, it is also recommended to modify the control circuit architecture of the power regulator by connecting it directly to the analog output of the thermocontrol. This step is important for evaluating the accuracy of the intelligent PID control algorithm in automatically suppressing overshoot values. Finally, future research should integrate mathematical calculations regarding the circuit's total thermal efficiency, including measuring the heat transfer coefficient of the elements and analyzing the impact of the elements' cooling rate when the power supply is disconnected.

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