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Reduction of Starting Current Surge in Single-Phase Induction Motor Using Arduino Nano

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ABSTRAK

Motor induksi satu fasa mengalami lonjakan arus tinggi saat proses starting yang berpotensi menurunkan kualitas daya dan mempercepat kerusakan komponen listrik. Penelitian ini bertujuan merancang dan menguji sistem soft starter motor induksi satu fasa berbasis Arduino Nano untuk membatasi arus awal motor. Metode yang digunakan adalah pengendalian resistansi seri secara bertahap menggunakan modul relay yang dikendalikan Arduino Nano, dengan pemantauan parameter tegangan, arus, dan daya secara real-time menggunakan sensor PZEM-004T. Pengujian dilakukan dengan membandingkan arus starting motor sebelum dan sesudah penerapan sistem soft starter pada beberapa kondisi operasi. Hasil pengujian menunjukkan bahwa sistem mampu menurunkan arus starting sebesar 15%–20% dibandingkan kondisi tanpa soft starter, dengan karakteristik penurunan arus yang stabil. Analisis menunjukkan bahwa pembatasan arus tersebut efektif mengurangi stres listrik tanpa mengganggu proses percepatan motor. Kesimpulannya, sistem soft starter yang dikembangkan berhasil memenuhi tujuan penelitian dan layak diterapkan sebagai solusi sederhana dan ekonomis untuk pengendalian arus awal motor induksi satu fasa.

Kata kunci: Arduino Nano, lonjakan Arus Awal, Motor Induksi Satu Phasa, PZEM-004T, Soft Start.

ABSTRACT

Single-phase induction motors experience high inrush current during the starting process, which can degrade power quality and accelerate electrical component deterioration. This research aims to design and evaluate an Arduino Nano–based soft starter system for a single-phase induction motor to limit the starting current. The proposed method employs stepwise series resistance control using relay modules driven by the Arduino Nano, while electrical parameters including voltage, current, and power are monitored in real time using a PZEM-004T sensor. Experimental tests were conducted by comparing the motor starting current before and after the implementation of the soft starter under several operating conditions. The results demonstrate that the proposed system is able to reduce the starting current by 15%–20% compared to direct-on-line operation, with stable and consistent current reduction characteristics. The analysis indicates that the current limitation effectively reduces electrical stress on the motor without adversely affecting the acceleration process. It can be concluded that the developed soft starter system successfully meets the research objectives and is suitable as a *simple and cost-effective solution for controlling the starting current of single-phase induction motors.*

***Keywords**: Arduino Nano, Initial Current Surge, Single Phase Induction Motor, PZEM-004T, Soft Start.*

1. INTRODUCTION

Single-phase induction motors are fundamental components in both domestic and industrial applications, providing mechanical power for various devices such as household fans, water pumps, and automated systems. Their widespread utilization is largely due to their structural simplicity, low maintenance requirements, and high operational reliability (Arifin & Umar, 2021). These characteristics make them indispensable in numerous energy conversion systems, especially in low- to medium-power applications where efficiency and dependability are essential (Filiani, 2024).

Despite their advantages, single-phase induction motors are prone to a significant operational issue—an excessive inrush current occurring during the start-up process. This transient current can reach magnitudes five to seven times higher than the nominal current, thereby imposing severe electrical and thermal stress on the system (Nugraha et al., 2022). Prolonged exposure to such surges may deteriorate motor performance, reduce power quality, accelerate insulation wear, and ultimately increase maintenance costs due to frequent component failures.

To mitigate these adverse effects, soft-start technology has been recognized as an effective technique for limiting current surges (Zaki et al., 2021). The primary principle of this method lies in the gradual regulation of voltage supplied to the motor, enabling smoother acceleration and reduced starting current. This research proposes an innovative yet cost-efficient implementation of the soft-start approach by incorporating resistors to restrict inrush current during initial operation. However, the use of resistors alone can cause power losses, thereby necessitating an intelligent control mechanism to dynamically engage and disengage the resistors based on motor conditions (Laksono & Abdillah, 2023).

how to effectively reduce the high inrush current that occurs during the starting process of a single-phase induction motor using a simple and cost-efficient soft-start method; how to design a microcontroller-based soft-start system capable of controlling and disengaging current-limiting resistors in a controlled manner; and to what extent the proposed system is able to reduce the starting current quantitatively while maintaining stable motor operation. In addition, this study seeks to address the lack of integrated solutions that combine current measurement, control, and switching mechanisms within a single, compact system for single-phase induction motor applications.

In this study, the Arduino Nano microcontroller serves as the core control unit of the proposed soft-start system. The design integrates resistors, relays, and a PZEM-004T sensor to achieve precise measurement and efficient current regulation (Amirah et al., 2023). The integration of these components allows for adaptive control of the start-up process, ensuring reduced electrical stress and enhanced reliability. Furthermore, the system is designed to operate autonomously, providing real-time monitoring and feedback to maintain stability during motor start-up.

This research addresses a gap in previous studies, where comprehensive integration of Arduino-based control, sensing, and switching elements in single-phase motor soft-start systems has been limited. The developed system aims to enhance motor efficiency, ensure smoother starting performance, and extend the overall lifespan of electrical equipment. Ultimately, the findings are expected to contribute to the development of practical and reliable soft-start technologies, offering valuable insights for industrial applications focused on improving operational stability and energy efficiency.

2. METODS

2.1 *System Architecture Design*

The architecture of the proposed system is centered on the Arduino Nano, which serves as the primary control unit. Acting as the core of the design, the Arduino Nano orchestrates the automation of the motor's soft-start process, a critical function intended to significantly reduce the inrush current that typically occurs during the initial energization of the motor (Rizdam F. Muzakki, 2022). To achieve this goal, the system architecture is organized into three major functional units: the processing unit, the sensing unit, and the actuation unit.

The processing unit is responsible for data management, analysis, and decision-making, enabling the system to respond intelligently to changing electrical conditions. The sensing unit continuously monitors key electrical parameters such as voltage, current, and power in real time, ensuring accurate feedback for control operations. Meanwhile, the actuation unit executes the control signals generated by the processing unit, using relay mechanisms to regulate current flow during the motor's startup sequence.

Through the coordinated operation of these three subsystems, the overall system achieves a smooth, gradual, and well-regulated motor start-up, as illustrated in Figure 1. This integrated design not only enhances operational efficiency and reliability but also minimizes electrical stress on both the motor and the connected power network by ensuring controlled current flow during the starting phase.

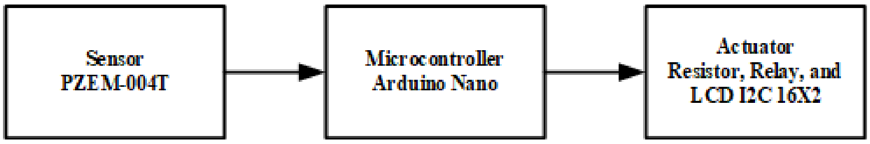


Figure 1. Soft start system architecture design

2.2 *Processing Unit*

The processing unit functions as the central intelligence of the system, with the Arduino Nano serving as the primary controller responsible for managing the entire soft-start operation. Its core function involves acquiring real-time data from the sensing unit, processing the information to evaluate the motor's operating conditions, and transmitting control signals to the actuation unit to regulate the startup process. Despite its compact dimensions of approximately 4.5 × 1.8 cm, the Arduino Nano offers performance capabilities comparable to the Arduino Uno, making it highly suitable for embedded control applications (Atha Ezrafi et al., 2023). The microcontroller is well-regarded for its efficiency, flexibility, and adaptability in systems that require compact design without sacrificing computational performance. Several key characteristics justify its selection for this application (Siregar et al., 2023):

a. Compact size

Its small form factor allows integration into systems with limited installation space, making it suitable for embedded and industrial applications.

b. Comprehensive I/O capability

Featuring 14 digital input/output pins (six of which support PWM) and eight analog input pins, it enables the connection of multiple sensors and actuators, thereby increasing system versatility.

c. Ease of prototyping

Its breadboard-compatible design simplifies circuit assembly, soldering, and testing, facilitating rapid system development.

d. Simplified programming

Fully compatible with the Arduino IDE, which employs C/C++ language syntax, and equipped with a mini-USB interface for both code uploading and serial communication with external devices. Through these advantages, the Arduino Nano provides a reliable and flexible platform for implementing soft-start motor control systems that require precise timing, efficient data processing, and compact physical integration.

2.3 *Sensor Unit*

The sensor unit employs the PZEM-004T module to continuously measure the motor's real-time electrical parameters, including voltage, current, and power (Chairunnisa & Wildian, 2022). Accurate sensing data obtained from this module are essential for the Arduino Nano to manage the transition between the *soft-start* and normal operating phases effectively. As such, sensor feedback serves as a critical input to ensure optimal system performance and protection. The PZEM-004T is a reliable and cost-effective instrument designed for the real-time measurement of AC electrical quantities, making it widely applicable in residential, commercial, and industrial monitoring systems (Amri et al., 2023). Its affordability, high accuracy, and ease of integration have made it a preferred choice for applications such as home automation, smart metering, and energy management systems (Prabowo et al., 2023). Specifically, the PZEM-004T version 3.0 is capable of measuring several essential electrical parameters, namely:

a. Voltage (V)

Voltage represents the potential difference between two points in an electrical circuit. It serves as the driving force that pushes electric charges to flow through the conductor. The magnitude of voltage directly affects the current and power output of the system.

b. Current (A)

Current refers to the rate of electric charge flow per unit time through a circuit. It is a key indicator of how much electrical energy is being transferred to the load. The stability of current flow is essential to ensure efficient motor operation and prevent excessive heating.

c. Active Power (W)

Active power is the useful portion of electrical energy converted into mechanical or thermal work. It can be calculated using the equation (1).

$$P = V \times I \times cos\varphi \tag{1}$$

With:

P : Active Power (W)
V : Voltage (V)
I : Current (A)
Cosφ : Power Factor

d. Power Factor (PF)

The power factor indicates the efficiency of electrical power utilization within a system. Its value ranges from 0 to 1, with higher values representing more efficient energy conversion. Lower power factor values are commonly found in inductive loads, such as electric motors, which cause phase shifts between voltage and current.

e. Energy (Wh/kWh)

Energy represents the cumulative amount of electrical power consumed over a specific period. It is expressed in watt-hours (Wh) or kilowatt-hours (kWh), consistent with standard utility billing units such as those used by PLN. Monitoring energy usage helps evaluate system efficiency and operational cost.

f. Frequency (Hz)

Frequency denotes the number of alternating current (AC) cycles that occur each second. It determines how quickly the current changes direction in an electrical system. In Indonesia, the standard AC frequency is 50 Hz, ensuring compatibility with national electrical infrastructure. A notable feature of the PZEM-004T is its detachable current transformer (CT) for non-intrusive current measurement. The clamp-type CT can be conveniently placed around a live conductor without physically disconnecting the circuit, thus enhancing user safety and installation simplicity. With its ability to accurately capture multiple electrical parameters and its safe, user-friendly design, the PZEM-004T module provides a practical and effective solution for engineers, researchers, and industrial practitioners in monitoring and optimizing electrical energy usage.

2.4 *Actuation Unit*

The actuation unit represents a crucial subsystem responsible for transforming electrical signals into mechanical actions that control the operation of the motor. Functioning as the “muscle” of the system, it enables mechanical responses such as switching, movement, and regulation. In this research, the actuation unit comprises three primary components: resistors, relays, and the LCD I2C 16×2 display. Each element performs a specific role in ensuring that the motor’s soft-start process operates safely, efficiently, and reliably.

a. Resistor

Resistors are employed to limit the initial inrush current during motor startup by directing the electrical current through them at the moment of activation (Abdussamad, 2022). As passive components, resistors restrict current flow according to their resistance value, measured in ohms (Ω). The relationship among voltage, current, and resistance is governed by Ohm’s Law like equation (2) (Gede Wiratma Jaya, 2023):

$$V = I \times R \tag{2}$$

With:

V : Voltage (V)

I : Current (A)

R : Resistance (Ω)

This equation demonstrates that current decreases when resistance increases, provided the voltage remains constant. Within this system, the resistor functions as a temporary current limiter. When the motor is initially energized, current flows through the resistor to suppress the surge of inrush current. Once the motor reaches its nominal speed, the resistor is bypassed—typically via a relay or contactor—to allow the full current to flow. Consequently, the resistor acts as a transient “buffer,” protecting both the motor and associated circuitry from excessive startup currents that could cause electrical or thermal stress.

b. Relay

The relay serves as an electronically controlled switch, managed directly by the Arduino Nano. Upon detecting that the motor’s current has stabilized, the Arduino activates the relay to bypass the resistor and deliver the full supply voltage to the motor. Relays act as intermediaries between low-power control circuits and high-power load circuits, allowing the microcontroller to safely control larger electrical devices such as motors, pumps, or lamps (Sinaga et al., 2022).

When the coil is energized, it produces a magnetic field that attracts the armature, altering the contact positions and changing the circuit state. When de-energized, the spring mechanism returns the armature to its initial position. This mechanism ensures safe electrical isolation between the low-voltage control side and the high-voltage power side, enhancing both safety and reliability of the overall system (Suseno, 2022).

c. LCD I2C 16×2 Display

The LCD I2C 16×2 module functions as the system's user interface, displaying real-time electrical parameters and operational status. This enables users to monitor the system conveniently and ensures transparency in performance evaluation (Rizakir & Sukarno, 2025). The module integrates a standard Liquid Crystal Display (LCD) with an I2C (Inter-Integrated Circuit) communication adapter, which simplifies wiring by reducing the number of data connections from 7–11 pins in a conventional LCD to only two communication lines—SDA (data) and SCL (clock)—along with power and ground (Filhaq et al., 2023).

At the core of the I2C interface lies an I/O expander chip, typically the PCF8574, which serves as a communication bridge between the microcontroller and the LCD. It receives serial commands from the Arduino via the I2C protocol and converts them into parallel signals required by the LCD. This configuration significantly reduces pin usage on the microcontroller, enabling efficient hardware resource allocation.

By minimizing communication complexity and optimizing hardware utilization, the LCD I2C 16×2 module enhances both the practicality and scalability of the overall system, supporting efficient real-time monitoring and user interaction.

2.5 *Determining the Size of the Resistor Used*

To mitigate the high inrush current that occurs during motor startup, this study employs a resistor as a voltage-dropping and current-limiting component. During the initial energization of an induction motor, a substantial current surge is required to overcome mechanical inertia and establish the magnetic field. If this surge is not properly controlled, it can lead to component degradation, thermal stress, or even total system failure. Consequently, the inclusion of a resistor in the soft-start circuit serves to attenuate the initial current flow, ensuring a smoother and safer startup process. The resistor value (R) is determined based on the relationship between electrical power, voltage, and current, as expressed through the following equations (3) to (5) (Harahap & Adam, 2021):

$$P = V \times I \tag{3}$$

$$P = (I \times R) \times I \tag{4}$$

$$P = I^2 \times R \tag{5}$$

With:

P : Power (W)

V : Voltage (V)

I : Current (A)

R : Resistance (Ω)

In this system, the resistor is connected in series with the motor during the soft-start phase. Its primary role is to temporarily limit the current by increasing the circuit's overall resistance, allowing the motor to accelerate progressively until it reaches nominal speed. Once stable operation is achieved, the resistor is bypassed—typically via a relay—to allow full voltage to be applied directly to the motor. This approach effectively reduces mechanical stress on the motor shaft and electrical stress on circuit components. Furthermore, the total resistance required for the soft-start process can be configured through a combination of series or parallel connections, depending on the desired current-limiting characteristics. The equivalent resistance of the network is calculated using the following relationships like equation (6) and (7) (Untoro, 2025):

$$\frac{1}{R_{Parallel}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n} \tag{6}$$

$$R_{Series} = R_1 + R_2 + \cdots + R_n \tag{7}$$

With:
$R_{Parallel}$: Parallel resistance (Ω)
R_{Series} : Series resistance (Ω)
R_1 : 1st resistance (Ω)
R_2 : 2nd resistance (Ω)
R_n : N-th resistance (Ω)
By properly designing the resistor configuration, the soft-start system achieves a controlled balance between current limitation and available starting torque. This balance is essential to ensure optimal motor performance, minimize energy losses, and enhance the overall reliability and service life of the motor system.

By employing both equations, it becomes possible to increase the resistance value using Equation (5) and to further adjust the total resistance through the application of Equation (7) in order to reduce the starting current. Based on this approach, Equation (8) is formulated to explicitly describe the utilization and integration of the preceding equations in quantifying the reduction of the initial current.

$$\mathrm{P} = \mathrm{I}^2 \times (\mathrm{R}_0 + \mathrm{R}_1) \tag{8}$$

With:

P : Power (W)
V : Voltage (V)
I : Current (A)
R_0 : Resistance before intervention (Ω)
R_1 : Resistance intervention (Ω)

2.6 *Flowchart of Process*

When the system is energized, the Arduino Nano immediately initiates serial communication with the PZEM-004T sensor to obtain real-time measurements of voltage and current. These electrical parameters constitute the primary input data for both monitoring and control operations. The user can select between two operational modes—Measurement Mode and Soft Start Mode—through a selector switch integrated into the system. In Measurement Mode, the system operates solely as a monitoring device. The PZEM-004T sensor continuously measures key electrical quantities such as voltage, current, power, and power factor. These values are transmitted to the microcontroller and displayed on the LCD I2C 16×2 module in real time. This mode allows users to observe the motor’s electrical performance under normal operating conditions without interfering with its operation. Conversely, when Soft Start Mode is selected, the system activates a power-limiting circuit specifically designed to manage the high inrush current that occurs during motor startup. Upon motor activation, the PZEM-004T sensor detects a significant rise in current. In response, the Arduino Nano executes a predefined control sequence that directs the current to flow through the resistor network first. This controlled process limits the initial current surge, thereby reducing both electrical and mechanical stress on the motor components.

Throughout the soft start phase, the LCD display provides continuous real-time updates of voltage and current values, allowing users to visually monitor the stabilization process. The soft start period is programmed to last approximately two seconds, after which the Arduino Nano triggers the relay to bypass the resistor network. This action applies the full supply voltage directly to the motor terminals, marking the transition to steady-state operation. If the user intends to modify power-related parameters such as the soft start duration or resistor configuration—these adjustments must be performed while the system remains in Soft Start Mode. This precaution ensures that parameter changes occur under controlled conditions, thereby maintaining system safety, operational reliability, and the integrity of the motor's startup performance.

Figure 2 presents the flowchart of the system that has been described previously. The flowchart illustrates the operational sequence and control logic implemented in the proposed system.

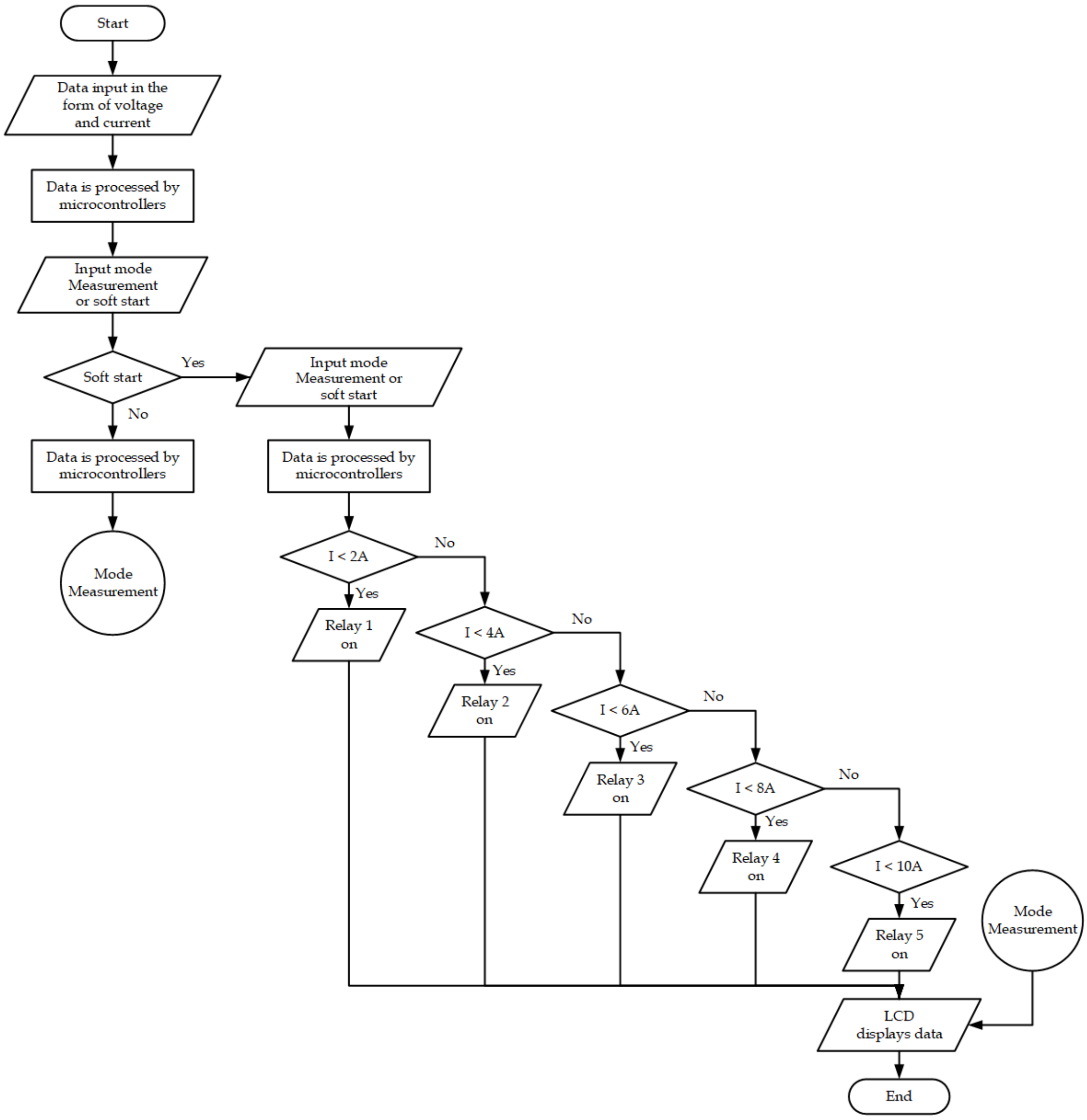


Figure 2. Flowchart of the control system

2.7 *Calculating the Percentage of Current Attenuation*

An essential indicator in assessing the performance of a soft start system is the current attenuation percentage, which quantifies the system's ability to reduce the inrush current that arises during the initial operation of the motor. This parameter reflects the system's effectiveness in alleviating electrical and mechanical stress on both the motor and its supporting circuitry. A higher attenuation percentage signifies a more effective soft start process, leading to improved motor protection, enhanced operational efficiency, and extended equipment lifespan. The calculation of current attenuation percentage is conducted by comparing the current magnitude measured before and after the application of the soft start mechanism. The relationship is mathematically expressed as follows equation (9):

$$Percentage = \frac{I_0 - I_1}{I_1} \times 100\% \quad (9)$$

With:

Pecentage: Current attenuation percentage (%)

I_0 : Start current before using soft start (A)

I_1 : Start current after using soft start (A)

This equation provides a straightforward method for evaluating the degree of current reduction achieved by the system. By determining this percentage, researchers and engineers can quantitatively assess the effectiveness of the soft start control strategy in minimizing startup transients and enhancing overall motor reliability.

3. RESULTS AND DISCUSSION

3.1 *Planning*

Prior to conducting the experimental phase, analytical calculations were performed to determine the optimal resistor values required for the system as a means to achieve the main objectives of this research, namely reducing the inrush current during motor start-up, improving electrical stability, and ensuring smoother and more reliable motor operation. The selection of an appropriate resistance value is crucial, as it directly influences the system's capability to suppress the inrush current that occurs during the motor's startup phase and to limit excessive electrical and mechanical stress on the motor and power network. In this study, five operating modes were designed, each corresponding to a distinct nominal current level based on the test load capacity, in order to evaluate the effectiveness of the proposed soft-start strategy under different operating conditions. For each mode, the resistor value was calculated to ensure precise regulation of the voltage supplied to the motor during the initial start-up period, thereby supporting the research goal of achieving controlled current reduction while maintaining adequate starting torque and overall system efficiency. The main objective of this calculation is to limit excessive current flow at startup, thereby maintaining operational safety, electrical stability, and component longevity. The design process also considered the motor's electrical characteristics and rated current to achieve optimal system performance. Equations (8) served as the basis for determining the resistor values, with the final results summarized in Table 1.

Table 1. Planning of the Resistor to be Used

Mode	Maximum Active Power (Watt)	Voltage (Volt)	Maximum Current (Ohms)	Maximum Resistance (Ohms)	Current Reduction Target (%)		Large Current Drop (Ampere)		Required Resistance (Ohms)		Resistors Required (Ohms)		Large Resistors Available and Used in Research (Ohms)
					Min	Max	Min	Max	Min	Max	Min	Max	
1	450	220	2	112.5	15	20	0.3	0.4	155.709	175.781	43.209	63.281	47
2	900	220	4	56.25	15	20	0.6	0.8	77.855	87.891	21.605	31.641	22
3	1320	220	6	36.667	15	20	0.9	1.2	50.750	57.292	14.083	20.625	15
4	1760	220	8	27.5	15	20	1.2	1.6	38.062	42.969	10.562	15.469	12
5	2200	220	10	22	15	20	1.5	2	30.450	34.375	8.450	12.375	10

After establishing the appropriate resistance values, the subsequent stage involved the design and integration of the complete soft-start system. At its core, the Arduino Nano microcontroller serves as the central control unit responsible for managing all processes. The PZEM-004T sensor continuously monitors real-time electrical parameters, including voltage and current, while an LCD I2C 16×2 display provides an intuitive visual interface for monitoring system performance. The overall design framework was divided into two main stages: (1) hardware development, involving circuit assembly and component integration, and (2) software implementation, where control algorithms were programmed to regulate the soft-start sequence. This integrated design ensures a reliable, stable, and user-friendly system capable of effectively reducing current surges during induction motor startup.

3.2 *Component Integration*

The system integrates several key components that function in a coordinated and synchronized manner. Push buttons are incorporated as input controls for selecting operational modes and display views, each interfaced with the Arduino Nano through pull-down resistors to ensure stable signal readings. A fuse is also included as a protective element to safeguard the system from potential overcurrent or short-circuit conditions. The PZEM-004T sensor module forms the primary sensing component, directly interfaced with the Arduino Nano. Its current transformer (CT) enables non-invasive current measurement, enhancing both safety and accuracy. Real-time voltage and current data acquired from the sensor are transmitted to the Arduino for processing and subsequently displayed on the LCD I2C 16×2 module. The actuation unit consists of two major subcircuits: the soft-start control circuit and the display circuit. The soft-start circuit connects the Arduino Nano to an NPN transistor, relay, and resistor network, facilitating safe control between low-voltage and high-voltage sections. The LCD I2C display serves as the user interface, presenting operational data in real time to enable efficient monitoring and user interaction. Based on the overall system architecture described previously, an integrated configuration of the system components is formulated and comprehensively illustrated in Figure 3.

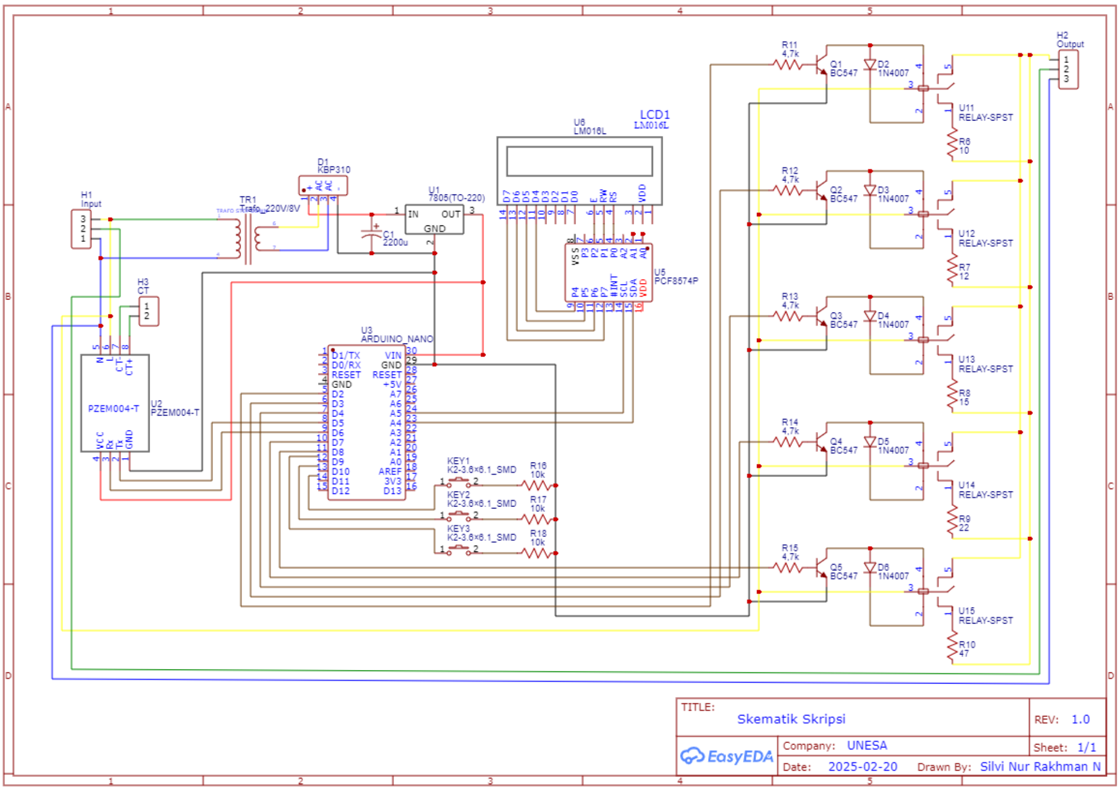


Figure 3. Component Integration

3.3 *Programming and Calibration*

The software development stage involved writing and uploading a program to the Arduino Nano to execute the soft-start control algorithm. The calibration process for the PZEM-004T sensor ensured high measurement accuracy across voltage, current, and power parameters. After calibration, the complete system was tested to verify component coordination and overall functionality.

Comprehensive testing was conducted to assess the system’s ability to reduce inrush current and ensure smooth power transitions. The testing procedures included:

a. Data acquisition: Real-time recording of voltage, current, and power using the PZEM-004T sensor.
b. Repetitive trials: Conducting four repeated tests under identical load conditions to minimize random error.
c. Data averaging: Calculating mean values from multiple trials to improve measurement reliability.

The experimental data were analyzed to verify that the observed outcomes aligned with the theoretical predictions.

3.4 *Experimental Results*

The experimental evaluation was conducted by testing the system on five different electrical devices, as summarized in Table 2. The corresponding data acquisition process and experimental setup are illustrated in Figure 4, which outlines the procedure used to collect electrical parameters during the testing phase.

Table 2. Spesification of tools

Num	Name fo Tools	Anotation of Tools	Active Power Measured (Watt)	Voltage (Volt)	Frequency (Hertz)
1	Hand drill	Tool 1	300	220	50-60
2	Small Hand Grinder	Tool 2	300	220	50-60
3	Sitting Grinder	Tool 3	1200	220	50-60
4	Big Hand Grinder	Tool 4	1200	220	50-60
5	Compressor	Tool 5	1100	220	50-60

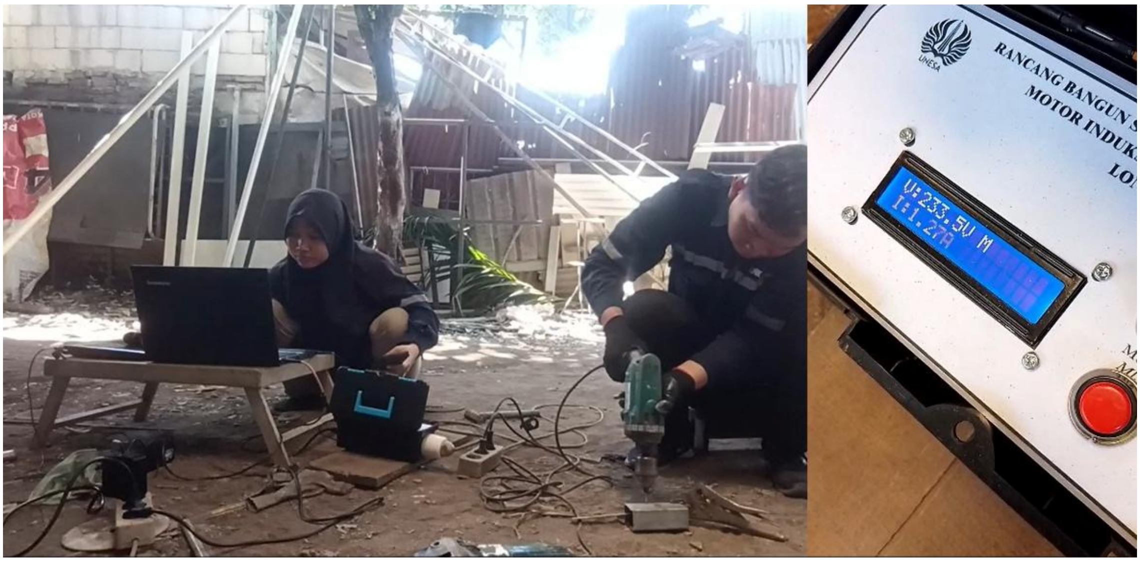
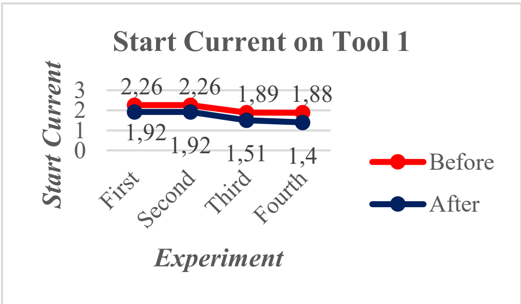


Figure 4. data acquisition process

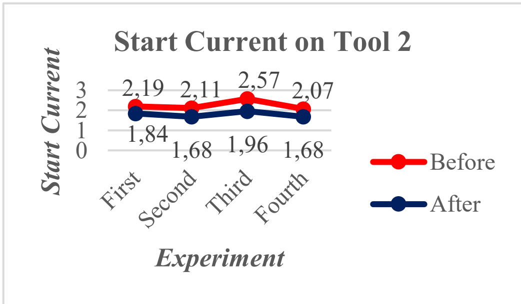
The experimental findings of the soft-start system are summarized in Table 2. These results illustrate the system's performance across multiple test loads and operating modes. To enhance interpretability, the numerical data were further represented graphically in Figure 5, allowing visual comparison between current values before and after applying the soft start system.

Table 3. Experimental Measurement Results of Soft Start Implementation

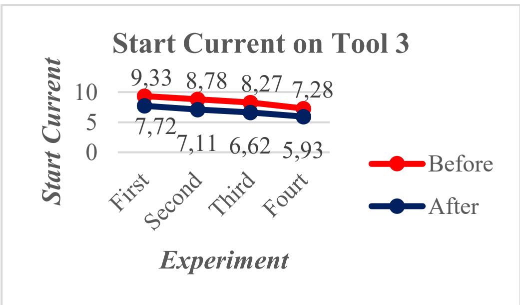
Num	Active Power Measured (Watt)	Voltage (Volt)	Nominal Current (Ampere)	Mode	Peak Starting Current (Ampere)							
					Experiment 1		Experiment 2		Experiment 3		Experiment 4	
					Before	After	Before	After	Before	After	Before	After
1	300	233,5	1,24	1	2,26	1,92	2,26	1,92	1,89	1,51	1,88	1,4
2	300	231,7	1,37	1	2,19	1,84	2,11	1,68	2,57	1,96	2,07	1,68
3	1200	223,9	4,25	3	9,33	7,72	8,78	7,11	8,27	6,62	7,28	5,93
4	1200	227,1	4,8	3	9,37	7,61	8,53	7,15	9,94	7,95	9,58	7,94
5	1100	223,5	4,7	3	11,8	9,33	9,23	8,1	9,71	8,55	10,42	8,75



(a)



(b)



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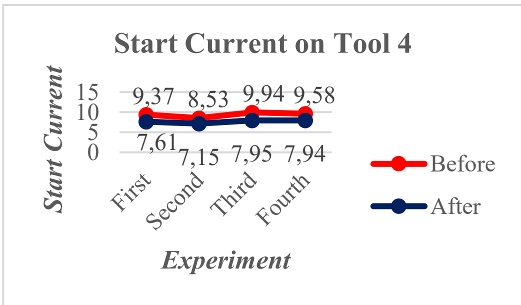
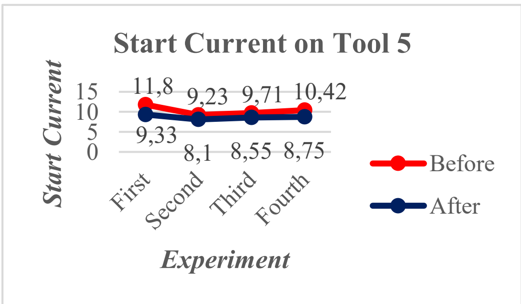


(d)



(e)

Figure 5. (a) Start current graph on tool 1, (b) Start current graph on tool 2, (c) Start current graph on tool 3, (d) Start current graph on tool 4, and (e) Start current graph on tool 5

Across all experiments, the implementation of the soft start mechanism demonstrated a clear reduction in inrush current. For instance, in Figure 5(a), the average startup current decreased from approximately 2.26 A to 1.4 A, while Figure 5(b) shows a reduction from 2.57 A to 1.96 A. Similarly, Figure 5(c) and Figure 5(d) display significant reductions, where peak currents were reduced from 9.33 A to 7.72 A and 9.94 A to 7.95 A, respectively. The largest reduction occurred in Figure 5(e), where the initial current dropped from 11.8 A to 9.33 A.

These findings confirm that the system effectively mitigates startup current surges, thereby reducing mechanical and electrical stress on the motor and improving system reliability.

3.6 *Current Reduction Analysis*

The percentage of current reduction was calculated using Equation (8) to quantitatively assess the system's performance in attenuating inrush currents. The results, summarized in Table 3, indicate that all operating modes achieved the desired reduction range of 15%–25%, with the average reduction across tests falling within the target range.

Table 4. Percentage Reduction of Starting Current in Soft Start Experiments

Num	Power (Watt)	Mode	Current Attenuation Percentage (%)					Information
			Experiment 1	Experiment 2	Experiment 3	Experiment 4	Average	
1	300	1	17.708	17.708	25.166	34.286	23.717	Target Achieved
2	300	1	19.022	25.595	31.122	23.214	24.738	Target Achieved
3	1200	3	20.855	23.488	24.924	22.766	23.008	Target Achieved
4	1200	3	23.127	19.301	25.031	20.655	22.029	Target Achieved
5	1100	3	26.474	13.951	13.567	19.086	18.269	Target Achieved

Table 5. Validation Test of Soft Start

Starting Current Validation Test Result				
Tool 1	Tool 2	Tool 3	Tool 4	Tool 5
0.989	0.996	0.993	0.966	0.981

Each mode was further analyzed to compare performance with and without the soft start mechanism. This comparative evaluation validates that the system consistently meets design expectations, as shown in Table 4, which presents the validation test results for each mode, yielding correlation coefficients ranging from 0.966 to 0.996 indicating strong alignment between theoretical and experimental data.

3.7 *Discussion*

The experimental results confirm that the proposed Arduino Nano–based soft starter effectively reduces the starting current of single-phase induction motor loads under all tested operating conditions. As summarized in Table 2 and illustrated in Figure 5, the implementation of the stepwise series resistance control consistently decreased peak starting current across different power levels. For 300 W loads, the starting current was reduced from a maximum of 2.57 A to 1.40 A, while for higher loads of 1100–1200 W, the peak current decreased from up to 11.8 A to 9.33 A. These results indicate that the soft starter performs reliably for both low- and high-power applications.

Quantitative evaluation of starting current attenuation, presented in Table 3, shows that all operating modes achieved reductions within the targeted range of 15%–25%. The average attenuation values varied between 18.27% and 24.74%, demonstrating consistent performance across repeated experiments. The close alignment between experimental results and the planned resistor values (Table 1) confirms that the resistor selection method effectively limits inrush current while maintaining stable motor acceleration. Variations observed in individual trials are attributed to load characteristics and transient conditions during startup rather than control instability.

Further validation, as shown in Table 4, yielded correlation coefficients between 0.966 and 0.996, indicating strong agreement between theoretical calculations and experimental measurements. This validates the accuracy of the analytical model and the reliability of the implemented hardware–software integration. Overall, the results demonstrate that the proposed soft starter successfully meets the research objectives by providing effective starting current attenuation, improved electrical stability, and a practical, cost-effective solution for single-phase induction motor applications.

4. CONCLUSION

Based on the experimental results obtained in this study, it can be concluded that the proposed Arduino Nano–based soft start system is capable of effectively reducing the starting current surge of single-phase induction motors. Experimental testing conducted on five electrical devices with different load characteristics demonstrated a consistent reduction in peak starting current after the implementation of the soft start mechanism. The measured current attenuation ranged from approximately 15% to 25% across all tested modes, which meets the design targets established during the planning stage. The experimental data presented in Tables 2 and 3 and visualized in Figure 5 confirm that the gradual insertion of series resistance during the motor start-up phase successfully limits excessive inrush current while maintaining stable motor operation. The results also indicate good repeatability, as evidenced by multiple experimental trials under identical operating conditions. Furthermore, the validation analysis showed strong agreement between calculated expectations and experimental measurements, with correlation coefficients ranging from 0.966 to 0.996. Although this study did not explicitly derive a detailed mathematical model of the induction motor, the experimental findings provide sufficient empirical evidence that the proposed soft start strategy improves start-up performance by mitigating electrical and mechanical stress during initial energization. Within the tested power range of up to 1200 W, the system operated reliably and consistently achieved the intended current reduction. In summary, the developed system offers a practical and implementable solution for reducing inrush current in single-phase induction motors using a microcontroller-based approach. The results of this research support its applicability for low- to medium-power motor applications, while further investigations involving higher power ratings and broader operating conditions are recommended to extend its industrial relevance.

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