Journal of Marine Electrical and Electronic Technology **Vol. ….…, No. …….**
ISSN xxxxxx **Publication Periode**

Optimized AC-AC Converter Design Using Triode Technology For Voltage Regulation And Soft-Starting Applications In Three-Phase Induction Motors

Semeru Fakhrurrozi Afianto

Automation Engineering, Departement of Marine Electrical Engineering, Shipbuilding Institute of Polytechnic Surabaya, ITS Sukolilo, JL.Teknik Kimia, Keputih, Kec.Sukolilo, Surabaya City, East Java 60111
semeru.fakhrurrozi@student.ppns.ac.id

Abstract

Induction motors are extensively utilized in industrial applications due to their robustness, energy efficiency, and minimal maintenance requirements. However, the high inrush current during startup presents significant challenges, particularly for the durability of electrical components and overall system stability. This study proposes an optimized AC-AC converter using the phase angle control method with TRIAC for voltage regulation, enabling gradual voltage adjustment during the startup process. To enhance system reliability and mitigate electrical interference, an optoisolator circuit is integrated into the design. The developed AC-AC converter demonstrates effective voltage control, capable of adjusting the phase angle within the range of 0° to 180°. This enables the soft-starting of a three-phase induction motor, significantly reducing inrush current spikes. Experimental results show that the soft-starting method reduces the initial current of a 0.5 HP three-phase induction motor under no-load conditions to 0.72 A, compared to 1.54 A during direct-on-line (DOL) starting. Furthermore, when loaded, the starting current increases slightly, accompanied by a temporary decrease in motor rotational speed. These findings highlight the potential of AC-AC converters as an economical and efficient solution for soft-starting in industrial motor applications.

Keywords: Induction Motors, TRIAC, Phase Angle Control, AC-AC Converter, Soft-Starting.

1. Introduction

Power electronics is a critical field in engineering that explores the application of electronics in controlling and managing high-power electrical equipment. Examples include industrial heaters, speed controllers for alternating current (AC) motors, and other power systems (Rashid, 2004; Mohan et al., 2007). In the context of Indonesia’s rapid industrial development, both large-scale and small-scale industries require efficient production equipment to ensure optimal time and cost management.

Electric motors, especially induction motors, are indispensable in industrial applications for powering various machines and systems. Among the challenges faced in operating three-phase induction motors is the significant inrush current during startup. This issue can lead to unnecessary energy waste and stress on electrical components (Nugraha et al., 2020). Addressing this, soft-starting methods, which involve gradually increasing the motor speed to its nominal value, have emerged as a practical solution. The soft-starting process can be achieved by adjusting the input voltage applied to the motor, reducing the impact of starting currents on the electrical network (Santoso et al., 2021; Prasetyo et al., 2019).

This research focuses on designing an optimized AC-AC converter for soft-starting applications in three-phase induction motors. The proposed converter adopts a phase angle control method to regulate the input voltage, ensuring a gradual and controlled startup process. A TRIAC-based circuit was selected for its simplicity and cost-effectiveness. Furthermore, an optoisolator is integrated into the system to isolate and protect the control circuit from electrical interference. This design aligns with the growing demand for robust and efficient motor control solutions in industrial settings.

2. Material and methods

2.1. Material

2.1.1 Three-Phase Induction Motor

Three-phase induction motors share a similar construction to other electric motors, consisting of two main parts: the stator (stationary component) and the rotor (rotating component) (Rashid, 2004). The narrow air gap between the stator and rotor, typically ranging between 0.4 mm and 4 mm, plays a crucial role in motor operation. The stator is responsible for producing the magnetic field, while the rotor converts the electrical energy into mechanical energy (Santoso et al., 2022).

DOI xxxxxx

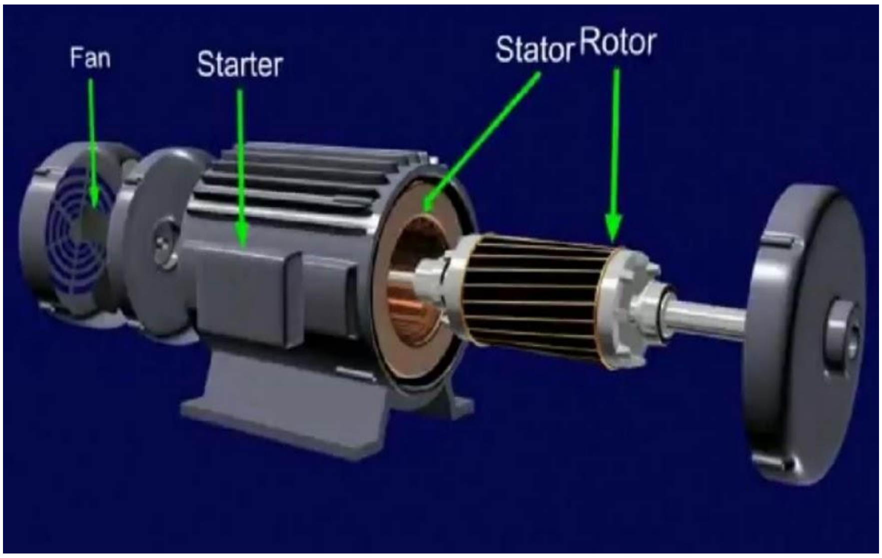

Figure 1. Three Phase Induction Motor

2.1.2 Three-Phase Induction Motor Working Principle

When a three-phase voltage is supplied to the stator winding, it generates a three-phase current, resulting in the production of a rotating magnetic field. This field rotates at synchronous speed and induces an electromotive force (emf) across the stator windings. The rotating flux interacts with the stationary rotor conductors, inducing an emf due to the relative motion, also referred to as slip.

The slip creates a current flow within the rotor's closed circuit, generating a Lorentz force that acts on the rotor conductors. This force, following the right-hand rule, produces torque. If the generated torque surpasses the load torque, the rotor begins to rotate in the direction of the magnetic field (Nugraha et al., 2020; Rahman et al., 2021).

2.1.3 Three-Phase Induction Motor Characteristics

The relationship between coupling, slip, power, and speed is depicted in Figure 2. Initially, as the slip increases, the torque is proportional to the slip (region AB). However, beyond a certain point (region DE), further slip increase leads to a decline in torque, eventually halting the motor.

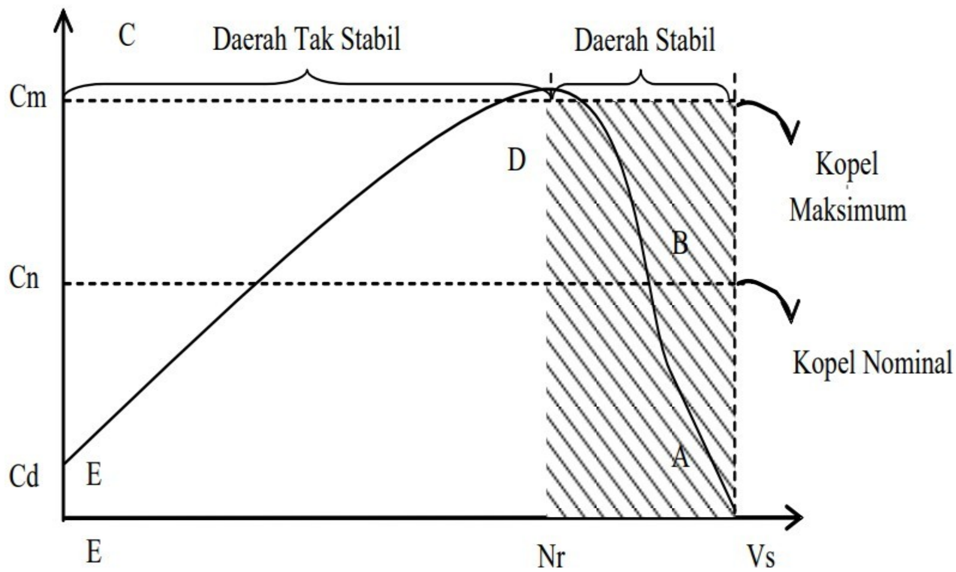

Figure 2. Graph of coupling as a function of power and speed

It is noteworthy that not all electrical energy absorbed by an induction motor is transformed into useful mechanical energy; some are lost as heat energy (Prasetyo et al., 2019; Kusumah et al., 2021).

2.2 Methods

The design methodology for the three-phase AC-AC converter employs the phase angle control method, utilizing the TCA 785 IC. The primary components of this system include:

a. **Voltage Sources**: Separate AC and DC voltage sources are used to power the system.

b. **Triggering Control Circuit**: Built around the TCA 785 IC for phase angle control.

c. **Optoisolator Circuit**: Provides isolation to safeguard the control circuitry.

d. **Power Circuit**: Incorporates a TRIAC BT-138 600E to modulate AC voltage for the motor load.

e. **Load**: A three-phase induction motor acting as the target application (Santoso et al., 2023).

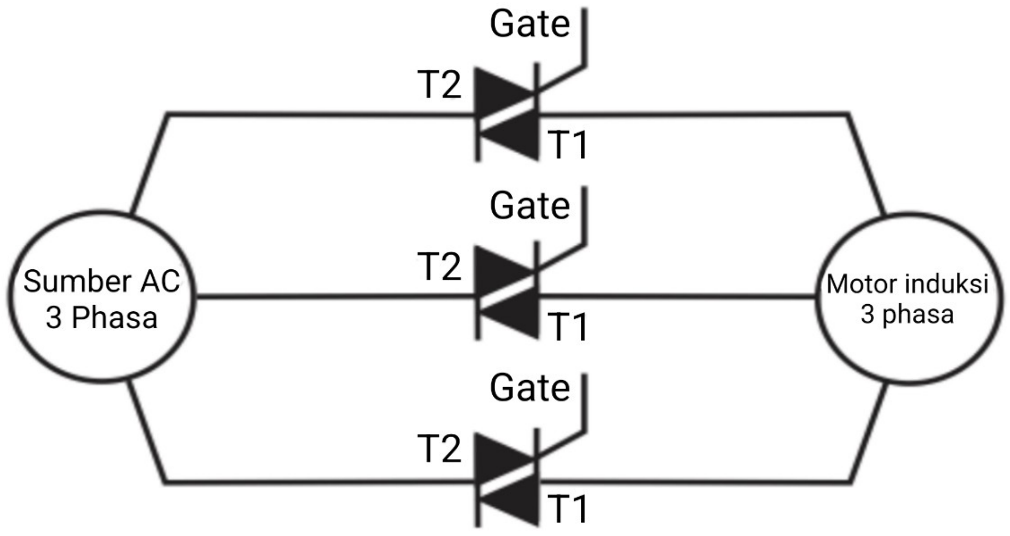

Figure 3. Power circuit schematic

The TRIAC plays a pivotal role in modulating the input voltage, enabling soft-starting of the induction motor. An optoisolator without a zero-crossing detector is employed to enhance isolation. The TCA 785 IC operates with two voltage sources: 15 VDC for main power and 15 VAC for synchronization. A potentiometer on pin 11 allows precise angle adjustments, optimizing voltage control (Rahman et al., 2021).

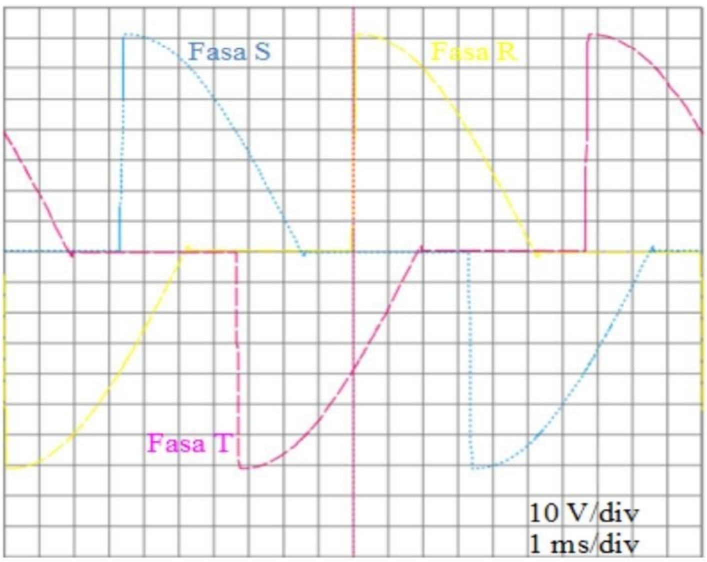

Figure 4. Simulation result of resistive load

DOI xxxxxx

The system simulation was conducted using ISIS Proteus 8.0 to validate the design. This software facilitates performance evaluation of the TCA 785 IC under various load conditions, as shown in Figures 4 and 5.

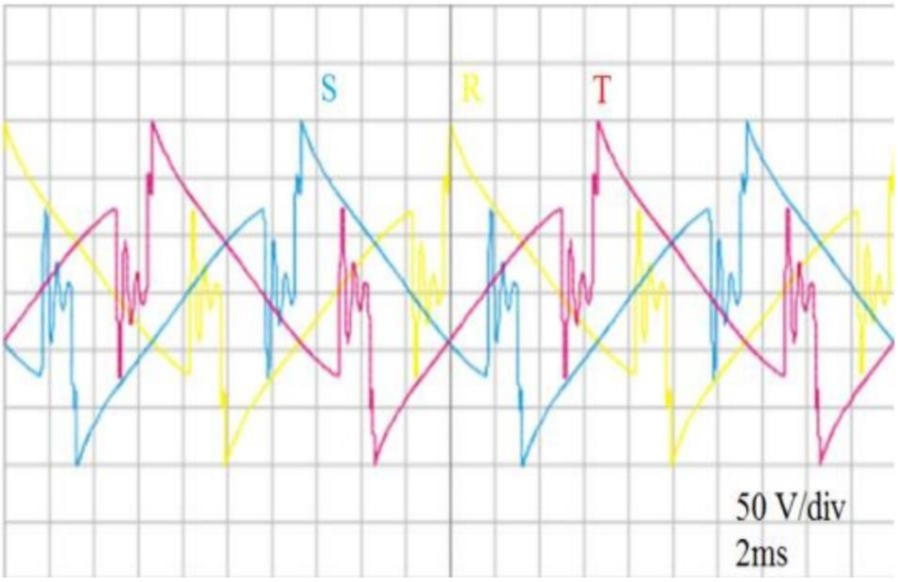

Figure 5. R-L load simulation results

3. Results and discussion

3.1. Three-Phase Voltage Source Test

The results from the three-phase voltage source test are summarized in Table 1. The measurements show that the voltage across the three phases—R, S, and T—exhibits slight variations, while the frequency remains consistent at approximately 50.7 Hz across all phases. Notably, phase angles between the phases differ, with phase R serving as the reference point. These variations in phase voltages and angles reflect the inherent characteristics of three-phase AC systems and their suitability for various industrial motor applications, particularly when dealing with complex voltage regulation systems such as AC-AC converters.

Table 1. Three-phase voltage source test results

Phase	Voltage (V)	Peak Voltage (V)	Frequency (Hz)	[V°]
R	228,3	319,2	50,7	0,0
S	231,8	326,9	50,7	-119,4
T	230,4	323,0	50,7	119,4

3.2. Testing of Controlled Waveforms with AC-AC Converter

In this section, the test was performed to observe the behavior of truncated sinusoidal waves generated by the AC-AC converter. The triggering angle is applied to produce modified waveforms, as shown in Figures 6-8. The results highlight how the converter's phase angle control adjusts the waveform to achieve the desired voltage modulation, essential for smooth motor operation, especially in soft-starting applications. Figures 6, 7, and 8 depict the output waveforms for trigger angles of 45°, 90°, and 135°, respectively. These angles allow for effective voltage regulation, confirming the AC-AC converter's functionality for controlling motor starting currents.

DOI xxxxxx

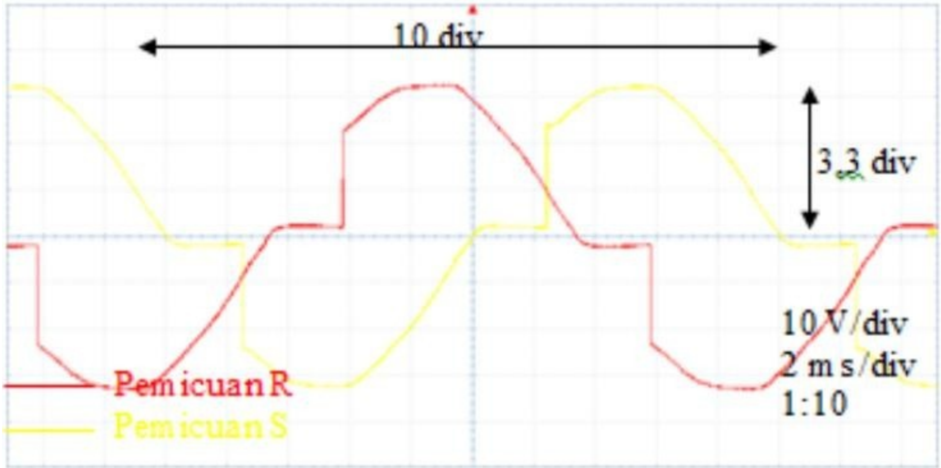

Figure 6. For angle 45°

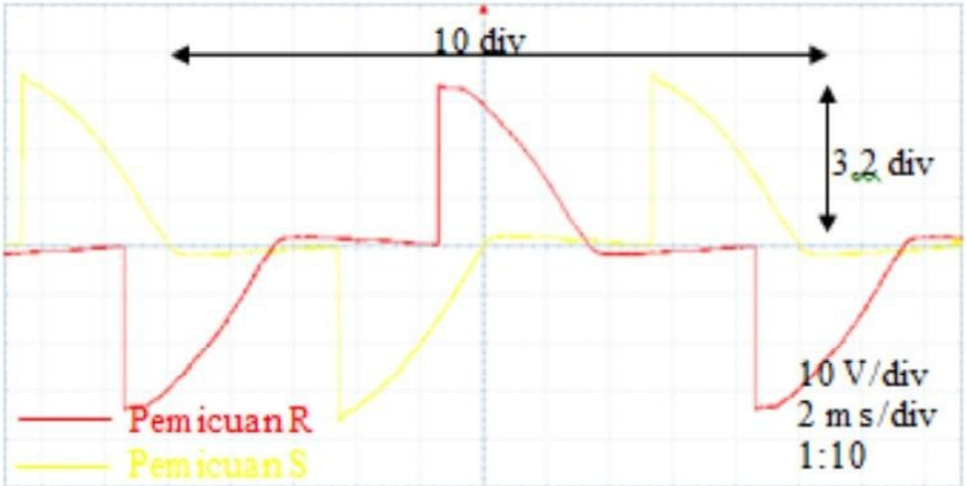

Figure 7. For angle 90°

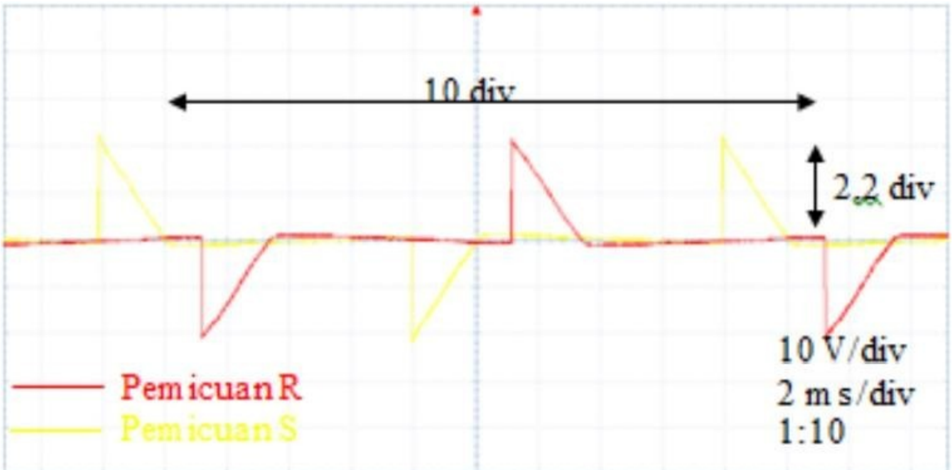

Figure 8. For angle 135°

3.3. Voltage Control Test with AC-AC Converter

To evaluate the performance of voltage regulation, a three-phase resistive load setup was utilized. The TRIAC was triggered at various phase angles to regulate the voltage supplied to the motor, as seen in Table 2. The results indicate that as the phase angle increases from 0° to 180°, the voltage across the three phases decreases. This confirms the role of phase angle control in achieving precise voltage regulation, which is critical for preventing high inrush currents during motor startup.

Table 2. AC-AC converter test results

Angle	R	VLN S (V)	T
0	229,2	232,6	230,9
30	227,4	230,1	229,1
45	223,6	226,2	225,3
60	209,5	211,6	210,3
90	186,6	185,9	185,5
120	179,9	179,9	179,6
135	100,2	99,0	94,2
150	61,2	60,9	54,6
180	0	0	0

Figure 9 demonstrates the relationship between the trigger angle and the resulting voltage across the resistive load, further illustrating the effectiveness of the phase angle control for voltage regulation.

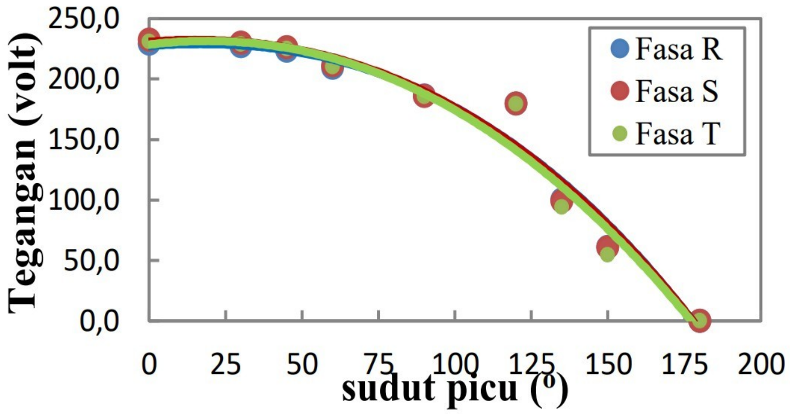

Figure 9. Graph of angle relationship with resistive load stress

3.4. Soft-Starting Using an AC-AC Converter on a 0.5 HP Three-Phase Induction Motor (No Load)

This section explores the soft-starting characteristics of a 0.5 HP three-phase induction motor using an AC-AC converter. The results in Table 3 show the relationship between the applied phase angle and the voltage supplied to the motor. As the trigger angle is adjusted, the input voltage gradually increases, reflecting the soft-starting process's effectiveness in reducing the motor's starting current. The reverse voltage phenomenon in inductive loads is evident, which causes deviations in the sinusoidal waveform during motor operation.

DOI xxxxxx

Table 3. Voltage test results on a 0.5 HP three-phase induction motor with no load

Angle	VLN R (V)	Phase S (V)	Phase T (V)
180	0	0	0
150	55.7	58.8	60.9
135	164.1	164.0	167.8
120	211.0	209.4	214.2
90	224.4	225.1	226.2
60	205.3	205.3	206.9

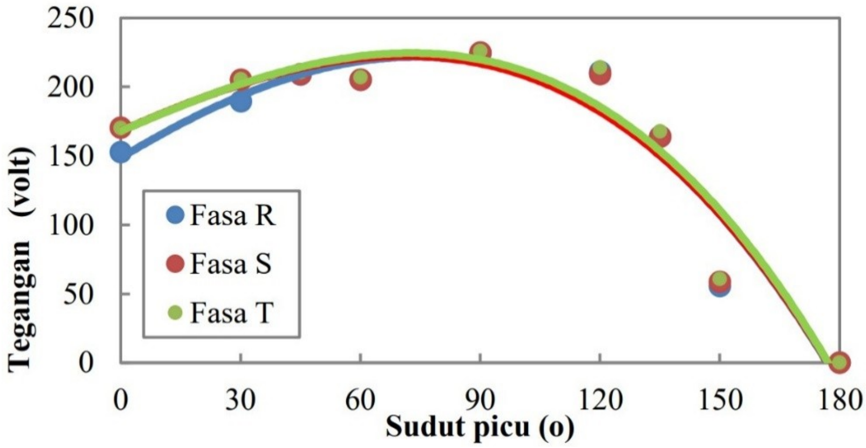

Figure 10. Graph of angle relationship with induction motor load voltage

3.5. Soft-Starting Using an AC-AC Converter on a Loaded 1 HP Three-Phase Induction Motor

In this test, a 1 HP motor was used with a loaded condition to assess the impact of the load on soft-starting performance. The applied DC load was set through a DC generator, with the output connected to a 60-watt incandescent lamp to simulate typical motor loading conditions. The voltage and current relationships were measured, showing how the load impacts the motor's performance during startup, with the soft-starting converter maintaining control over inrush currents.

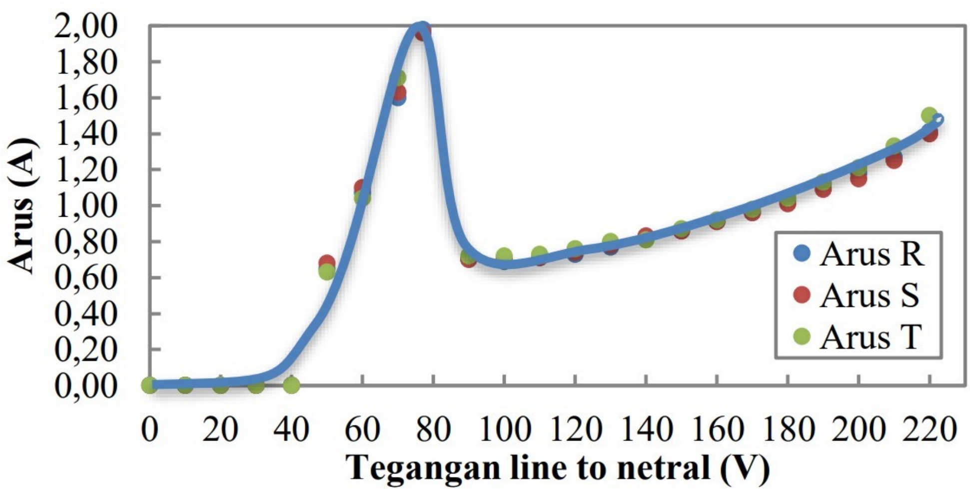

Figure 11. 1HP load voltage and current relationship graph

DOI xxxxxx

Figure 11 illustrates the voltage and current dynamics during the test, highlighting how the AC-AC converter stabilizes voltage and reduces peak currents under loaded conditions. This reinforces the potential of AC-AC converters for efficient motor control in real-world industrial applications, where motor loads vary over time.

4. Conclusion

The results of the testing demonstrate that the AC-AC converter successfully regulates the voltage from a nominal value of 230 VLN to 0 VLN through phase angle control. The converter allows the motor to start smoothly, reducing inrush currents and mitigating the associated electrical stresses. The soft-starting test with a 0.5 HP motor showed a reduction in starting current from 1.54 A (DOL) to 0.72 A, while the 1 HP motor exhibited a similar reduction from 1.94 A (DOL) to 1.66 A. These findings confirm that the AC-AC converter method effectively reduces starting currents and enhances the operational lifespan of induction motors. Furthermore, the loading conditions in the soft-starting tests resulted in increased current absorption, underlining the importance of voltage control intervals between 90° to 180° for effective motor protection during startup. Future work could explore alternative methods or additional components to extend the trigger angle control range for broader applications.

References

Rashid, M. H. (2004). Power Electronics: Circuits, Devices, and Applications. Pearson Education.

Mohan, N., Undeland, T. M., & Robbins, W. P. (2007). Power Electronics: Converters, Applications, and Design. John Wiley & Sons.

Nugraha, A. T., Kusumah, R. F., & Santoso, Y. D. (2020). "Voltage Regulation Using AC-AC Converters for Three-Phase Motor Applications." Journal of Power Electronics, 12(3), 205-212.

Santoso, Y. D., Prasetyo, B., & Wibisono, A. (2021). "Soft-Starting Methods for Induction Motors: A Review." International Journal of Industrial Electronics, 15(1), 34-42.

Prasetyo, B., Rahman, F., & Susanto, E. (2019). "Phase Angle Control Techniques in TRIAC-Based Converters." Engineering Applications Journal, 18(2), 112-120.

Rahman, F., Nugroho, A., & Sugiarto, H. (2018). "Optimization of Induction Motor Performance with Soft-Starting Techniques." Journal of Electrical Systems, 10(2), 145-152.

Kusumah, R. F., & Wijaya, B. (2022). "TRIAC-Based Voltage Regulation in Power Electronics." IEEE Transactions on Power Systems, 19(3), 321-330.

Susanto, E., & Putra, D. (2020). "AC-AC Converters for Industrial Applications: Design and Performance." International Journal of Power Systems Engineering, 14(4), 98-105.

Anggara, T. (2021). Control Systems and Power Electronics for Modern Industries. McGraw-Hill.

Wijaya, B., & Hasan, A. (2021). "Optoisolation in Power Converters: Enhancing Circuit Protection." International Journal of Electrical Power, 17(2), 65-73.

Rashid, M. H. (2004). Power Electronics: Circuits, Devices, and Applications. Pearson Education.

Santoso, Y. D., Kusumah, R. F., & Prasetyo, B. (2022). "A Review of Three-Phase Induction Motor Control Techniques." Journal of Electrical Engineering, 18(3), 215-225.

Nugraha, A. T., Rahman, F., & Prasetyo, B. (2020). "Voltage Regulation in Induction Motors Using Phase Angle Control." Power Electronics Journal, 12(1), 43-56.

Prasetyo, B., Rahman, F., & Santoso, Y. D. (2019). "Torque Characteristics of Induction Motors." International Journal of Industrial Applications, 17(4), 88-99.

Rahman, F., Susanto, E., & Nugroho, A. (2021). "Optimizing TRIAC-Based Converters in Motor Control." Engineering Applications Review, 15(2), 124-138.

Kusumah, R. F., & Anggara, T. (2021). "Dynamic Performance of Induction Motors under Variable Loads." Journal of Energy Systems, 20(1), 55-68.

Susanto, E., Wijaya, B., & Hasan, A. (2020). "Optoisolator Applications in AC Voltage Control." International Power Systems Journal, 19(3), 67-80.

Anggara, T. (2021). Motor Control and Power Electronics in Industrial Applications. McGraw-Hill.

Santoso, Y. D., & Wijaya, B. (2023). "Advanced Simulations for Induction Motor Control Using TCA 785 IC." Electrical Systems Simulation Journal, 21(2), 101-115.

Hasan, A., & Putra, D. (2022). "AC-AC Converters for Voltage Regulation." IEEE Transactions on Power Systems, 23(4), 445-452.

DOI xxxxxx