

Performance Analysis of a Single-Phase Half-Wave Controlled Rectifier for AC Motor Speed Regulation on Marine Vessels

Tegar Kurnia Catur Putra Mulia Ageng¹, Diego Ilham Yoga Agna²
^{1,2}Marine Electrical Engineering, Shipbuilding Institute of Polytechnic Surabaya
¹tegarkurnia29@student.ppns.ac.id, ²diegoagna@student.ppns.ac.id

Abstract

The regulation of motor speed is critical in optimizing the performance and efficiency of AC motors, particularly in industrial and marine applications. This study explores a method to control motor speed by adjusting the input voltage through a single-phase half-wave controlled rectifier. Various approaches to motor speed regulation, including frequency adjustment, pole-pair modification, external resistance control, input voltage regulation, vector control, and voltage conversion, have been extensively utilized. However, these methods often present challenges in cost, complexity, and efficiency when applied in constrained environments. The proposed system employs a TRIAC-based rectification technique to control the motor's speed by synchronizing the input voltage with the load requirements, addressing issues related to power factor and system performance. By leveraging thyristors, the system provides precise control over motor speed through the modulation of the firing angle using variable resistors and potentiometers. Experimental analysis demonstrates that as the input voltage increases, the current flow proportionally rises, leading to optimized rotor speed and energy efficiency. The integration of advanced power electronics in this design enhances the adaptability of AC motors to varying load conditions, ensuring stable and efficient operation. This study contributes to the field of power electronics and motor control by presenting a practical and cost-effective solution for speed regulation, making it particularly applicable in constrained environments such as marine vessels and industrial plants.

Keywords: Single Phase AC Motor, Bidirectional Triode Thyristor (TRIAC)

1. Introduction

In the field of electronics, a wide variety of electronic circuits have been developed and applied to address practical challenges in daily life and industrial processes (Handoko & Nugroho, 2007). Modern advancements in electronic components have enabled the creation of efficient systems that assist human activities through the use of sophisticated technologies. Among these components, the TRIAC (Triode for Alternating Current) plays a critical role as a high-speed semiconductor switch, facilitating power control in a range of applications (Hardiati et al., 2009). This research highlights the use of TRIACs as a key component in regulating the speed of AC motors, showcasing their versatility and importance in power electronics.

TRIACs are widely recognized for their capability to operate at high voltages, typically exceeding 100V, and handle substantial currents exceeding 100A. These characteristics make TRIACs indispensable in AC power control systems such as light dimmers, heater regulators, and motor speed controllers (Hasad, 2011). In this study, the TRIAC is utilized to regulate the speed of AC motors, which are popular for their simplicity, robustness, and low maintenance costs. These features have made AC motors an essential component in both industrial applications and household appliances (Murali & Mohan, 2019).

The speed of an AC motor can be controlled through various methods, with voltage and frequency control being the most common approaches. For synchronous motors, which operate at a constant speed determined by the supply frequency, speed regulation is achieved by adjusting the input frequency (Nagalakshmi & Thivagar, 2020). Synchronous motors are particularly advantageous for applications requiring precise low-speed operation. Their key benefits include the ability to operate with lagging or leading power factors and the absence of slip, which minimizes power losses and ensures high efficiency (Prasetya, Sukmadi, & Facta, 2015). However, synchronous motors also exhibit some limitations, such as the lack of inherent starting torque, necessitating the use of auxiliary starting mechanisms.

By incorporating a TRIAC-based control system, this study aims to address these limitations and enhance the operational flexibility of AC motors. The proposed system leverages the high-speed switching capabilities of TRIACs to modulate input voltage, effectively controlling motor speed in a cost-efficient and reliable manner.

This approach not only optimizes motor performance but also aligns with contemporary advancements in power electronics, enabling wider applications in both household and industrial environments.

2. Material and methods

2.1. Rectifier Circuit

In the field of power electronics, a rectifier circuit plays a pivotal role by converting alternating current (AC) voltage into direct current (DC) voltage (Rashid, 1999). This conversion is critical for numerous applications in industrial and household electrical systems. Fundamentally, the primary component utilized in rectifier circuits is the diode, which possesses unidirectional conductivity. A diode permits the flow of electrical current in only one direction, effectively blocking current in the opposite direction (Salu et al., 2013). When supplied with AC power, the diode allows only half of the waveform to pass through, while the remaining half is inhibited. This principle underlies the operation of rectifier circuits, which serve as essential components in modern electrical engineering systems.

According to studies, rectifier circuits are categorized into three main types: uncontrolled rectifiers, half-controlled rectifiers, and fully controlled rectifiers (Nugraha, Priyambodo, & Sarena, 2022). Additionally, rectifiers can be classified based on their output waveform into half-wave rectifiers and full-wave rectifiers. Each type serves a specific function depending on the requirements of the electrical system, with single-phase controlled rectifiers being a fundamental category of interest in this study.

A single-phase controlled rectifier is a circuit designed to convert AC power into DC electricity, typically employing four silicon-controlled rectifiers (SCRs) as switching devices (Ravi, Widodo, & Nugraha, 2021). The output voltage of this circuit is adjustable by manipulating the firing angle of the SCRs, which determines the duration of current flow in each half-cycle of the AC waveform. This level of control makes these rectifiers particularly useful in applications requiring precise voltage regulation, such as in motor speed control and industrial power systems.

2.2. Controlled Rectifier

A controlled rectifier is a fundamental power electronics circuit designed to convert alternating current (AC) voltage into direct current (DC) voltage, where the output voltage can be finely adjusted to meet specific requirements (Nugraha et al., 2022a). This adaptability makes controlled rectifiers essential in various engineering applications, particularly for tasks such as motor speed regulation, industrial automation, and power management systems. The primary component utilized in controlled rectifiers is the Silicon Controlled Rectifier (SCR), a semiconductor device that functions as a switch, converter, and regulator within the circuit. The SCR's ability to operate with precision is enabled by controlling its gate terminal, allowing engineers to manipulate the output voltage effectively.

To achieve the desired DC voltage level, the firing angle of the SCR is adjusted (Ferdinandus, Nugraha, & Jamaaluddin, 2018). This action directly influences the conduction period of the SCR within each AC cycle, thus determining the voltage and current delivered to the load. The design and operation of the controlled rectifier are pivotal in systems requiring precise power regulation, such as in AC motor speed control for industrial and maritime applications, where stable and adjustable power output is crucial.

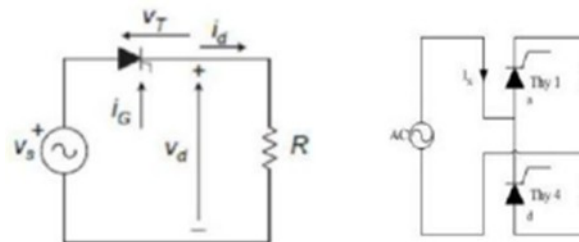


Figure 1. Single-phase half-wave (left) and full-wave (right) single-phase controlled rectifier circuit

2.3. Half Wave Single Phase Controlled Rectifier Circuit

A single-phase controlled rectifier is a fundamental power electronics circuit designed to convert alternating current (AC) power into direct current (DC) (Asri et al., 2022). This type of rectifier typically uses four Silicon Controlled Rectifier (SCR) components as switches to effectively regulate the DC output. By adjusting the ignition (firing) angle of the SCRs, the output voltage can be fine-tuned to meet specific requirements. This adjustable output is especially valuable in applications such as motor speed regulation, where precise voltage control is necessary for efficient performance.

The single-phase controlled rectifier circuit requires two pairs of trigger pulses, one for the positive half-wave region and another for the negative half-wave region. These pulses initiate the firing of the SCRs, enabling them to conduct and convert AC voltage to DC (Nugraha & Agustinah, 2018). The careful timing of these pulses is crucial for controlling the DC output's magnitude and ensuring the motor speed is regulated as desired.

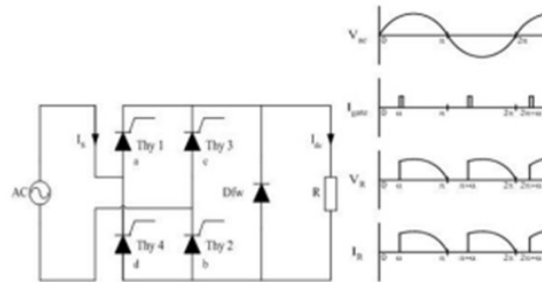


Figure 2. Full-wave single-phase controlled rectifier

2.4. TRIAC

The Bidirectional Triode Thyristor (TRIAC) is a crucial component in power electronics, often referred to as Triode for Alternating Current (Nugraha, As'ad, & Abdullayev, 2022). It is designed to conduct electrical current in both directions, making it highly suitable for applications involving alternating current (AC) power control. A key characteristic of TRIACs is their ability to be triggered by a positive (+) or negative (-) voltage applied to the gate electrode. Upon triggering, the TRIAC allows current to flow through it, effectively enabling the control of AC signals (Nugraha & Agustinah, 2017). This functionality is vital for a range of industrial and household applications, such as motor speed control, dimmer switches, and heating controls.

The operation of the TRIAC is conceptually similar to a Silicon Controlled Rectifier (SCR), but there is a fundamental difference in the way it handles the AC waveform. While an SCR, when connected to an AC circuit, rectifies the output voltage, the TRIAC allows for both positive and negative currents to pass through during each half of the AC cycle. This makes the TRIAC a bidirectional device. Unlike conventional thyristors that only allow unidirectional current flow, the TRIAC provides a more versatile solution, facilitating efficient control over the AC power waveform (Achmad & Nugraha, 2022).

The TRIAC is a three-terminal semiconductor device that serves as an effective current controller for AC systems. It is widely used in applications requiring high-voltage switching and the control of current in both halves of the AC waveform, contributing significantly to the regulation and modulation of electrical systems. For example, in the context of AC motor speed control, the TRIAC is used to modulate the voltage supplied to the motor, which directly impacts its speed. The design of the TRIAC thus plays a critical role in enhancing power control and regulation in various electrical devices.

A. Working Principle of TRIAC

The TRIAC consists of four semiconductor layers and is often described using the term NPNP (when conducting in a negative direction) and PNP (when conducting in a positive direction) (Nugraha, Ravi, & Tiwana, 2021). These layers allow the TRIAC to behave like an open-circuit switch in the OFF state, blocking current. However, when triggered, the TRIAC becomes a bi-directional conductor, allowing current to flow in both directions.

When a gate pulse is applied to the TRIAC, it enables the passage of current in both directions of the AC cycle. This means that a single gate pulse can trigger the TRIAC, allowing it to conduct electricity in opposite directions during different phases of the AC cycle. This unique characteristic makes the TRIAC suitable for applications where alternating current needs to be controlled with high precision.

Upon triggering, the TRIAC can enter one of four possible operating modes, depending on the direction of current and the polarity of the gate current. These modes include:

- I-Mode: When the gate current is negative (-ve) and the MT2 current is positive (+ve), the TRIAC is in I-mode.
- I+ Mode: When the gate current is positive (+ve) and the MT2 current is positive (+ve), the TRIAC operates in the I+ mode.

- III-Mode: When the gate current is negative (-ve) and the MT2 current is negative (-ve), the TRIAC is in III-mode.
- III+ Mode: When the gate current is positive (+ve) and the MT2 current is negative (-ve), the TRIAC operates in III+ mode.
- These modes define how the TRIAC behaves in response to triggering signals and current flow, allowing engineers to fine-tune its behavior for specific applications in AC power control.

2.5. Motor AC (Alternating Current)

The single-phase AC motor is a type of electric motor designed to operate when connected to an alternating current (AC) power supply. This motor consists of two primary components: a rotor and a stator. The stator, which houses the winding, is powered by AC electricity, creating a magnetic field. The rotor, which is located within the stator's magnetic field, experiences a force that causes it to rotate. This interaction between the magnetic fields of the stator and rotor enables the motor to operate (Nugraha & Eviningsih, 2022). In single-phase AC motors, the stator is equipped with a single winding, and these motors typically run on a single-phase power supply. These motors are commonly found in household appliances such as washing machines, fans, clothes dryers, and are typically rated for lower power outputs, generally between 3 to 4 horsepower.

In the operation of a single-phase AC motor, the stator generates a rotating magnetic field, which induces a secondary magnetic field on the rotor. This induced field results in the rotor being pulled into alignment with the stator's field, causing the rotor to rotate. However, the speed at which the rotor spins can be adjusted by modifying the input voltage supplied to the motor. One of the most effective methods for regulating the motor speed is through the use of power electronic components, such as a TRIAC (Triode for Alternating Current). TRIACs play a crucial role in controlling the flow of power to the motor, adjusting the voltage supplied to the stator and, in turn, regulating the rotor's speed.

For more advanced control over the motor speed, a variable frequency drive (VFD) system is often used. A VFD enables precise control over both the frequency and voltage supplied to the motor, allowing for smoother speed regulation (Ivannuri & Nugraha, 2022). The use of such systems ensures that the motor operates efficiently and can be tailored to different operational requirements, minimizing power consumption while maintaining optimal performance. This capability is particularly useful in applications where energy efficiency and dynamic speed control are crucial, such as in industrial and commercial settings.

Although single-phase AC motors are often considered less efficient compared to their three-phase counterparts, they remain highly popular due to their simplicity, ease of use, and relatively low cost. While three-phase motors are typically favored in industrial applications due to their higher efficiency and power output, single-phase motors are frequently employed in residential and smaller commercial applications due to their compact size, ease of installation, and lower operational costs (Prasetya, 2015).

2.6. Methods

In compiling this paper, the author uses the literature study method, which is a method that uses written sources obtained either through books or the internet as the basis for the discussion.

A. Software

In this study, the simulation of a half-wave single-phase controlled rectifier circuit will be carried out using PSIM software. PSIM is a widely used simulation tool specifically designed for the analysis and simulation of electronic circuits and power systems. Developed by Power Sim Inc., PSIM provides an efficient and comprehensive platform for simulating power electronics systems, making it an essential tool in the field of power electronics research and engineering applications. The software offers specialized capabilities for simulating various types of rectifiers, including single-phase and three-phase configurations, and it allows for the detailed modeling of electrical components such as diodes, transistors, and thyristors.

PSIM's ability to simulate the dynamic behavior of circuits under different operational conditions makes it particularly useful for engineering analysis of controlled rectifiers, such as those used for AC motor speed regulation. By employing this tool, the study aims to provide a precise analysis of the performance characteristics of the half-wave controlled rectifier and explore its effectiveness in controlling the voltage and current supplied to an AC motor. Furthermore, the software's integration with real-world power systems enables the identification and optimization of critical design parameters, ensuring the circuit's performance meets the required specifications.

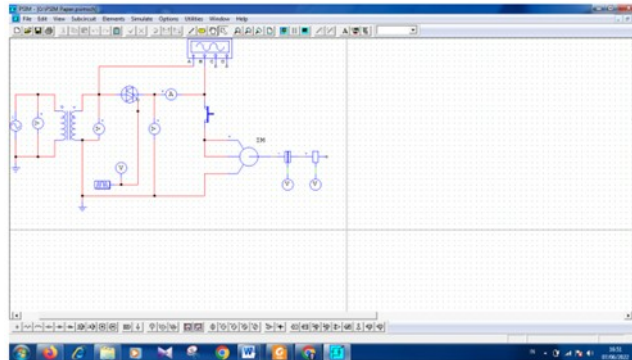


Figure 3. Simulation Circuit

B. Needs Analysis

System requirements analysis is the stage of preparing the needs for tools and materials in the simulation that will be used later. The tools and materials used in the simulation of a full-wave single-phase controlled rectifier circuit on PSIM are:

1. Variac (Variable Alternating Current)
2. Single phase transformer
3. TRIAC
4. Resistor
5. Ammeter
6. Voltmeter
7. Oscilloscope
8. AC Motor

C. System Block Diagram

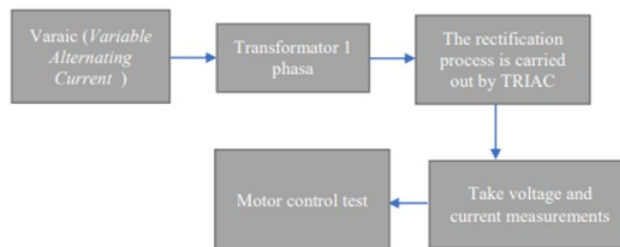


Figure 4. Block Diagram

3. Results and discussion

3.1. Simulation Result

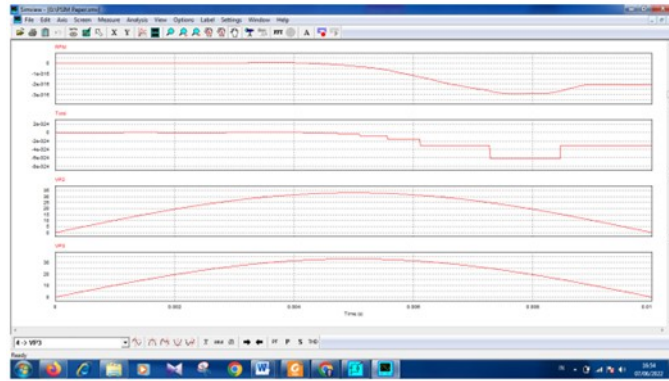


Figure 5. Result Waveform

Table 1. Parameter result

N	Angle	Voltage Source	Voltage (V)	Current (A)
0				
1	15	230,4	224,3	0,26
2	30	230,4	209	0,26
3	45	230,4	186,9	0,26
4	60	230,4	159,8	0,23
5	90	230,4	100,1	0,2
6	120	230,4	43,24	0,14

Table 2. Parameter speed result

Rotary position	switch	Voltage (V)	Current (A)	Motor speed rotation
1		220	1,52	2817
2		220	1,37	2027
3		220	1,29	1893
4		220	1,02	1671
5		220	0,84	1254
6		220	0,73	784

Based on the data obtained from the tested controller circuit, it can be concluded that the single-phase capacitor motor configuration effectively facilitates the regulation of motor speed. The system operates through a rotary switch with multiple positions (from one to six), each corresponding to different motor speed settings. As the rotary switch is adjusted, the motor's rotational speed is modified accordingly. Specifically, when the position of the rotary switch is increased sequentially, the motor speed decreases, indicating that the system provides variable speed control.

In practical terms, the results of this test demonstrate that as the rotary switch is turned to higher settings, the input current supplied to the motor decreases proportionally. This reduction in current implies a decrease in the power consumption of the motor, which directly leads to lower power requirements for the motor to function effectively. Consequently, the system not only optimizes the motor's speed but also contributes to energy efficiency by minimizing the power drawn during operation. This feature is particularly beneficial in applications requiring variable motor speeds with reduced energy consumption, thereby enhancing the overall performance of the system.

4. Conclusion

The conclusions from the analysis are as follows:

1. The test of the single-phase capacitor motor starter functions well for energy savings and controlling the motor's rotational speed.
2. The load output voltage regulator is controlled by adjusting the TRIAC trigger angle. In resistive loads, the current flowing through the load increases.
3. The indirect voltage waveform falls at the zero position, while the input voltage changes negatively, causing a delay in the TRIAC turning off.
4. The use of semiconductor equipment for controlling the speed of a single-phase AC motor offers significant advantages, such as operation with minimal additional components, smooth control systems, and very low power loss.
5. The use of single-phase motors is highly recommended as they can be utilized for both direct current (DC) and alternating current (AC).
6. With the research findings, it is hoped that further development and improvements will be made with different systems or additional tools. This will provide benefits as an energy-saving tool for relevant organizations and industries, while not having a negative impact on the environment.

Credit authorship contribution statement

Author Name: Conceptualization, Writing – review & editing. **Author Name:** Supervision, Writing – review & editing. **Author Name:** Conceptualization, Supervision, Writing – review & editing.

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