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Full-Wave Controlled Single-Phase AC Regulator: Design and Performance Analysis

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Abstract

An alternating current (AC) regulator is a device designed to control the root mean square (RMS) output voltage for various applications. These include motor speed regulation, lamp dimming, temperature control for heating systems, and other power modulation tasks. The regulation of RMS voltage is achieved by adjusting the activation angle of the power switch, which in turn delays the output voltage waveform. This functionality categorizes the AC regulator as a phase delay control system. This study focuses on the design, implementation, and performance analysis of a single-phase full-wave AC regulator using a silicon-controlled rectifier (SCR). The research provides a detailed investigation into the waveform characteristics of current and voltage across varying load conditions, offering insights into efficiency, harmonic distortion, and operational stability. The findings are intended to advance the application of AC regulators in engineering fields, with a particular emphasis on improving reliability and energy efficiency in low and medium-power systems..

Keywords: Control, Waveform, SCR

1. Introduction

Technology in the industrial sector is one of the most rapidly evolving fields, driven by advancements in human civilization (Nugraha et al., 2023). This evolution is evident across applications in electrical engineering and related disciplines. In the industrial sector, there is a growing demand for technologies capable of performing automated control functions across various devices and systems efficiently (As'ad, Yuniza, & Nugraha, 2022).

One critical component in these systems is the AC regulator, which serves to control the root mean square (RMS) output voltage (Petrović, 2020). AC regulators find applications in motor speed control, lamp dimming, heating temperature regulation, and other power modulation tasks. The RMS voltage is regulated by adjusting the firing angle of the power switch, which delays the output voltage waveform (Zhou et al., 2023). Consequently, this type of control is commonly referred to as phase delay control (Gift, 2000).

Generally, AC regulators employ silicon-controlled rectifiers (SCRs) or TRIACs as power switches (Agna, Yuniza, & Nugraha, 2022). There are two primary types of AC regulators: half-wave and full-wave. In a half-wave AC regulator, only the positive voltage waveform is delayed. Such regulators typically utilize a single SCR and an anti-parallel diode (Fauzi et al., 2024). However, half-wave AC regulators are less commonly deployed in practical applications due to their inherent limitations, such as reduced power efficiency and increased harmonic distortion (Rahman et al., 2024).

Conversely, full-wave AC regulators delay both the positive and negative voltage waveforms (Mu'in et al., 2023). This type of regulator employs either two anti-parallel SCRs or a single TRIAC as the power switch (Amrullah et al., 2023). Full-wave AC regulators are more versatile and efficient, making them suitable for a wide range of industrial and engineering applications..

2. Material and methods

2.1. Silicon Control Rectifier (SCR)

The Silicon-Controlled Rectifier (SCR) is a type of thyristor that functions as a controllable diode, enhanced with a gate terminal for regulating the phase angle of the electrical signal passing through it (Bisson & Dyer, 1959). Structurally, the SCR is a semiconductor device composed of a four-layer PNPN (Positive-Negative-Positive-Negative) arrangement, featuring three PN junctions labeled J1, J2, and J3 from the anode. The device has three terminals: the anode, cathode, and gate (Murphy & Nambiar, 1961).

a. Operating Mechanism

To effectively utilize the SCR, a comprehensive understanding of its operational states is essential. The SCR transitions between two primary conditions:

- Conducting State (ON): The SCR enters this state when triggered by a gate current (Wang et al., 2022). A small voltage is applied to the gate relative to the cathode (specific to the

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product's specification), allowing gate current to flow. This process causes the SCR to conduct electrical current between the anode and cathode.

- Non-Conducting State (OFF): To cease conduction, a commutation technique is applied. This involves reducing the voltage across the SCR to zero, halting the current flow (Du et al., 2020). The SCR remains in this non-conducting state until it is retriggered.

The SCR operates effectively within the 0°-180° phase angle, reflecting the fundamental characteristics of diodes (Chang et al., 2021). Within this range, phase control is achievable, enabling precise regulation of the electrical waveform.

b. Phase Control and Commutation

The process of triggering an SCR involves applying a gate current to initiate conduction. Once triggered, the SCR continues conducting until the voltage across its terminals drops to zero through commutation. The commutation method is critical for phase regulation, as it determines when the SCR stops conducting and resets for subsequent operation.

This capability makes SCRs integral to phase delay control systems, such as those used in single-phase AC regulators. By controlling the phase angle, SCRs regulate the RMS voltage output, enabling applications in motor speed control, lamp dimming, and temperature regulation.

c. Relevance to Full-Wave AC Regulators

In full-wave AC regulation, SCRs are employed in configurations that allow bidirectional current control. This setup typically involves two anti-parallel SCRs or a TRIAC. The precise triggering and commutation of these components facilitate efficient voltage and current modulation, which is essential for improving performance in engineering applications, particularly those requiring high reliability and low harmonic distortion.

2.2. *Thyristor*

A thyristor is a semiconductor device designed with four alternating layers of PNPN material, forming three PN junctions (Muhammad et al., 2020). The device comprises three primary terminals: the anode, cathode, and gate. Its unique architecture allows for effective current control in various power applications, as illustrated in the figure below (not included).

a. Controlled Rectification

Thyristors are often referred to as controlled rectifiers due to their capability to regulate current flow through the gate terminal (Zhang et al., 2022). This gate acts as a control mechanism, enabling the user to manage the device's switching behavior. The switching, or ignition, of the thyristor is typically initiated by applying a positive voltage across the gate and cathode terminals (Chen et al., 2023). This induces a gate current that transitions the thyristor into a conductive state, allowing current to flow from the anode to the cathode.

The ignition process is heavily influenced by the zero-crossing point of the AC waveform, which determines the delay in the gate current application. This delay directly impacts the phase control and the regulation of the output voltage, making the thyristor a critical component in phase-controlled systems.

b. Extinguishing Mechanism

Once in the conductive state, the thyristor can be turned off by reducing the forward current below a threshold known as the holding current (IH) (Rotenberg et al., 2020). This extinction process is crucial for applications that require precise timing and controlled interruptions in the current flow. The ability to control the conduction and extinction of the thyristor makes it suitable for various power control systems, including AC voltage regulators, motor speed controllers, and dimming circuits.

In single-phase full-wave AC regulators, thyristors are employed in configurations that enable bidirectional control of the AC signal. This is often achieved through the use of anti-parallel thyristors or TRIACs, which allow for seamless control over both the positive and negative cycles of the AC waveform. The accurate timing of the gate signal and the proper management of holding currents are essential for maximizing performance, reducing harmonic distortions, and ensuring efficient energy usage.

2.3. Methods

In this study, a comprehensive research method has been implemented, which includes several key stages: the design and simulation of a full-wave controlled single-phase AC regulator circuit utilizing a Silicon-Controlled Rectifier (SCR), experimentation with various load conditions, circuit assembly, testing, data collection, and subsequent analysis. The primary objective of the research is to evaluate the performance of the full-wave controlled single-phase AC regulator circuit under different operational scenarios.

The design and simulation of the SCR-based AC regulator circuit were carried out using PSIM® simulation software, a powerful tool for power electronics design, to model the entire system and predict its behavior. This simulation step is crucial for assessing the performance and functionality of the regulator circuit before physical implementation, ensuring that theoretical predictions align with practical expectations.

a. Operational Modes of the Single-Phase AC Regulator:

The designed single-phase AC regulator can be operated in three distinct modes, determined by the ignition angle (α) relative to the phase angle (φ) of the input AC signal:

- Large Ignition Angle (α > φ):
  In this mode, the SCR is triggered later in the phase cycle, causing the output current to become discontinuous. This condition occurs when the ignition angle is significantly larger than the phase angle, leading to an incomplete current waveform and reduced power delivery.
- Small Ignition Angle (α < φ):
  When the ignition angle is smaller than the phase angle, the regulator enters a mode where one of the SCRs fails to turn on. This can result in incomplete conduction, compromising the performance of the regulator. This mode demonstrates the challenges in controlling the timing of the SCR triggering to ensure reliable operation.
- Equal Ignition and Phase Angle (α = φ):
  In this mode, the ignition angle is precisely equal to the phase angle, allowing the SCR to turn on at the optimal point in the AC cycle. As a result, the output current becomes continuous, ensuring smooth and stable power delivery to the load. This ideal operating condition provides efficient regulation and is the target for achieving optimal performance.

The results from the simulation and experimentation phase provide valuable insights into the design and operational characteristics of the full-wave single-phase AC regulator (Rajendran et al., 2021). The ability to control the ignition angle allows for precise modulation of the output voltage, which is essential for various applications such as motor speed control, lamp dimming, and temperature regulation.

By analyzing different ignition angles and their effects on the output current, this study contributes to advancing the design and optimization of power electronic circuits, particularly in industrial applications. Moreover, the findings can inform future research into improving the efficiency and reliability of SCR-based systems, ensuring they meet the demands of modern electrical and engineering systems.

3. Results and discussion

In full-wave AC regulators, the ignition delay is applied to both the positive and negative halves of the AC waveform. This approach allows for more precise control of the output voltage and current, providing improved performance over half-wave regulators. To achieve this, the system utilizes either two Silicon-Controlled Rectifiers (SCRs) connected in parallel or a TRIAC (Triode for Alternating Current), which can control both halves of the AC cycle effectively. The use of SCRs or TRIACs ensures that the regulator can modulate the output signal in both the positive and negative phases of the waveform, enhancing the overall stability and efficiency of the regulator.

For the experimental setup, two different types of load configurations were tested: a resistive load (R) and a combined resistive-inductive load (RL). The resistive load primarily tests the regulator's response to purely resistive conditions, whereas the RL load simulates more complex real-world scenarios where both resistance and inductance affect the circuit behavior.

Upon completing the simulation, the input voltage waveform under these various load conditions was captured. The waveform highlights the impact of the ignition delay on the AC signal and provides valuable insights into the behavior of the regulator under different operational scenarios. The results help to understand how the phase delay, controlled by the SCRs or TRIAC, influences the performance and efficiency of the regulator.

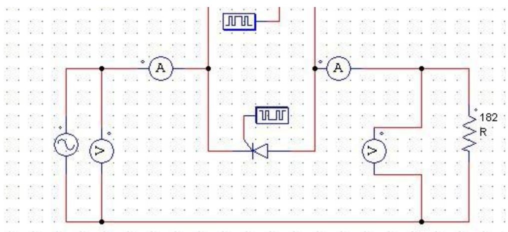

Figure 1. Full Wave 1 Phase Regulator Circuit with SCR with load R

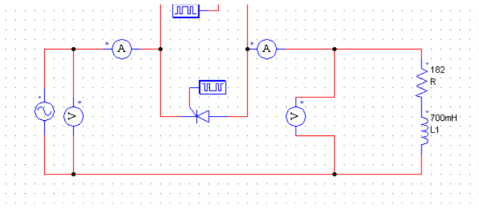

Figure 2. Full Wave 1 Phase Regulator Circuit with SCR with RL load

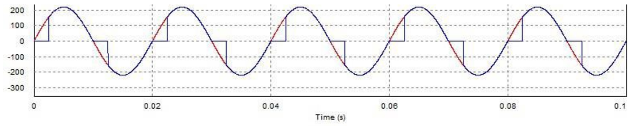

Figure 3. Input Voltage Waveform

Seen as in the picture above, that the full-wave ac regulator delays ignition on the positive and negative waves.

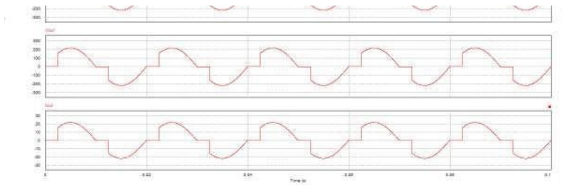

Figure 4. *Load R Input and Output Waveforms*

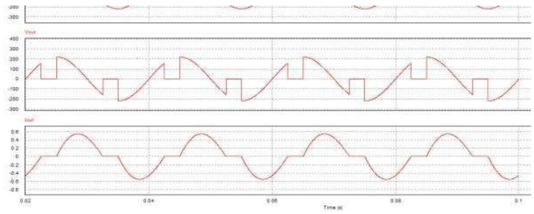

Figure 5. *Load RL Input and Output Waveforms*

Figures 5 and 4 present the simulation results obtained using PSIM software for the full-wave controlled single-phase AC regulator. The simulations were conducted under two distinct load configurations: a purely resistive (R) load and a resistive-inductive (RL) load. These configurations were chosen to assess the impact of different load characteristics on the regulator's performance.

Table 1. *Observation Results Using R Load*

Vref SCR	Input		Output				
	Vrms	Irms	Vm	Vrms	Vdc	Irms	Idc
0	220	21,9	311,12	219	198	21,9	1,08
1	220	22	311,12	220	198	22	1,08
2	220	21,8	311,12	218	198	21,8	1,08
4	220	21,6	311,12	216	198	21,6	1,08
6	220	21,4	311,12	214	198	21,4	1,08
8	220	21,2	311,12	212	198	21,2	1,08
10	220	21	311,12	210	198	21	1,08

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Table 2. *Observation Results Using RL Load*

Vref SCR	Input		Output				
	Vrms	Irms	Vm	Vrms	Vdc	Irms	Idc
2	220	0,55	311,12	214	198	0,55	1,08
4	220	0,54	311,12	212	198	0,54	1,08
6	220	0,54	311,12	210	198	0,54	1,08
8	220	0,53	311,12	208	198	0,53	1,08
10	220	0,52	311,12	204	198	0,52	1,08

The experimental data reveals that the average output voltage remains remarkably stable at approximately 198 Volts, irrespective of changes in the Vrms and Irms values. This consistent output voltage was maintained despite fluctuations in the load, highlighting the regulator's ability to deliver a steady voltage under different conditions. Furthermore, the output current consistently remained at 1.08 Ampere, indicating that the system effectively regulated the current flow regardless of load variations.

The key observation is that the Vrms value of the output voltage periodically varied, showing a reduction in voltage as the reference voltage (Vref) of the Silicon-Controlled Rectifier (SCR) increased. This phenomenon is typical in controlled rectifier circuits, where adjusting the Vref influences the phase angle, thereby modifying the voltage delivered to the load.

Tables 1 and 2 provide a comprehensive summary of the experimental results for both R and RL load configurations. The data shows a noticeable difference in the Vrms values, with the resistive load (R) exhibiting more stable voltage behavior compared to the resistive-inductive load (RL). The RL load, due to the inductive reactance, introduces more variability in the output waveform, resulting in a slightly lower Vrms value.

4. Conclusion

Based on the analysis of the experimental data, it can be concluded that the designed and implemented controlled rectifier successfully controls the output voltage, output current, and input current of a single-phase full-wave AC regulator. The results demonstrate that the system effectively allows for precise regulation of the desired output voltage and current. This capability to adjust and stabilize the output parameters underscores the potential applications of such regulators in various industrial sectors, including motor speed control, lighting dimming, and heating systems.

The successful realization of this controlled rectifier circuit provides valuable insights for further development in power electronics, specifically in enhancing the efficiency and stability of power regulation systems. Moreover, the findings align with current engineering research goals, as they demonstrate a reliable method for regulating both voltage and current in single-phase AC systems. These results are significant for advancing the design of controlled rectifiers used in complex industrial applications where voltage and current stability are critical.

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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