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Load Effect Analysis on Single-Phase AC Voltage Regulator for Enhanced Power System Performance

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Abstract

The Single-Phase AC Voltage Regulator plays a pivotal role in controlling the root mean square (RMS) output voltage (Vrms output) for various applications, including motor speed control and power modulation in electrical systems. The regulation of Vrms is achieved by adjusting the firing angle of the power switch, which introduces a delay in the output voltage waveform. Consequently, this type of voltage regulator is often referred to as a phase delay controller. This study investigates the performance of a full-wave single-phase AC voltage regulator under various load conditions using Silicon Controlled Rectifiers (SCR). The research employs a simulation-based approach using PSIM software to model and analyze the current and voltage waveforms, offering insights into the dynamic behavior of the system under resistive, inductive, and mixed load variations. The findings provide a deeper understanding of the load effects on voltage regulation efficiency, highlighting the importance of optimizing regulator design for enhanced performance and reliability in real-world applications.

Keywords: AC Voltage Regulator, RMS Voltage Control, PSIM Simulation, Load Variation, SCR, Phase Delay Control.

1. Introduction

The rapid development of industries is closely intertwined with advancements in technology, including in the electrical engineering field. One of the critical components in alternating current (AC) power control applications is the Triode for Alternating Current (TRIAC), which is commonly used for regulating voltage and current in AC systems. TRIAC, a bidirectional semiconductor switch, enables high voltage control in both positive and negative cycles of the AC waveform (Rahman et al., 2021).

AC voltage regulators are widely employed in both residential and industrial applications. For instance, they are used in dimmer switches for lighting systems and temperature regulation in water heating systems (Nugraha et al., 2020). The fundamental principle involves converting a constant AC voltage into a variable AC voltage by utilizing TRIAC components or two thyristors connected in an anti-parallel configuration. The conduction angle of the TRIAC or thyristor is controlled by adjusting the phase angle of the trigger voltage. The output voltage of the regulator depends on the phase angle of the trigger, and it ceases when the input voltage reaches zero due to line commutation or when the trigger angle reaches 180° (Agung et al., 2019).

Rectifiers are another vital application of power converters, converting alternating current (AC) into direct current (DC). Rectifiers are extensively used in electronic devices that require DC power sources, including computers and televisions. Based on their characteristics, rectifiers are classified into half-wave, full-wave, and bridge rectifiers, with further differentiation based on whether they use diode components or controlled power switches (Putra et al., 2021).

Non-linear loads, such as rectifiers, can degrade power quality by introducing harmonics into electrical systems. Harmonics are distortions in voltage and current waveforms, deviating from the ideal sinusoidal waveform of a single fundamental frequency (50/60 Hz for AC systems) (Widodo et al., 2022). The magnitude of harmonic distortion is commonly quantified using Total Harmonic Distortion (THD). The increasing use of non-linear loads, including electronic devices, has exacerbated harmonic issues, leading to overheating, reduced equipment lifespan, and inefficiencies in electrical systems (Santoso et al., 2020).

Harmonics can also create a high neutral current, posing risks to electrical installations and causing damage to connected equipment. To mitigate harmonic effects, passive filters consisting of resistors (R), inductors (L), and capacitors (C) are often employed to reduce distortion and improve power quality (Zulkarnain et al., 2021). This study focuses on analyzing the load effects on single-phase AC voltage regulators to enhance the performance and reliability of power systems.

2. Material and methods

2.1. Material

2.1.1 Rectifier

Alignment is the process of converting alternating current (AC) or voltage into direct current (DC) or voltage. Rectifiers, as defined by Moorthy et al. (2005), Lander (1993), and Sigh & Kanchanadhani (2007), are classified into three categories: uncontrolled, half-controlled, and fully controlled. In a controlled rectifier, the unidirectional voltage generated is dependent on the supply voltage or its source voltage, and on the point in the wave period when the thyristor or SCR is triggered (known as the trigger angle α). A rectifier circuit is composed of one or more diodes, where the process produces a DC output voltage, although harmonic components still need to be filtered out. The current and voltage output at a load can be determined as either input or output. Key performance parameters of a rectifier include power, efficiency, voltage, and ripple factor, which can be mathematically expressed as:

- Power:

$$P_{dc} = V_{dc} \cdot I_{dc} \quad (1)$$

$$P_{ac} = V_{ac} \cdot I_{ac} \quad (2)$$

- Efficiency:

$$\eta = \frac{P_{dc}}{P_{ac}} \quad (3)$$

- Voltage:

$$V_{dc} = \frac{1}{T} \int_0^t V(t) \cdot dt \quad (4)$$

$$V_{ac} = \sqrt{\frac{1}{T} \int_0^t V^2(t) \cdot dt} \quad (5)$$

- Ripple Factor:

$$FF = \frac{V_{rms}}{V_{dc}} \quad (6)$$

2.1.2 Thyristor

A thyristor is a semiconductor component that functions as a switch, operating similarly to a diode but with a gate that adjusts the ignition angle to control the output voltage. The output voltage can be applied to a dimmer circuit, often used as a lamp dimness controller. According to study results, the output voltage generated by the back-to-back thyristor circuit can be controlled by adjusting the ignition angle from 0° to 180°. This voltage is inversely proportional to the output, meaning that as the ignition angle increases, the output voltage decreases. The development of power electronics, particularly with the invention of the thyristor, has revolutionized the application of converters and inverters for AC/DC voltage regulation and motor speed control, offering more efficient, flexible, and economical solutions for various industries, such as in AC motor drives and electric heaters (Nugraha et al., 2020).

2.1.3 Voltage Regulator

Effective control of AC voltage is crucial due to the increasing demand for regulated voltage in equipment powered by varying voltages, including both AC and DC supplies. Voltage regulation can be achieved by adjusting the magnitude of the source signal, thereby influencing the output voltage. In principle, this control can be implemented using silicon-controlled rectifiers (SCRs), as illustrated in the following equation:

$$V_{out} = \sqrt{\frac{n}{n+m}} \cdot V_s \tag{7}$$

Where n and m represent the on and off durations of the SCR, respectively, and Vs is the source voltage.

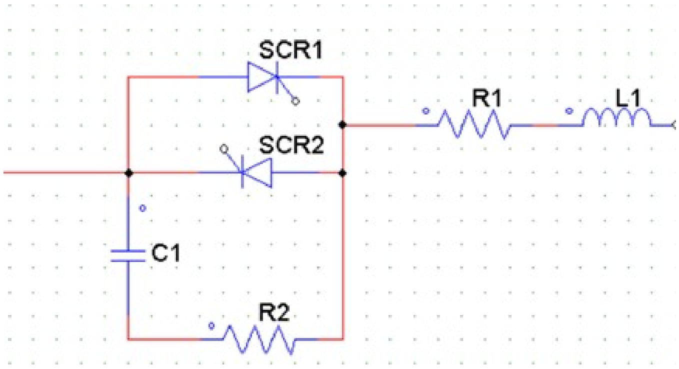

Figure 1. SCR Circuit

2.1.4 SCR (Silicon Controlled Rectifier)

The SCR, a type of thyristor, is a semiconductor device with three terminals: the anode, cathode, and gate. The gate controls the conduction state of the SCR, enabling phase regulation of AC signals. SCRs are commonly used in applications such as voltage regulation and motor control. The SCR operates by triggering via the gate, which allows current to flow from the anode to the cathode. Once the SCR is turned on, it remains on until the current drops below a specified holding current (I_h). The control of SCRs is essential in AC/DC voltage regulators, where they provide precise voltage control by cutting the AC waveform at the appropriate points (Prahasti et al., 2018). The gate trigger allows precise control over the timing of the conduction phase, making the SCR an indispensable component in modern power electronic systems.

2.2 Methods

This study utilizes a structured methodology involving several steps: designing and simulating the SCR-based single-phase AC voltage regulator circuit, followed by circuit assembly, experimental testing, data acquisition, and comprehensive data analysis. Initially, the design and simulation of the fully controlled single-phase AC voltage regulation circuit using SCRs are carried out with the aid of PSIM® software to evaluate the overall system performance. The focus of the simulation is on analyzing various load conditions and observing the corresponding effects on the circuit's behavior.

The single-phase AC regulator under consideration can operate in three distinct modes, each defined by different phase angle ignition characteristics:

a. Large Phase Angle Ignition ($\alpha\ \varphi > 90°$): In this mode, the output current is discontinuous, leading to a non-constant power output. The increased phase angle results in a significant reduction in the time the SCR remains on, which causes the output current to fluctuate significantly, ultimately affecting the overall stability of the system.
b. Small Phase Angle Ignition ($\alpha\ \varphi < 90°$): In this mode, one of the SCRs fails to trigger or turn on, leading to an imbalance in the regulator’s operation. The smaller phase angle limits the time for which the SCR conducts, and under certain conditions, this may cause the regulator to operate inefficiently or fail to maintain the desired output voltage.
c. Equal Phase Angle Ignition ($\alpha\ \varphi = 90°$): When the ignition angle is perfectly aligned with the phase angle, the output current becomes continuous. This configuration ensures a smooth and stable voltage output, which is critical for applications requiring precise voltage control, such as in sensitive equipment or systems that need to minimize power fluctuations.

This method of analysis allows for a detailed understanding of how different operating conditions affect the performance of the AC voltage regulator, especially with varying load conditions. By adjusting the phase angle, the regulator can be fine-tuned for optimal efficiency, reducing the impact of unwanted harmonics and providing a stable voltage supply to the connected load.

3. Results and discussion

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In the analysis of full-wave AC voltage regulators, the ignition delay is considered for both the positive and negative half-waves of the AC cycle. This configuration typically utilizes two SCRs arranged in parallel or, alternatively, a TRIAC. After performing the simulation, the input voltage waveform was captured and is illustrated in Figure 2 below, which shows the behavior of the regulator under varying conditions.

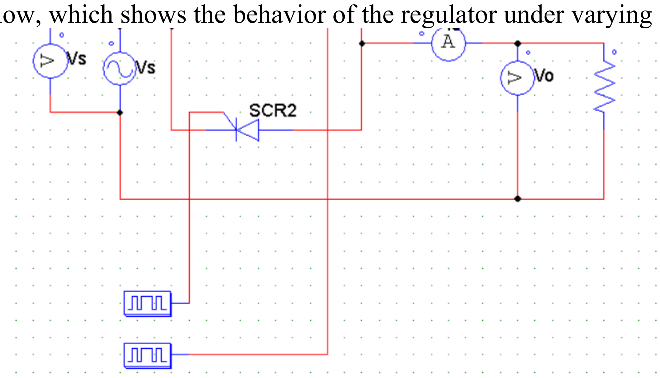

Figure 2. Full-wave Single-Phase AC Voltage Regulator Circuit with SCRs and Resistor Load

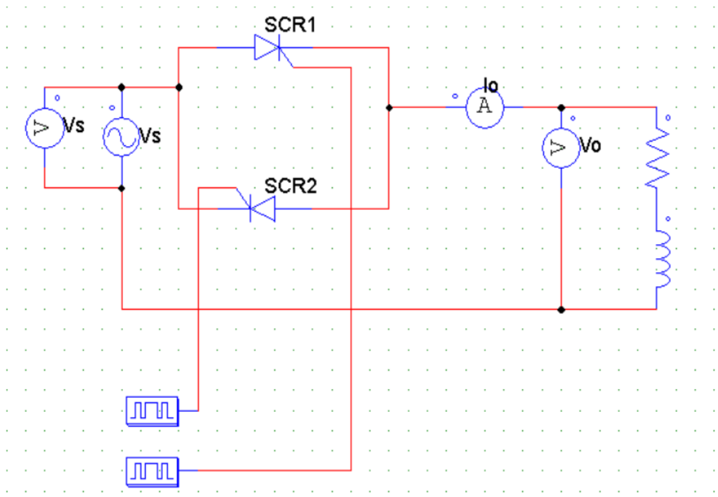

Figure 3. Full-wave Single-Phase AC Voltage Regulator Circuit with SCRs and Resistor Load

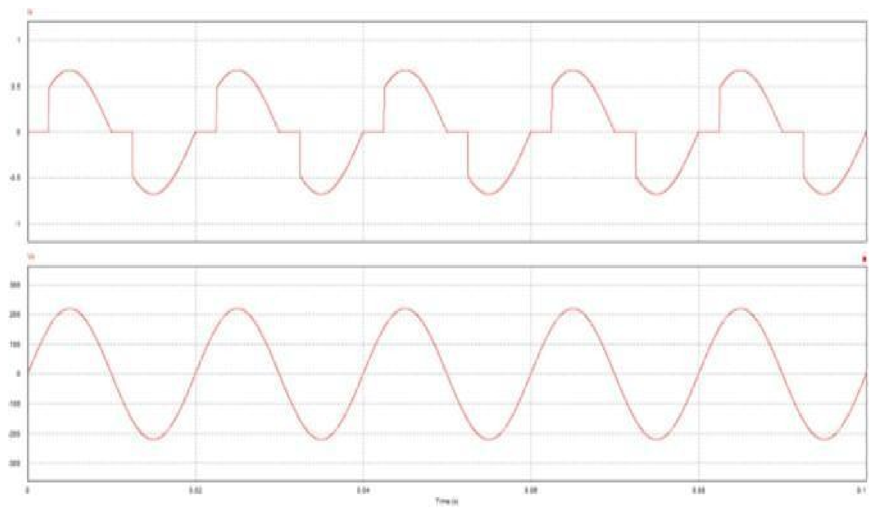

Figure 4. Input Voltage Waveform

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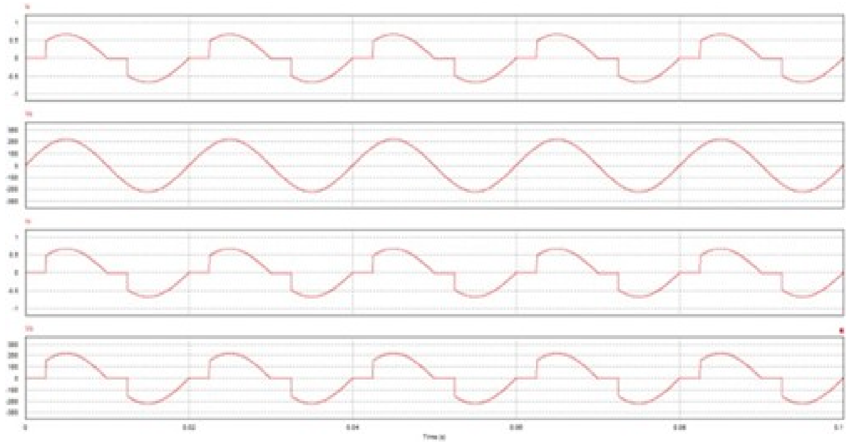

Figure 5. Load Input and Output Waveforms

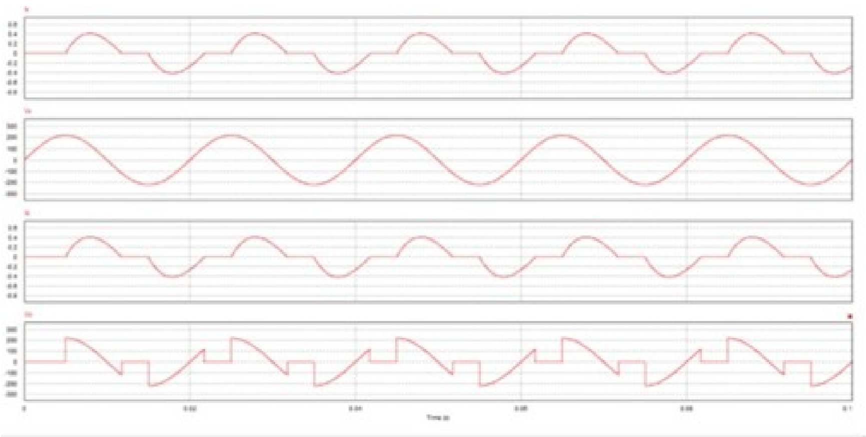

Figure 6. RL Load Input and Output Waveforms

As observed in the PSIM simulation results, particularly in Figures 5 and 6, significant differences in the Vrms voltage and Irms current are noted between the systems using resistive (R) loads and inductive-resistive (RL) loads. These variations are essential in understanding how different load types affect the performance of the voltage regulator, providing deeper insights into the regulator's behavior under diverse operational conditions.

Table 1. Results of Observations with Resistor Load (R)

α (Degrees)	R (Ohms)	Vs (rms) (Volts)	Vo (rms) (Volts)	Io (rms) (Amps)	Input Voltage (V)	Output Voltage (V)	Input Current (I)	Output Current (I)
15	325	155.56	155.56	0.477	220	0.67	220	0.67
30	325	155.56	153.31	0.471	220	0.67	220	0.67
45	325	155.56	148.28	0.456	220	0.67	220	0.67
60	325	155.56	139.50	0.429	220	0.67	220	0.67
75	325	155.56	126.68	0.389	220	0.67	220	0.67
90	325	155.56	109.88	0.338	220	0.67	220	0.67
100	325	155.56	97.164	0.298	220	0.67	220	0.67

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Table 2. Results of Observations with RL Load

α	R (Ohm)	L mH	Vs(rms) (Volt)	Vo(rms) (Volt)	Io(rms) (A)	input		Output	
						V	I	V	I
15	325	500	155.56	155.53	0.431	220	0.55	219	0.55
30	325	500	155.56	154.63	0.426	220	0.54	219	0.54
45	325	500	155.56	149.62	0.403	220	0.50	219	0.50
60	325	500	155.56	140.93	0.369	220	0.43	219	0.43
75	325	500	155.56	128.22	0.323	220	0.28	220	0.28
90	325	500	155.56	111.54	0.268	220	0.21	1.10	0.21
100	325	500	155.56	98.95	0.228	220	0.21	1.10	0.21

The rectifier circuit was tested using a fixed input voltage while varying the phase angle. From the experimental data, it is evident that the output voltage in the circuit with a purely resistive load (R) remains constant at 219 Volts, even though the Vrms and Irms values fluctuate. Conversely, in the RL load configuration, the voltage begins to decrease as the phase angle reaches 90° and 100°, which corresponds to a reduction in the performance of the voltage regulator.

The experimental results presented in Tables 1 and 2 show a clear trend where the output voltage with a resistive load (R) maintains a constant value despite varying phase angles. This is contrasted with the RL load circuit, where the output voltage decreases as the phase angle increases. Notably, the reduction in the Vrms value for the resistive load is more significant compared to the decrease observed in the RL load.

3. Conclusion

Based on the analysis of the observation data, it is clear that the output voltage (Vrms) periodically decreases as the phase angle increases. This phenomenon is more pronounced in the system with a resistive load (R), where the decrease in Vrms is more substantial compared to the RL load system. The results underscore the importance of load type in determining the effectiveness of a full-wave AC voltage regulator.

The behavior of the voltage regulator under different load conditions offers crucial insights into the design of more efficient power systems. The findings from this study can guide future research and improvements in voltage regulation, particularly in enhancing system performance under varying load conditions. Moreover, the simulation results serve as a valuable tool for engineers seeking to optimize the performance of AC voltage regulators in practical applications.

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