Conference of Electrical, Marine and Its Application
Vol. xx, No xx, Month-Year ISSN:

# Development of Single-Phase AC Voltage Regulator for Renewable Energy Empowerment: Rural Generator Case Study

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**ABSTRACT**

*This research focuses on the development of a single-phase AC voltage controller designed using SCR TIC126, diodes, IC regulators, Op-Amp LM324N, and other essential electronic components. The module is capable of producing variable AC voltage levels based on the triggering angle of the SCR, while maintaining a fixed output frequency. The output voltage waveform is analyzed through simulation using the PSIM software and verified mathematically. The key parameter measured is the Vrms output voltage. The observed differences between simulated, and mathematical values are minimal, ensuring reliability. The triggering angles used in this study are 45°, 60°, and 90°, with a resistive load of 5 W and 100 Ω. The source voltage applied is a low AC voltage of 12.8 V at a frequency of 50 Hz. This study is contextualized within a renewable energy program aimed at empowering rural communities. By utilizing this voltage controller, the research explores its potential in enhancing the performance of small-scale generators used in off-grid areas, particularly in enabling stable and efficient electricity supply for households and community facilities. The findings highlight the module's applicability in community empowerment programs, offering a practical and scalable solution for improving energy access in underserved regions.*

**Key Word**: *AC Voltage controller, PSIM, SCR, and Op-Amp LM324N.*

## I.INTRODUCTION

Power electronics is a core subject taught in the Automation Engineering program at Politeknik Perkapalan Negeri Surabaya, focusing on the application of various electronic components for the conversion and control of electrical power[1]. The use of power electronic components facilitates precise and efficient power conversion and control, enabling the desired output to be achieved with accuracy[2]. The rapid advancement of technology has expanded the applications of power electronics, making it an essential field of study for automation engineering students.

Power electronics is widely applied across various fields that involve electrical equipment with high power requirements[3]. Industries, for example, rely on high-power electrical energy for devices such as heaters, motors, coolers, pneumatic systems, conveyors, and other large-scale machinery[4][5]. Traditional methods of operation using human labor are inefficient and often lead to losses for companies. To overcome these challenges, industries are increasingly adopting power electronic systems to provide effective control mechanisms for high-current and high-voltage devices[6]. These systems offer efficient solutions for managing and automating industrial processes.

The field of power electronics continues to evolve, with significant advancements in circuit design and application. Numerous industries have embraced the benefits of power electronics in their operations. The progress in science and technology has further accelerated the development of power electronics, making it a mandatory subject for electrical and automation engineering students[7]. The objective is to equip students with theoretical knowledge, practical skills, and application-based understanding of power electronics.

A fundamental topic covered in the power electronics curriculum is the control of single-phase AC voltage and single-phase AC generators[8]. One of the essential areas of study in power electronics is AC-to-AC converters. In this research, a prototype of an AC-to-AC converter is designed with a fixed frequency but variable output voltage. By utilizing SCR components, the trigger angle can be controlled, allowing the Vrms output voltage to be adjusted according to specific requirements. The system operates with resistive loads to demonstrate the functionality of the designed circuit.

A single-phase uncontrolled rectifier circuit is integrated with a single-phase AC generator as its output component. The AC generator functions as a power generation machine that converts mechanical energy into electrical energy[9]. Alternating current generators (AC generators) are synchronous machines, often referred to as alternators or synchronous generators. The term "synchronous generator" reflects the rotor's rotation, which matches the magnetic field's rotational speed on the stator. This synchronization generates alternating current (AC) electricity. The principle behind this operation is Faraday's Law, which states that a conductor exposed to a changing magnetic field induces an electromotive force (EMF)[10].

Based on the background and fundamental theory described above, the primary challenge lies in developing an integrated single-phase AC voltage regulator circuit for single-phase AC generators. To address this issue, the study aims to design and implement a circuit capable of regulating the output voltage of a single-phase AC generator. The integrated system is simulated to analyze the output characteristics, with the generator receiving electrical input from a rectifier circuit and converting it into mechanical energy.

# II.METHODOLOGY

## 1. Single-phase AC voltage regulator

The single-phase AC-AC converter circuit is designed to produce a variable AC output voltage from a fixed AC source[11]. This converter utilizes two thyristor components connected in an anti-parallel configuration or a single TRIAC (Triode for Alternating Current). The single-phase AC-AC converter is commonly referred to as an AC-AC voltage controller.

When a thyristor switch is connected between the AC source and the load, the energy flow can be controlled by varying the RMS value of the AC voltage applied to the load[12][13]. The alternating current from the source will flow through the load during each half-cycle of the source voltage period[14]. The RMS value of the load voltage can be adjusted by changing the triggering angle, denoted as 'α', of the thyristor.

The basic principle of the single-phase AC-AC voltage control circuit, as shown in Figure A, consists of a pair of SCRs (Silicon-Controlled Rectifiers) connected back-to-back (also known as anti-parallel or invers-parallel) between the AC supply and the load. This connection allows for symmetrical full-wave two-way control, and the SCR pair can be replaced with a TRIAC, as shown in Figure B, for low-power applications.

Alternative configurations are shown in Figures C and D. Figure C uses two diodes and two SCRs to provide a common cathode connection, simplifying the gate circuit without the need for isolation. Figure D features a single SCR and four diodes to reduce device costs, although this increases conduction losses. The combination of SCRs and diodes, known as a thyrode controller, as shown in Figure E, offers half-wave asymmetric voltage control, providing savings on components but introducing DC components and additional harmonics. This makes it less practical for general use, except for low-power heating loads.

Phase control involves conducting the load current for a selected period within each cycle of the input voltage, while on/off control connects the load for several cycles of the input voltage and disconnects it for the subsequent cycles (integral control cycle)[15]. Alternatively, the switch may be turned on and off multiple times within the half-cycle of the input voltage, commonly known as Pulse Width Modulation (PWM) for AC voltage control.

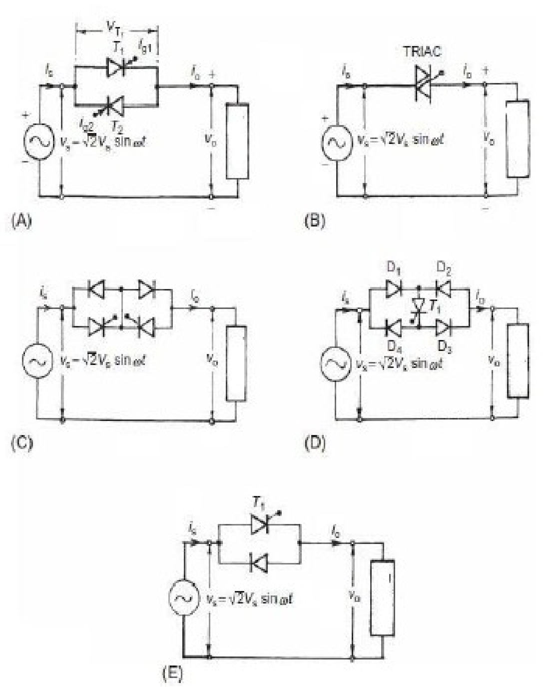


*Figure 1. Single-phase AC voltage controller:*

*(A) full wave, two SCRs in inverse-parallel;*
*(b) full wave with triac;*
*(c) full wave with two SCRs and two diodes;*
*(d) full wave with four diodes and one SCR;*
*(E) half wave with one SCR and one diode in antiparallel.*

For full-wave symmetric phase control, the SCRs T1 and T2 in Figure 2.1A each operate based on α and π + α, relative to the zero crossing of the input voltage. By varying α, the power flow to the load is controlled through voltage regulation during the half-cycle alternation. During one half-cycle, while one SCR conducts current, the other remains reverse-biased due to the voltage drop across the conducting SCR. The operational principle for each half-cycle is similar to that of a half-wave controlled rectifier, and a similar approach can be used for circuit analysis.

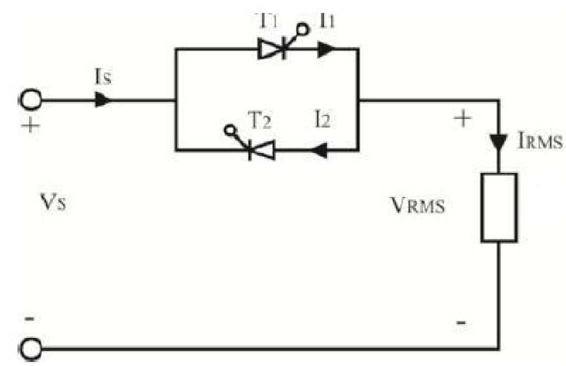


*Figure 2. Single phase AC voltage regulator circuit*

## 2. Single-phase AC generator

A generator, as a power generation unit, is coupled with the shaft of a transmission unit. The type of generator used can be either a direct current (DC) generator or an alternating current (AC) generator, depending on the intended application. An AC generator, or alternator, is a component that converts mechanical energy into electrical energy[16]. Currently, generators are utilized as power plants, with AC generators or alternators operating on the same principle of electromagnetic induction as DC generators.

A synchronous generator (alternator) is an electrical machine that transforms mechanical energy into electrical energy through electromagnetic induction. When a synchronous generator is loaded, it will exhibit different characteristics depending on the type of load it carries. The nature of the load determines the power factor of the generator. The power factor is a measure of how efficiently the machine can deliver usable power[17]. Therefore, by adjusting the excitation current in the generator, the reactive power required by the generator can be controlled, and the power factor of each generator can be optimized when operating in parallel.

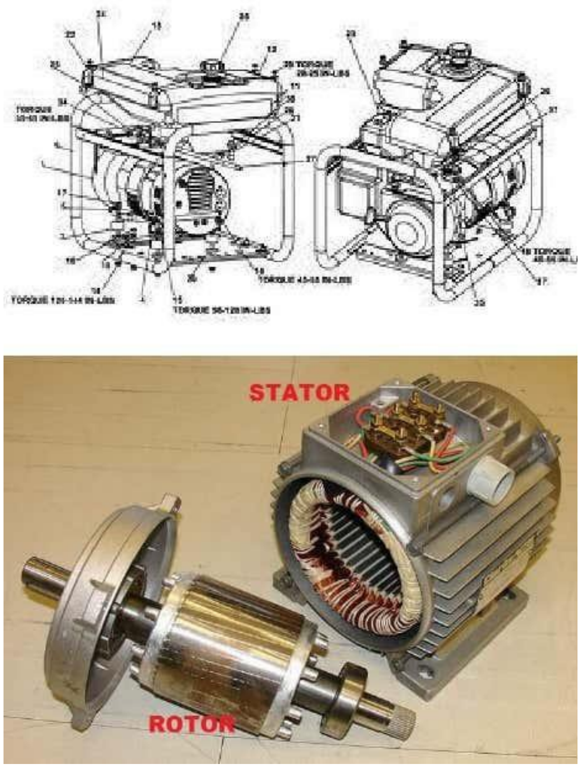


*Figure 3. Single-phase AC generator*

A generator serves as a power generation unit, with its shaft connected to the output shaft of the transmission unit. The type of generator used can either be a direct current (DC) generator or an alternating current (AC) generator, depending on the specific application[18]. AC generators, also known as alternators, are components that convert mechanical energy into electrical energy. Currently, AC generators are widely used as power plants, operating on the same electromagnetic induction principle as DC generators[19].

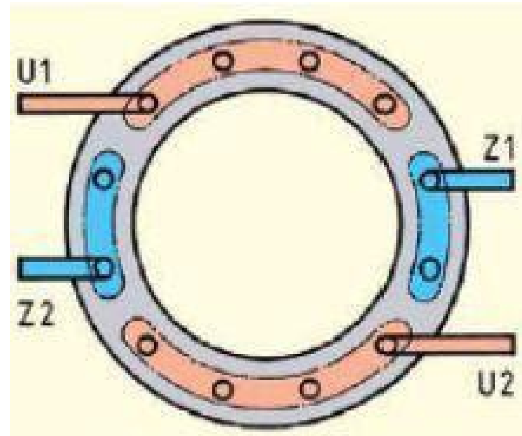


*Figure 4. generator windings*

An induction generator operates on the same principles and construction as an induction motor, which is widely used. The key difference is that an induction generator requires a prime mover, making the rotor speed higher than the stator speed, in order to generate voltage[20]. Induction generators are predominantly used in remote areas where access to electricity is limited. They are typically employed in small-scale power generation, such as in wind and micro-hydro power plants. However, one of the challenges with induction generators is that the output voltage is not constant. Therefore, a control system is necessary to regulate the output voltage of the induction generator. By using a voltage regulation system, the output voltage of the induction generator can become self-excited, providing a smoother and more stable voltage without ripple, thus improving its reliability.

## 3. Method

AC-to-AC power electronic converters generally function to receive alternating current (AC) power with a fixed frequency and amplitude, then transform it for delivery to a system that requires AC voltage with either a different amplitude or frequency[21]. These AC-to-AC converters can provide variable RMS voltage to the load while maintaining a fixed frequency, and they are commonly known as AC voltage controllers. The following diagram illustrates the basic concept of an AC voltage controller circuit.

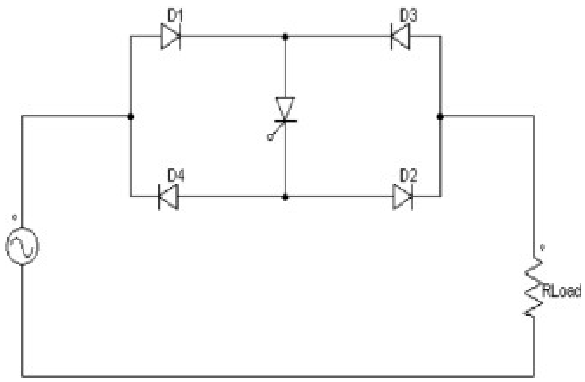


*Figure 5. Basic Concept of AC voltage controller*

In general, the system operation shown in Figure 5 can be described in Table 1. This system operates in two cycles: the positive (+) cycle and the negative (-) cycle. The components that function during the positive cycle are D1, D2, and SCR, while the components that operate during the negative cycle are D2, D3, and SCR.

*Table 1. Conduction Table*

| cycle | D1 | D2 | D3 | D4 | SCR |
|---|---|---|---|---|---|
| **Positive** | 1 | 1 | 0 | 0 | 1 |
| **Negative** | 0 | 0 | 1 | 1 | 1 |

When the SCR is tigered at an angle of $\alpha$, it will produce a voltage waveform output (Vo) on the positive cycle side, while the negative cycle side is tigered at an angle of $\pi + \alpha$ as shown in Figure 6[22], where the load used in this study is resistive.

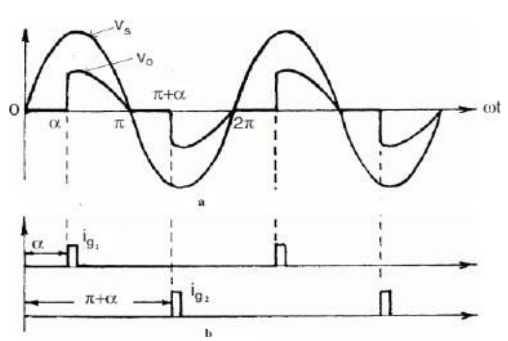


*Figure 6. Waveform of cycle*

# III.RESULT & DISCUSION

## 1.Result

- Calculation

  Mathematical analysis was carried out at angles of 45˚, 60˚, 90˚ to determine the variations in voltage and current produced at each of these angles. This analysis process uses equation (1), which is the basic formula in calculating voltage in alternating current (AC) systems. The maximum voltage of the AC source used in this calculation is 12.8 Volts, which is the peak value of the source voltage. By using this voltage value at predetermined angles, it is expected to obtain a deeper understanding of the behavior of voltage and current in AC systems at certain angular conditions, which can then be used to design or optimize voltage regulator systems or other applications in power systems.

  $$V_{RMS} = \sqrt{\frac{1}{T}\int_0^T V^2 d\theta}$$

  - 45 ° = 8,63 V
  - 60 ° = 8,12 V
  - 90 ° = 6,4 V
- Simulation

  The following is a simulation analysis conducted using the PSIM program to model the AC voltage system under various angle conditions. In this simulation, the maximum voltage of the AC source used is 12.8 volts, and the analysis is performed at 45˚, 60˚, 90˚. The PSIM program is used to visually represent the waveform of the output voltage at each of these angles. The results of this simulation are expected to provide a clearer understanding of the voltage characteristics in the AC system, which can be used for performance evaluation and optimization of voltage regulator designs or other applications in electrical power systems. The output waveform produced from this simulation will provide useful information for further analysis regarding system stability and efficiency under actual operating conditions.

- 45 °

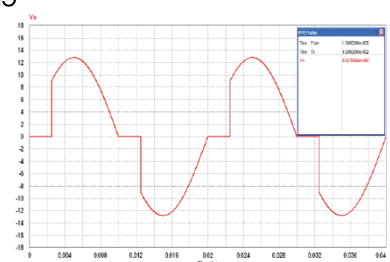

*Figure 7. Result Waveform from 45 °*

*The simulation results show that the RMS voltage obtained from this angle is measured to be 8,63 volts. This value indicates the system's ability to regulate the output voltage effectively at the specified angle, confirming the accuracy and reliability of the simulation in replicating real-world conditions. The results also highlight the variation in RMS voltage corresponding to different angles, demonstrating the system's dynamic response to changes in input parameters*

- 60 °

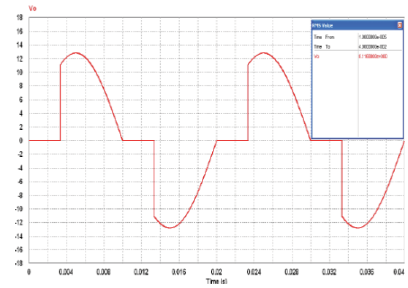

*Figure 7. Result Waveform from 60 °*

*The simulation results show that the RMS voltage obtained from this angle is measured to be 8,12 volts. This value indicates the system's ability to regulate the output voltage effectively at the specified angle, confirming the accuracy and reliability of the simulation in replicating real-world conditions. The results also highlight the variation in RMS voltage corresponding to different angles, demonstrating the system's dynamic response to changes in input parameters*

- 90 °

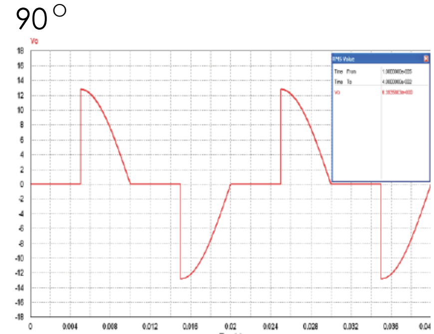

*Figure 7. Result Waveform from 90 °*

The simulation results show that the RMS voltage obtained from this angle is measured to be 6,39 volts. This value indicates the system's ability to regulate the output voltage effectively at the specified angle, confirming the accuracy and reliability of the simulation in replicating real-world conditions. The results also highlight the variation in RMS voltage corresponding to different angles, demonstrating the system's dynamic response to changes in input parameters

## 2.Discussion

The waveform is then used as input for the Zero Crossing Detector (ZCD circuit). To produce a DC output voltage of +12V and -12V, this waveform is connected to a capacitor filter and the LM7812 and LM7912 voltage regulator ICs.

The comparison of the output Vrms voltage from the controlled AC waveform, in terms of simulation and mathematical calculations, is shown in Table below. The results from simulation and calculations exhibit negligible differences.

Table 2. Comparation voltage RMS

| **No** | ***Trigger Angle*** | ***Output rms Voltage (V)*** | |
|---|---|---|---|
| | | *Mathematical* | *Simulation* |
| ***1*** | *45 °* | *8,63* | *8,63* |
| ***2*** | *60 °* | *8,12* | *8,12* |
| ***3*** | *90 °* | *6,39* | *6,4* |

# IV.CONCLUSION

1. The single-phase AC voltage regulator circuit is capable of generating an AC waveform with a constant frequency, while the output RMS voltage varies according to the specified angle. This voltage variation demonstrates the circuit's ability to adjust the output to meet the required settings, providing flexibility in voltage control.

2. The measured and simulated results show minimal differences, indicating that the simulation provides highly accurate results and closely reflects real-world conditions. This suggests that the model used in the simulation is reliable for practical applications.

3. Although there is a slight difference between the theoretical calculations and the simulation measurements, the discrepancy is very small and not significant. This indicates that both theoretical analysis and simulation experiments support each other effectively.

4. The small difference is attributed to the precision of manual calculations, particularly concerning rounding errors or the number of decimal places used. Higher precision in calculations and data acquisition could minimize these differences, but overall, the observed discrepancy does not significantly affect the conclusions drawn from the simulation results.

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