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Design and Implementation of a Single-Phase AC Voltage Controller for Engineering Applications

John Vernando Purba
Marine Electrical Engineering, Shipbuilding Institute of Polytechnic Surabaya
jvernando03@student.ppns.ac.id

Abstract

This study presents the design and implementation of a single-phase AC voltage controller utilizing an SCR TIC126, diode, IC regulator, op-amp LM324N, and additional electronic components. The developed module generates variable AC voltage output by adjusting the triggering angle of the SCR, while maintaining a constant output voltage waveform frequency. The analysis of the output voltage waveform was conducted through mathematical modeling and simulation using the PSIM software. Experimental measurements were compared with simulation results, focusing on the root mean square (Vrms) of the output voltage under varying trigger angles—specifically 45°, 60°, 90°, and 135°. The tests were performed using a low-resistance load of 5W 100Ω, powered by a source voltage not exceeding 12.8 volts at a frequency of 50 Hz. Discrepancies between simulation, mathematical predictions, and experimental results were analyzed to evaluate the performance and accuracy of the controller under different operating conditions. The findings demonstrate the controller's potential for efficient voltage regulation in engineering applications, emphasizing its reliability in handling varying load conditions.

Keywords: AC Voltage controller, PSIM, SCR, and Op-Amp LM324N

1. Introduction

Power electronics is a crucial field within engineering, focusing on the application of electronic systems to control and transform electrical power (Kumar, Mahendar, & Shruthi, 2014). This discipline is especially important in managing high-power devices, including industrial heating systems and AC motor speed controllers (Rashid, 2004). One of the central topics within power electronics is the development of AC-to-AC converters, which are designed to transform AC voltage while customizing output parameters to meet specific requirements (Singh & Khanchandani, 2007)

This research is dedicated to designing and implementing a prototype AC-to-AC converter that operates under a fixed-frequency concept and offers variable output voltage capabilities (Hart, 2011). The system employs a Silicon Controlled Rectifier (SCR) as its primary component, enabling precise control of the trigger angle. This feature allows the root mean square (Vrms) output voltage to be adjusted according to operational needs (Nugraha, Ramadhan, & Shiddiq, 2022).

The proposed system is optimized for use with resistive loads, ensuring efficient power regulation tailored for practical applications. By focusing on these aspects, the research highlights the versatility and practicality of AC-to-AC converters in real-world scenarios, particularly in industrial and energy systems (Utomo & Nugraha, 2021).

Through this innovative design, the study demonstrates the potential of SCR-based converters to provide reliable and adaptable power solutions (Zakariz, Nugraha, & Phasinam, 2022). The ability to manage voltage output effectively aligns with the broader goals of power electronics, emphasizing its role in enhancing energy efficiency and control across various industries.

2. Material and methods

2.1. Literature

AC-to-AC power electronic converters play a crucial role in electrical systems by transforming alternating current (AC) input with a fixed frequency and amplitude into a form suitable for diverse applications (Nugraha, Ravi, & Tiwana, 2021). These converters are commonly employed to supply systems that demand variable AC voltage amplitudes while maintaining a constant frequency. A specialized category of AC-to-AC converters designed to deliver a variable root mean square (Vrms) voltage output at a fixed frequency load is referred to as

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an AC voltage controller (Zakariz, Nugraha, & Phasinam, 2022). This device has garnered significant attention for its applications in industrial systems, such as motor speed controllers, dimmers, and other precision power regulation systems (Nugraha, Ravi, & Tiwana, 2021). Figure 1 illustrates the fundamental concept of an AC voltage control circuit, forming the basis for its operation and application.

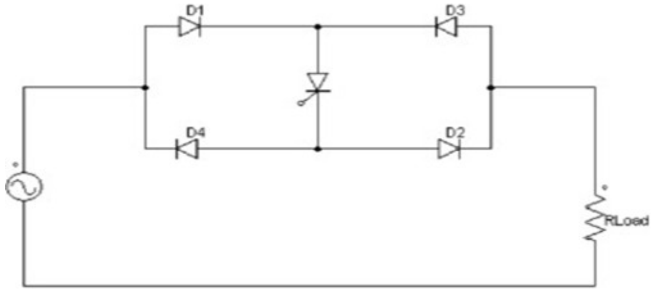

Figure 1. Basic Concept of an AC Voltage Controller

The operational framework of the AC voltage controller, as depicted in Figure 1, consists of a two-cycle mechanism: the positive cycle (+) and the negative cycle (-). During the positive cycle, components such as diode D1, diode D2, and the Silicon Controlled Rectifier (SCR) are engaged in controlling the flow of current through the circuit. Conversely, during the negative cycle, diodes D2 and D3, along with the SCR, play a pivotal role in regulating current flow. This alternating operation of components ensures efficient modulation of the AC voltage delivered to the load (Nugraha et al., 2022). Table 1 provides a detailed overview of the working mechanism, specifying the roles of individual components across the two cycles.

The design and implementation of such an AC voltage controller necessitate meticulous engineering to ensure reliability, precision, and adaptability to various resistive and inductive loads (Realdo, Widiarti, & Nugraha, 2021). By leveraging modern electronic components and techniques, the developed system offers improved performance and scalability (Ravi, Widodo, & Nugraha, 2021). This study also focuses on evaluating the converter's performance through simulations, mathematical modeling, and experimental validation, highlighting the practical viability and technological significance of AC voltage controllers in contemporary engineering applications (Nugraha, As'ad, & Abdullayev, 2022).

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 triggered at an angle it will produce a voltage wave output (Vo) on the positive cycle side, while on the negative cycle side it is triggered at an angle + as shown in Figure 2, where the load used in this study is resistive (Asri et al., 2022).

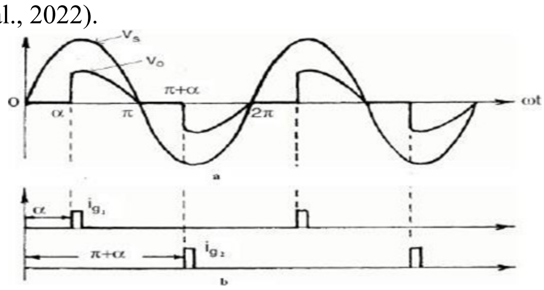

Figure 2. Fig. 2. (a) Input voltage waveform (Vs) and output (Vo), (b) SCR trigger wave

RMS voltage or effective stress is a voltage that shows the average value of the square root of a periodic stress wave, mathematically it can be written by equation below (Nugraha et al., 2022).

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$$Vrms=\sqrt{\frac{1}{T}[\int_{\sigma}^{\pi} v(t)^2 . dt+\int_{\pi+a}^{2\pi} v(t)^2 . dt]}$$

Where is :
Vrms = RMS Voltage (Volt)
T = Period of the output waveform (s)
V(t) = the equation of the output waveform with respect to a function of time

The single-phase AC voltage control circuit design in this study was built following the block diagram as shown in Figure 3 below.

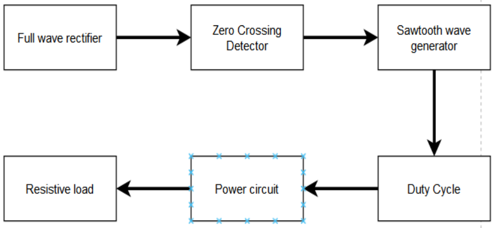

Figure 3. Block diagram

A. Power Supply Circuit

The full-wave rectifier serves as a critical component in converting alternating current (AC) voltage signals into direct current (DC) voltage. This DC voltage acts as a stable power source for all elements within the control circuit. The rectification process is achieved through a circuit configuration comprising diodes, capacitors, and voltage regulator ICs, specifically the LM7812 and LM7912 (Ivannuri & Nugraha, 2022). These regulators ensure the delivery of consistent +12V and -12V DC outputs. This dual-polarity voltage output is essential for powering both analog and digital subsystems within the controller, thereby enhancing the reliability and efficiency of the overall system. Figure 4 illustrates the schematic layout of this rectifier circuit and its interconnection with other critical modules.

Beyond its role as a power source, the output of the full-wave rectifier is also utilized as an input for the Zero Crossing Detector (ZCD) circuit. The ZCD is a pivotal subsystem in AC voltage control applications, as it detects the precise moments when the AC signal crosses the zero-voltage point. This information is crucial for synchronizing the triggering angle of the Silicon Controlled Rectifier (SCR) in the AC voltage controller (Achmad & Nugraha, 2022). Accurate zero-crossing detection ensures that the switching operations are performed at the optimal phase of the AC cycle, minimizing electrical noise and improving the overall performance of the system. The integration of the rectifier and ZCD circuits underscores the design's precision and suitability for engineering applications that demand high levels of accuracy and control.

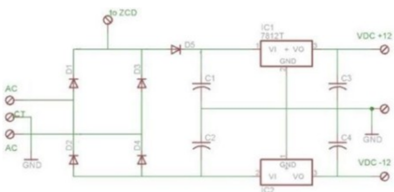

Figure 4. Full wave rectifier circuit

B. Duty Cycle

The duty cycle circuit in this design incorporates a variety of essential electronic components to control the operation of the Silicon Controlled Rectifier (SCR). Key components include resistors, the operational amplifier IC LM324N, diodes, and a potentiometer. Each of these components plays a vital role in shaping the pulse-width modulation (PWM) signal, which is used to regulate the trigger angle of the SCR. The PWM signal, which varies in width, determines the timing of the SCR's conduction, thereby adjusting the output voltage to meet the system's requirements. By modifying the width of the PWM pulse, the potentiometer allows precise control over the trigger angle, thus enabling fine-tuning of the AC voltage delivered to the load. This design approach ensures the adaptability and versatility of the voltage controller for different engineering applications. Figure 5 illustrates the circuit diagram, showing the arrangement of these components and their interconnections.

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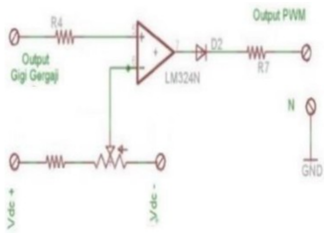

Figure 5. Duty cycle circuit

In engineering systems, especially in power electronics, precise control of the duty cycle is crucial for optimizing system performance. The use of an operational amplifier, such as the LM324N, ensures high accuracy in the generation of the PWM signal (LM 324 Data Sheet, n.d.). This enhances the overall stability and responsiveness of the voltage controller. The integration of diodes further protects the circuit by preventing reverse voltage from affecting the components. The potentiometer, by offering adjustable resistance, gives the operator a convenient way to modify the duty cycle and, consequently, the SCR trigger angle. This configuration is particularly advantageous in applications where the voltage regulation needs to be dynamic and adaptable to varying load conditions. The ability to fine-tune the duty cycle through this circuit makes it suitable for a wide range of industrial and consumer applications requiring reliable and efficient AC voltage control.

C. Power Circuit

The power circuit of the AC voltage regulator is composed of several critical electronic components designed to effectively manage and regulate the output voltage. The circuit includes four diodes, which function as part of a full-wave rectifier to convert alternating current (AC) into direct current (DC), and a single Silicon-Controlled Rectifier (SCR) model TIC126, which plays a central role in controlling the output voltage. The SCR is triggered by a pulse-width modulation (PWM) signal, which adjusts its conduction time and, in turn, controls the voltage delivered to the load. The power circuit also integrates a resistive load of 5W/100Ω, as depicted in Figure 6, which allows the system to regulate the power flow while maintaining a stable output voltage under varying load conditions. This configuration ensures that the AC voltage regulator can meet the required voltage levels while maintaining efficiency and reliability in engineering applications.

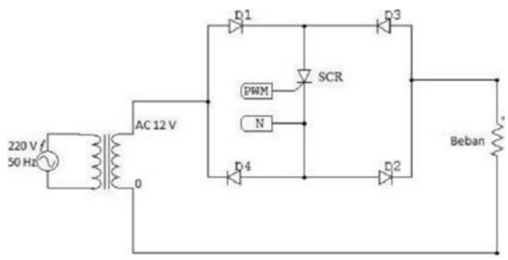

Figure 6. Power circuit

In terms of its engineering application, this power circuit design is suitable for a range of industrial and consumer systems where stable AC voltage control is necessary. The combination of diodes and the SCR provides a robust solution for efficiently managing the AC-to-DC conversion process and controlling the voltage output to a load. The 5W/100Ω resistor serves as a load to simulate practical operating conditions, ensuring that the voltage regulation works effectively across a variety of scenarios. Furthermore, the simplicity of this power circuit, coupled with its high efficiency, makes it an ideal choice for applications where space, cost, and performance are key factors. By implementing this design, engineers can achieve precise control over AC voltage, making it an essential tool in various sectors such as power distribution, motor control, and heating systems.

3. Results and discussion

3.1. Result

A. Power supply circuit test

The waveform generated after passing through the bridge diode rectifier can be observed in Figure 7. This rectified waveform, which initially consists of pulsating DC voltage, is then fed into the Zero Crossing

Detector (ZCD) circuit. The ZCD circuit plays a crucial role in detecting the point where the voltage waveform crosses zero, which is essential for triggering the SCR (Silicon-Controlled Rectifier) at the appropriate time to regulate the output voltage. The ZCD's function ensures that the AC voltage waveform is synchronized with the required control parameters, facilitating accurate and efficient voltage regulation for engineering applications. This input waveform, after processing through the ZCD, is subsequently used to generate a stable DC output of +12V and -12V, which is essential for powering the control circuitry of the AC voltage regulator.

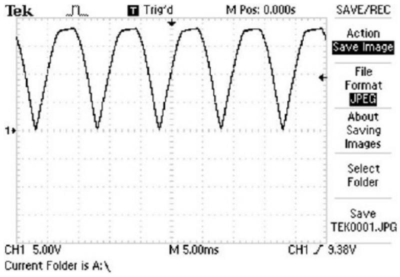

Figure 7. Full wave rectifier result

B. Duty cycle circuit test

The measurement results from the duty cycle circuit are illustrated in Figure 8, where the variation in the duty cycle pulse width is clearly visible. The pulse width modulation (PWM) signal is generated by comparing a sawtooth waveform with a voltage that is adjusted by varying the resistance of the potentiometer in the circuit. This comparison results in the modulation of the pulse width, which directly influences the triggering of the Silicon-Controlled Rectifier (SCR) in the AC voltage control system. The changing pulse width is critical for controlling the effective RMS voltage supplied to the load. As the resistance value of the potentiometer is adjusted, the corresponding change in the duty cycle ensures precise regulation of the output voltage, thus allowing the system to respond dynamically to different load conditions and operational requirements.

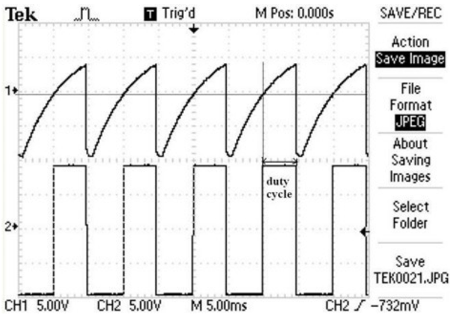

Figure 8. Duty cycle rectifier result

C. Power circuit test

Testing of the power circuit was conducted to evaluate the performance and functionality of the AC voltage controller. The key focus during testing was the impact of varying trigger angles—specifically 45˚, 60˚, 90˚, and 135˚—on the output voltage. These angles were selected because they correspond to different phases of the AC waveform, directly influencing the conduction time of the SCR and, subsequently, the output voltage. By adjusting the trigger angle, the system was able to control the effective RMS voltage supplied to the load. The maximum AC voltage from the source was limited to 12.8 Volts, ensuring the system operated within a safe and stable voltage range. The testing aimed to validate the ability of the controller to adjust the output voltage in a controlled manner, providing flexibility for various engineering applications such as motor speed control, lighting systems, and heating devices.

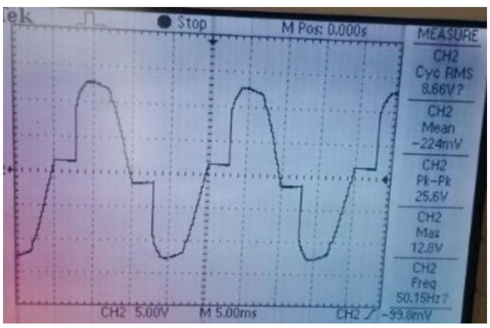

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Figure 9. Measurement result at 45º

Figure 10. Measurement result at 60º

Figure 11. Measurement result at 90º

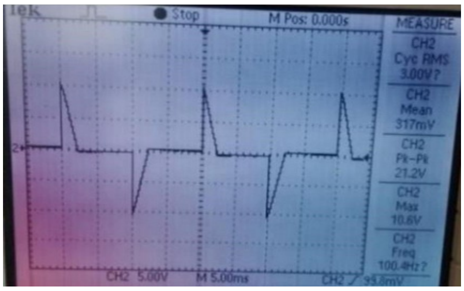

Figure 12. Measurement result at 135º

D. Systematic Analysis

Mathematical analysis was carried out at 45˚, 60˚, 90˚, and 135˚ angles using equation (1), where the maximum voltage of the AC source used was 12.8 Volts.

- VRMS for 45˚

$$V_{rms}=\sqrt{\frac{1}{T}[\int_{\sigma}^{\pi} v(t)^2.dt+\int_{\pi+a}^{2\pi} v(t)^2.dt]}$$

$$V_{rms}=\sqrt{\frac{1}{2\pi}\left[\int_{45°}^{180°}(12{,}8\sin t)^2.dt+\int_{225°}^{360°}(12{,}8\sin t)^2.dt\right]}$$

$$V_{rms}=8{,}63\,Volt$$

- VRMS for 60˚

$$V_{rms}=\sqrt{\frac{1}{T}[\int_{\sigma}^{\pi} v(t)^2.dt+\int_{\pi+a}^{2\pi} v(t)^2.dt]}$$

$$V_{rms}=\sqrt{\frac{1}{2\pi}\left[\int_{60°}^{180°}(12{,}8\sin t)^2.dt+\int_{240°}^{360°}(12{,}8\sin t)^2.dt\right]}$$

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$$V_{rms}=8{,}12\,Volt$$

- VRMS for 90˚

$$V_{rms}=\sqrt{\frac{1}{T}[\int_{\sigma}^{\pi} v(t)^2.dt+\int_{\pi+a}^{2\pi} v(t)^2.dt]}$$

$$V_{rms}=\sqrt{\frac{1}{2\pi}\left[\int_{90^\circ}^{180^\circ}(12{,}8\sin t)^2.dt+\int_{270^\circ}^{360^\circ}(12{,}8\sin t)^2.dt\right]}$$

$$V_{rms}=6{,}4\,Volt$$

- VRMS for 135˚

$$V_{rms}=\sqrt{\frac{1}{T}[\int_{\sigma}^{\pi} v(t)^2.dt+\int_{\pi+a}^{2\pi} v(t)^2.dt]}$$

$$V_{rms}=\sqrt{\frac{1}{2\pi}\left[\int_{135^\circ}^{180^\circ}(12{,}8\sin t)^2.dt+\int_{315^\circ}^{360^\circ}(12{,}8\sin t)^2.dt\right]}$$

$$V_{rms}=2{,}726\,Volt$$

E. Simulation Analysis

Simulation analysis is carried out using the PSIM program, while the output waveform can be seen in Figure 13 to 16 below.

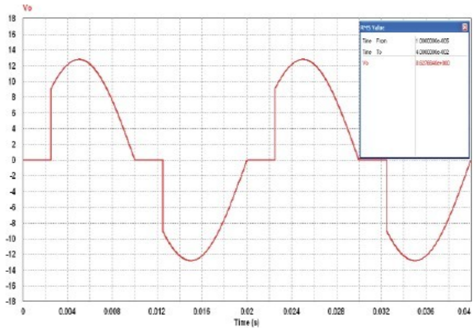

Figure 13. Measurement software result at 45º

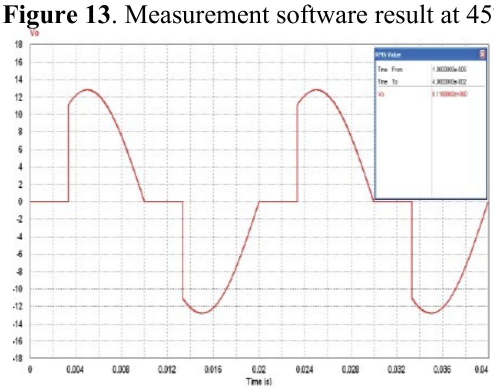

Figure 14. Measurement software result at 60º

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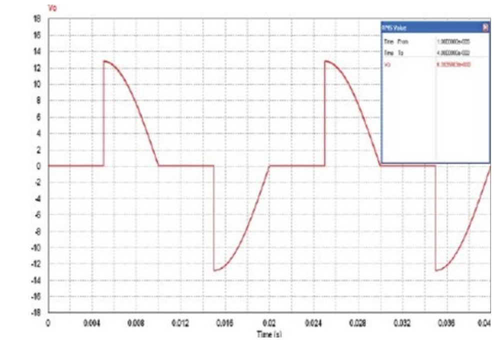

Figure 15. Measurement software result at 90º

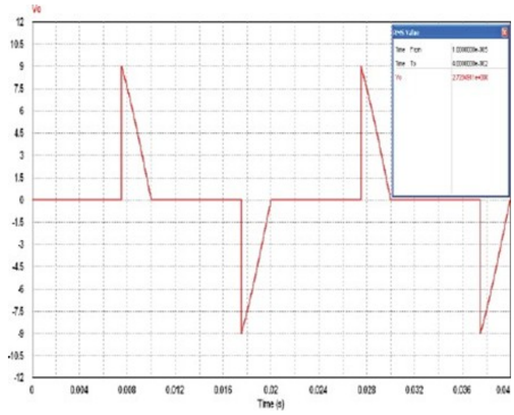

Figure 16. Measurement software result at 135º

The comparison of the root mean square (Vrms) output voltage of the controlled AC waveform, derived from measurements, simulations, and mathematical calculations, is presented in Table 2. The results indicate that the differences between the measured, simulated, and theoretical (mathematical) values are minimal, signifying a high degree of accuracy and consistency in the system's performance. The observed consistency across all three methods (measurement, simulation, and theoretical) validates the reliability of the AC voltage controller in maintaining stable output voltage across various test conditions. The measurements, conducted through a direct oscilloscope reading, showed only slight deviations, which are expected due to practical factors such as component tolerances and environmental conditions. This consistency is critical for engineering applications where precise voltage control is essential for optimal system performance.

Table 1. Conduction Table

No	Trigger Angle	Vrms Voltage Output (Volt)		
		Measurement	Simulation	Mathematics
1	45°	8,66	8,63	8,63
2	60°	8,11	8,12	8,12
3	90°	6,45	6,39	6,4
4	135°	3	2,72	2,72

4. Conclusion

The single-phase AC voltage control circuit is designed to generate an AC waveform with a fixed frequency, while allowing the output RMS voltage to vary according to the desired control angle. This ability to regulate the voltage is crucial for applications that require precise and adjustable voltage levels. The system operates by controlling the phase angle of the triggering signal applied to the SCR, thereby adjusting the time at which the AC waveform is allowed to conduct, and thus altering the average output voltage. The key advantage of this system is its simplicity and efficiency, as it provides continuous control over the output voltage without requiring complex modifications to the AC power source.

In terms of performance evaluation, the results from both measurement and simulation show minimal differences, indicating that the circuit operates as expected. The small discrepancies between the measured and simulated results can be attributed to real-world factors such as component tolerances, parasitic effects, and environmental conditions, which are not always accounted for in simulations. Nonetheless, these results underscore the reliability and accuracy of the controller, affirming its suitability for engineering applications that demand stable voltage regulation. The consistency between the two methods further validates the effectiveness

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of the control system in both theoretical and practical environments, making it a viable solution for use in various industrial and commercial systems where voltage adjustment is required.

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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