MARI

MULTIDISCIPLINARY APPLIED RESEARCH AND INNOVATION
e-ISSN: 2773-4773

Vol. 7 No. 2 (2026) 63-71
https://publisher.uthm.edu.my/periodicals/index.php/mari

AC Power Controller with a Programmable Interface

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DOI: https://doi.org/10.30880/mari.2026.07.02.009

Article Info

Received: 1 March 2026
Accepted: 1 May 2026
Available online: 30 June 2026

Keywords

AC power control, ESP32, Programmable Interface, MIT App Inventor, Smart Energy System

Abstract

This project presents the development of a programmable AC power controller to enhance energy efficiency, safety, and user convenience. The system enables precise control over AC loads by utilizing the ESP32 microcontroller, a TRIAC, an optoisolator, and a user-friendly interface comprising a keypad, LCD, potentiometer, and a mobile application. Users can adjust brightness or power output manually or remotely via the Blynk app over Wi-Fi. Integrating a firing angle control mechanism allows for effective modulation of AC power. Preliminary testing demonstrates accurate performance in regulating the brightness of a tungsten filament bulb, with the system built under a cost constraint. The results highlight the system's scalability for applications in smart homes and industrial settings. Future enhancements include IoT-based data monitoring, AI-driven optimization, and renewable energy integration.

1. Introduction

The demand for efficient power management has become increasingly important due to the rising cost of electricity and the global emphasis on sustainable energy consumption. Conventional AC power controllers typically rely on simple resistive dimmers and manual switches, which are often inefficient, generate significant energy loss in heat, and lack adaptability for modern energy-saving applications [1]. These systems do not provide users with real-time feedback or programmable control, limiting their functionality in dynamic environments such as smart homes or industrial automation [2].

Advancements in microcontroller-based control systems have addressed many of these limitations by introducing digital firing angle control for AC loads using TRIAC-based circuits. By manipulating the firing angle, it is possible to control the portion of the AC waveform that powers a load, enabling effective regulation of light intensity, motor speed, and heating elements [3]. Recent studies highlight the widespread use of microcontroller-based AC controllers in lighting control, ceiling fan speed regulation, and energy-efficient heating systems [4]. This digital approach provides greater precision, adaptability, and energy savings than conventional analogue dimmers.

Furthermore, integrating human-machine interfaces (HMI) such as keypads, LCD screens, and mobile applications significantly enhances the usability of these systems [5]. Wireless technologies like Wi-Fi and Bluetooth enable remote control through platforms such as MIT App Inventor or Blynk, aligning with the current trend toward Internet of Things (IoT) applications [6]. This shift towards more intelligent energy management systems provides users real-time monitoring, greater flexibility, and the ability to optimize energy consumption remotely.

Safety is a key factor in designing AC power controllers. High-voltage AC systems pose significant risks if proper isolation between control and load circuits is not maintained. Therefore, optoisolators, zero-cross detection circuits, and snubber networks are crucial to ensure operational safety, reduce electrical noise, and prevent false triggering [7], [8]. Studies also emphasize the need for protection mechanisms such as overcurrent detection, thermal shutdown, and electromagnetic interference (EMI) suppression to ensure long-term reliability, especially in industrial settings [9].

This project was inspired to create a fundamental open-source TRIAC-based AC dimmer design commonly found in electronics learning communities. While such designs are functional for hobbyist applications, they often lack critical safety and usability features. Therefore, this project introduces key modifications, including optoisolation using the MOC3021, robust zero-cross detection, snubber circuits for TRIAC protection, and an expanded programmable interface consisting of a keypad, potentiometer, LCD, and Wi-Fi-enabled mobile app. This enhanced AC power controller aims to offer a safer, more efficient, and user-friendly solution that is scalable for both smart home and industrial energy management applications.

2. Methodology

2.1 System Block Diagram

This study describes the methodology for developing the AC Power Controller with a programmable interface. The main objective of this methodology is to provide a detailed explanation of the project's design, including how the system operates, the hardware components used, and the modifications applied to improve performance and safety. The methodology covers several critical aspects of the project: the overall project design concept, the selection and specification of materials and components, and the circuit design incorporating zero-cross detection, TRIAC triggering, and optoisolation for safe AC load control. In addition, the methodology presents the system's operational flow through a detailed flowchart and a block diagram as shown in Fig. 1, clearly illustrating the interaction between input devices (keypad, potentiometer, and mobile app), the ESP32 microcontroller as the processing unit, and output devices such as the TRIAC module and LCD. This comprehensive approach ensures the system achieves its intended functionality of allowing manual and remote control of AC loads, emphasising energy efficiency, user convenience, and operational safety.

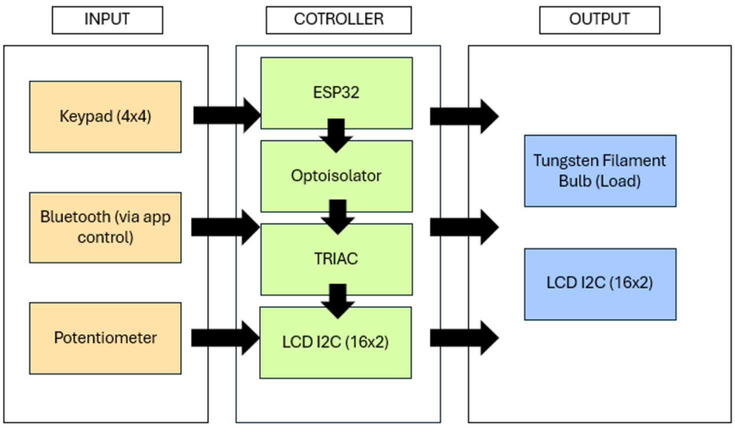

Fig. 1 *System block diagram*

The flowchart in Fig. 2 illustrates the operational process of the AC Power Controller, starting with three input methods: the keypad, the potentiometer, and the mobile application. Users can either input a specific brightness level through the keypad, adjust the brightness manually using the potentiometer, or set the desired power level remotely via the mobile app connected to the ESP32 through Wi-Fi. Once an input command is given, the ESP32 processes the data to determine the desired brightness or power level. The microcontroller then prepares to control the AC output based on this input while ensuring electrical safety through an optoisolation mechanism, which protects the low-voltage circuit from the high-voltage AC side. This step is crucial to avoid electrical hazards and ensures safe communication between the control circuit and the power-driving TRIAC.

Following the input processing and safety check, the ESP32 controls the TRIAC firing angle, regulating how much AC waveform is delivered to the connected load, typically a lamp or small appliance. At the same time, the system provides real-time feedback on the current brightness level through the LCD, keeping the user informed. The regulated AC power is then delivered to the load based on the user's setting. The system enters a loop that continuously checks whether the user wants to change the brightness or power level. If a new input is detected, the system recalculates the firing angle and updates the output accordingly. If no changes are made, the system

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maintains the current brightness level, and the load continues to operate at the set value. This flow ensures smooth, accurate, responsive control while giving users flexibility through manual and remote interfaces.

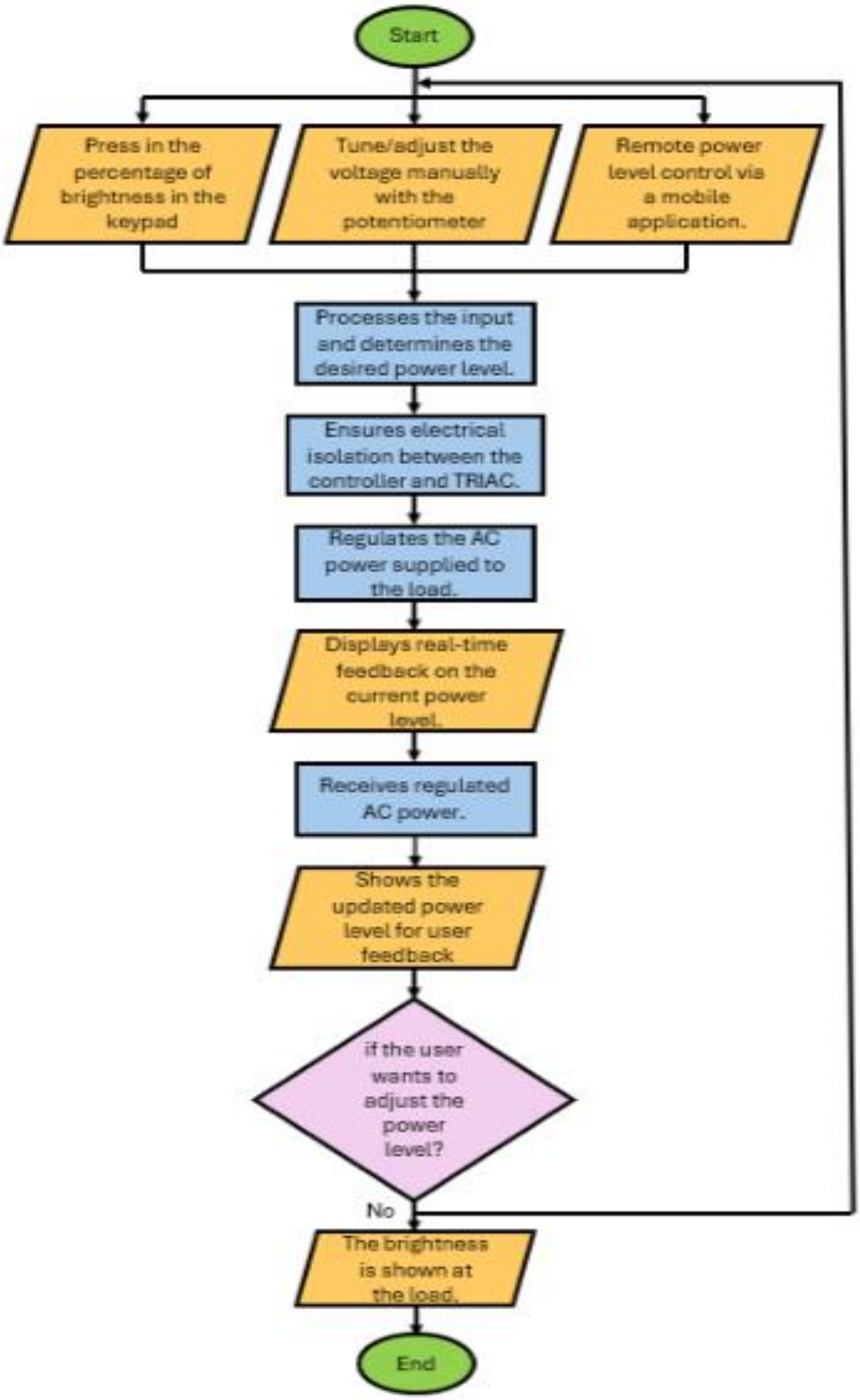


Fig. 2 *Flowchart of AC Power Controller with Programmable Interface*

2.2 Schematic Circuit

The components selected for this project were carefully chosen based on their compatibility, functionality, and ability to control AC loads safely. The central controller is the ESP32 development board. It is a powerful microcontroller featuring dual-core processing, integrated Wi-Fi, Bluetooth, multiple GPIO pins, and high processing speed, making it highly suitable for real-time control and wireless communication tasks. The AC power modulation is handled by a TRIAC (BT136), capable of switching AC loads up to 4S, allowing for effective brightness control of lighting and small household appliances. To ensure electrical isolation between the ESP32 and the high-voltage AC side, an optoisolator (MOC3021) is utilised, enabling safe gate triggering of the TRIAC without exposing the low-voltage controller to mains voltage. The zero-cross detection circuit is an essential safety and accuracy component, designed using a diode bridge, resistors, and an optocoupler such as the PC817. This circuit detects the exact moment the AC waveform crosses zero volts, allowing the ESP32 to synchronise the TRIAC firing accurately. This approach minimises electrical noise, prevents flickering, and improves the overall efficiency of the dimming process.

User inputs are managed through a 4x4 matrix keypad, allowing users to set precise brightness levels in percentage form manually. Additionally, a 10kΩ potentiometer provides an alternative analogue input method for gradual brightness adjustment. The output feedback is displayed through a 16x2 I2C LCD, providing real-time information about the current brightness level and system status. The controller is also equipped with remote access capability via a mobile application developed using the Blynk platform. It utilises the ESP32's built-in Wi-Fi to allow users to control the system wirelessly from their smartphones.

The circuit design and simulation were carried out using EasyEDA, an online-based electronic design automation (EDA) tool that supports schematic design as shown in Fig. 3 and simulation, including components such as TRIACs, optoisolators, and AC load systems. EasyEDA was selected over microcontroller-only simulators because it provides the capability to simulate AC circuits realistically, allowing for accurate validation of the TRIAC firing circuit, zero-cross detection, and optoisolation functionalities. Meanwhile, the software development for the ESP32 microcontroller was completed using the Arduino IDE environment with ESP32 board support, offering extensive libraries for keypad handling, LCD control, and Wi-Fi communication. This combination of EasyEDA for hardware validation and Arduino IDE for microcontroller programming ensured that the system was tested accurately and functioned reliably under manual and remote-control operations.

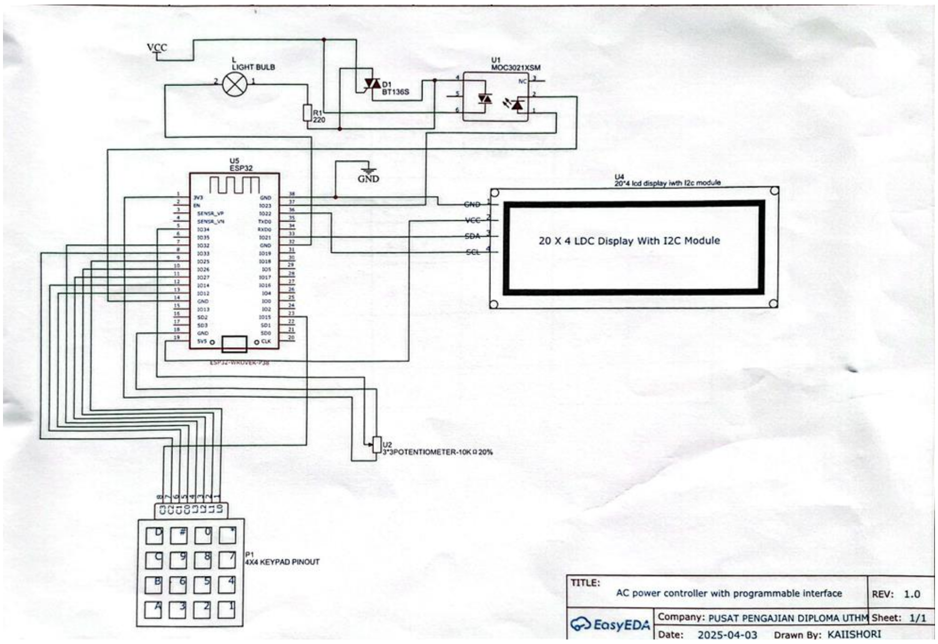


Fig. 3 *Schematic circuit diagram*

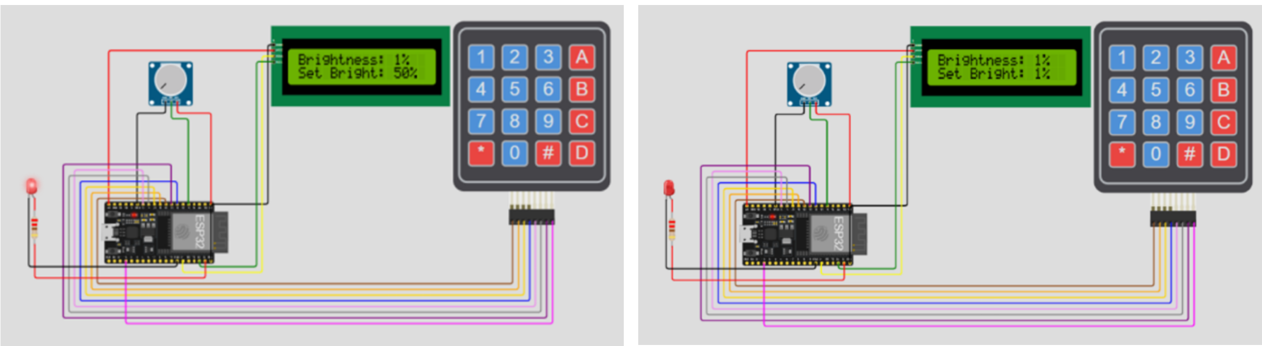
2.3 Simulation

The circuit simulation for this project was carried out using the Wokwi Simulator, a widely used platform for simulating microcontroller-based systems. The primary objective of the simulation was to verify the correct functioning of the ESP32 microcontroller logic, including reading input signals from the 4x4 keypad, interpreting analogue input from the 10kΩ potentiometer, handling Wi-Fi communication via the Blynk platform, and updating the output on the 16x2 I2C LCD. The simulation ensured that the microcontroller could accurately process input commands from both manual controls and the Blynk platform, then translate these commands into output signals that would, in physical hardware, control the TRIAC firing delay to adjust AC brightness. A simulated zero-cross detection signal was used in the Wokwi simulation as a digital pulse input, enabling the ESP32 to synchronize correctly with each AC waveform cycle for accurate firing angle calculation.

The Blynk platform was tested in two forms, namely the Blynk Mobile Application and the Blynk Authorised Web Dashboard, as shown in Fig. 6. Both platforms utilised a slider interface that allowed users to control the brightness level from 0% to 100% in real-time. The command generated from the slider adjustment was transmitted via Wi-Fi to the ESP32 microcontroller, where it was processed to compute the corresponding firing angle delay for the TRIAC. This delay determined how much of the AC waveform was delivered to the load, adjusting the brightness accordingly. Any changes made through the slider were immediately reflected on the 16x2 LCD, providing real-time feedback on the current brightness level. Although the Wokwi simulator does not support real-time Wi-Fi networking, the logic simulation confirmed that the ESP32 responded accurately to virtual slider inputs from both the mobile application and the authorised web dashboard. The results demonstrated that the ESP32 firmware effectively handled brightness control commands from both remote platforms in addition to manual input controls, ensuring reliable and consistent operation across all interfaces.

3. Results and Discussions

After completing the simulation and hardware development phases, the system underwent comprehensive testing to evaluate its performance, functionality, and reliability. This stage assessed whether the AC Power Controller with a programmable interface operated as intended under manual and remote-control conditions. The testing process aimed to verify the accuracy of brightness control as shown in Fig. 4, through the keypad, potentiometer, and Blynk platform, along with the responsiveness of the LCD feedback and the stability of the TRIAC triggering mechanism.



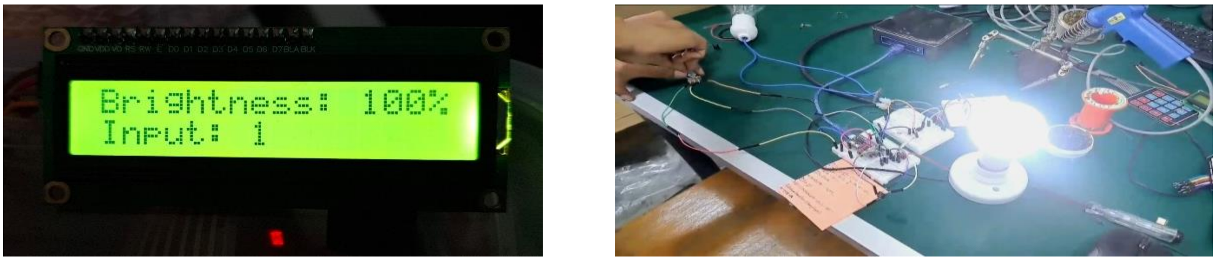
(a) **(b)**

Fig. 4 *(a) Simulation when the brightness is set to 50%; (b) Second simulation when the brightness is set to 1%*

3.1 Results

Fig. 5 (a) displays the output of the 16x2 LCD, the primary feedback interface for users during system operation. The LCD provides real-time information about the current brightness level set through the keypad, potentiometer, or Blynk slider. It shows the brightness in percentage form, making it easy for users to monitor and confirm their selected settings. During testing, the LCD consistently updated its display whenever the brightness level changed, whether through manual inputs or remote commands. This feedback mechanism is essential for ensuring users know the current output status without relying on guessing or observing the light intensity alone. Additionally, the LCD helps confirm that the ESP32 accurately processes the firing angle calculations based on user inputs, serving both as a functional display and a troubleshooting tool to verify that the control logic operates correctly.

Fig. 5(b) shows the behaviour of the LED (or lamp) output display, which visually represents the AC load's brightness level corresponding to the control inputs. The LED's intensity increases or decreases smoothly as the user adjusts the brightness using the keypad, potentiometer, or Blynk slider. This demonstrates that the TRIAC firing angle control functions properly, modulating the load's power according to the calculated delay after each zero-cross event. The LED display is crucial for visually validating that the hardware responds accurately to the control signals. During testing, the LED brightness changes were immediate and proportional to the values set by the user, confirming that the ESP32's output signals correctly influenced the TRIAC gate. This physical indicator complements the LCD by providing a real-time visual cue of system performance and successful dimming operation.

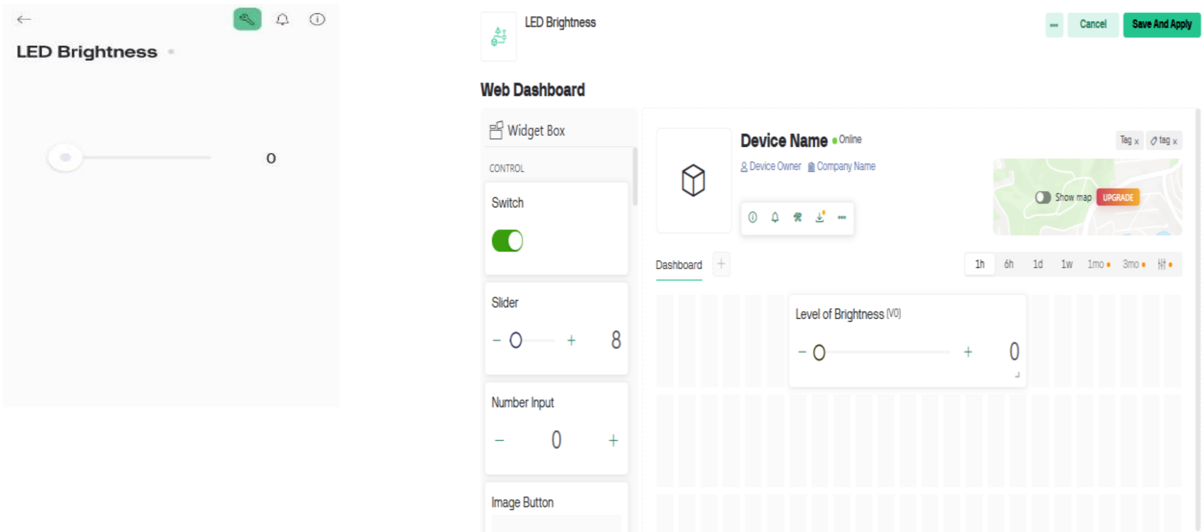


(a) **(b)**

Fig. 5 *(a) LCD output display; (b) LED display*

Fig. 6 (a) shows the interface of the Blynk Mobile Application, which features a smooth slider control that allows users to adjust the brightness level of the AC load in real time. The slider ranges from 0% to 100%, giving users full control over how much power is delivered to the load. When the user adjusts the slider on the app, the command is transmitted via Wi-Fi to the ESP32 microcontroller, which processes the input and calculates the corresponding firing angle delay for the TRIAC. This adjustment directly controls how much of the AC waveform is allowed through to the load, effectively modulating the brightness. Any changes made on the mobile app are instantly reflected on the 16x2 LCD display, providing real-time feedback about the current brightness level. This mobile app interface enhances user convenience by enabling remote control of the load without needing to interact directly with the physical hardware.

Fig. 6 (b) displays the Blynk Authorised Web Dashboard, which mirrors the functionality of the mobile app but operates through a web browser interface on desktops or laptops. Like the mobile version, the web dashboard also includes a slider that allows precise control of the brightness percentage in real time. Adjusting the slider on the website sends the corresponding brightness value to the ESP32 over Wi-Fi, which then computes the necessary TRIAC firing delay based on the input. The updated brightness value is immediately displayed on the 16x2 LCD, ensuring that users can verify their adjustments visually. This web-based interface is particularly useful for users who prefer managing their devices from a computer rather than a smartphone. The successful operation of both the mobile and web-based Blynk platforms during simulation confirms that the system's remote-control logic is reliable, consistent, and integrates seamlessly with manual controls such as the keypad and potentiometer.



(a) **(b)**

Fig. 6 *(a) Interface of the Blynk Mobile Application; (b) displays the Blynk Authorised Web Dashboard*

Table 1 in Appendix A presents the relationship between the AC power controller system's firing angle, output voltage, and brightness levels under different input methods, including the keypad, potentiometer, and Blynk mobile app. Table 1 compares the theoretical output voltage with the actual lab-tested output voltage displayed on the LCD and the corresponding brightness levels measured on the bulb in lumens for both filament and LED loads. Table 1 also highlights how changes in the firing angle directly affect the power delivered to the load, which influences the output voltage and the brightness level of the connected lamp. It demonstrates the system's effectiveness in accurately modulating brightness based on user inputs from manual and remote controls. The recorded values verify the correct functioning of the TRIAC-based firing angle control system, confirming that the ESP32 microcontroller processes inputs correctly and delivers consistent output responses across different dimming levels. Additionally, the remarks section provides a qualitative description of the brightness condition, ranging from "Full Bright" to "Off", corresponding to the measured lumens and voltage at each firing angle setting.

Fig. 7 illustrates the relationship between the firing angle and the output voltage and brightness level of the AC power controller system. It visually represents how increasing the firing angle gradually reduces the output voltage supplied to the load and consequently lowers the brightness of the connected bulb. Fig. 7 is generated based on theoretical calculations and lab-tested data collected during the experiment. It clarifies how the TRIAC-based dimming control functions in response to different input methods, including the keypad, potentiometer, and Blynk App. Observing the trends of the graph in Fig. 7 makes it evident how effective the firing angle adjustment is in regulating brightness, demonstrating the accuracy and consistency of the ESP32-controlled system. Fig. 7 supports the data presented in Table 1 and offers an immediate visual interpretation of the relationship between input control settings and output performance.

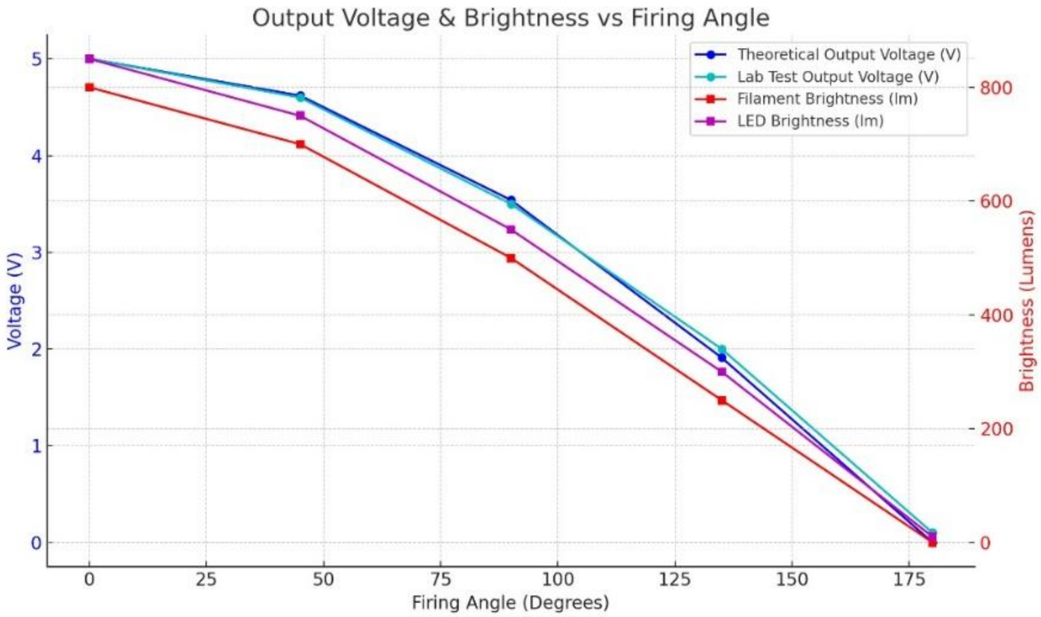


Fig. 7 *Relationship between Firing Angle, Output Voltage and Brightness Level of the AC Power Controller graph*

3.2 Discussion

Based on the results obtained from both the simulation and hardware testing, the project demonstrated a high level of accuracy in controlling the brightness of the AC load through firing angle modulation. The comparison between the theoretical output voltage and the lab-tested output voltage displayed on the LCD showed minimal discrepancies within an acceptable margin of error for TRIAC-based dimming circuits. The brightness levels measured in lumens for filament and LED bulbs closely matched the expected output relative to the firing angle. This indicates that the ESP32 microcontroller accurately computed the firing angle delays based on user inputs from the keypad, potentiometer, and Blynk app slider and effectively controlled the TRIAC to modulate power delivery to the load. The consistency between the data displayed on the LCD and the actual brightness output further confirms the system's reliability.

Overall, the project process ran smoothly, with the system responding accurately to manual and remote commands in real-time. The zero-cross detection circuit functioned correctly, ensuring that the TRIAC firing was synchronized with the AC waveform, which is crucial for stable dimming without flickering. Additionally, integrating the Blynk mobile app and web dashboard allowed seamless remote control, which performed as expected during testing. While minor fluctuations were observed at very low voltage levels, particularly with LED loads, this behaviour is typical due to the differences in how LEDs handle low currents compared to filament bulbs. No significant delays, failures, or malfunctions were detected during the testing phases, indicating that the hardware design and software programming were implemented effectively. These findings confirm that the project achieved its intended objectives, delivering a reliable, safe, and user-friendly AC power controller with programmable and remote-control features.

4. Conclusion

In this project, it can be concluded that the efforts to design and develop an AC Power Controller with a Programmable Interface successfully met the project's objectives. The system effectively addressed the problem stated in the problem statement: the inefficiency and lack of flexibility in traditional AC dimmers. The system enabled precise, real-time brightness control by implementing firing angle control using an ESP32 microcontroller, along with zero-cross detection, TRIAC triggering, and versatile input options such as the keypad, potentiometer, and Blynk app. The output was displayed on the 16x2 LCD, providing feedback on the brightness level, and the dimming function worked accurately for both filament and LED bulbs. The project demonstrated that it could solve the identified problem by providing a safer, programmable, and more efficient AC dimmer solution.

Despite the success, several improvements can be made to enhance the functionality and reliability of the project. A key hardware issue encountered during testing involved the soldering of the output bulb wire, where a DC wire was mistakenly used instead of a proper AC-rated wire. This error resulted in unstable output where the bulb would flash intermittently or fail to operate correctly, as the DC wire was not designed to handle AC load, leading to signal inconsistency. This highlights the importance of using correct AC-rated wiring for output connections in AC circuits to ensure safety and functional reliability. Future improvements include adding real-time current and power monitoring, expanding the system to handle multiple output channels, and incorporating advanced features such as voice control, scheduling, and cloud integration. In conclusion, the project has successfully achieved its intended goals, solved the identified problem, and provided a strong foundation for further development into a more robust and fully featured smart AC power controller.

Acknowledgement

The authors would like to thank the Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia for its support.

Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Kaiishori Balamurugan, Ziana Che Ros;* ***data collection:*** *Kaiishori Balamurugan;* ***analysis and interpretation of results:*** *Kaiishori Balamurugan, Ziana Che Ros;* ***draft manuscript preparation:*** *Kaiishori Balamurugan. All authors reviewed the results and approved the final version of the manuscript.*

Appendix A

Table 1 *System testing results*

Voltage (Input)	Firing Angle (Degrees)			Theoretical Output Voltage (V)	Lab Test Output Voltage on LCD (V)	Lab Test Output Voltage on Bulb (Lumens)		Remarks	
	Keypad	Potentiometer	Mobile App			Filament	LED	Filament	LED
230V	0° (0%)	0° (0%)	0° (0%)	5.00V	5.00V	800 lm	850 lm	Full Bright	Full Bright
	45° (25%)	45° (25%)	45° (25%)	4.62V	4.60V	700 lm	750 lm	Bright	Bright
	90° (50%)	90° (50%)	90° (50%)	3.54V	3.50V	500 lm	550 lm	Medium	Medium
	135° (75%)	135° (75%)	135° (75%)	1.91V	2.00V	250 lm	300 lm	Dim	Dim
	180° (100%)	180° (100%)	180° (100%)	0.00V	0.10V	0 lm	10 lm	Off	Off

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