Developing an ESP32-Based VAR Comp ensator Board for Practical Modules: Enhancing Power Stability Education through Innovative Implementation

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Abstract. This research presents the design and implementation of an ESP32-based Var Compensator Board for use as a practicum module in power stability education. The board aims to provide a cost-effective, efficient, and user-friendly tool for understanding and analyzing power stability in electrical systems. Utilizing the robust processing capabilities and wireless communication features of the ESP32 microcontroller, the board simulates various power stability scenarios by adjusting reactive power (Var) compensation in real-time. Extensive testing has demonstrated the board^s accuracy and reliability, with interactive features such as real-time data monitoring and wireless control enhancing the practical learning experience. Additionally, the board is designed to be easily modifiable, allowing for customization and further development to suit specific electrical system needs. This innovative module bridges the gap between theoretical knowledge and practical application, preparing students for industry challenges and contributing to the advancement of electrical engineering education. The efficiency of Var compensation has been tested across varying load conditions, demonstrating its effectiveness in maintaining power stability.

Keywords: Capacitor Bank, ESP32, Power Factor Control, Practical Module, Reactive Power Compensation.

1 Introduction

In the field of Electrical Engineering education, particularly in the context of power systems and stability, the availability of practical modules that effectively simulate real-world scenarios is crucial. Practical modules not only bridge the gap between theoretical knowledge and real-world application but also enhance the hands-on learning experience of students. However, despite the rapid advancements in technology and the increasing complexity of power systems, there remains a significant gap in the availability of programmable, reconfigurable, and data-driven practical modules, especially in the area of power stability control.

ICIESC 2024, September 17, Medan, Indonesia

DOI 10.4108/eai.17-9-2024.2353112

Several studies have emphasized the importance of integrating modern technology into engineering education to enhance student learning outcomes. For instance, Oliva et al. [1] highlight that hands-on laboratory experiences are crucial for students to understand complex power systems, yet many existing labs rely on outdated or rigid equipment that limits the scope of experimentation. Similarly, Ma et al. [2] emphasize the need for flexible and programmable modules that allow students to engage with evolving technologies, particularly in power systems where dynamic stability is a key concern. These studies underline the need for practical modules that not only simulate real-world conditions but also provide opportunities for reprogramming and data collection to deepen students' understanding.

At the Department of Electrical Engineering, Universitas Negeri Medan, the existing practical modules for power stability are limited in their ability to adapt to evolving educational needs. Current modules often lack the flexibility for reprogramming and do not have the capability to capture and utilize data for further analysis or system improvements. This limitation not only restricts the scope of practical experiments but also hinders the ability to develop more advanced educational tools that can cater to the dynamic nature of power systems. Moreover, final-year students are often accustomed to working with limited data sets for their research due to the manual data collection processes involved. This constraint often results in inadequate data that does not meet statistical requirements for thorough analysis and robust conclusions. García-Sánchez et al. [3] stress the importance of data-driven approaches in modern engineering labs, where the collection and analysis of data from practical experiments can lead to continuous improvements in educational content and methodology.

The absence of such advanced modules presents a critical gap in the body of knowledge and resources available to students and educators. A programmable and data-capable Var compensator board could address this gap by offering a versatile platform for practical experimentation. This platform would enable students to engage with complex scenarios in power stability, allowing them to reprogram the board for various conditions and to collect data that can be used for both immediate educational feedback and long-term development. With this module, students would also be able to gather sufficient data in accordance with statistical guidelines, thereby enhancing the quality of their research and the validity of their conclusions. Wang et al. [4] suggest that the use of Internet of Things (IoT)-based devices, such as ESP32, in educational modules enhances the interactivity and flexibility of experiments, providing students with a more immersive learning experience.

The development and implementation of an ESP32-based Var compensator board for power stability education represent a significant step towards modernizing the curriculum. By introducing a module that is both programmable and capable of data logging, this research aims to provide a more robust educational tool that can adapt to future advancements in power systems. Furthermore, the ability to analyze collected data opens opportunities for continuous improvement of the practical modules, ensuring that they remain relevant and effective as educational resources. The significance of this research lies in its potential to transform the way power stability is taught, providing students with a deeper understanding of the complexities involved in maintaining stability in power systems. Additionally, it offers a framework for continuous innovation in educational tools, which can be adapted and improved over time to meet the ever-changing demands of the industry. The integration of modern technology, such as ESP32 microcontrollers, aligns with the growing emphasis on digital transformation in educational methods, as noted by Liang et al. [5].

2 Literature Review

2.1. Basic Concepts of VAR in Power Systems

The concept of Volt-Ampere Reactive (VAR) is fundamental to understanding power systems, particularly in the context of alternating current (AC) networks. VAR represents the reactive power in a system, which is the portion of electricity that does not perform any actual work but is necessary for maintaining the voltage levels required to deliver active power (measured in watts). Reactive power arises from the presence of inductance and capacitance in the system, and it plays a critical role in ensuring the stability and efficiency of power transmission.

VAR is crucial for maintaining voltage stability in power systems. Insufficient reactive power can lead to voltage instability, potentially causing system collapse or inefficient power distribution. On the other hand, excessive reactive power can cause voltage levels to rise above desired limits, leading to energy losses and equipment damage. Therefore, effective management of VAR is essential for optimizing power stability and energy efficiency in electrical networks [6].

2.2. The Role of VAR Compensators in Power Systems

VAR compensators are devices used to manage reactive power in power systems, thereby improving voltage stability and reducing power losses. The technology behind VAR compensators has evolved significantly, with modern systems incorporating sophisticated controls and automation. There are different types of VAR compensators, including Static VAR Compensators (SVCs) and Static Synchronous Compensators (STATCOMs), each with its specific applications and benefits.

The primary function of a VAR compensator is to inject or absorb reactive power as needed to maintain voltage levels within the desired range. This capability is critical in preventing voltage instability and ensuring that the power system operates efficiently. The benefits of VAR compensators include enhanced power stability, reduced transmission losses, and improved power quality, which are vital for both industrial and commercial power consumers [7].

2.3. Utilization of ESP32 in Power System

ESP32 is a low-cost, low-power system-on-chip microcontroller with integrated Wi-Fi and Bluetooth capabilities, making it a versatile tool for control applications in power systems. Its rich set of features, including multiple GPIO pins, ADCs, DACs, and PWM outputs, allows for a wide range of applications in power control and monitoring.

In power system projects, ESP32 has been utilized for various control applications, including remote monitoring, smart grid implementations, and automation of power distribution systems. Its ability to connect to the internet enables real-time data collection and control, making it an excellent choice for modern power system applications where connectivity and data processing are crucial [8].

2.4. ESP32-Based Development Board for VAR Compensation

The development of an ESP32-based development board for VAR compensation involves designing hardware that integrates the necessary components to manage reactive power effectively. The ESP32 serves as the central processing unit, controlling the VAR compensator through its digital and analog interfaces.

The hardware design includes integrating sensors for voltage and current measurement, as well as components like capacitors or inductors that are used in the compensation process. The system architecture is designed to be modular and scalable, allowing for easy upgrades and adaptations to different power systems. The development board also includes software components for monitoring and controlling the VAR compensator, providing a comprehensive solution for managing reactive power [9].

2.5. Teaching Power Stability through Practical Modules Based on ESP32

Teaching power stability concepts using practical modules is essential for providing students with hands-on experience that bridges the gap between theory and practice. ESP32-based modules offer a flexible and interactive platform for such education, allowing students to engage directly with the hardware and software involved in power system control.

These modules can simulate real-world scenarios in power stability, such as voltage regulation and reactive power management. By using ESP32, students can learn to program and control the compensator, collect data, and analyze the impact of different control strategies on power stability. This approach not only enhances their understanding of power systems but also equips them with practical skills in microcontroller programming and system integration [10].

3 Research Methodology

This study aims to develop and test an ESP32-based VAR (Voltage-Ampere Reactive) compensator board to be used as a practical module in power stability education. The research methodology will consist of the following stages:

Development of the ESP32-Based VAR Compensator Board. The initial stage involves designing and constructing the ESP32-based VAR compensator board. The board is designed to detect and compensate for reactive voltage (VAR) in electrical systems. The hardware design includes integrating current and voltage sensors, along with supporting components such as an OLED display and relays to control power compensation. In addition, ESP32-based software will be developed to automatically control the system.

Testing Reprogrammability. Reprogrammability is an essential aspect of this module. Therefore, the module will be tested to ensure that its embedded software can be updated or modified easily. This will involve replacing the installed power compensation algorithm and evaluating how the system responds to changes in real-time.

Testing the Module's Response to Power Factor Changes. To ensure the module's effectiveness, the study will also test the system's response to power factor changes. The power factor will be varied by adding inductive or capacitive loads to the system. The module is expected to detect these changes and automatically compensate for VAR to stabilize the power factor at the desired level. The system’s response will be analyzed based on its speed and accuracy in restoring the power factor stability.

4 Result and Discussion

4.1. Result

This research will develop a power stability practical module that can be repeatedly programmed according to learning needs. The module design is shown in Figure 1, with the main components consisting of an ESP32, capacitor bank, current and voltage sensors, a TRIAC for controlling reactive power output, and a display device in the form of an OLED LCD.

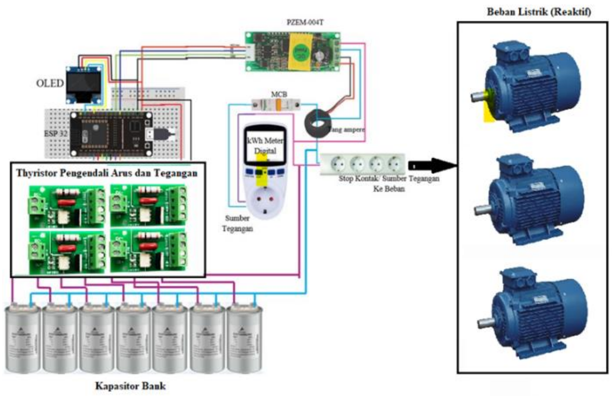


Fig. 1. Module Design.

Based on the final design in Figure 1, the first stage involves planning and preparing the required components. Key components such as the ESP32, capacitor bank, current and voltage sensors, TRIAC, and OLED display are selected according to the agreed design specifications. Once the components are obtained, they are assembled according to the circuit diagram. This process includes connecting the components onto the circuit board and testing the connections to ensure proper functionality. The ESP32 microcontroller is then programmed for a trial run to manage the module's functions, including reading sensor data, controlling reactive power output through the TRIAC, and displaying information on the OLED screen. The results can be seen in Figure 2.

Fig. 2. Final results of module development.

After assembly, the module undergoes thorough testing to ensure all components function correctly, particularly its programmability and response to changes in reactive power under load. If discrepancies are found, calibration is performed, especially in the sensor readings and power control through the TRIAC. The control technique used in this testing is Proportional (P) control, as shown in Fig. 3. The control action is proportional to the error, which is the difference between the desired value and the actual value, based on the comparison between the proportional control action (Kp) and the error signal (e(t)). This comparison process can be represented by Equation 1.

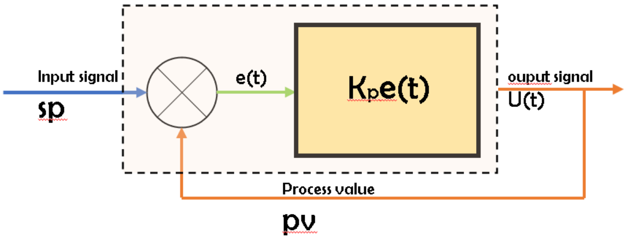


Fig. 3. Propotional control method .

$$U(t) = Kp.e(t) \quad (1)$$

where:

$$e(t) = sp - pv$$

The results of the programming test are then demonstrated based on the module's response in adjusting reactive power compensation to the reactive power required by the load. The improvement will be observed based on the power factor value achieved with a set point of 0.9. The results are shown in Chart 1.

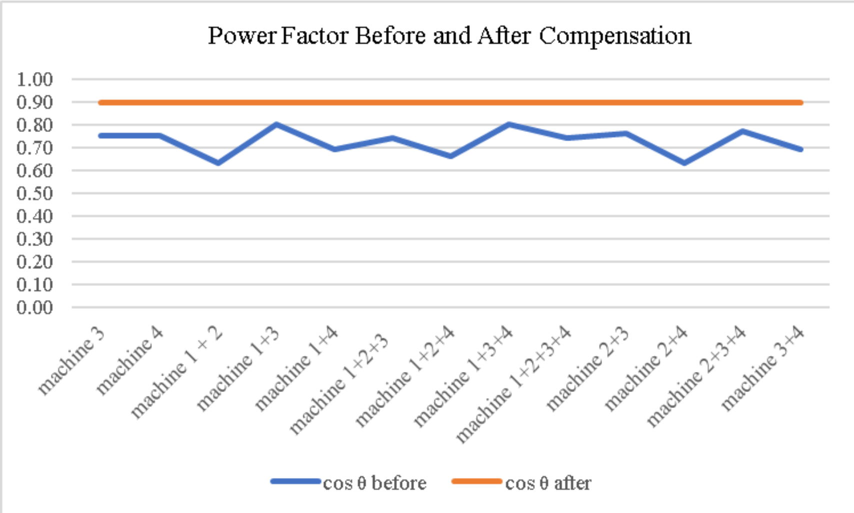
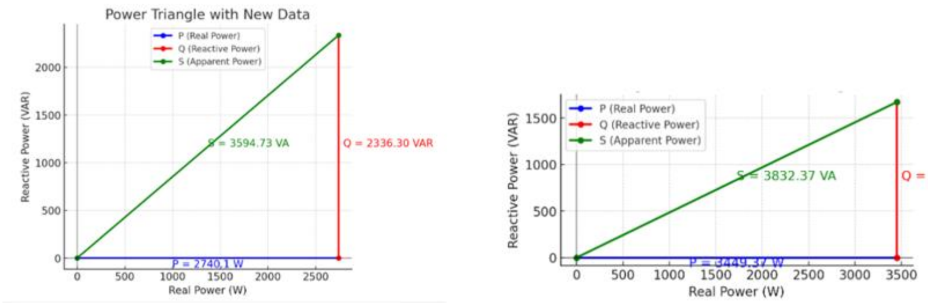


Chart 1. Comparison of Power Factor Before and After Being Controlled by the VAR Compensator Module.

Based on the improvement in the power factor shown in Chart 1, Figures 4 (a) dan (b) also illustrate the comparison between apparent power, active power, and reactive power before and after reactive power compensation is applied.



(a) before compensation (b) after compensation

Fig.4. Comparison of Power Factor Before and After Being Controlled by the VAR Compensator Module.

Meanwhile, the validation results of the device were obtained by involving 50 respondents, namely students who were taking the electrical circuits laboratory course. The validation results from the respondents can be seen in Table 1.

Table 1. The validation results of the VAR module by 50 respondents.

Question Items	Corrected item-total correlation	Question Items	Corrected item-total correlation
Ease of installation	0.612	Learning flexibility	0.701

User interface clarity	0.745	Instructor support	0.685
Power factor accuracy	0.81	Practical Usefulness	0.53
Respone Time	0.678	System Stability	0.722
Material Quality	0.49	Overall Recommendation	0.659

(source: research result, 2024*)*

4.2. Discussion

Based on the results shown in Chart 1 and the accompanying table, it is clear that the VAR compensator module not only meets the target of improving the power factor to 0.9 but does so consistently across different load combinations. The chart likely illustrates the improvement in power factor values visually, emphasizing the significant reduction in reactive power after compensation. For instance, the initial low power factor values, such as 0.63 for the combination of machine 1 and machine 2, are raised to the optimal 0.9, as also seen in the data.

The improvement reflected in both the chart and table reinforces the effectiveness of the compensator in stabilizing the system. This leads to more efficient energy use, as less reactive power is circulating in the network. Furthermore, this uniform improvement across various machine combinations demonstrates the flexibility and reliability of the module in different operational scenarios, ensuring that the system can maintain a high power factor regardless of the specific loads being handled.

In Figure 4(a), before the reactive power compensation module was implemented, the system exhibited a large difference between the apparent power (S) and the real power (P) due to the significant reactive power (Q) present, measured at 2336.30 VAR. This high reactive power led to a less efficient system, where a larger portion of the supplied power was not converted into useful work. This inefficiency, as previously discussed by researchers such as [11], is commonly observed in systems with inductive loads, such as industrial motors or variable-speed drives, which increase reactive power and subsequently electrical losses.

Following the implementation of the VAR compensation module, as seen in Figure 4(b), reactive power decreased to 1670.00 VAR. This reduction not only minimized the difference between apparent and real power but also reduced the phase angle, improving system efficiency. Studies, including those by [12], have shown that reducing reactive power through compensation techniques, such as the use of capacitor banks or PV inverters, can lead to significant improvements in power factor, lower energy losses, and enhanced system stability.

The validation results of the VAR module, as outlined in Table 1, were gathered from 50 respondents, specifically students participating in an Electrical Circuit lab. The table presents the corrected item-total correlation for various aspects of the module's performance, indicating how well each item aligns with the overall evaluation. This approach is consistent with prior research methodologies used to assess educational tools in technical settings, such as the work by [13].

From a technical perspective, **Power Factor Accuracy** achieved the highest correlation score of 0.81, suggesting that this feature was perceived as highly accurate by the respondents. This finding aligns with similar studies where accuracy of power factor control was identified as a key indicator of the system's effectiveness [14]. Additionally, **User Interface Clarity** scored

0.745, reinforcing the importance of a user-friendly interface in technical modules, as highlighted by previous research on user-centered design [15]. Other aspects, such as **Ease of Installation** and **Response Time**, also performed well, with scores of 0.612 and 0.678, respectively. These results suggest that the module is both easy to use and responsive in practice, aligning with prior research emphasizing ease of use as a critical factor in educational technology adoption [16]. However, **Material Quality** received the lowest score of 0.49, indicating a need for improvement in the physical construction of the module, a concern commonly raised in studies focusing on the durability of lab equipment [17].

From an educational perspective, **Learning Flexibility** was highly rated with a correlation of 0.701, indicating that the module offers adaptable learning opportunities, which has been emphasized in previous studies on flexible learning environments [18]. System Stability was another strong performer with a score of 0.722, underscoring the module's reliability in various practical scenarios. Meanwhile, **Instructor Support** (0.685) and **Overall Recommendation** (0.659) further validated the module's usability, consistent with findings from research highlighting the importance of teacher support in technical learning environments [19]. However, **Practical Usefulness**, with a score of 0.53, suggests there is room for improvement in making the module more effective in hands-on learning contexts, as echoed in studies advocating for better integration of theory and practice in technical education [20].

These validation results offer a comprehensive view of the module's strengths and areas for improvement, aligning with established research while providing actionable insights for future development..

5 Conclusion

This research successfully designed a VAR compensation module based on the ESP32 microcontroller. The resulting module meets the expected performance, allowing for programmable power factor correction, even though it currently utilizes a Proportional control technique. The results demonstrate the module's ability to compensate for reactive power through the available capacitor bank, despite varying operational loads. However, further investigation is needed to assess whether other control techniques can maintain the same performance. Additionally, response time for power factor correction under reactive power increases should be measured. Given that the ESP32 includes Wi-Fi functionality, future development should focus on integrating wireless data transmission for improved data collection capabilities.

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