Optimization of IoT-based monitoring system for automatic power factor correction using PZEM-004T sensor

Maman Somantri[1], Mochamad Rizal Fauzan[1], Irgi Surya[2]
[1]Electrical Engineering Education, Faculty of Engineering and Industrial Education, Universitas Pendidikan Indonesia, Bandung, Indonesia
[2]Department of Electrical Engineering, College of Electrical Engineering and Computer Science, National Taipei University of Technology, Taipei, Taiwan

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ABSTRACT

Power factor correction (PFC) is crucial for improving energy efficiency and reducing excessive power consumption, especially in inductive loads commonly found in household and industrial environments. Conventional PFC methods often rely on manual capacitor switching, which is inefficient and impractical for real-time applications. This study proposes an IoT-based automatic power factor monitoring and correction system that dynamically adjusts the power factor using real-time data analysis. The system integrates NodeMCU ESP32 and the PZEM-004T sensor to monitor electrical parameters and automatically switch capacitors based on power factor conditions. The research follows the ADDIE approach (analysis, design, development, implementation, evaluation) to ensure a structured development process. Experimental results demonstrate an average power factor improvement of 48.77% and a reduction in current consumption by 39.90%, significantly enhancing energy efficiency. The system's web-based interface allows real-time monitoring with an average data transmission response time of 207.67 ms, ensuring efficient remote management. Compared to existing systems, the proposed approach eliminates manual intervention and optimizes PFC adaptively. Future research should focus on expanding system reliability, testing on larger-scale applications, and integrating artificial intelligence (AI) for predictive power factor adjustments.

Corresponding Author:

Irgi Surya
Department of Electrical Engineering, College of Electrical Engineering and Computer Science
National Taipei University of Technology
Taipei, Taiwan
Email: irgi.surya88@gmail.com

1. INTRODUCTION

Power factor issues are a major challenge in electrical energy management, particularly for household and industrial devices that operate with high inductive loads such as refrigerators, air conditioners, and electric motors. A low power factor leads to increased electricity consumption, higher operational costs, and inefficiencies in power distribution, affecting not only individual consumers but also the overall electrical grid [1]. Ideally, a good power factor falls between 0.85 and 1, indicating that most of the power used is active power with minimal reactive power losses [2]. However, many household devices still suffer from low power factor conditions, leading to unnecessary energy waste and rising electricity costs [3]. Beyond individual households, low power factor contributes to higher peak demand on the electrical grid, forcing power companies to overcompensate with additional generation capacity, which increases overall energy production costs [4], [5]. Thus, improving power factor is not only crucial for reducing household electricity bills but also essential for enhancing energy sustainability at a larger scale.

Despite advancements in internet of things (IoT) technology, many power factor correction (PFC) systems still rely on manual or semi-automated methods, such as controlled capacitor banks, which require human intervention for adjustment [6], [7]. IoT has the potential to provide real-time monitoring and control, allowing power factor to be corrected autonomously without human input [8]. However, many existing IoT-based PFC systems are still limited to data visualization and monitoring rather than real-time adaptive correction, leaving a significant gap in fully automated power factor optimization [9]. Some studies have proposed semi-automated capacitor switching systems, but these still require user-triggered actions, reducing their efficiency and practicality in dynamic household environments where loads fluctuate continuously [10]. Thus, a fully automated IoT-driven approach is necessary to enhance PFC by dynamically adjusting capacitors in response to real-time electrical load variations.

To address these challenges, this research proposes an IoT-based automatic PFC system that not only monitors but also dynamically improves power factor in real time. The system integrates NodeMCU ESP32 and the PZEM-004T sensor, enabling continuous measurement of voltage, current, power, and power factor, while automatically switching capacitors to maintain an optimal power factor above 0.85 [11], [12]. Unlike previous studies that still require manual or semi-automated control, the proposed system operates independently, minimizing human intervention while ensuring an efficient response to changing electrical load conditions [13]. The PZEM-004T sensor is selected due to its high accuracy and ease of integration with IoT platforms, making it a suitable choice for an automatic correction system. With a web-based monitoring interface, users can track real-time power factor values, receive alerts about inefficient power usage, and let the system automatically adjust the capacitor switching without manual operation. The objective of this research is to develop and implement an IoT-based automatic power factor monitoring and correction system, demonstrating its ability to reduce electricity costs and improve energy efficiency. This research contributes by (1) designing and developing a fully automated IoT-based PFC system, eliminating the need for manual capacitor switching; (2) integrating real-time monitoring with adaptive capacitor switching to dynamically maintain an optimal power factor; and (3) evaluating the system's effectiveness across different inductive loads, providing a comparative analysis with conventional correction methods. The remainder of this paper is structured as follows: Section 2 describes the research methodology, including system architecture, hardware, and software design. Section 3 presents experimental results on power factor improvements, current reduction, and system responsiveness. Section 4 discusses key findings, limitations, and comparative analysis. Finally, section 5 concludes the study and outlines future research directions.

2. METHOD

2.1. Research design

This research adopts the ADDIE approach (analysis, design, development, implementation, and evaluation) in developing an IoT-based power factor improvement monitoring system. The ADDIE model provides a structured framework for designing and developing technology-based products, ensuring that each phase of the process is systematically addressed [14], [15]. As illustrated in Figure 1, the research begins with the analysis phase, where a literature review is conducted to identify existing issues in PFC and determine the problem formulation. The design phase involves the development of system architecture and tool design, specifying hardware and software components. In this stage, the selection of appropriate materials is carried out to ensure the feasibility of the prototype [16].

The development phase includes the hardware prototyping process, where the system is tested incrementally, starting with one relay and expanding to four relays, alongside the development of the user interface software. The implementation phase consists of functional testing and limited trials on electrical loads to validate system performance, ensuring that the web integration system operates in real-time. Finally, the evaluation phase analyzes system performance based on experimental results, comparing the obtained data with expected performance standards [17], [18]. The findings are used to assess the effectiveness of the IoT-based PFC system and provide recommendations for future improvements. This structured methodology ensures that the developed system is scalable, reproducible, and capable of optimizing PFC efficiency.

2.2. Review findings

The review of previous research highlights two relevant studies in the field of IoT-based PFC. The first study, introduced an energy monitoring prototype for IoT-based PFC, demonstrating its potential for remote monitoring. However, despite the ability to track power factor changes, the system still relied on manual control for adjustments [19]. The second study, explored new methodologies to enhance power factor in home appliances. Despite the improvements introduced, this study did not incorporate real-time IoT-based control for adaptive PFC [20]. Both studies demonstrated the role of IoT in PFC but remained limited in automation, indicating the need for a fully autonomous PFC system that can dynamically adjust capacitor switching without human intervention.

To further investigate research trends in IoT-based PFC, a bibliometric analysis was conducted using 4,357 database records, as illustrated in Figure 2. The analysis identified 14,225 author keywords, but only 90 keywords appeared at least 15 times. These keywords were classified into five main research clusters, where red represents Cluster 1, green represents Cluster 2, blue represents Cluster 3, yellow represents Cluster 4, and purple represents Cluster 5. The connections between keywords illustrate their relationships, while the node size reflects their frequency in existing studies. The bibliometric analysis revealed that very few studies have explored the integration of MQTT with PFC systems, and no prior research has combined MQTT with the PZEM-004T sensor and PHP-MySQL as a real-time backend server. This gap in the literature emphasizes the novelty of the proposed system, which integrates IoT-based monitoring and automated capacitor switching to optimize power factor dynamically [21].

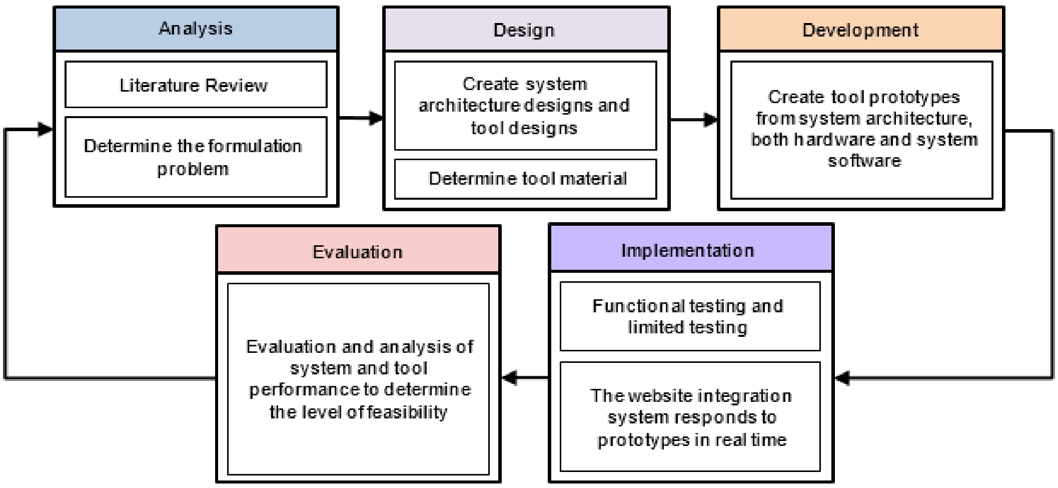

Figure 1. Research methods

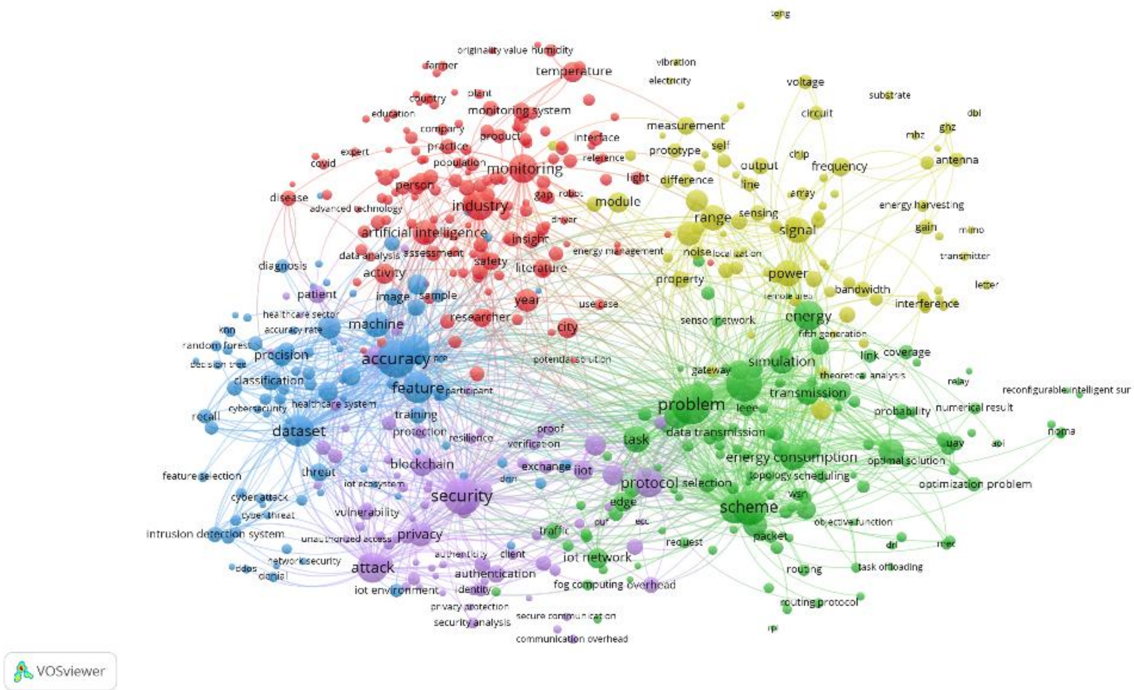

Figure 2. Analysis bibliometrix

2.3. Architecture and block diagram system

The architecture of the IoT-based PFC system is designed to enable real-time monitoring and automatic capacitor switching for optimizing power factor. As illustrated in Figure 3, the system consists of three major components: the user interface, IoT communication network, and electrical load control system.

The user interface (UI) allows users to monitor and control the power factor through devices such as computers, laptops, smartphones, or tablets connected to the internet. This feature provides remote access to system parameters, enabling efficient power factor management without requiring direct manual operation. The interface is supported by a web-based dashboard, which presents real-time data on voltage, current, power factor, apparent power, and reactive power.

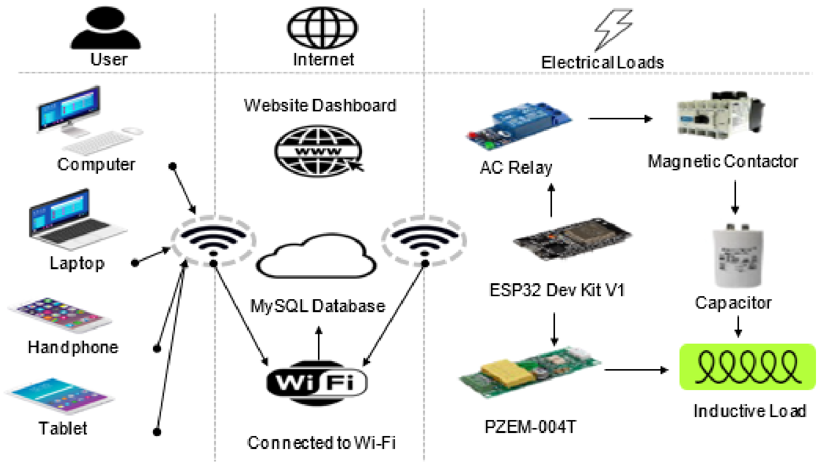

Figure 3. System consists of three major components

The IoT communication network ensures seamless data transfer between the monitoring system and the database. The PZEM-004T sensor module measures electrical parameters and transmits the data to a MySQL database via a PHP server. This allows real-time updates on the web dashboard, providing instant feedback to users. The NodeMCU ESP32 Dev Kit V1 acts as the core microcontroller, processing sensor data and executing automatic capacitor switching based on real-time power factor conditions. The system is designed to maintain a power factor above 0.85, ensuring improved energy efficiency [22].

The electrical load control system consists of AC relays, magnetic contactors, and a capacitor bank. The relay module enables dynamic capacitor switching, allowing the system to respond to fluctuations in power factor. The magnetic contactor ensures safety by managing high current loads, preventing potential damage to the circuit. The capacitor bank comprises multiple capacitors of different values, which are selectively activated based on real-time power factor readings. This adaptive switching mechanism minimizes reactive power losses, optimizing the overall power consumption [23].

As illustrated in Figure 4, the IoT network topology connects all components to a centralized system. The user interface section provides remote access to monitoring data via a Wi-Fi-based communication system. The ESP32 microcontroller acts as the data processing hub, transmitting sensor measurements to the cloud-based database. By leveraging IoT network services, users can monitor power factor variations, adjust system settings, and analyze historical data through the dashboard. This architecture enables real-time decision-making, ensuring that the system continuously adapts to changing load conditions for optimal PFC [24], [25].

2.4. Flowchart system

The development of the tool begins when the device is powered on and attempts to establish a Wi-Fi or internet connection. If the connection fails, the system remains in a standby state until a connection is established. Once connected, the ESP32 microcontroller logs into the PHP server and accesses the web domain to display the real-time monitoring dashboard. The PZEM-004T sensor measures key electrical parameters, including voltage, current, real power, apparent power, reactive power, and power factor. The collected data is then transmitted to the MySQL server via PHP scripts, where it is processed and displayed on the dashboard. This setup allows users to monitor the system remotely, providing a real-time visualization of power factor performance and energy consumption.

For automatic PFC, the system employs a relay-based capacitor switching mechanism, as illustrated in Figure 5. If the power factor (PF) is 0, all relays remain off to avoid unnecessary capacitor activation. If the PF is below 0.86, the system dynamically applies a combination method to optimize relay switching and activate the appropriate capacitors for compensation. Once the PF exceeds 0.86, the system enters Relay Holding Mode, maintaining the activated capacitors to sustain an optimal power factor. This automated approach eliminates the need for manual intervention, ensuring efficient energy management and reactive power compensation while continuously adapting to varying electrical loads. The flowchart in Figure 5 visually represents this process, detailing each stage from system startup, data acquisition, and transmission, to PFC logic using relay activation.

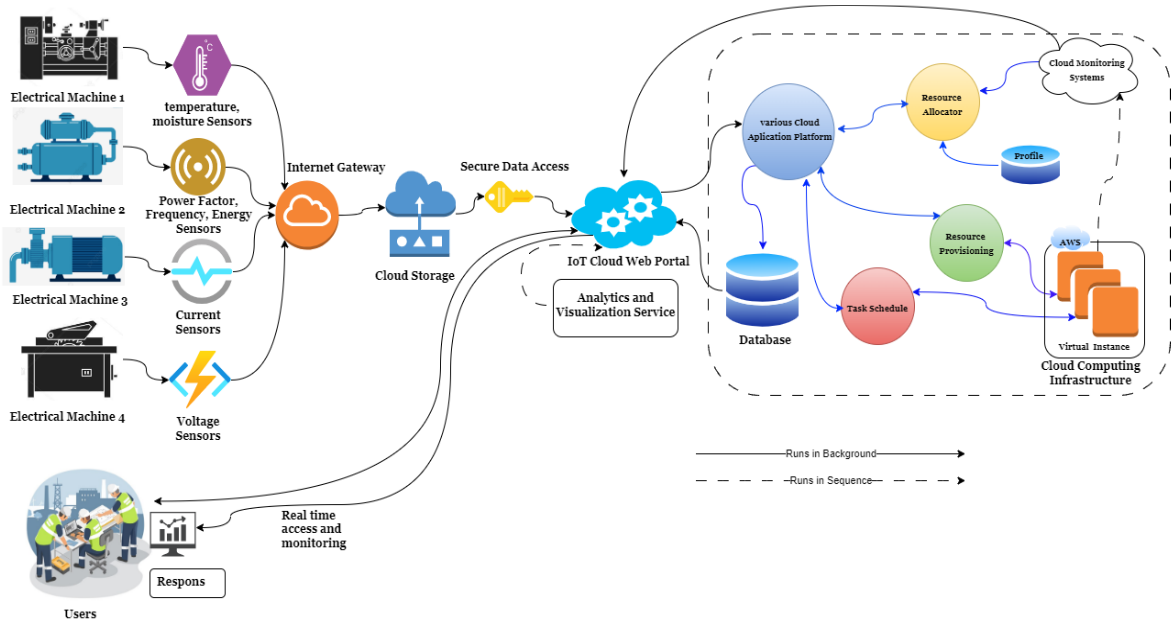

Figure 4. IoT network topology between hardware and software

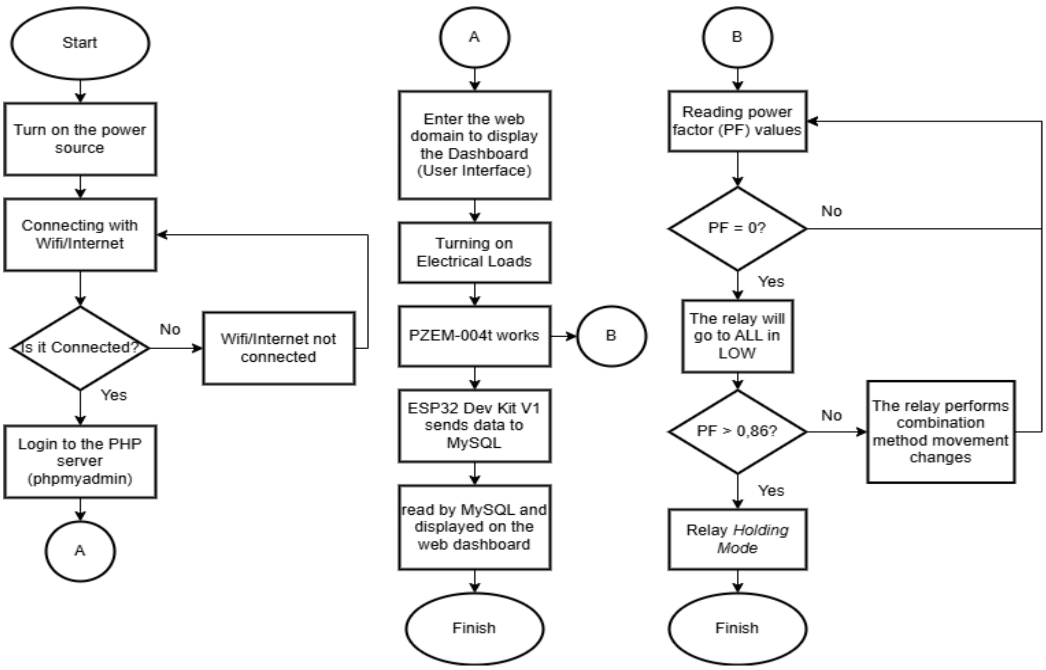

Figure 5. Flowchart system

2.5. Hardware design

The hardware design of the automatic PFC system integrates several electronic components to dynamically adjust capacitance based on real-time power factor measurements. As illustrated in Figure 6, the system consists of an ESP32 microcontroller, a PZEM-004T sensor, relays, magnetic contactors, and a capacitor bank. The ESP32 Dev Kit V1 serves as the central control unit, executing real-time monitoring and capacitor switching decisions based on power factor readings. The PZEM-004T sensor measures electrical parameters such as voltage, current, real power, apparent power, reactive power, and power factor, transmitting data to a MySQL server via a PHP-based web interface for real-time monitoring and logging.

The capacitor bank selection plays a crucial role in achieving efficient PFC. The system employs four capacitors with values of 5 µF, 8 µF, 12 µF, and 16 µF, chosen based on their effectiveness in compensating for inductive loads while maintaining flexibility in correction. These values are selected to ensure that a wide range of power factor deficiencies can be addressed with optimal efficiency. Lower values (5 µF and 8 µF) provide fine-tuned corrections, while higher values (12 µF and 16 µF) allow larger corrections when dealing with significantly low power factor conditions. The combination of these capacitors provides a scalable solution, allowing incremental adjustments to optimize power factor dynamically.

The relay module and magnetic contactors are essential for executing capacitor switching. As shown in Figure 7, four relays are connected in parallel to the capacitor bank, enabling dynamic selection of capacitor combinations to match the specific PFC requirements of the load. The parallel relay configuration allows the system to engage different capacitance values without overcompensating, thereby reducing reactive power losses and improving overall energy efficiency. Additionally, the magnetic contactor circuit ensures safety and reliability, isolating high-current components to prevent relay burnout and electrical arcing.

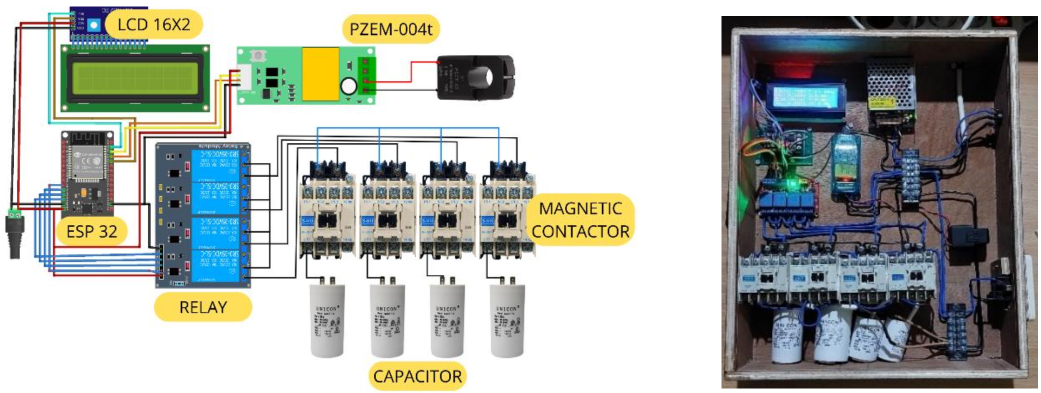

Figure 6. Results of development automatic PFC monitoring tool

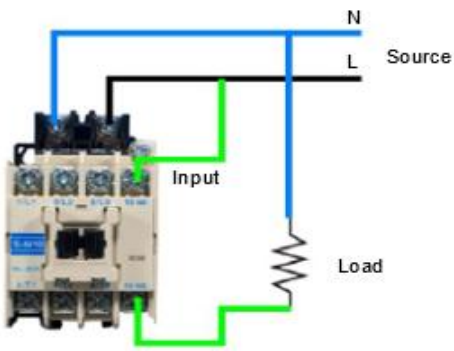

Figure 7. Magnetic contactor circuit

The automation strategy for PFC relies on a relay-based switching algorithm, which determines the optimal combination of capacitors to activate. The total number of relay movement combinations is calculated using the combinatorial formula:

$$C(n,k) = \frac{n!}{k!(n-k)!} \quad (1)$$

In combinatorial mathematics, $n!$ (n factorial) represents the product of all positive integers from 1 to n, signifying the number of ways to arrange n elements in a set. Similarly, $k!$ (k factorial) denotes the product of all positive integers from 1 to k, which is the number of ways to arrange k selected elements. Additionally, $(n-k)!$ (n minus k factorial) is the product of all positive integers from 1 to $(n-k)$, representing the number of ways to arrange the remaining elements when k elements are selected from the set.

The results of the combination of movements from (1) of the four installed relays produce different movement patterns with the (2)-(5).

1. $k = 1$:
$$C(4,1) = \frac{4!}{1!\times(4-1)!} = \frac{4!}{1!\times 3!} = \frac{4\times3\times2\times1}{1\times(3\times2\times1)} = 4 \quad (2)$$

2. $k = 2$:
$$C(4,2) = \frac{4!}{2!\times(4-2)!} = \frac{4!}{2!\times 2!} = \frac{4\times3\times2\times1}{(2\times1)\times(2\times1)} = 6 \quad (3)$$

3. $k = 3$:
$$C(4,3) = \frac{4!}{3!\times(4-3)!} = \frac{4!}{3!\times 1!} = \frac{4\times3\times2\times1}{(3\times2\times1)\times1} = 4 \quad (4)$$

4. $k = 4$:
$$C(4,4) = \frac{4!}{4!\times(4-4)!} = \frac{4!}{4!\times 0!} = \frac{4\times3\times2\times1}{4\times3\times2\times1\times1} = 1 \quad (5)$$

From this, the system generates 15 distinct relay activation patterns, ensuring adaptability for various load conditions. Table 1 provides a breakdown of these relay activation combinations, showing how different capacitors are engaged based on the required PFC. Table 2 presents the capacitor values associated with each relay, further detailing how incremental adjustments are made for optimal compensation.

By integrating these components, the system is capable of automatically adjusting PFC based on real-time demand. The physical implementation, as shown in Figure 6, ensures a compact, reliable, and scalable design, making it suitable for industrial and commercial applications that require continuous power factor optimization. The combination of fine-tuned and high-capacitance values enhances correction precision, ensuring that the system effectively reduces reactive power losses and improves overall power quality.

Table 1. Combination movement generated from 4 relays

Movement to	Relay active				Description
	1	2	3	4	
1	✓				1
2		✓			2
3			✓		3
4				✓	4
5	✓	✓			1, 2
6	✓		✓		1, 3
7	✓			✓	1, 4
8		✓	✓		2, 3
9		✓		✓	2, 4
10			✓	✓	3, 4
11	✓	✓	✓		1, 2, 3
12	✓	✓		✓	1, 2, 4
13	✓		✓	✓	1, 3, 4
14		✓	✓	✓	2, 3, 4
15	✓	✓	✓	✓	1, 2, 3, 4

Table 2. Value of capacitor shown

No relay	Capacitor size
1	5uF
2	8uF
3	12uF
4	16uF

2.6. Software design

The software design for the IoT-based power factor monitoring and improvement system consists of a web-based infrastructure that processes, stores, and displays sensor data in real time. As illustrated in Figure 8, the system follows a structured workflow where sensor data is transmitted, received, stored, and displayed via a web interface. The process begins with data transfer from the ESP32 microcontroller, which continuously reads electrical parameters such as voltage, current, power, frequency, energy, and power factor using the PZEM-004T sensor. This data is transmitted via the "datasend.php" script, which acts as the gateway for receiving and forwarding data to a MySQL database. The database then stores the data using several PHP scripts, including "currentcheck.php" for current readings, "voltagecheck.php" for voltage measurements, "frequencycheck.php" for frequency data, "energycheck.php" for cumulative energy consumption, "powercheck.php" for real power values, and "powerfactorcheck.php" for storing power factor values.

Once stored, the system retrieves and visualizes the data using "index.php", which serves as the main user interface for monitoring. This dashboard provides a real-time graphical representation of all electrical parameters, allowing users to analyze trends, detect anomalies, and optimize PFC strategies remotely. The web-based design ensures accessibility from any device, enabling remote supervision and decision-making for efficient energy management. The IoT-based infrastructure enhances automation by integrating real-time monitoring and data logging, ensuring that PFC adjustments are data-driven and optimized for dynamic load conditions.

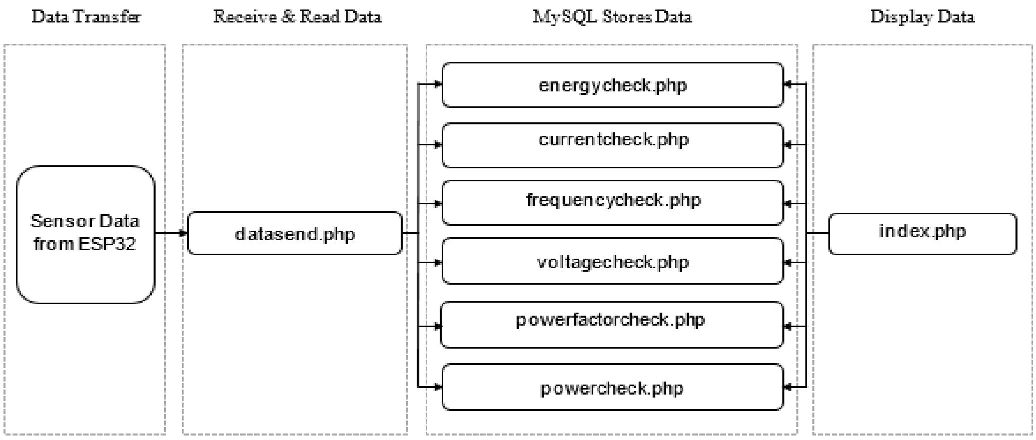

Figure 8. Website infrastructure workflow

3. RESULTS AND DISCUSSION

3.1. Performance testing on variative inductive loads

A series of tests were conducted on various inductive loads to evaluate the effectiveness of the monitoring system and PFC capabilities. The tests included measurements on a TL lamp with an initial power factor of 0.35, a TL lamp with an initial power factor of 0.5, two TL lamps with an initial power factor of 0.35 connected in parallel, two TL lamps with an initial power factor of 0.5 connected in parallel, a combination of one TL lamp with a power factor of 0.35 and another with 0.5 connected in parallel, and an AC motor. These variations were chosen to analyze how different load conditions influence the system's ability to improve power factor.

Figure 9 presents a comparative analysis of power factor improvement before and after correction using the proposed system. The results indicate a significant increase in power factor across all tested loads. A TL lamp with an initial power factor of 0.35 demonstrated an increase of 54.12%, while a TL lamp with an initial power factor of 0.5 improved by 45.26%. When two TL lamps with an initial power factor of 0.35 were connected in parallel, the power factor increased by 56.67%, and for two TL lamps with an initial power factor of 0.5, the improvement was 45.83%. Furthermore, a combination of one TL lamp with a power factor of 0.35 and another with 0.5 resulted in a 53.26% improvement, while the AC motor exhibited an increase of 37.5%.

These findings indicate that the proposed IoT-based PFC system effectively adjusts capacitor switching to optimize power factor dynamically. Unlike traditional capacitor banks that rely on fixed-value capacitors, this system automatically determines the optimal capacitor combination in real-time, ensuring precise and efficient correction without overcompensation. This capability allows the system to adapt to varying load conditions, making it highly suitable for applications requiring real-time power factor adjustments [26].

Furthermore, the average power factor improvement across all tested loads was 48.77%, demonstrating the robustness and scalability of the developed system. This improvement is essential for reducing reactive power losses, increasing energy efficiency, and ensuring that electrical loads operate closer to unity power factor. Maintaining a high power factor minimizes transmission losses and unnecessary power dissipation, which is particularly beneficial for industrial and commercial applications where energy optimization is a critical factor.

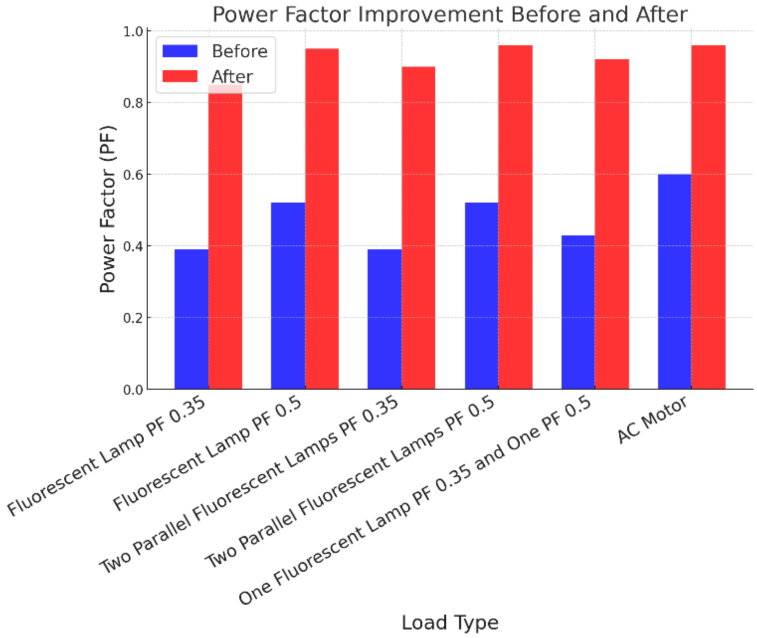

Figure 9. Comparison of power factor measurement before and after improvement

3.2. Reduction in current consumption

The data presented in Figure 10 demonstrates a significant reduction in current consumption for each type of load after the implementation of the proposed PFC system. This reduction is a direct result of improved power factor, which minimizes reactive power and enhances overall energy efficiency. For instance, a TL lamp with an initial power factor (PF) of 0.35 exhibited a current reduction of 58.08%, while a TL lamp with a PF of 0.5 experienced a decrease of 46.34%. When two TL lamps with PF 0.35 were connected in parallel, the current consumption dropped by 29.78%, whereas two TL lamps with PF 0.5 in parallel showed a reduction of 47.43%. Additionally, a combination of one TL lamp with PF 0.35 and another with PF 0.5 resulted in a 19.53% decrease in current, while the AC motor demonstrated a reduction of 38.25%. These findings highlight the effectiveness of the developed system in reducing current draw across a variety of inductive loads.

On average, the current reduction across all tested loads was 39.90%, indicating that the intervention using the proposed research tool significantly enhances power usage efficiency. This decrease in current is critical in optimizing energy consumption, as lower current draw reduces transmission losses, heating effects, and stress on electrical components. In practical applications, this means that electrical systems can operate with less strain on conductors and transformers, leading to extended equipment lifespan and improved power quality.

The results also validate the capability of the system to dynamically adjust capacitor activation, ensuring that only the required compensation is applied to achieve optimal PFC. This dynamic approach differs from conventional static capacitor banks, which often lead to overcompensation or underutilization of capacitors, reducing overall system efficiency. Compared to prior studies, which utilized fixed-value capacitors, this system provides a more flexible and adaptive correction mechanism, ensuring efficient current consumption under various load conditions [27]. By reducing the current flow while maintaining the same power output, this system significantly enhances energy efficiency, making it particularly beneficial for industrial applications where high-power electrical loads are used continuously. The decrease in current consumption also translates to lower electricity costs, reduced heat generation, and a more sustainable power management system [28], [29].

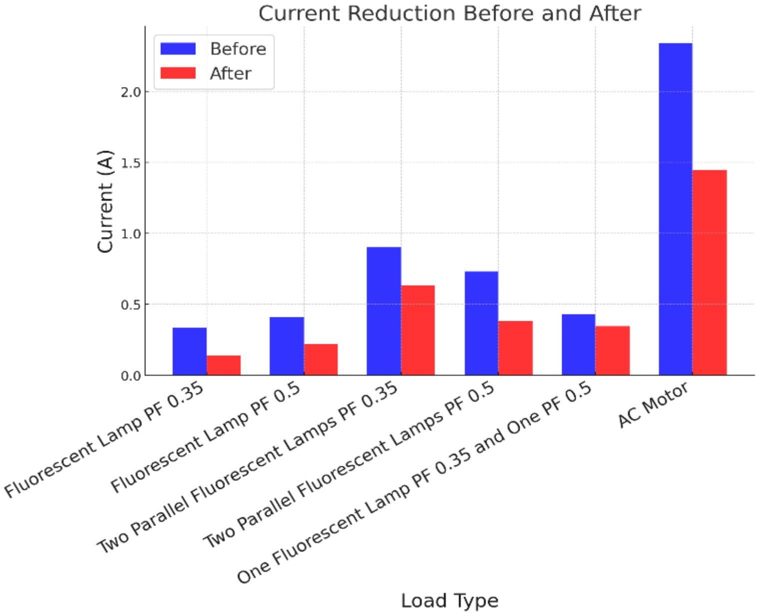

Figure 10. Comparison of current measurement before and after improvement

3.3. Real-time monitoring and system responsiveness in PFC

The dashboard plays a critical role in the IoT-based power factor monitoring and improvement system, enabling real-time monitoring and efficient power management. Developed using PHP, the dashboard displays six key electrical parameters: voltage (V), current (I), energy (kWh), power (W), frequency (Hz), and power factor (PF). By providing a user-friendly interface, this system allows users to analyze power consumption patterns and optimize energy usage dynamically. Additionally, the dashboard supports both light and dark modes, enhancing user experience by allowing display customization to reduce eye strain under different lighting conditions, as illustrated in Figure 11.

To evaluate system performance, response time for data transmission was measured across various parameters, including current, voltage, frequency, energy, power, and power factor. Each parameter's data retrieval is executed through individual PHP scripts, such as "checkcurrent.php" for current, "checkvoltage.php" for voltage, and similar scripts for other parameters. These tests were conducted under a 4G network with an average speed of 22 Mbps, ensuring realistic operating conditions. The average response times for each parameter are summarized in Table 3.

Figure 11. Dashboard display on the website page

Table 3. Average response time for data transmission

Parameter	Script name	Average response time (ms)
Current	checkcurrent.php	223
Voltage	checkvoltage.php	193
Frequency	checkfrequency.php	207
Energy	checkenergy.php	189
Power	checkpower.php	217
Power factor	checkpowerfactor.php	217
Overall average		207.67

The results indicate that the overall average response time across all parameters is 207.67 ms, with individual response times ranging from 189 ms to 223 ms. This latency range of 100–220 ms demonstrates that the system operates within an acceptable threshold for real-time monitoring and analysis. Such performance is critical for effective power factor management, ensuring that updates to capacitor switching and power factor adjustments occur without significant delay. Compared to conventional monitoring systems, which may experience higher latency due to database overload or inefficient scripting, the proposed system maintains consistent and reliable performance within typical cellular network conditions [30]. By leveraging fast data transmission and a responsive dashboard, this system facilitates efficient decision-making in power factor optimization. The ability to provide real-time updates on power consumption trends enhances operational efficiency and energy-saving strategies, making the system suitable for industrial and commercial applications where power management is crucial [31].

3.4. Discussion

The evaluation of the IoT-based power factor monitoring and correction system highlights its ability to dynamically adjust capacitor switching and optimize power factor in real time. The system demonstrated significant improvements over conventional PFC methods, particularly in its ability to provide real-time adjustments based on actual load conditions [32]. Unlike traditional fixed capacitor banks or manually controlled relay switching, which can lead to overcompensation or undercompensation depending on load fluctuations, the proposed system integrates real-time monitoring through the PZEM-004T sensor and dynamic relay switching mechanisms, ensuring precise and adaptive PFC. Previous studies [19], [33] indicate that conventional PFC techniques achieve efficiency levels between 70-85%, whereas the developed system successfully improves power factor by an average of 48.77%. Additionally, a current consumption reduction of 39.90% further validates the system’s effectiveness in minimizing reactive power losses, contributing to improved energy efficiency. The response time evaluation shows that the system achieves an average latency of 207.67 ms, allowing low-latency real-time monitoring and capacitor switching, making it suitable for dynamic load applications.

Although the system demonstrated a significant impact on PFC, there are limitations in the load variations used for testing, which were restricted to TL lamps and an AC motor. The TL lamp was chosen as a common household inductive load, while the AC motor was selected to represent the heaviest load condition in this study, assessing the system’s ability to handle increased inductive power demands. While the system effectively optimized power factor for these tested loads, further validation is required for larger industrial motors, transformers, and other high-capacity inductive devices. Future research should focus on expanding system testing for higher power loads and enhancing efficiency through machine learning-based predictive control for capacitor switching. Additionally, integrating edge computing architectures could minimize cloud dependency and reduce response time, ensuring greater reliability in industrial applications. These improvements will help the system evolve into a fully autonomous PFC solution, making it an ideal energy management system for both commercial and industrial sectors.

4. CONCLUSION

This study successfully developed an IoT-based power factor monitoring and correction system that adapts to variations in electrical loads. Utilizing 15 automatic switching patterns, the system significantly improves power factor, achieving an average increase of 48.77% and a 39.90% reduction in current consumption. Additionally, the system enables real-time monitoring through an intuitive web-based interface, with an average response time of 207.67 ms, ensuring accurate and up-to-date data. Compared to conventional methods that require manual intervention, this automated approach enhances overall energy efficiency and electrical system reliability.

The primary advantage of this system lies in its dynamic PFC automation, eliminating the need for manual adjustments while optimizing energy consumption efficiently. Future research could explore further integration with artificial intelligence (AI) to predict and optimize power factor adjustments more effectively. Additionally, expanding the system's implementation to larger-scale industrial applications could be a key focus to maximize energy efficiency across various sectors.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
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R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The author confirms that there are no conflicts of interest to declare.

INFORMED CONSENT

Informed consent was obtained from all participants involved in this research.

ETHICAL APPROVAL

All procedures involving animals were conducted in accordance with applicable national regulations and institutional guidelines for their care and use.

DATA AVAILABILITY

Data supporting the conclusions of this study can be provided by the corresponding author upon reasonable request. However, any data that might reveal participants' identities or sensitive information are not publicly accessible due to privacy considerations.

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BIOGRAPHIES OF AUTHORS

Dr. Maman Somantri S.Pd., M.T. is a Lecturer in the Department of Electrical Engineering Education, Faculty of Engineering and Industrial Education, Universitas Pendidikan Indonesia, Bandung, Indonesian. received a bachelor's degree in Electrical Engineering Education at the Indonesian University of Education, received a master's degree M.T. in the field of Electrical Engineering at the Bandung Institute of Technology, and received his doctorate in Technology and Vocational Education at the Indonesian University of Education. The research and publications carried out are very experienced both on a national scale indexed by SINTA and on an international scale indexed by Scopus. The research interests include the information technology, vocational Education, internet of things, artificial intelligence, automation industry, electronics, and TVET. He can be contacted at email: msomantri@upi.edu.

Mochamad Rizal Fauzan S.Pd. is a recent graduate from the Electrical Engineering Education Study Program with a concentration in Industrial Electronics at Faculty of Engineering and Industrial Education, Universitas Pendidikan Indonesia, Bandung, Indonesian. Actively involved with other lecturers in conducting research. He researches interests are internet of things, artificial intelligence, computer vision, machine learning, deep learning, image processing, data mining, and VR or AR Technology in Education. He can be contacted at email: rizalfauzan@upi.edu.

Irgi Surya S.Pd. is a graduate bachelor's degree in an electrical engineering education study program, Department of Electrical Engineering Education, Faculty of Technology and Vocational Education, Universitas Pendidikan Indonesia, Bandung, Indonesia. He is currently pursuing master degree from Department of Electrical Engineering, College of Electrical Engineering and Computer Science, National Taipei University of Technology, Taipei, Taiwan. The research interests include the internet of things for agriculture and aquaculture, artificial intelligence, automation industry, electronics, and TVET. He can be contacted at email: t113998402@ntut.org.tw.