EMITOR: Jurnal Teknik Elektro

Design and Development of a Wireless Energy Meter with Automatic Cos phi Corrector Feature Based on Internet of Things

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Abstract – *The increasing need for energy efficiency and more accurate monitoring of energy consumption has driven the development of intelligent energy metering systems. This Final Project discusses the development of Wireless Energy Meter that integrates sensor technology and data analysis for better monitoring and prediction of energy consumption. The main objective of this research is to improve understanding of household energy consumption patterns and develop power factor improvement algorithms that can provide better use of energy efficiency in the future. At the first stage, the system is implemented using energy sensors connected to the household electrical network. The data obtained from this sensor is sent to the Thingspeak application for later monitoring. The second stage involves developing an algorithm to automatically correct the power factor that the capacitor will later embed to correct cos phi if the existing power factor is less than a predetermined set point. The results of this study show that the system that has been developed is able to provide real-time monitoring of energy consumption and improve electricity quality for better energy efficiency in the future. This can help users to be more efficient in energy use, identify potential savings, and reduce environmental impact. In addition, this system can be used by equipment in households whose purpose is to optimize the use of daily electricity loads.*

Keywords – *Wireless Energy Meter; Power Factor Correction; Internet of Things; Energy Efficiency; Real-time Monitoring.*

I. Introduction

ELECTRICAL energy is a vital component in everyday life and serves as the backbone of modern infrastructure. However, the increase in energy consumption, population growth, and recent lifestyle changes have placed significant pressure on electrical energy systems [1]. Advances in internet technology and intelligent systems have sparked interest in using the internet to control and monitor electrical energy usage, both in homes and buildings [1–3]. The development of the Internet of Things (IoT) facilitates information access from anywhere while enhancing efficiency in industrial and household tasks [4].

In this context, the development of a Wireless Energy Meter with the capability to predict energy consumption represents a significant step toward improving energy use efficiency and optimizing power grid management, particularly in household industries like SMEs. The development of a Wireless Energy Meter with predictive capabilities is a significant advancement in energy efficiency and grid management, particularly for SMEs [5, 6]. These meters, often based on IoT technology, can monitor power consumption in real-time and provide data for demand management systems [7, 8]. They also offer the potential for remote access and control of energy data, as well as the automation of household appliances [8–10]. Furthermore, the use of Industry 4.0 technologies, such as big data and IoT, can enhance the predictive capabilities of these meters, allowing for more accurate energy consumption forecasts [11, 12]. Electrical energy usage in household industries often relies on PLN (Indonesia's state electricity company) resources [13]. PLN often imposes additional charges if the power factor falls below a certain threshold [14]. A low power factor can result in inefficient use of electrical energy and increase electricity bills [15].

Methods such as Capacitor Banks can be used to improve the power factor [16]. An IoT-based power meter is expected to provide real-time remote monitoring to assist electricity users in managing their energy consumption [17–20]. This can enhance the efficiency of household electrical equipment and help users adjust

The manuscript was received on November 29, 2023, revised on July 3, 2024, and published online on July 26, 2024. Emitor is a Journal of Electrical Engineering at Universitas Muhammadiyah Surakarta with ISSN (Print) 1411 – 8890 and ISSN (Online) 2541 – 4518, holding Sinta 3 accreditation. It is accessible at https://journals2.ums.ac.id/index.php/emitor/index.

their consumption patterns based on monitoring household electricity usage. The Thingspeak application is used for data acquisition during monitoring to observe data trends [21]. A relay is also embedded in this device for conditioning purposes; if the power factor is less than the set point, the relay will switch conditions to improve the power factor through capacitors arranged in series and parallel with the load.

II. Research Methods

Electrical energy is a vital component in everyday life and serves as the backbone of modern infrastructure. However, the increase in energy consumption, population growth, and recent lifestyle changes have placed significant pressure on electrical energy systems [1]. Advances in internet technology and intelligent systems have sparked interest in using the internet to control and monitor electrical energy usage, both in homes and buildings [1–3]. The development of the Internet of Things (IoT) facilitates information access from anywhere while enhancing efficiency in industrial and household tasks [4].

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Methods such as Capacitor Banks can be used to improve the power factor [16]. An IoT-based power meter is expected to provide real-time remote monitoring to assist electricity users in managing their energy consumption [17–20]. This can enhance the efficiency of household electrical equipment and help users adjust their consumption patterns based on monitoring household electricity usage. The Thingspeak application is used for data acquisition during monitoring to observe data trends [21]. A relay is also embedded in this device for conditioning purposes; if the power factor is less than the set point, the relay will switch conditions to improve the power factor through capacitors arranged in series and parallel with the load. A range of studies have explored the use of relays in power factor correction systems. Vijay [22] and Patil [23] both developed systems that use relays to switch capacitor banks, with the relay controlled by an Arduino board. Rahman [24] and Pampalle [25] similarly used relays in their systems, with the latter also incorporating Internet of Things (IoT) technology for remote monitoring. Vinodini [26] and Sari [27] both discussed the use of automatic power factor correction (APFC) systems, with Vinodini focusing on the use of microcontrollers and Sari incorporating IoT technology. Mbinkar [28] and Ali [29] both used microcontrollers to control reactive power compensation, with Ali specifically focusing on three-phase systems. These studies collectively demonstrate the potential of relays in power factor correction systems, particularly when integrated with microcontrollers and IoT technology.

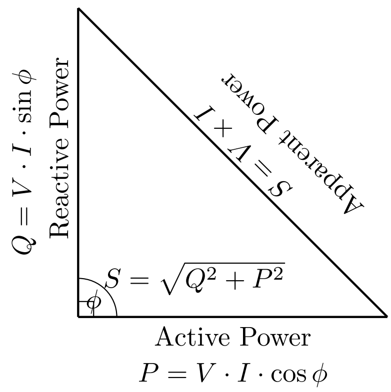

Figure 1: Power Triangle

i. Theoretical Foundation

Electrical power is a measure of the rate at which electrical energy is consumed in an electrical load system. It is measured in watts (W) and is the product of the voltage (V) and the current (I) flowing in a circuit. Electrical power quantifies the rate of energy transfer within a circuit. The greater the power, the more energy is used or produced over a specific time period.

Apparent power, denoted as S, is the combination of active power and reactive power, measured in volt-amperes (VA). It represents the power supplied by the electrical source in a circuit and is given by the equation:

$$S = V \times I \tag{1}$$

where S is the apparent power in volt-amperes, V is the voltage in volts, and I is the current in amperes. Apparent power can also be calculated using the formula:

$$S = \sqrt{Q^2 + P^2} \tag{2}$$

where Q represents the reactive power in VAR (volt-amperes reactive) and P represents the active power in watts.

Active power, denoted as P, is the actual power used to perform work in an electrical system, measured in watts (W). It typically results in mechanical work (such as in electric motors) or heating (such as in lamps) and is given by the equation:

$$P = V \cdot I \cdot \cos\phi \tag{3}$$

where P is the active power in watts, V is the voltage in volts, I is the current in amperes, and ϕ is the phase angle.

Figure 2: PZEM-004T v3 Sensor

Reactive power, denoted as Q, is associated with electrical devices that store and release energy in the form of electromagnetic fields. It is measured in volt-amperes reactive (VAR) and is necessary for maintaining voltage stability in the power system. The reactive power is given by the equation:

$$Q = V \cdot I \cdot \sin\phi \tag{4}$$

where Q is the reactive power in VAR, V is the voltage in volts, and I is the current in amperes. Reactive power can also be calculated using the formula:

$$Q = \sqrt{S^2 - P^2} \tag{5}$$

where Q is the reactive power in VAR, S is the apparent power in VA, and P is the active power in watts.

The power triangle is a crucial concept in electrical engineering used to visualize the relationship between active power (P), apparent power (S), and power factor ($\cos\phi$) in an AC circuit. It aids in understanding and analyzing power parameters in AC circuits as look in figure 1.

The power triangle is also useful for identifying low power factor issues in circuits and designing solutions to improve power factor, such as using AC capacitors for reactive power compensation. Understanding the power triangle concept helps in planning and managing the efficiency and quality of power in electrical systems [20]. The power triangle is used to calculate reactive power (Q) in a circuit with the following formula:

$$Q = S \cdot \sin\phi \tag{6}$$

ii. Power Meter

This study uses the PZEM-004T power meter figure 2. This sensor module measures voltage, current, power, power factor, frequency, and energy in electrical loads. Manufactured by Peacefair, it comes in two models: 10 Ampere and 100 Ampere.

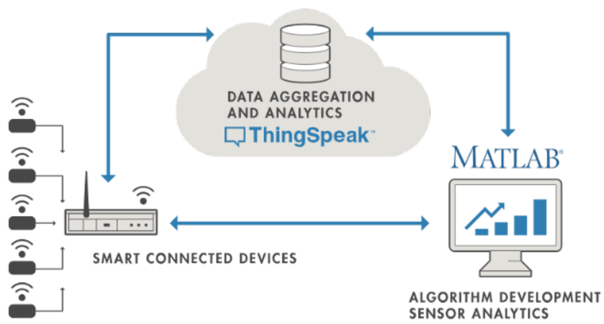

Figure 3: Thingspeak Platform

The PZEM-004T module can be connected to a load and the ESP32S, providing data through RX and TX serial communication. It has been widely used in various projects, including energy consumption monitoring prototypes. The sensor's features include a power button for clear/reset energy, a power measurement range of 0 99 kW, a voltage measurement range of 80 260 VAC, and a current measurement range of 0 10 A. Specifications include working voltage (80 260 VAC), rated power (10 A/2200 W), working frequency (45–65 Hz), and measurement accuracy (0.5%). This sensor is selected for its all-in-one features compared to other sensors on the market. Additionally, its small dimensions allow for compact PCB fabrication.

iii. Remote Monitoring

In the remote monitoring part, this research uses several parameters forming the system, consisting of IoT (Internet of Things) with the Thingspeak platform connected to the ESP32S microcontroller programmed in Arduino IDE figure 3. IoT devices communicate with a central system to automate processes and make daily tasks more efficient. Household-scale IoT implementation aims to improve efficiency, productivity, and monitoring of electrical equipment by collecting and analyzing real-time data from devices and sensors integrated into the IoT system.

The second parameter is the Thingspeak application, an IoT platform that allows users to connect physical devices to the internet, collect sensor data, and analyze it in real-time. One of its unique features is the Channel API, enabling users to create data channels accessible publicly or privately. Data sent to these channels can be accessed via API, allowing integration with various applications and external systems. Users can configure rules (scenarios) that trigger specific actions when certain conditions are met [30].

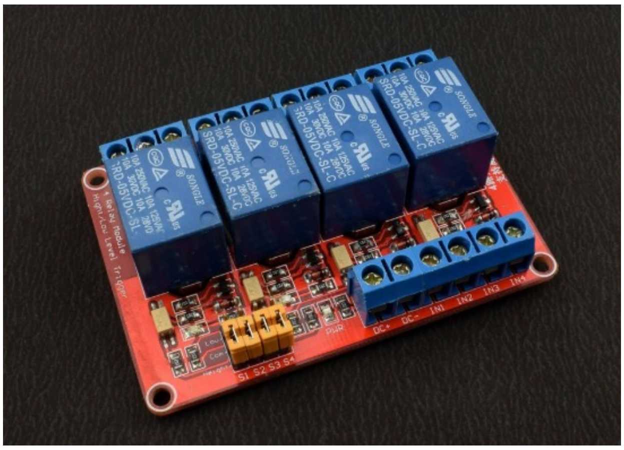

Figure 4: Relay Quad Channel

iv. Power Factor Correction

Power factor is the ratio of active power (P) to apparent power (S). It is the cosine of the phase angle between the voltage and current in a system. Power factor ranges from 0 to 1, where a value closer to 1 indicates a better power factor in the system. It is calculated as Equation (7).

$$\begin{aligned}\text{Power Factor } (\text{Cos } \phi) &= \frac{P}{S} = \frac{W}{VA} \\ &= \frac{V \times I \times \cos\phi}{V \times I} \\ &= \cos\phi\end{aligned} \quad (7)$$

Figure 5: AC Capacitor

A power factor closer to 1 indicates efficient use of electrical power in a circuit. A high power factor shows that most of the power supplied by the source is effectively used for performing work, with minimal waste.

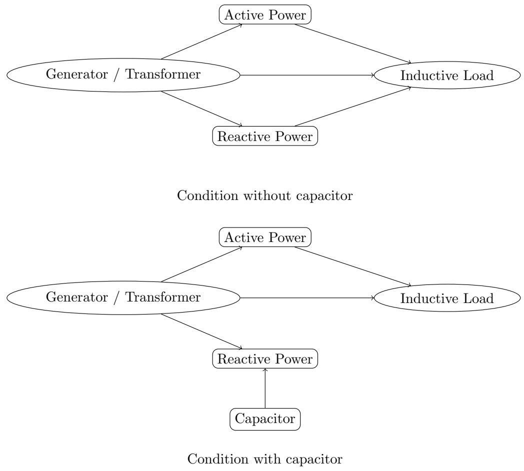

Figure 6: Capacitor Compensation Illustration

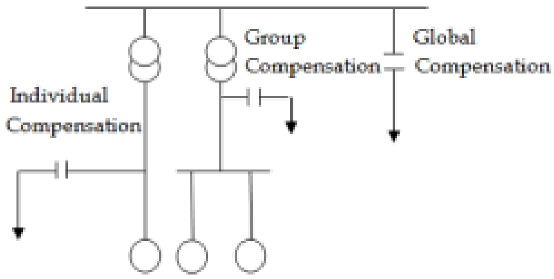

Figure 7: Capacitor Installation Method

1. **Unity Power Factor:** This condition occurs when the active power and apparent power in an electrical system are equal, resulting in $\cos\phi = 1$.
2. **Leading Power Factor:** This condition often occurs in electronic devices like capacitors in electrical circuits, where the current leads the voltage in phase.
3. **Lagging Power Factor:** This condition occurs when the current lags behind the voltage in phase in an electrical circuit, often due to inductive loads like motors and transformers [31].

Improving power factor involves reducing the reactive power consumed by inductive loads to enhance system efficiency. The formula for power factor correction using capacitors is:

$$C = \frac{P \times (\tan\phi_1 - \tan\phi_2)}{2 \times \pi \times \text{Freq} \times V^2} \quad (8)$$

where C is the Capacitor (F), P is the Power (Watts), $\tan\phi$ is the Correction Value, π is 3.14, Freq is the Frequency (Hz), and V is the Voltage (Volts).

A quad-channel relay figure 4 provides an economical and practical solution for controlling multiple electrical devices in various contexts, such as households,

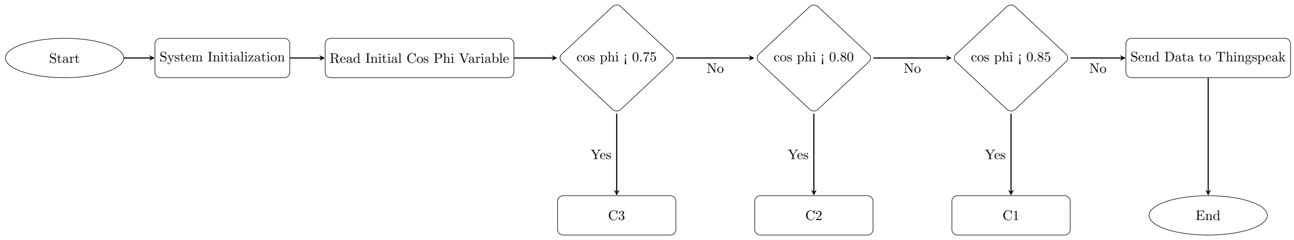

Figure 8: System Flowchart

industries, and electronic experimentation projects. AC capacitors figure 5 improve power factor by providing reactive power to balance the reactive power generated by inductive loads, thus enhancing system efficiency. Figure 6 illustrates the difference in reactive power consumption before and after compensation. Capacitors provide reactive power to inductive loads, improving power factor. In this system design, capacitors are installed using the group compensation method figure 7. This method involves installing multiple capacitor panels on a sub-distribution panel (SDP) to compensate for the load. The goal is to improve the power factor to approach 1 (unity power factor). This method is one of three capacitor bank installation methods, including global compensation, individual compensation, and group compensation [**?**].

v. Tool Design

The Wireless Energy Meter system uses the ESP32S microcontroller to process data from the PZEM-004T current and voltage sensor. The PZEM-004T sensor reads various AC electrical variables, including current, voltage, cos ϕ, and kWh consumed by the load. Capacitors are used to improve the cos ϕ value if it is detected by the PZEM-004T sensor to be less than a certain set point (0.85, 0.80, 0.75), which is a reference from PLN (cos $\phi < 0.85$) based on the Indonesian Minister of Energy and Mineral Resources Regulation No. 7 of 2010/Chapter III/Article 5/Paragraph 1. The Quad Channel Relay changes the switch condition to Normally Close (NC) if cos ϕ is less than the set point, and Normally Open (NO) if it is more than the set point, with the condition change performed in parallel. In the Normally Open (NO) condition, current bypasses the circuit as no cos ϕ improvement is needed, whereas in the Normally Close (NC) condition, the circuit connects to the capacitor. Three capacitors with different capacitance values are used to compensate for the required value, connected in parallel in the system.

The IoT-based monitoring system uses the Thingspeak application, which enables remote control of IoT devices and electronic projects via mobile devices. This application provides a customizable user interface, facilitating the management of various devices and sensors. In this implementation, the Thingspeak application connects via WiFi by sending a token generated from the Thingspeak application to the microcontroller. Once connected, the Thingspeak application can monitor load variables such as current, voltage, cos ϕ, and kWh. Thus, this system enables efficient monitoring and control of loads utilizing IoT technology.

As shown in Figure 8, if the initial cos ϕ value is 0.26, the system will activate C3, C2, and C1 sequentially to improve the initial cos ϕ. If the initial cos ϕ value is 0.91, which does not require improvement, the system will bypass all condition checks. The results are then sent to the Thingspeak IoT platform [32, 33].

III. Results and Discussion

The purpose of this testing method is to evaluate the performance of the PZEM 004T sensor in reading voltage, current, and power factor values from a load. The measurement results from this sensor will be compared with readings from conventional measuring instruments, such as an ammeter for current, a voltmeter for voltage, and a power factor meter for power factor, which are considered as reference values. Another goal of this testing is to examine to what extent the Wireless Energy Meter system can provide accurate and comparable results to calibrated laboratory instruments. To facilitate the analysis of test results, error factors are calculated using certain equations as seen in Equation III.

$$\text{Error} = \frac{\text{Measured Value} - \text{Reference Value}}{\text{Reference Value}} \times 100\%$$

i. Data Analysis

In this system test, an analysis will be conducted on the effects of inductive, capacitive, and resistive load characteristics such as fans, lamps, drill presses, soldering irons, capacitors, and AC electric motors on the system's power factor. Data from these various loads will be monitored through a serial monitor and the Thingspeak application to analyze voltage, current, cos phi, and relay status conditions. The main objective is to observe how the system performs power factor correction through capacitor compensation [34, 35]. The effect of different capacitor values on the cos phi of each load and load combination will also be analyzed. Additionally, this project will calculate whether the capacitor compensation values align with the power factor correction formula. As a preliminary step before data analysis, data verification between the PZEM 004T sensor, a multimeter, and a power factor meter is conducted to ensure that voltage, current, and cos phi measurements meet standards and avoid reading errors Table 1. This aims to ensure the accuracy of measurement results before further analysis [31, 36, 37].

Table 1: Cos phi before compensation

Load	**V**	**I**	**Cos phi**
Lamp	222.6	0.13	1
Soldering Iron	225.4	0.23	1
Fan	218.3	0.52	0.81
AC Electric Motor	222.7	2.52	0.26
Drill Press	216.8	6.51	0.71
Lamp + AC Motor + Drill Press	216	8.43	0.62

Table 2: Cos phi after compensation

Load	**V**	**I**	**Cos phi**
Lamp	222.6	0.13	1
Soldering Iron	225.4	0.23	1
Fan	218	0.5	1
AC Electric Motor	218	0.77	1
Drill Press	217.1	3.91	0.98
Lamp + AC Motor + Drill Press	214.8	5.32	0.88

Table 3: Apparent Power (VA), Active Power (Watt), and Reactive Power (VAR) before Compensation

Load	*VA*	Watt	VAR
Lamp	28.9	28.9	0
Soldering Iron	52.5	52.5	0
Fan	113.5	91.9	79.92
AC Electric Motor	561.2	145.9	541.91
Drill Press	1411	1002	993.9
Lamp + AC Motor + Drill Press	1820	1128	1429.4

After compensation using capacitors Table 2, the analysis shows that power factor correction improves the efficiency of electrical quality without reducing electrical harmonics. By compensating for the load, electricity savings from PLN can be achieved by considering the reduction in apparent power for each load. For example, for the AC Electric Motor before compensation, the apparent power was 561.2 VA, the reactive power was 541.91 VAR, and the active power was 145.9 Watts. After compensation, the apparent power decreased by 70%, the reactive power by 100%, and the active power increased by 13%. For the Drill Press, the apparent power decreased by 39.8%, the reactive power by 82.96%, and the active power decreased by 16.9%. However, it should be noted that the decrease in active power can occur because the resulting cos phi is still less than 1, leading to a difference between apparent power and real power Table 3 and Table 4.

Table 4: Apparent Power (VA), Active Power (Watt), and Reactive Power (VAR) after Compensation

Load	*VA*	Watt	VAR
Lamp	28.9	28.9	0
Soldering Iron	52.5	52.5	0
Fan	109	109	0
AC Electric Motor	167.8	167.8	0
Drill Press	848.8	831.8	169.3
Lamp + AC Motor + Drill Press	1140	1003	543

Table 5: Total Efficiency of Apparent Power (ψ), Active Power (A_P), and Reactive Power (V_r) after Compensation

Load	ψ	A_P	V_r
Lamp	0%	0%	0%
Soldering Iron	0%	0%	0%
Fan	3.9%	18.6% ↑	100%
AC Electric Motor	70%	15% ↑	100%
Drill Press	39.8%	16.9% ↓	82.96%
Lamp + AC Motor + Drill Press	37.3%	11% ↓	62%

Using capacitors for compensation impacts electricity savings, especially in terms of apparent power. Thus, the system can handle more loads, allowing for broader household appliance usage. However, in terms of real power, efficiency depends on the cos phi value achieved by the system Table 5. If cos phi = 1, real power will increase before compensation, indicating high system efficiency because the power factor is unity, and there is no reactive power. However, if there is slight lagging, real power can decrease, indicating more efficient electricity usage. Therefore, the conclusion can be drawn that using capacitors for compensation can be adjusted to the goal of saving electricity or improving electricity usage efficiency for certain loads.

IV. Conclusion

Based on the testing and discussion of the final project titled ”Design and Development of a Wireless Energy Meter with an Automatic Cos Phi Corrector Feature Based on the Internet of Things,” several key points can be concluded. First, the combination of sensors, microcontrollers, and capacitors in the system has proven to work well. This system allows users to remotely monitor loads because it is IoT-based through the Thingspeak platform. Additionally, the PZEM 004T sensor stands out with its all-in-one feature, capable of reading voltage, current, power, energy, cos phi, and frequency, making it superior to other sensors on the market. Second, the use of the Automatic cos phi correction method has proven effective and can be applied on a household scale. Lastly, the compensation from capacitors to improve the cos phi produced by inductive loads has proven to save electrical power and increase the capacity of household electricity usage.

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