Development of an ESP32-based microcontroller system for current, power, and energy monitoring of generator units

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Abstract. The reliability of electrical systems in the industrial sector, especially shipping and logistics, relies on optimal generator unit performance as a backup power source. However, manual monitoring of generator electrical parameters such as current, power, and energy still poses risks of recording errors and delayed problem detection. To address this, this research designs and implements a generator electrical parameter monitoring system based on the ESP32 microcontroller using IoT technology. The system integrates PZEM-016 sensors for each phase (R, S, T) to measure current, power, and energy, with data transmitted via RS485 to TTL UART for ESP32 processing. Data is displayed locally through an OLED screen and can be accessed wirelessly via an HTML web server hosted by ESP32 in Access Point mode, eliminating the need for internet access. This study improves previous works by combining local and web-based real-time monitoring, adding Wi-Fi AP functionality, and enabling flexible remote access. The system undergoes testing with various load scenarios such as cell phone charger, laptop charger, and no load to demonstrate its accuracy and ability to differentiate load characteristics. Results show that the system accurately reads and displays data in real-time, enhances monitoring efficiency, and supports reliable generator operation monitoring in industrial environments.

1 Introduction

The development of Internet of Things (IoT) technology has opened up various opportunities in the development of more efficient, integrated, and remotely accessible monitoring and control systems [1]-[4]. One of the devices that are widely utilized in the implementation of IoT is the ESP32 microcontroller, which is equipped with integrated Wi-Fi and Bluetooth features [5][6]. This advantage makes the ESP32 one of the main choices in the development of IoT applications, as it simplifies the data communication process and allows for real-time and wireless device integration [7][8].

In physics, the generator operates on the principle of electromagnetic induction outlined by Faraday's Law: when a magnetic flux changes over time within a conductor loop, it generates an electromotive force (EMF), manifesting as an alternating voltage (V) at the generator's terminals. When a load is connected, this generated voltage causes an electric current (I) to flow through the circuit; the instantaneous electrical power (P) supplied to the load is the product of voltage and current, ($P(t) = V(t) \times I(t)$), and under steady sinusoidal conditions, the active power is given by ($P = V_{rms} \times I_{rms} \times \cos\phi$, where ϕ is the phase angle between V and I). The mechanical torque applied to the rotor (from an engine or turbine) is transformed into electrical power, making precise, real-time measurement of I, V, and P crucial to evaluate genset performance, identify overloads/unbalance, and facilitate predictive maintenance [9].

In the powerpack units or gensets, real-time performance monitoring is crucial [10][11]. This is aimed at ensuring smooth operations and preventing potential damages that can cause downtime or operational disruptions [12]-[14]. Important parameters that need to be continuously monitored include electrical current (Amperes), power (Watts), and electrical energy (kWh) [15][16]. Data from these parameters is vital for evaluating the efficiency and operational condition of gensets [17]-[19]. However, in practice, the monitoring process is still often carried out manually or using systems that are not fully integrated [20][21]. This results in delays in anomaly detection and requires additional time and resources [22]. Therefore, an automated monitoring system capable of acquiring and transmitting data in real-time, and which can be accessed remotely, is needed [23]-[25].

As a solution, this project designs a monitoring system based on the ESP32 microcontroller equipped with a PZEM-016 sensor to measure electrical parameters such as current, power, and energy [26]-[29]. This system is also equipped with device control capabilities through that can be remotely controlled via a web server hosted by the ESP32 [30][31]. The data obtained from the sensors will be wirelessly transmitted via Wi-Fi, allowing operators or technicians to access it from any location using web-based devices [32]. With this system, the monitoring process of the generator

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units is expected to be conducted more efficiently, quickly, and accurately [33]-[35]. This not only improves operational reliability but also minimizes the risk of undetected early damage [36]. Overall, the application of IoT technology in this generator monitoring system is expected to significantly contribute to energy management and operational efficiency [37]-[39].

The research contributions are as follows: the development of a microcontroller-based ESP32 generator set monitoring system, the measurement and monitoring of main electrical parameters (current, power, energy) using the PZEM-016 CCT sensor [40][41], the provision of real-time data access through an ESP32-based web server [42], and the enhancement of the efficiency and operational reliability of the generator set unit [43].

2 Research method

Data collection in this research was carried out through interviews, observations, and field documentation [44]. Secondary data was obtained directly from the company, along with the techniques for data collection and processing in the conducted research.

In Fig. 1 explain the methodology for completing the tasks in this project was initiated with a survey and data collection on the generator units [45]. The initial stages were carried out through direct observation of the generator installation to determine the electrical system configuration, the type of generator used, and the physical and technical conditions related to electrical data collection [46]. Additionally, interviews were conducted with field technicians to obtain information regarding generator usage patterns, load capacity, and technical challenges frequently encountered in monitoring electrical parameters.

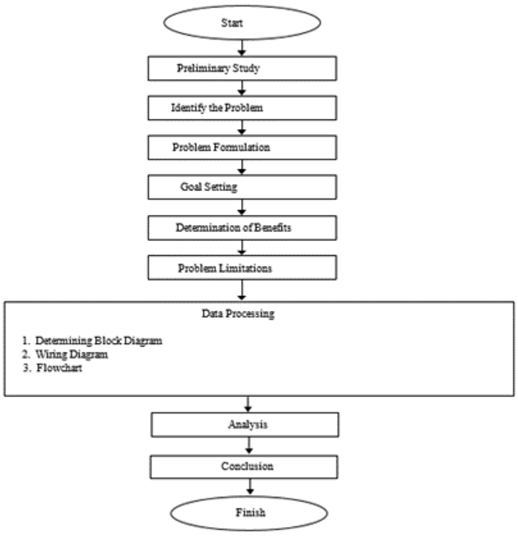

Fig. 1. Research methodology flowchart.

Subsequently, direct measurements of current, power, and energy parameters were taken on each generator phase using the PZEM-016 sensor, which is integrated with the ESP32 microcontroller [47]. This device is designed to collect data in real-time and display it through two media: an OLED screen as a local display and a web interface accessible via the ESP32's internal Wi-Fi network [48].

The data obtained is then analyzed to evaluate the reliability of the monitoring system, the stability of sensor readings, and the effectiveness of data display in supporting remote monitoring [49]. The analysis also includes testing the RS485 interface communication and system stability when operated under various load conditions. The objective of this stage is to ensure that the designed system can function optimally in a dynamic industrial environment.

The project's completion strategy not only emphasizes technical aspects but also focuses on developing an energy-efficient, efficient, and responsive monitoring system tailored to operational needs in the field [50]. The implementation of IoT technology via the ESP32 is expected to enhance the effectiveness of generator monitoring and support digital transformation in energy management within the industry [51].

The block diagram of the electrical parameter monitoring system flow can be seen in Figure 2. It provides an overview of how the ESP32-based system integrates multiple sensors and communication modules to measure, process, and display electrical parameters such as current, power, and energy from the generator in real time.

Fig. 2 shows the workflow of the current, power, and energy monitoring system of the ESP32 microcontroller-based generator set. The system starts from the three-phase generator terminal (R, S, and T), where each phase is measured using three PZEM-016 CCT sensor modules. Each module is tasked with reading electrical parameters such as voltage, current, power, and energy from one phase separately.

Fig. 2. Block diagram.

The data from these three sensors is then sent via RS485 communication, which is then converted into a TTL UART signal using the RS485 to TTL UART module. This conversion is important so that the data can be processed by the ESP32 microcontroller, which is the controlling center of the system. The ESP32 is responsible for processing the data from the three sensors, then displaying the measurement results into two interfaces, namely locally through an OLED screen and remotely through an HTML Web hosted directly by the ESP32 using an Access Point (AP)-based WiFi connection.

Through the integration of all these components, this system is able to monitor electrical parameters in real-time, accurately, and flexibly, both for on-site monitoring and remote monitoring without the need for an external internet connection.

3 Results and discussion

The overall testing process indicates that the designed system maintains stability and accuracy across various load conditions, confirming the reliability of both the PZEM-016 sensors and the ESP32 microcontroller in real-time data acquisition. Furthermore, the system's response time and consistency during continuous operation demonstrate its suitability for industrial applications that require continuous and precise monitoring of generator performance.

The results of the wiring diagram shown in Fig. 3 that has been put together can be observed in Fig. 4 below. This illustration depicts the real physical setup of the system, demonstrating how every element such as the ESP32 microcontroller, PZEM-016 sensors, and RS485 communication modules are linked together to create a fully operational monitoring circuit.

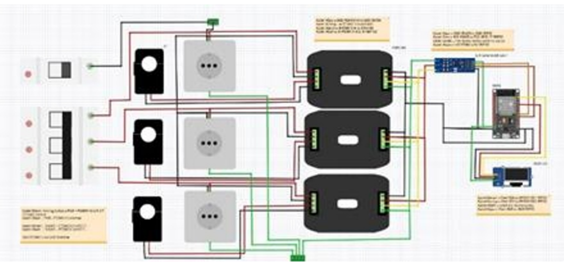

Fig. 3. Wiring diagram.

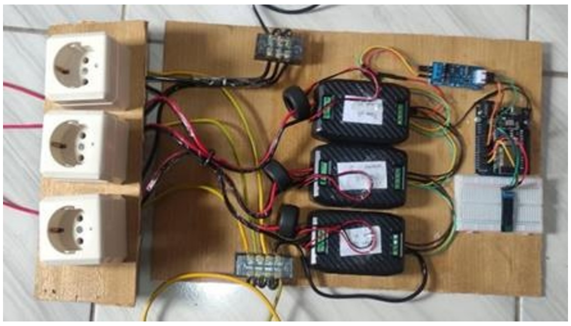

Fig. 4. Assembled wiring.

The generator functions as the primary power source in this system. The current from each phase (R, S, and T) is transmitted to individual PZEM-016 sensor modules that measure electrical parameters such as current (in amperes), power (in watts), and energy consumption (in kWh). Each phase is equipped with its own PZEM-016 sensor to ensure independent and precise measurement. The PZEM-016 receives AC voltage input from the generator through the AC+ and AC– terminals, while the current is detected through the CT coil surrounding each phase wire. These modules record real-time electrical data and convert it into digital form using the RS485 communication protocol.

The digital output from each PZEM-016 is transmitted via RS485 communication lines (pins A and B) and then converted into TTL signals through the RS485-to-TTL UART module, enabling processing by the ESP32 microcontroller. This setup supports reliable, noise-resistant communication over longer distances. The ESP32 collects data from the three PZEM sensors via serial communication (TX2 and RX2), processes it, and displays the information in two ways: the OLED display sequentially shows data for each phase, allowing direct on-site monitoring of the generator.

Additionally, the ESP32 operates as a local server (Access Point), allowing users to access monitoring data via any device connected to its Wi-Fi network, even without internet access. Power sockets are linked to the phase and neutral outputs of the generator, where loads such as phone or laptop chargers can be connected. When a load is active, the PZEM sensor detects variations in current and power, transmits the data to the ESP32, and displays it automatically. Users can conveniently observe the electrical parameters either through the OLED screen near the generator or by accessing the ESP32's local IP address (http://192.168.4.1) from a smartphone or laptop.

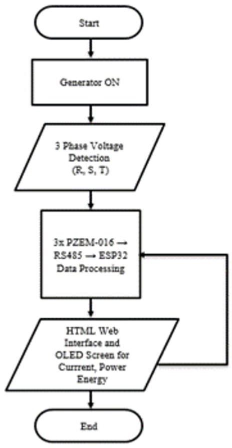

Fig. 5. Diagram flowchart.

In Fig. 5, the flowchart illustrates the working process of the ESP32 microcontroller-based system for monitoring current, power, and energy. The process begins when the generator is activated. Once the generator is turned on, the system starts receiving three-phase voltage inputs from the generator, namely the R, S, and T phases. These voltages are then directed into the measurement circuit for further processing.

Each phase is monitored using three PZEM-016 sensor modules, which measure electrical parameters such as current (Ampere), power (Watt), and energy (kWh). The measurement results from the three sensors are sent via the RS485 communication line, which is then received and processed by the ESP32 microcontroller as the system control center.

The ESP32 microcontroller processes the data collected from all sensors in real time. Once the data is successfully processed, the system presents the monitoring results through two display interfaces. The first interface is an OLED screen that provides local visualization of electrical parameters, allowing users to directly observe the current, power, and energy values at the generator site. The second interface is an HTML-based web page hosted by the ESP32 in Access Point mode, enabling wireless access to monitoring data through devices such as smartphones or laptops without requiring an external internet connection.

Through this configuration, the system enables automatic, efficient, and flexible monitoring of generator electrical parameters, both locally and remotely. The flowchart diagram in Figure 5 illustrates the workflow of the ESP32-based current, power, and energy monitoring system for a three-phase generator set. The process begins at the *Start* stage, where all system components receive power and the microcontroller initiates the monitoring program. Subsequently, the generator is activated as the primary power source, supplying three-phase voltages—R, S, and T—that are fed into the monitoring circuit via the designated input lines.

Each phase is measured independently using three PZEM-016 sensor modules, each responsible for detecting the real-time values of current, power, and energy on its respective phase. The measurement data are transmitted through the RS485 communication protocol, converted into TTL signals, and then received by the ESP32 microcontroller for further processing. The ESP32 efficiently processes all incoming data and displays the results through two visualization platforms. The first is the OLED display, which provides direct on-site monitoring, particularly useful for technicians in the field. The second is a web-based interface that can be accessed via the ESP32's Wi-Fi network configured in Access Point mode. Through this interface, users can wirelessly monitor electrical parameters in real time using mobile or desktop devices without the need for an external internet connection.

Hence, this system offers a practical and adaptable solution for real-time electrical parameter monitoring of three-phase generator sets, supporting both local and remote observation.

In Fig. 6 below shows the initial appearance of the web page hosted by ESP32 before a thorough system trial was conducted. At this stage, although the structure of the web page has been well established, some parts of the monitoring data have not been completely filled. This is due to the unstable communication between the PZEM-016 sensor and the ESP32, as well as the incomplete reading of data from all phases of the genset. Therefore, in this display, some electrical parameter values are not shown or still have a value of zero.

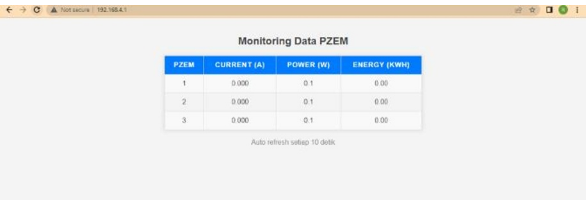

Fig. 6. Results before the trial.

In Figure 7 it can be seen that all the necessary data – namely Current (A), Power (W), and Energy (kWh) – has been successfully displayed in full and in real-time. Each parameter is read from three PZEM-016 sensors, each representing phases R, S, and T on the generator set. This display can be easily accessed through a browser by connecting the device to the Wi-Fi Access Point created by the ESP32, without the need for an internet connection.

The successful change in appearance from Figure 6 to Fig. 7 demonstrates that the monitoring system has functioned according to the project's objectives, which are to provide wireless, automatic, and user-friendly access to generator monitoring. With a simple yet informative table layout, technicians or general users can quickly read and understand the operational conditions of the generator comprehensively.

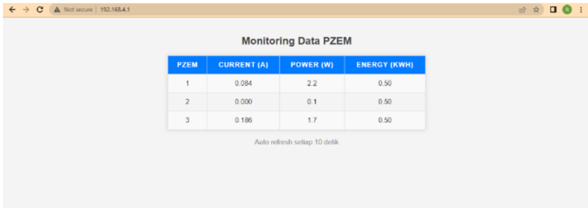

Fig. 7. Results after the trial.

In the testing phase of the ESP32 microcontroller-based generator monitoring system, three units of PZEM-016 sensors were tested, each of which was used to measure electrical parameters on three separate phases. Each sensor is tested with different load conditions to ensure the system's ability to read data accurately according to variations in the electric current flowing.

The PZEM 1 sensor is used to measure the charging load of a cell phone (cell phone charger). The measurement results show a current of 0.084 Ampere and a power of 2.2 Watts. This value is relatively low and in accordance with the power consumption characteristics of cell phone charging. Meanwhile, the PZEM 2 sensor is not given a load or left in a state without a connection to an electrical device. The readings showed a current of 0.000 Ampere and a power of 0.1 Watt, indicating that there was no active current flowing in that phase. The PZEM 3 sensor was used to measure the laptop charging load. Based on the monitoring results, the current detected was 0.186 Ampere with a power of 1.7 Watts. This value indicates that laptops require higher power than cell phones, and the system successfully distinguishes the power consumption characteristics of each load.

All three sensors showed an energy value of 0.50 kWh, which is likely due to the short duration of the test so that the accumulated energy has not changed significantly. All measurement data is displayed in real-time through a web interface page accessed through the ESP32's local IP address (192.168.4.1), and is updated automatically every 10 seconds. From these results, it can be concluded that the monitoring system has worked effectively in measuring current, power, and energy parameters accurately, and is able to adjust readings based on variations in the applied load.

In Fig. 8 On the display, the system successfully displays real-time electrical parameter data from the 3rd PZEM-016 sensor, to measure cell phone charger, and the results of the measurements: Current (I), Power (P), and Energy (E). The values displayed are I = 0.08 A, P = 2.3 W, and E = 0.53 kWh.

This data shows that the sensor has successfully read and sent information to the ESP32, then displayed locally via OLED. This display makes it easier for users or technicians to monitor electrical conditions without having to access the web server, thus increasing efficiency in direct supervision in the field.

Fig. 8. OLED screen display results.

In terms of performance, the proposed ESP32-based generator monitoring system demonstrates several notable strengths. The integration of the PZEM-016 sensor with the ESP32 microcontroller enables accurate and real-time measurement of current, power, and energy parameters for each generator phase. The dual-interface data display through the OLED screen and the ESP32-hosted web server provides both local and wireless monitoring capabilities, which enhance operational flexibility and accessibility in industrial environments without requiring an external internet connection. The use of RS485 communication also ensures stable data transmission and minimizes noise interference during long-distance monitoring.

However, the system still has certain limitations that could be addressed in future work. The current design lacks an automatic notification or alarm mechanism to alert operators in abnormal conditions, such as overload or unstable voltage. Furthermore, the system does not yet support data logging or cloud-based storage, which limits long-term analysis of generator performance and energy trends. Connectivity is also restricted to Access Point mode, preventing integration with broader IoT dashboards or online platforms. Overcoming these limitations in future developments such as adding remote alerts, historical data storage, and cloud connectivity will significantly improve the reliability, scalability, and practicality of the monitoring system.

4 Conclusion

The ESP32 microcontroller-based three-phase generator set current, power, and energy monitoring system that has been designed and implemented is proven to work effectively and efficiently. By utilizing the PZEM-016 sensor, the system is able to read real-time electrical parameters on each phase of the generator set, then display them either locally through an OLED screen or wirelessly through a WiFi-based web server provided by ESP32. The ESP32's ability to run Modbus RTU communication, manage data display, and form a WiFi Access Point network makes this tool very flexible for monitoring needs in industrial environments. In addition, the use of a web interface that can be accessed without an internet connection provides added value, especially in locations that are difficult to reach by networks, such as port areas or field facilities.

In the future, there is still room for development to make this tool more reliable and functional. One development suggestion is to add a remote notification feature, such as SMS or email, in case of abnormal conditions in the system (e.g. current exceeding the limit or unstable power). In addition, integration with historical data storage, either cloud-based or SD card-based, can enrich energy usage analysis and support data-driven generator maintenance planning. The system can also be further developed with Station mode, so that it can be connected to the internet network and remotely controlled through an IoT dashboard based on platforms such as Blynk or ThingSpeak. With this development, the device is not only a monitoring system, but also part of a control and early warning system that supports the digitalization of energy management as a whole.

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