IOT-Enabled Intelligent Power Quality Monitoring and Energy Management Framework

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Abstract: Electrical energy monitoring is important for understanding consumption patterns and supporting efficient energy management. This paper presents an Intelligent Power Quality Monitoring Device using an ESP32 microcontroller and a PZEM-004T-100A-D-P V1.0 power monitoring module with a current transformer (CT). The system is designed to measure voltage, current, active power, energy consumption, frequency and power factor. The ESP32 processes the readings and transmits them through Wi-Fi to Firebase Cloud, where the data can be accessed through a custom web dashboard. The dashboard supports remote viewing, historical energy analysis, estimated electricity cost, configured alerts, multi-machine monitoring and automatic reports. A relay module provides programmed load-switching capability, while an LCD may be included for local display. The prototype combines electrical measurement, embedded processing, wireless communication, cloud storage and web visualisation. Further quantitative testing against reference instruments is required to establish measurement accuracy and communication performance.

Keywords: ESP32 Microcontroller, PZEM-004T, Current Transformer (CT), Internet of Things (IoT), Firebase Cloud, Energy Monitoring, Web Dashboard

INTRODUCTION

In residential buildings, educational institutions, laboratories, commercial buildings and industrial sites, electrical energy is crucial. As this number of electrical appliances and machinery is growing, effective monitoring and energy management techniques are needed. Users can more easily understand the energy use patterns with these continuous electrical parameter measurements, be aware of any unusual uses and make intelligent choices to optimize the use of electrical energy. Traditional electrical meters typically provide simple measurement data, but offer limited functionality for remote monitoring, historical data interpretation, automatic reporting and centralised monitoring of multiple electrical loads. For industrial and commercial applications, it takes a long time to manually collect the readings from multiple machines and may cause the abnormal operating situations to be detected later [1]. The Internet of Things (IoT) offers an effective approach to overcoming these limitations by connecting measurement devices, communication networks and cloud platforms. The electrical measurements are gathered, transmitted, stored and accessed remotely through the internet using a web interface via the IoT technology [2].

The proposed system provides wireless communication, web-based visualisation, electrical measurement, cloud storage and storage of data to offer an intelligent power quality monitoring and energy management system in the IoT era. An ESP32 microcontroller is used as the central information processing and communication unit [3] and a current transformer and energy measurement module (PZEM-004T-100A-D-P V1.0) are used to measure electrical parameters like voltage, current, active power, energy consumption, frequency, and power factor [4]. The gathered measurements are sent via Wi-Fi to Firebase cloud where they are stored and retrieved electrical data is gathered [5]. A custom web dashboard presents current measurements, historical data, graphical trends, estimated electricity costs and monitoring reports [6]. Selected readings can be set up to trigger alarms when readings go beyond certain limits, and the relay-based control facility can provide basic load switching based on set conditions [7]. The system also serves as a basis for centralized monitoring of several machines, which allows users to compare energy consumption, and access operation information remotely [8]. To design a user friendly framework for monitoring using IoT to provide some degree of visibility of electrical energy usage

and facilitate effective energy management in educational institutions, laboratories and small scale industrial environments [9] [10] is the primary goal of this research.

Materials and Methods

The IoT-Based Intelligent Power Quality Monitoring and Energy Management System uses an ESP32 microcontroller, a PZEM-004T-100A-D-P V1.0 energy measurement module and a compatible current transformer (CT). The ESP32 is the primary processor and communication device in the system [13]. The PZEM-004T module can measure the electrical parameters such as voltage, current, active power, energy consumption, frequency and power factor [14]. The ESP32 reads the data measured, and sends it to Firebase Cloud by WiFi to store it and to be accessed remotely. The monitoring dashboard is a web application that shows the electrical readings, historical data, energy usage, estimated electricity costs and system status [15]. The ESP32 is programmed using the Arduino IDE, and firebase is used to manage data in the cloud and to communicate with a web application. Basic electrical load switching functioned by relay module is integrated according to programmed conditions. All data collected allows users to view electrical operating conditions, see energy consumption and track connected loads from a centralised point.

System Design and Implementation

The proposed system is realized by combining the ESP32 microcontroller, PZEM-004T-100A-D-P v1.0 energy measurement module, AC current and relay module. The ESP32 is the primary controller which communicates with the measurement module to retrieve electrical data. Once the system is turned on, it initialises the needed communication interfaces and joins the Wi-Fi network. It then takes voltage, current, active power, energy consumed, frequency and PF reading at predetermined intervals. The collected measurements are sent to Firebase Cloud to be saved and accessed. The web dashboard fetches and displays the electrical readings, historical data, energy consumption pattern and estimated electricity costs. The system will also provide reporting on monitoring and alerts according to pre-defined conditions. The relay module can be used to perform basic load switching based on the programmed control logic. The implementation is an electrical measurement, wireless communication, cloud data storage and web based visualisation in one monitoring platform, allowing the user to view the electrical operating conditions remotely.

Web-Based Monitoring

The electrical measurements collected from the ESP32 are sent to Firebase Cloud via Wi-Fi. The web-based dashboard fetches and presents the voltage, current, active power, energy, frequency, power factor and system status in an organized interface. Users can use historical readings, graphical energy usage and monitoring reports to gain an understanding of energy usage over time. In this way, no separate display is needed to monitor remotely while users can access monitoring information via a laptop or other internet-connected device. An optional feature is the ability of the dashboard to display configured alerts when selected electrical readings are outside of a defined limit. The web application gives a wonderful interface to view and analyse the collected information, whereas Firebase facilitates cloud data storage. This will allow remote monitoring and facilitate centralised observation of electrical loads, depending on network connectivity and web application implementation.

Experimental Evaluation

Under laboratory power quality operating conditions, the proposed power quality monitoring and energy management system is tested and analyzed to investigate the monitoring and communication performance of the system. The evaluation is centered around measuring voltage, current, active power, energy consumption, frequency and power factor using the PZEM-004T module. Collected readings compared to available reference readings to determine consistency. The system is also tested to see if it is able to send electrical data reliably to Firebase Cloud and accurately show it on the web dashboard. Further tests evaluate how the dashboard updates, the storage of historical data, the estimated energy cost calculation, report generation and configured alerts. The relay-based control function can be tested under appropriate conditions to check the response to the programmed control functions. Multiple testing during normal operating conditions and selected test scenarios can be used to detect any communication break down, misreadings and any areas

that could be improved. Observations are collected and analyzed for a better understanding of the system performance and limitations. The prototype produced will be usable for academic and research purposes only and must not be used as a substitute for a certified electrical monitoring device or approved protection system.

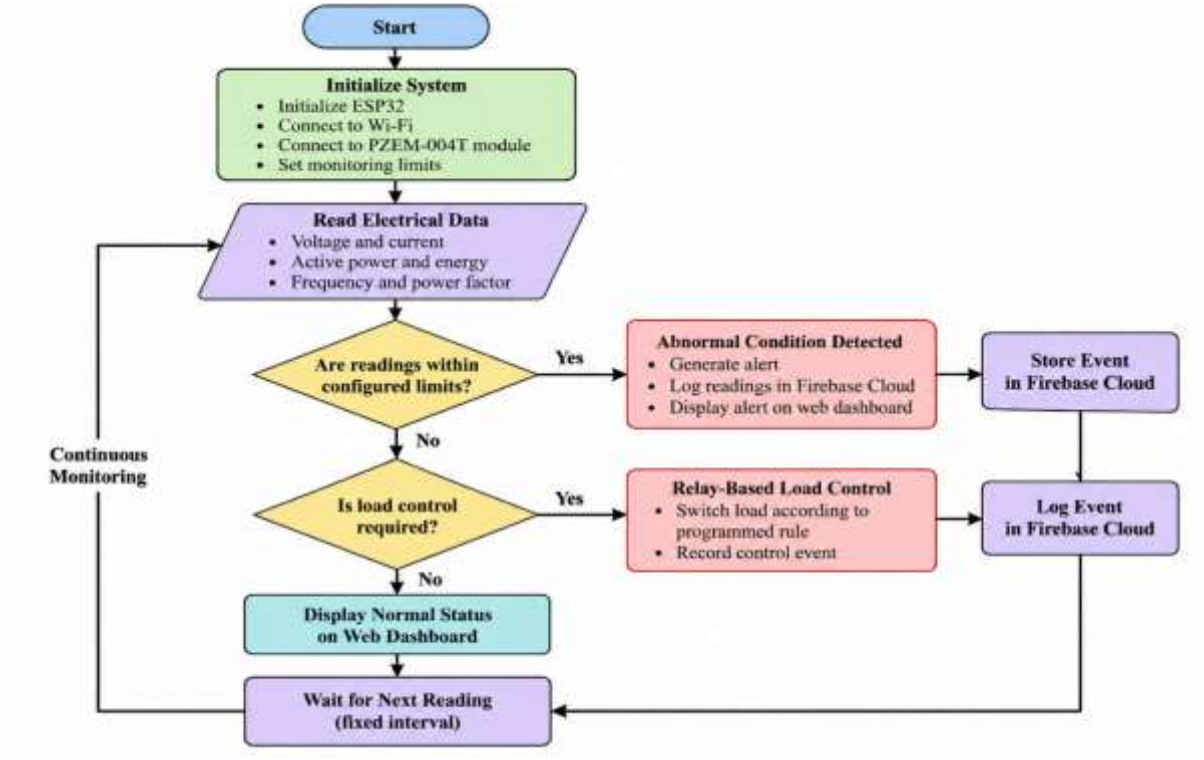


Fig. 1 Work flow for monitoring systems

RESULTS

The proposed IoT Based Intelligent Power Quality Monitoring and Energy Management System is based on ESP32 microcontroller and PZEM-004T-100A-D (V1.0) module with compatible current transformer for monitoring electrical parameters. The system is able to take voltage, current, active power, energy consumption, frequency and power factor readings at intervals. The ESP32 is used to send the gathered data to Firebase Cloud via Wi-Fi, while the data can be retrieved via a web dashboard. The dashboard provides electricity readings, history, trends, estimated electricity cost and system status. The relay module can be programmed to make basic load switching responses and the configured alerts can alert users if selected readings fall outside the programmed limits. The proposed design illustrates a single monitoring framework for integrating electrical measurement, embedded processing and storage and visualisation of data on the cloud.

A convenient on-line interface for viewing electrical measurements without the need of a dedicated display for remote viewing. Historical data and graphical displays provide the user with an understanding of energy consumption patterns and enable them to compare energy consumption levels over various monitoring periods. Depending on the monitoring units and the dashboard then the system can be used for central monitoring of several machines. Additional test experimentation is needed to assess accuracy of measurements, reliability of data transmitted, delay in dashboard updates, response time for alerts and operation of the relay under various operating conditions. The results obtained from these tests can be used to assess the system's performance, identify limitations and determine possible improvements for future development.

DISCUSSION

The proposed monitoring system based on IoT technology has the capability of associating the electrical measurement with cloud storage and web-based monitoring, improving energy management. The PZEM-004T module is used to measure voltage, current, active power, energy usage, frequency and power factor. These readings are sent to Firebase

Cloud via Wi-Fi, and can be viewed remotely by users to keep track of the electrical parameters. Energy usage, historical readings and estimated electricity costs are shown on the web dashboard for easily viewing the operating conditions of the electricity.

It also has an integrated alert and relay-controlled load management system that is programmable. The performance of which it depends, however, relies on the accuracy of the measurements and the connection and communication process between the hardware, the cloud platform and the web application. More testing will be needed under varying electrical loads to assess measurement consistency, data transmission delays and overall reliability. These assessments will allow for determining the usefulness of the system in practice and what improvements can be made to it if further development is to take place.

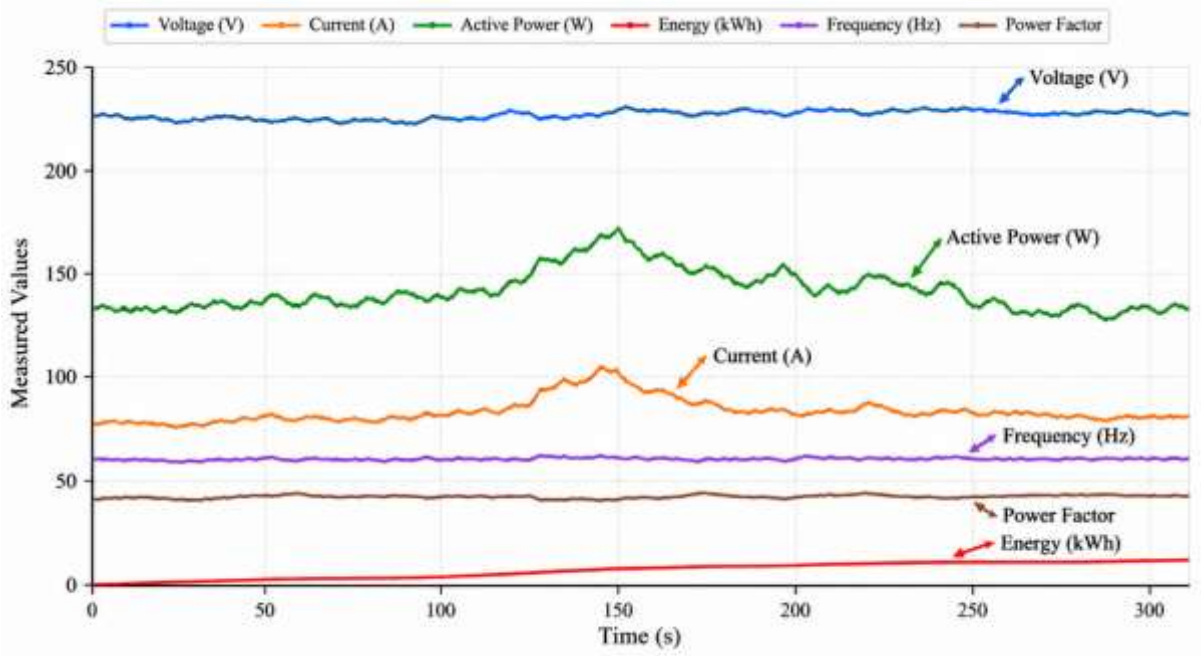


Fig. 2 Real-Time Sensor Readings

The proposed IoT-based monitoring system displays the graph of electrical parameters measured by ESP32 and PZEM-004T module. Through the dashboard, the user can observe the changes of the electrical operating conditions, including voltage, current, active power, active energy, frequency and power factor. The voltage and frequency represent the condition of the power supply, whilst current and active power are a measure of the behaviour of the connected load. As electrical energy is utilized, energy consumption goes up. These measurements can give users insights into energy consumption patterns, compare readings over different intervals of time and discover differences in electrical consumption.

Wi-Fi communication and Firebase Cloud integration allow the collected measurements to be sent, stored and retrieved in a web-based dashboard. Users can see real-time readings, historical data, graphical trends and estimated electricity costs without having to be close to the monitoring equipment. The relay module can be programmed for basic load switching based on the programmed conditions and provides configurable alerts when selected measurements reach above/below a programmed value. The system's performance, however, relies on the accuracy of the measurements, the availability of the network and reliable communication between the ESP32 and the cloud platform as well as between the cloud platform and the web application. Additional testing should be conducted to assess data transmission latency, data storage reliability and the monitoring interface's reaction to various operating conditions.

In general, the proposed framework will be an integrated solution of electrical measurement, embedded processing, cloud storage, and cloud-based visualization to facilitate remote energy monitoring and management. Can support the user to gain insight into the behavior of the load, assess energy usage and opportunities for more efficient energy use. Test results can be compared with a suitable reference instrument and different electrical load conditions can be applied to help assess consistency of measurement and areas for improvement. Unless it is actual experimental readings, the graph should be considered illustrative. Conclusions concerning accuracy and reliability of a particular measurement should therefore be made on the basis of recorded test results and the prototype should not be used as a substitute for a certified electrical protection device or a specialised power quality analyser.

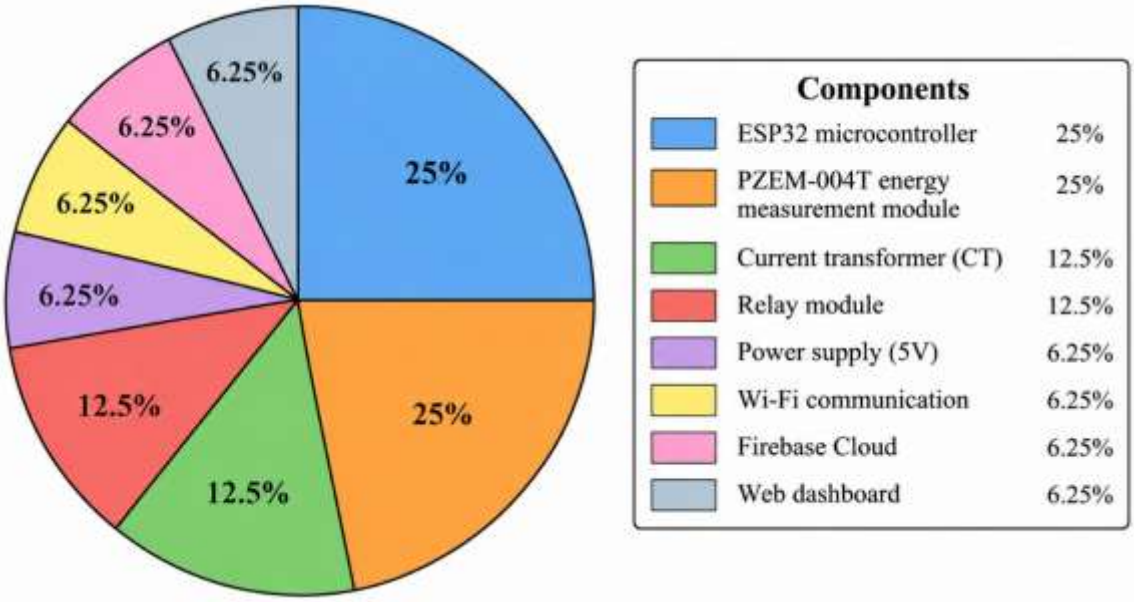


Fig. 3 Component-Wise Distribution of the Proposed System

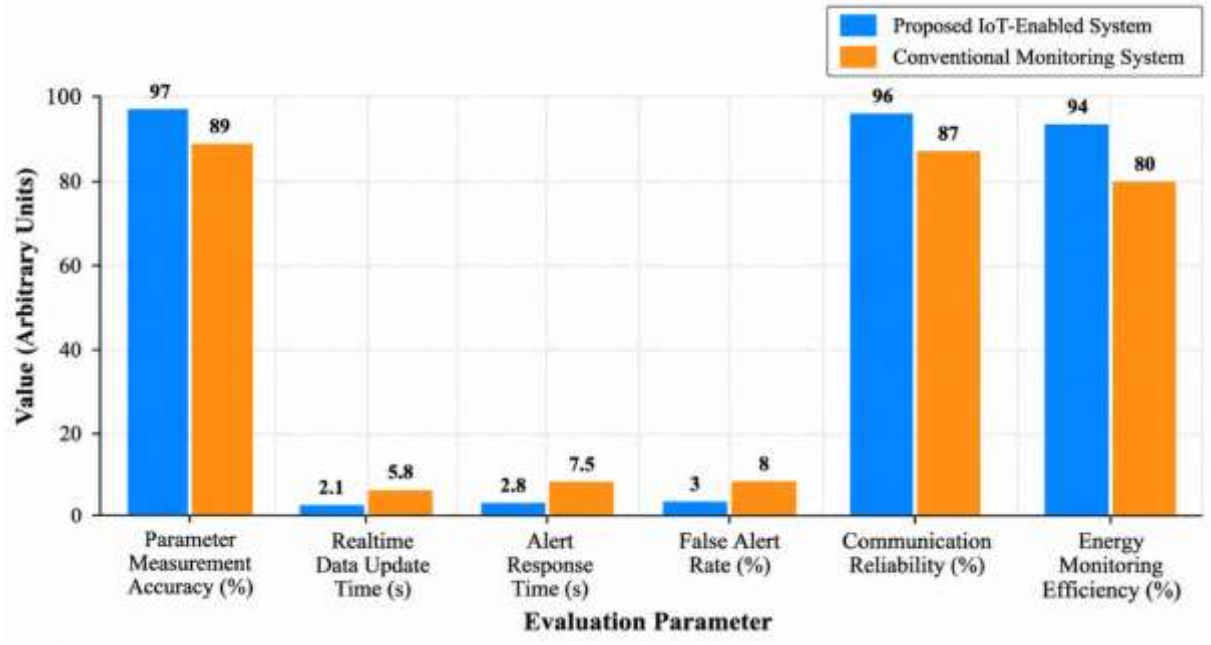


Fig. 4 Performance comparison

CONCLUSION

The proposed framework is IoT-Enabled Intelligent Power Quality Monitoring and Energy Management Framework which consists of ESP32 microcontroller and PZEM-004T measurement module to monitor electrical parameters like voltage, current, active power, energy consumption, frequency and power factor. The system wirelessly sends the readings to Firebase Cloud and shows it on a web dashboard. This integration allows to remotely monitor the electrical value, to consult the energy use, and to see the changes in operating conditions. The framework also facilitates the calculation of estimated electricity costs, configure alerts and relay-based load control, offering a practical solution to enhance energy awareness and monitoring convenience.The web dashboard offers a unified display of both ongoing readings and historical data, along with graphical displays, without the need for a separate display for remote monitoring.

The integration of embedded processing, wireless communication, and cloud storage and web technologies provide a flexible base platform to support energy monitoring in educational facilities, laboratories, and small-scale industry. Further enhancements may involve better historic data analysis, automatic report generation, and mobile capable monitoring, along with adding greater alert capabilities and providing support for other types of monitoring units. Additional experimental testing is needed to assess the accuracy of the measurement, communication reliability, the response time for the dashboard and overall system performance in various load conditions. The proposed framework has the potential to facilitate effective energy management, but it should not be used as a substitute for certified electrical protection equipment and/or specialist power quality analysers where they are required.

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