Design of IoT Enabled Three Phase Power Quality Monitoring Unit Based on EmonLibCM Library

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Abstrak. Penelitian ini menyajikan pengembangan perangkat pemantau kualitas daya tiga fasa yang hemat biaya dan handal, menggunakan komponen yang mudah diperoleh serta pustaka sumber terbuka EmonLibCM. Perangkat ini mengatasi keterbatasan perangkat satu fasa yang ada, dengan menawarkan pemantauan komprehensif untuk aplikasi industri dengan kapasitas di atas 100 kVA. Arsitektur sistem memanfaatkan beberapa Arduino untuk pemrosesan data sensor dan Raspberry Pi untuk komunikasi data, penyimpanan, serta antarmuka pengguna. Node-RED digunakan untuk visualisasi data secara real-time pada dasbor yang ramah pengguna, sementara SQLite memungkinkan pencatatan data untuk analisis lebih lanjut. Perangkat ini secara akurat mengukur parameter listrik penting, termasuk tegangan, arus, daya aktif, daya semu, frekuensi, dan konsumsi energi, dengan rata-rata kesalahan kurang dari 5% dibandingkan dengan Power Quality Analyzer referensi. Penelitian ini berkontribusi pada pengembangan solusi pemantauan kualitas daya yang terjangkau dan mudah diakses, mendukung praktik manajemen energi yang lebih baik di lingkungan industri.

Kata kunci: pemantauan kualitas daya; sistem tiga fasa; node-red; pencatatan data; hemat biaya

Abstract. *This research presents the development of a cost-effective and reliable three-phase power quality monitoring device using readily available components and the open-source EmonLibCM library. The device addresses the limitations of existing single-phase devices, offering comprehensive monitoring for industrial applications with capacities above 100 kVA. The system architecture utilizes multiple Arduino boards for sensor data processing and a Raspberry Pi for data communication, storage, and user interface. Node-RED facilitates real-time data visualization on a user-friendly dashboard, while SQLite enables data logging for further analysis. The device accurately measures essential electrical parameters, including voltage, current, real power, apparent power, frequency, and energy consumption, with an average error of less than 5% compared to a reference Power Quality Analyzer. This research contributes to the advancement of affordable and accessible power quality monitoring solutions, promoting better energy management practices in industrial settings.*

Keywords: *power quality monitoring; three-phase systems; node-red; data logging; low-cost*

1. Introduction

Electrical energy is vital to modern industry, serving as a fundamental driver of productivity and economic growth [1]. Industries rely on electricity to power machines, automate processes, and maintain production lines [2]. To ensure the sustainability of electrical energy usage in industry, the electrical power quality has to be maintained. Power quality refers to how well the electricity delivered to electrical equipment matches the desired characteristics. It is an essential aspect of electrical power distribution and consumption, and it encompasses a wide range of parameters that impact the performance, reliability, and safety of electrical equipment. The measure of electrical power quality to meet the requirements of the devices is influenced by multiple factors, namely voltage level, unbalanced voltage, transients, power factor, etc. [3] From an economic perspective, poor power quality can result in significant financial losses. Equipment downtime, slower processes, and lower energy efficiency are some of the negative effects, which also extend to indirect costs like reduced labor productivity and lower product quality [4].

A solution to prevent poor power quality issues in industrial settings is to conduct power quality assessment by using a power quality monitoring. It is an electronic device typically installed in industrial, commercial, and utility settings, used to measure and record various electrical parameters. There are many commercial power quality monitoring units currently available in the market. Their specifications vary based on some parameters namely measurement capacity, features, and accuracy [5]. However, basically they have three main functions which are performing measurements, processing data, and establishing data communication [6] .

According to [5], the average cost of power quality monitoring is around 1000 euros. The cost can increase depending on the level of accuracy and resolution. While power quality monitoring units are powerful tools for assessing electrical power quality, their cost still becomes one of the prominent considerations in doing so [7]. High costs can hinder adoption of power quality monitoring for small and medium enterprises, especially those operating in developing countries. Addressing this challenge, many researchers have created various developments of low-cost power quality monitoring devices. Typically, the system architecture of a power quality monitoring unit consists of three main parts, namely sensors, microcontroller, and a server to record and display the results.

In a power quality monitoring unit, sensors are the most indispensable components. They function to read the electrical quantities and then transform it into proper analog signals. Sensors that are definitely required in the device are current and voltage sensors. The most common current sensors used in power quality monitoring include invasive and non-invasive type. The underlying principle of an invasive current sensor is by introducing the sensor into the current conducting path. The example implementation of this sensor is ACS712 module which is utilized by [8] and [9]. It exploits the working principle of Hall-effect. Although this sensor is applicable for AC current, it is best suited to DC current and is not ideally suited to electrically noisy environments [5]. Another type of invasive current sensor is the PZEM-004 module which comes with two types of measuring method, shunt resistor (max 10A) and solid core current transformer (max 100A). As recommended by [10], this module provides convenience because it also has a voltage sensor making it easier to measure power of many electric appliances.

The non-invasive current sensors, which make use of the split core current transformer principle, are ideally suited to monitoring applications within industrial facilities. They can be easily installed without interrupting the power system and production process [11]. An example of this kind of sensor available on the market is SCT-013. This kind of sensor has found extensive application in the development of power quality monitoring devices due to their relative simplicity whilst still providing reasonable accuracy [12]. However, according to the specification, SCT-013 can only measure current up to 100 A. This condition makes this type of sensor have a limited measurement range, especially for electrical systems with large power.

To process sensor measurement data, the power quality monitoring unit requires a microcontroller. Some sensors, for example the SCT-013 series, make measurements by generating analog electrical signals. These analog electrical signals need to be converted into digital data by the microcontroller. The analog signal generated by the SCT-013 is an alternating current signal. Since most of the microcontroller's analog signal input pins can only accept direct current signals, there is a necessity to place a conditioning signal circuit between the sensor and the microcontroller. Some types of sensors have built-in analog to digital converter features. In this case, data from sensors is acquired by the microcontroller through a data communication mechanism with a specific protocol. As an example, design by [10] proposes the usage of PZEM-004 modules which make use of serial data communication protocol. Hence, the implementation becomes much simpler and there is no need to build any signal conditioning circuit.

In prototyping their power monitoring units, many researchers ([13], [14], [15], [16], and [17]) utilize Arduino, the cost-effective microcontroller boards based on Atmel 8-bit AVR. Apart from its low price, Arduino's popularity is due to the large amount of support from library developers that makes it easier for users to create programs. Another microcontroller board that is gaining popularity due to its internet of things features is ESP module. Through NodeMCU firmware pre-loaded onto it, this microcontroller board enables wireless data communication via Wi-Fi or Bluetooth technology [18]. This ability is utilized to develop power monitoring units that permit their users to interact with their device remotely ([19], [20]) or to maintain the safety of the electrical equipment from fire hazard [21].

Data recording is a key feature of a power monitoring unit which is required to analyze the profile of an electrical system. Executing this feature certainly requires a server, such as a single-board computer, which has a computing power and data storage capacity more than a microcontroller. Raspberry Pi is the most popular single-board computer used to perform the task. Instead of using bulky personal computer desktop, many studies ([15], [16], [22], and [23]) opt to use Raspberry Pi for its relatively small size yet workable to meet some certain levels of computing demands. There are certainly other options for the device, for example NanoPi Air [24]. However, most of these alternatives have less supports from the developer’s community than Raspberry Pi.

A server in a power monitoring unit must possess not only computational capability but also features that facilitate the presentation of data in a user-friendly fashion. Due to the emphasis on modification flexibility, some researchers opt to create data visualization display designs from the ground up using programming tools such as PHP [25], Android applications ([9], [8]) HTML [24], and Flask Web [22]. Other academics employ data visualization tools that facilitate the creation of dashboards for users, such NodeRED [15], EmonCMS ([14], [16], [26]), Power BI [22], and Grafana [23]. A number of power monitoring unit innovations make use of IoT platform services like Blynk ([27], [28]), ThingSpeak ([29], [30]), myDevices [31], and Adafruit [32], which are made possible by the advancement of cloud technology. Nevertheless, there are drawbacks to using these services, such as reliance on the internet network and more expensive subscription fees.

One of the most extensively adopted open-source tools to promote the development of low cost power quality monitoring devices is EmonLib [33]. It is a programming library for microcontrollers, particularly Arduino, used to simplify electrical parameter measurements namely voltage, current, power (real and apparent), power factor, and energy consumption. The library is remarkably useful to convert analog signals from sensors into versatile digital numeric data. The adoption of EmonLib to develop power and energy monitoring units has been carried out in various designs. In addition to providing open-source softwares, OpenEnergyMonitor, the project that created EmonLib, also supplies some commercial power and energy monitoring-related products. Some researchers purchased these products to support their studies [34], [35], [26]. However, the products are limitedly available at certain areas, commonly in the United Kingdom and Europe market. Other EmonLib users decided to build their monitoring units by utilizing the more affordable components [36].

A summary of the research findings for creating a power monitoring device that makes use of EmonLib is shown in Table 1. Three criteria—power system measurement, the capability of the present sensor in use, and application cases—were used to evaluate earlier studies. The findings of earlier research investigations showed that single-phase electrical systems are the primary application for most power monitoring unit developments that use EmonLib. Since most of the electrical equipment is powered by a single phase, this is likely to occur. From the perspective of measuring capacity, the majority of the instruments created make use of existing sensors that have a capacity of less than 100 amperes. This condition arises as a result of the majority of developers using the non-invasive current sensor series YHDC SCT-013, which has a type with a maximum measurement capability of 100 amperes [37]. Furthermore, laboratory experiments were used for the majority of the research, according to the summary of the application instances. Given that the established devices' degree of applicability is still debatable when used in actual circumstances. This situation is undoubtedly not desirable. According to the explanation given above, there are still gaps in the development of EmonLib-based power monitoring equipment. The first is that the electrical system's power measurement capacity is limited to about 22 kVA for a single phase electrical system. The second is the lack of substantial real-world testing, particularly in industrial settings, of the created instrument.

Table 1. Summary of Research on Power Monitoring Devices.

Reference	Power System Measurement		Current Sensor Capacity		Application Case
	Single Phase	Three Phase	Less than 100 A	More than 100 A	
[34]	v		v		Household appliances
[28]	v		v		Household appliances
[15]	v		v		Household appliances
[14]	v			v	Laboratory experiment
[16]	v		v		Laboratory experiment
[17]	v		v		Laboratory experiment
[29]		v	v		Laboratory experiment
[38]	v		v		Laboratory experiment
[8]	v				Laboratory experiment
[22]	v		v		University Auditorium
[39]	v		v		Main Distribution Panel
[31]	v				Laboratory experiment
[9]	v				Laboratory experiment
This research		v		v	Industrial Low Voltage Main Distribution Panel

The present study is motivated by the shortcomings of earlier research to enhance the use of EmonLib in order to develop a power monitoring unit that can be utilized for industrial electrical system assessment. With a three-phase electrical system, industry often has fairly high electricity demands. The goal of this project is to use the open source EmonLib library to develop a three-phase power monitoring device with an adequate measuring capacity, specifically above 100 kVA. EmonLib offers a lot of potential for use in facilitating the creation of affordable power monitoring devices. In addition to enabling households to save energy, its use can assist companies, particularly small and medium-sized enterprises, to monitor their electricity consumption.

2. Research Method

This research follows the typical IoT waterfall methodology as proposed by [40]. It is a sequential development process that flows like a waterfall through all phases of a project. The methodology involves four steps, namely identification of requirements; design of the system; system development; and the system testing. A case study is provided to show how the proposed design in this research is implemented.

2.1. Identification of Requirements

This initial phase focuses on understanding the needs and goals of the project. It involves gathering information from stakeholders (such as the customer or end-users), defining the scope of the project, and establishing clear objectives. For the power monitoring device, the requirements included the ability to measure three-phase electrical systems, handle capacities above 100 kVA, provide real-time data visualization, and offer data logging capabilities.

2.2. Design of The System

Once the requirements are established, the next step is to create a detailed blueprint of the system. This includes selecting the appropriate hardware and software components, defining the system architecture, and developing algorithms for data processing and analysis. The design phase ensures that the system will meet the specified requirements and function effectively.

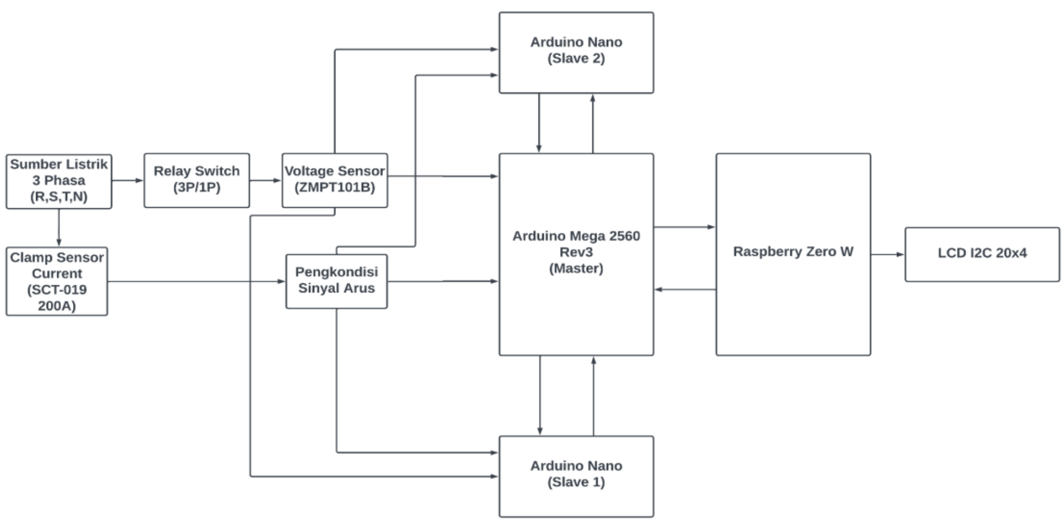

Figure 1. Components of The System

The system architecture, as depicted in Figure 1, reveals the key components and their interconnections.

a. Sensors: SCT-019 current sensors and ZMPT101B voltage sensors were chosen for their ability to accurately measure the targeted electrical parameters.
b. Microcontrollers: Arduino Nano and Arduino Mega boards were selected for data processing, with the Mega acting as the master controller and the Nanos as slaves for each phase. The choice of Arduino was likely influenced by its affordability, ease of use, and wide availability of supporting libraries, particularly the EmonLibCM library specifically designed for power monitoring applications [41].

c. Communication: The system utilizes serial communication between the Arduino boards and a Raspberry Pi Zero W, which acts as the central hub for data aggregation and visualization.
d. Data Visualization and Storage: Node-RED, a visual programming tool, was implemented on the Raspberry Pi to create a user-friendly dashboard for real-time monitoring. SQLite was used for data logging, allowing users to store and download historical data.

2.3. System Development

This phase involves the actual implementation of the design. It includes programming the microcontrollers, configuring the Raspberry Pi, setting up the network infrastructure, and constructing the physical enclosure for the device. The development phase requires a combination of technical skills and attention to detail to ensure that the system is built according to the specifications.

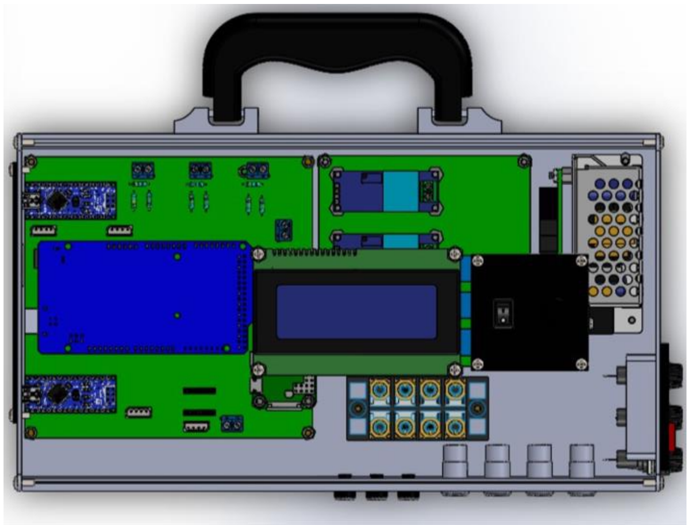

Figure 2. 3D Visualization of The Internal Layout

Figure 2 presents a 3D visualization of the internal layout of the power quality monitoring device's enclosure. This figure provides insights into how the various components are arranged and interconnected within the device.

2.4. System Testing

After the system is developed, it undergoes rigorous testing to verify its functionality, accuracy, and safety. This involves evaluating the device's performance under various conditions, comparing its measurements against a reference device, and assessing its ability to handle potential errors or failures. The testing phase is crucial for identifying any issues that need to be addressed before the device is deployed in a real-world setting.

The testing phase involved a multi-faceted approach to verify the device's performance:

a. Enclosure Testing
   The physical enclosure was evaluated for its ability to protect the electronic components and prevent electrical hazards.
b. Circuit Testing
   The circuits were rigorously tested using an oscilloscope and a multimeter to ensure signal integrity and proper operation of the sensor conditioning circuits.
c. Accuracy Validation

The sensor readings were compared with a reference Power Quality Analyzer to determine the accuracy of the device's measurements. The results showed that the device's measurements were within an acceptable tolerance of the reference device, with an average error of less than 5%.

3. Results and Discussion

3.1. Results

This section presents the results and findings of the research project, focusing on the development and testing of the three-phase power quality monitoring device.

3.1.1 Hardware Design and Assembly

The hardware implementation process began with a thorough consideration of the device's intended functionality and operational environment. This involved selecting appropriate components, designing circuit layouts, and constructing a robust enclosure to house the electronics.

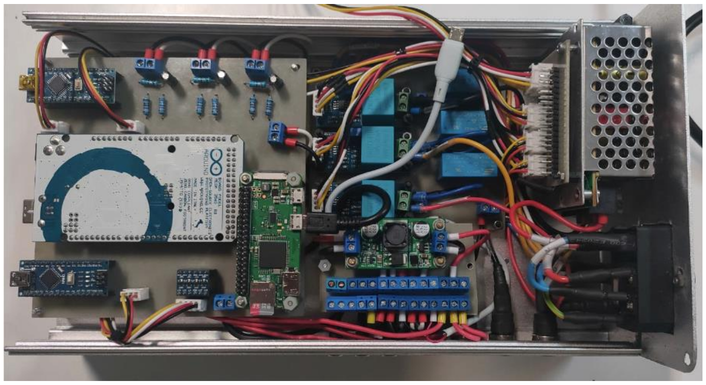

Figure 3. Internal View of The Device

Figure 3, depicting the internal view of the device's enclosure, highlights the practical realization of the design concepts. The image showcases the arrangement of essential components, including the Arduino Nano, Arduino Mega, Raspberry Pi Zero W, LCD screen, switches, and various connectors. The careful placement of these components within the aluminum enclosure, measuring 300mm x 170mm x 90mm, aims to ensure efficient wiring, minimize electromagnetic interference, and optimize heat dissipation.

Figure 4. The Complete Device

The enclosure, as revealed in Figure 4, is made of aluminum, measuring 300 mm x 170 mm x 90 mm. It includes several strategically placed openings:

a. Sensor Inputs: Openings are provided for connecting the SCT-019 current sensor and the ZMPT101B voltage sensor, allowing the device to acquire data from the electrical system.
b. Probe Connections: Dedicated openings facilitate the connection of external probes, expanding the device's measurement capabilities, potentially up to 1000 VAC.
c. LCD Display: An opening accommodates a 16x2 LCD screen, providing a visual interface for displaying real-time measurements and system status information.
d. Switches: Openings are allocated for various switches, including a brightness control for the LCD screen, a mode selector for switching between line-to-line and line-to-neutral measurements, and a power switch for controlling the device's operation.
e. Fuse: A fuse is integrated into the design to protect the device from overcurrent, enhancing its safety and reliability.
f. Power Input: An opening allows for the connection of a power source, enabling the device to operate.
g. Communication Ports: Openings are provided for the USB port of the Raspberry Pi Zero W and the communication ports of the Arduino Nano and Arduino Mega, facilitating data transfer and device configuration.

This comprehensive approach to enclosure design, as visualized in Figure 4, demonstrates a commitment to both functionality and practicality, ensuring the device's suitability for industrial applications where reliability and ease of use are paramount.

The hardware testing focused on verifying the functionality of the individual components and the overall system. The following tests were conducted:

a. Continuity Tests
   Using a multimeter, continuity checks were performed on all circuit connections to ensure proper electrical pathways.
b. Voltage and Current Measurements
   Voltage and current levels at various points in the circuit were measured using a multimeter and a clamp meter, respectively, to confirm that the sensors and the signal conditioning circuits were operating correctly.
c. Signal Integrity
   Oscilloscopes were used to visualize the waveforms of the voltage and current signals to ensure their quality and identify any distortions or noise.
d. Safety Features
   Functionality of safety features like fuses and surge protection was tested to ensure the device's protection against overcurrent and voltage spikes.

Figure 5. Hardware Tests.

These hardware tests confirmed the correct operation of the device's components and the overall circuit design, laying the foundation for the software development and integration.

3.1.2 Software Development and Integration

The software development involved programming the Arduino boards and the Raspberry Pi that drives the device's functionality, leveraging the hardware components. Key aspects of the software development included:

a. Sensor Data Acquisition and Processing
   Arduino Nano and Arduino Mega boards were programmed using the EmonLibCM library to acquire data from the current and voltage sensors, calculate electrical parameters like real power, apparent power, and power factor, and format the data for transmission.
b. Data Communication and Synchronization
   Arduino boards were programmed to communicate with each other and with the Raspberry Pi using serial communication protocols. The SoftwareSerial library in the Arduino IDE was used for robust data transmission between the Arduino boards, addressing the challenge of data collisions encountered during development.
c. Data Visualization and User Interface
   Node-RED on the Raspberry Pi was used to create a user-friendly web-based dashboard for real-time data visualization. The dashboard displays essential electrical parameters in numerical and graphical formats, providing users with an intuitive interface to monitor power quality.
d. Data Logging and Storage
   SQLite, a lightweight database management system, was implemented on the Raspberry Pi to store historical data acquired from the sensors. This data logging functionality allows for trend analysis and identification of long-term power quality issues.
e. Calibration and Configuration
   Node-RED was also utilized to implement calibration routines for the sensors and to provide configuration options for the device. This allows users to adjust the device's settings to match their specific monitoring requirements.

3.1.3 *Sensor Accuracy and Calibration*

To ensure the accuracy of the power quality monitoring device, the sensor readings were validated against a reference Power Quality Analyzer. The accuracy testing involved comparing the device's measurements for voltage, current, power factor, frequency, and energy consumption with those obtained from the reference instrument. The results of the accuracy testing are summarized in Table 2, indicating that the average error across all parameters and channels was less than 5%. This level of accuracy validates the device's reliability and suitability for monitoring power quality in industrial settings.

Table 2. Average Measurement Deviation Test Results for Line to Neutral Mode.

Error Tests	Channel 1 (R)	Channel 2 (S)	Channel 3 (T)
Avg. Voltage	0,11%	0,32%	0,15%
Avg. Current	3,32%	2,23%	2,58%
Avg. Active Power	1,99%	1,95%	1,89%
Avg. Apparent Power	3,84%	1,06%	4,56%

Avg. Frequency	0,08%	0,08%	1,62%
Avg. Power Factor	1,77%	1,81%	1,97%

The device also incorporates calibration routines, accessible through the web-based dashboard, to compensate for sensor variations and ensure long-term accuracy. The calibration process involves adjusting the sensor readings based on the readings obtained from a reference instrument.

3.2. Discussion

The discussion highlights the key outcomes, analyzes the device's performance, and addresses potential areas for improvement.

3.2.1. System Performance and Limitations

The developed three-phase power quality monitoring device demonstrated robust performance in measuring and recording essential electrical parameters. The system's real-time monitoring capabilities, data logging functionality, user-friendly dashboard, and calibration features make it a valuable tool for assessing power quality in industrial settings. The device's accuracy, as validated against a reference instrument, ensures reliable data acquisition and analysis.

However, the system does have some limitations:

a. Data Calibration Transmission Time
Sending calibration data from the Raspberry Pi to the Arduino boards takes a few seconds due to the need for communication between the multiple Arduino boards involved in the process.
b. Local Network Dependency
The device currently relies on a local network connection for data visualization and configuration, limiting its remote accessibility.
c. Limited Sensor Range
The project was designed for currents up to 200A and voltages up to 400VAC. While the probe can measure up to 1000VAC, the overall system has limitations for higher power applications.

3.2.2. Future Enhancements and Applications

This research project successfully developed a cost-effective and reliable three-phase power quality monitoring device that addresses the limitations of existing single-phase solutions. The device offers a comprehensive approach to power quality assessment, empowering users to identify and mitigate potential issues, contributing to improved energy efficiency and reduced operational costs. Building on this foundation, future research could focus on:

a. Implementing Remote Accessibility
Enhancing the device's software to enable remote monitoring and configuration via cloud platforms or mobile applications would significantly expand its usability and convenience.
b. Expanding Sensor Capabilities
Integrating additional sensors, such as temperature sensors, could provide a more comprehensive understanding of the system's operating conditions, enabling proactive maintenance and fault detection.
c. Developing Advanced Data Analytics
Implementing machine learning algorithms to analyze historical data could enable predictive maintenance, fault diagnosis, and energy consumption optimization.

The successful implementation of this project paves the way for broader adoption of power quality monitoring solutions in various settings, including:

a. Industrial Facilities

Monitoring power quality in industrial settings can help ensure equipment reliability, reduce downtime, and optimize energy consumption.

b. Commercial Buildings
Monitoring power quality in commercial buildings can enhance occupant comfort, protect sensitive electronic equipment, and improve energy efficiency.

c. Renewable energy systems
Monitoring power quality in renewable energy systems, such as solar and wind power plants, can ensure grid stability and optimize energy production.

By promoting wider access to affordable and reliable power quality monitoring solutions, this research contributes to the advancement of sustainable and efficient energy practices across various sectors.

4. Conclusion

The project successfully developed a functional and accurate three-phase power quality monitoring device using readily available and affordable components. The device utilizes the EmonLibCM library to measure essential electrical parameters, including voltage, current, real power, apparent power, frequency, and energy consumption. The device accurately measures and displays these parameters, with an average error of less than 5% when compared to a reference Power Quality Analyzer. This accuracy makes it suitable for various applications, including monitoring industrial power systems.

The system architecture comprises multiple Arduino boards (Nano and Mega) for sensor data processing and a Raspberry Pi Zero W for data communication, storage, and user interface. Data is transmitted wirelessly via Wi-Fi to a Node-RED dashboard, allowing users to monitor real-time parameters, download historical data in CSV format, and perform remote sensor calibration.

The device is housed in a robust and portable aluminum enclosure designed to ensure component safety and prevent electrical hazards. The design considered factors like signal integrity, heat dissipation, and ease of assembly and maintenance.

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