TEKNIKA
E-ISSN : 2337-3148
P-ISSN : 1693-6329
Volume 10 Number 2
October 2025
pp 46 – 56
DOI: https://doi.org/10.52561/teknika.v10i2.612
Url: https://jurnal.sttw.ac.id/index.php/jte/article/view/612

IoT IMPLEMENTATION BASED ON POWER QUALITY NETWORK ANALYZER FOR 3-PHASE INDUCTION MOTOR CONTROL

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ABSTRACT

This study presents the design and implementation of a Power Quality Network Analyzer (PQNA) employing an ESP32 microcontroller to monitor and analyze key power quality parameters, including voltage, current, power factor, and total harmonic distortion (THD) for each phase of a three-phase induction motor. Traditional monitoring systems rely on manual or fixed data acquisition methods, which are inadequate for achieving efficient real-time data analysis. In contrast, the proposed system utilizes the RS-485 communication protocol, ensuring robust and reliable industrial data transfer, and functions as a data gateway that transmits all acquired parameters to the Thinger.io cloud platform for real-time visualization and analytics. This configuration enables enhanced diagnostic capabilities and predictive maintenance, improving system reliability and operational efficiency. Furthermore, the project demonstrates the potential of IoT integration in enabling remote assessment of power quality, thereby minimizing motor downtime and facilitating data-driven decision-making for performance optimization in industrial environments. The proposed framework also contributes to the advancement of intelligent industrial automation, emphasizing how real-time data analytics can significantly enhance productivity and sustainability

Keywords: *power quality network analyzer meter; 3-phase induction motor; ESP32-C3 mini; RS-485; Thinger.io; power system quality.*

1. INTRODUCTION

In recent years, the Internet of Things (IoT) has significantly influenced the development of industrial automation and intelligent control systems. One of the critical applications of IoT technology lies in the monitoring and controlling of 3-phase induction motors, which are widely used in industrial operations due to their robustness and efficiency. However, maintaining optimal performance and ensuring power quality remain key challenges, particularly in large-scale manufacturing environments.

Integrating an IoT-based Power Quality Network Analyzer (PQNA) offers an innovative approach to real-time monitoring of electrical parameters such as voltage, current, power factor, and harmonics to address these challenges. This system enables continuous observation, early fault detection, and data-driven decision-making, thereby improving the reliability and efficiency of motor operations.

Implementing IoT in power quality analysis enhances energy efficiency and supports predictive maintenance, reducing downtime and operational costs. Engineers can remotely access performance data, analyze system trends, and optimize motor control strategies by connecting network analyzers to cloud-based monitoring platforms. Therefore, the study on IoT-based PQNA for 3-phase induction motor control is essential for advancing smart industry frameworks and achieving sustainable industrial automation.

The main problem addressed in this research is the absence of an integrated and real-time system capable of combining power quality (PQ) monitoring with the control of three-phase induction motors. In industrial applications, fluctuations in voltage, harmonics, and current imbalance often lead to decreased motor performance, unplanned downtime, and reduced operational efficiency. Conventional monitoring methods generally rely on offline data collection, which delays the detection of PQ disturbances and prevents immediate corrective action. Therefore, an Internet of Things (IoT)-based approach is required to provide continuous real-time monitoring, analysis, and control.

Previous studies have discussed the development of PQ network analyzers, IoT-based monitoring systems, and motor control strategies using Variable Frequency Drives (VFDs) independently. While these studies have demonstrated improvements in measurement accuracy [1], [2], data visualization, and motor protection, they often treat monitoring and control as separate subsystems. As a result, there remains a gap in integrating PQ analysis directly with motor control logic to enable automated responses to disturbances [3], [4].

This research seeks to fill that gap by developing an IoT-based power quality network analyzer that monitors electrical parameters and communicates with a control module to regulate the induction motor's operation automatically. In real time, the system incorporates edge computing to analyze PQ indicators while using secure cloud connectivity for data logging and predictive maintenance. The proposed solution aims to enhance system reliability, improve energy efficiency, and minimize human intervention in the control process.

To address these limitations, recent developments in Internet of Things (IoT)-based architectures have enabled more efficient and scalable solutions for power quality supervision in industrial systems. The integration of low-cost microcontrollers, such as the ESP32, with Power Quality Network Analyzers (PQNA) allows for real-time acquisition of voltage, current, frequency, and total harmonic distortion (THD) data [5], [6]. These data are transmitted wirelessly to cloud-based platforms such as Thinger.io or MQTT dashboards, facilitating remote monitoring, predictive maintenance, and early fault detection [7], [8]. This approach improves reliability and performance, enhances energy efficiency, and reduces operational costs [1]. As demonstrated in several experimental studies, IoT-integrated PQ monitoring systems can maintain stable power quality, minimize harmonic effects, and ensure balanced operation across all three phases [3], [9].

Ultimately, this study aims to design and implement an IoT-integrated PQ monitoring and control system capable of optimizing the performance of three-phase induction motors. The research advances intelligent industrial automation with improved responsiveness, efficiency, and operational safety by establishing a closed-loop connection between the PQ analyzer and the motor controller.

2. METHODS

This section details the methodology used to design and implement the PQNAIoT system, focusing on the components, system design, and data acquisition process.

2.1. System Design and Components

The system design and components section presents the overall architecture and key elements of the IoT-based power quality monitoring and control system for three-phase induction motors. The system integrates sensors, a power quality analyzer, an IoT gateway, a motor control unit, and a cloud-based interface. Each component works together to enable real-time data acquisition, analysis, and automatic control responses. This design ensures efficient, reliable, and intelligent operation within industrial automation environments. It is illustrated in Figure 1.

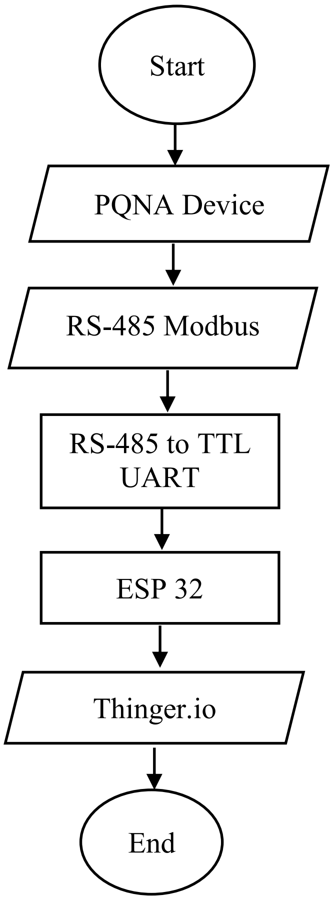

Figure 1. Flowcharts illustrating the process and design of system operations

The proposed system operates as an integrated IoT-based architecture designed to monitor and analyze power quality parameters in a three-phase induction motor system. The process begins with the Power Quality Network Analyzer (PQNA), which continuously acquires real-time measurements of voltage, current, power factor, and total harmonic distortion (THD) across all three phases. These parameters are essential for evaluating the electrical supply's quality, balance, and stability, serving as fundamental indicators of industrial power performance [7], [10].

Once measured, the data are transmitted via the RS-485 Modbus RTU protocol, a well-established industrial communication standard that provides differential signaling, high noise immunity, and reliable long-distance data transfer [11]. The differential RS-485 signal is converted into a UART-compatible serial format using an RS-485 to TTL/UART converter module to enable interfacing with the control microcontroller. This conversion facilitates seamless communication between the PQNA and the ESP32 microcontroller, which acts as the system's core processing and control unit [12].

The ESP32, equipped with a dual-core processor and integrated Wi-Fi interface, performs essential preprocessing tasks such as data filtering, validation, and formatting. Its computational efficiency and wireless capability suit IoT-based monitoring and control applications [7]. The validated and processed data are then transmitted to the Thinger.io cloud platform via an MQTT protocol, where they are stored and visualized through an interactive web dashboard. This cloud integration enables real-time monitoring, fault detection, and predictive maintenance, allowing operators to analyze system performance remotely and optimize energy consumption [10], [13].

Overall, this architecture combines robust industrial communication (Modbus RTU), intelligent microcontroller-based data processing (ESP32), and cloud-based visualization (Thinger.io), providing a scalable and energy-efficient solution for industrial power quality assessment and decision support.

2.2. Data Acquisition

The block diagram for data acquisition illustrates the flow of information within the IoT-based monitoring system, starting from sensor data collection to real-time analysis and control. This subsystem captures the three-phase induction motor's key electrical parameters. The power quality analyser processes the acquired signals and transmits them through the IoT gateway for further computation and cloud storage. Each stage in the diagram ensures accurate data conversion, filtering, and synchronization, enabling reliable monitoring and rapid response to power quality variations. This structured data acquisition framework is the foundation for intelligent motor control and predictive maintenance. It is shown in Figure 2.

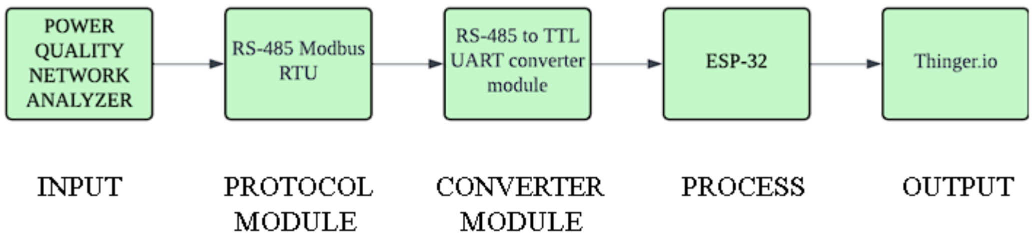

Figure 2. Block diagram for data acquisition

The data acquisition and transmission process from the Power Quality Network Analyzer (PQNA) to the Thinger.io cloud platform is implemented through an ESP32 microcontroller consisting of two main stages: protocol conversion and internet communication. The acquisition begins when the PQNA continuously measures key electrical parameters, including voltage, current, power factor, and total harmonic distortion (THD) within the three-phase induction motor control system. These measurements are transmitted using the RS-485 Modbus RTU protocol, providing a robust, noise-immune, long-distance industrial communication standard suitable for harsh environments.

The transmitted RS-485 signals are then passed through an RS-485 to TTL UART converter module, functioning as the protocol conversion interface. This module converts the differential RS-485 signals into TTL-compatible logic levels, enabling direct communication with the ESP32 UART interface. Once the data is restored, the ESP32 microcontroller performs data parsing, validation, and basic preprocessing to ensure accuracy and reliability.

After processing, the ESP32 transmits the data through its integrated Wi-Fi module to the Thinger.io IoT cloud platform, where the information is stored, visualized, and monitored through an online dashboard. This configuration enables users to observe real-time power quality conditions remotely, facilitating predictive maintenance, fault detection, and data-driven decision-making to improve system reliability and energy efficiency.

2.3. Experimental Procedure

The operation of the IoT-based power quality monitoring system for three-phase induction motor control follows a straightforward and systematic process. The entire setup is powered by a 5000 mAh power bank, which supplies regulated power to all components, including the ESP32-C3 Mini microcontroller, Power Quality Network Analyzer (PQNA), current transformers (CTs), and the RS-485 to TTL UART converter module. Upon power-up, the ESP32 initializes, establishes serial communication with the PQNA, and continuously configures the system to acquire power quality parameters.

The PQNA then begins measuring key electrical quantities such as voltage, current, power factor, and total harmonic distortion (THD) across the three phases of the induction motor. As the master device, the ESP32 periodically sends Modbus RTU requests via the RS-485 interface to retrieve these values from the PQNA. The acquired data are processed within the ESP32 to analyze the motor's operational characteristics and overall power quality performance.

Subsequently, the processed measurements are transmitted to the Thinger.io cloud platform using the MQTT communication protocol. Thinger.io provides a real-time visualization interface through dashboards, data buckets, and analytical charts that allow users to remotely monitor motor performance and evaluate power quality conditions from any location with internet access.

2.4. Project Design

The project design stage is fundamental in developing an effective IoT-based power quality monitoring system. This phase integrates hardware and software components to ensure seamless communication between sensors, microcontrollers, and data servers. Through careful planning and systematic design, the system architecture is structured to optimize data acquisition, processing, and transmission, providing accurate and real-time monitoring of three-phase induction motor performance. The design also emphasizes scalability, reliability, and efficiency to support industrial applications.

Figure 3 represents the physical design of the PQNAIoT system, showing the top and isometric views of the device enclosure. The design accommodates key components such as the Power Quality Network Analyzer (PQNA), RS-485 to TTL converter, and ESP32, featuring a compact and durable layout with mounting holes and a front display opening for easy monitoring and installation.

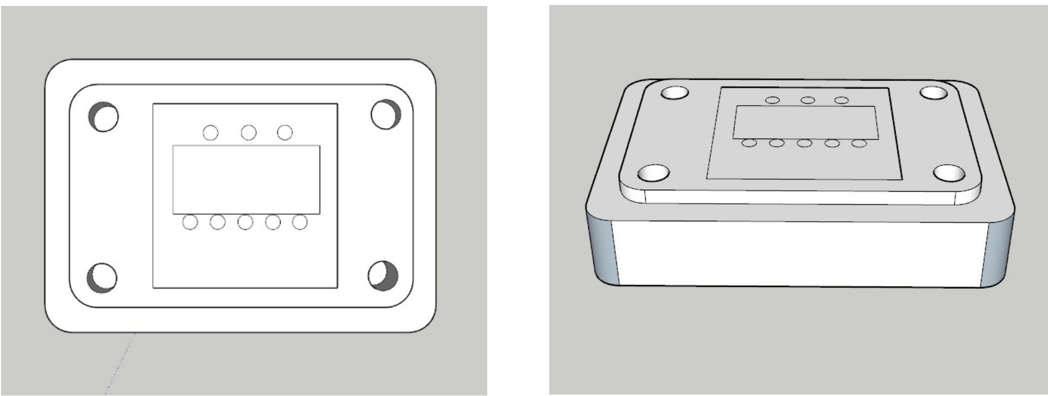

Figure 3. Project design of the PQNAIoT system

3. RESULTS AND DISCUSSION

This section presents the testing and evaluation results of the developed IoT-based Power Quality Network Analyzer (PQNA-IoT) system. The discussion includes system performance regarding cloud integration with Thinger.io, remote monitoring capability, and comparison with a commercial power quality analyzer. The analysis also covers sensor response, voltage behaviour, and measured power quality parameters of the three-phase induction motor control system. The experimental results demonstrate that the proposed PQNA-IoT system effectively provides accurate, real-time power quality monitoring and reliable data transmission for industrial applications.

3.1. Thinger.io Integration and Remote Monitoring

The developed PQNA-IoT system provides accurate and real-time monitoring of key power quality parameters for each phase (L1, L2, and L3) of a three-phase induction motor control system. Through seamless integration with the Thinger.io cloud platform, the system visualizes essential parameters such as voltage, current, power factor, and total harmonic distortion (THD%) for both voltage and current signals. For voltage measurements, the system displays the RMS value of each phase, enabling early detection of abnormalities such as voltage dips or surges that may affect motor performance. Phase-wise current readings allow users to monitor load distribution and identify potential issues such as overcurrent or phase imbalance.

The power factor is computed per-phase to assess how effectively electrical energy is utilized, where lower values indicate inefficiencies due to reactive components that degrade system performance. Similarly, the total harmonic distortion (THD%) for voltage and current is continuously evaluated to identify waveform distortions and non-linear load conditions. High voltage THD can cause waveform deformation and stress on equipment, while elevated current THD may result in overheating, increased power losses, and reduced efficiency. All these parameters are displayed in real time on the Thinger.io dashboard through graphical plots, allowing users to observe trends, detect anomalies, and implement preventive maintenance strategies to enhance power quality and ensure system reliability.

Figure 4 presents the Thinger.io dashboard consolidating all key power quality parameters into a single real-time display. It shows the three-phase induction motor system's RMS voltage, current, power factor, and THD% for each phase (L1, L2, and L3). The upper panels provide instantaneous readings for quick observation, while the lower plots visualize power factor variations and THD over time. This organized interface lets users easily monitor trends, detect anomalies, and ensure stable power quality and motor performance.

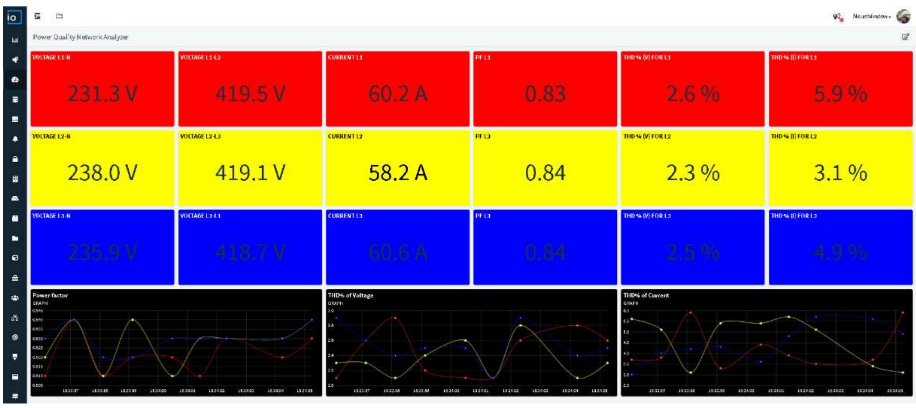

Figure 4. Thinger.io dashboard

3.2. Voltage and Current for Each Phase of Motor Chiller Water Pump

Figure 5 displays the line-to-neutral (L–N) voltages measured for each phase of the 40 HP three-phase induction motor. The readings indicate a well-balanced voltage condition within the acceptable operating range of a 230/400 V system, with tolerance limits of +10% and −6% at a frequency of 50 Hz. These measurements comply with the standard voltage specifications defined by the Suruhanjaya Tenaga (ST) in accordance with MS IEC 60038:2006 for low-voltage electrical systems in Malaysia.

Figure 5. Voltage L-N for each phase

Figure 6 presents the line-to-line (L–L) voltage readings for each phase of the three-phase induction motor, indicating a well-balanced and stable supply condition. The measured voltages for phases L1–L2, L2–L3, and L3–L1 fall within the nominal range of 415 V, confirming proper phase symmetry and operational consistency. The unit is equipped with illuminated phase indicators (L1, L2, L3) and five functional keys (F1–F5) for monitoring and parameter configuration. The system exhibits minimal phase-to-phase variation of approximately 1.6 V, demonstrating balanced voltage distribution and compliance with the standard 50 Hz operating frequency for industrial power systems.

Figure 6. Voltage L-L for each phase

Figure 7 illustrates the current measurements for each 40 HP three-phase induction motor phase. The readings show well-balanced phase currents, indicating that the load is evenly distributed across all phases. The motor operates as a chiller water pump in the Faculty of Chemical Engineering Technology building, ensuring effective heat dissipation and thermal exchange in the air-conditioning system. The closed-loop system runs continuously to maintain optimal cooling performance, with shutdowns occurring only during scheduled maintenance or fault conditions.

Figure 7. Current for each phase

Table 1 shows the hourly voltage and current readings for each phase of the three-phase induction motor. The voltages remain stable within the nominal range, and the current values are nearly equal across all stages, indicating a balanced load and steady operating conditions throughout the observation period.

Table 1. Data of voltage and current for each phase, red, yellow, and blue

Time	Voltage L-N (V)			Voltage L-L (V)			Current(A)		
hour	R	Y	B	R	Y	B	R	Y	B
8.00	240	239.6	241	415.7	416.1	417.2	54	56	52
9.00	241.2	240.8	242.1	417.4	417.6	418.8	55	54	56
10.00	240.4	239.9	241.3	415.9	416.3	417.5	56	55	57
11.00	239.3	238.9	240.1	414.3	414.7	415.8	58	57	57
12.00	239.8	239.5	240.8	415.2	415.6	417.1	59	60	61
13.00	239.7	239.6	240.2	414.9	414.5	414.6	54	56	55
14.00	239.7	239.2	240.2	415.6	416.3	415.9	56	55	53
15.00	239.5	239.7	239.9	414.6	414.2	416.3	53	55	56
16.00	239.7	239.2	240.5	415.5	415.1	414.8	53	55	53
17.00	239.8	239.2	240.4	414.9	415.4	416.2	53	51	50

3.3. Power Factor and THD% for Voltage and Current for Each Phase of Motor Chiller Water Pump

Table 2 shows that the power factor remains stable between 0.85 and 0.89, while the Total Harmonic Distortion (THD%) for both voltage and current stays within acceptable limits. This indicates that the overall power quality of the system is well maintained, ensuring efficient energy usage and reducing potential losses caused by harmonic distortions. The stable power factor demonstrates that the load is predominantly inductive but within a controllable range, contributing to consistent motor performance. Moreover, the acceptable THD% values confirm that the system design and filtering process effectively minimizes waveform distortions, resulting in smoother voltage and current signals. These findings verify that the implemented IoT-based Power Quality Network Analyzer successfully maintains balanced system operation and reliable motor control performance under various load conditions.

Table 2. Data of power factor and THD% of voltage and current for each phase, red, yellow, and blue

Time hour	Power Factor			THD% for Voltage			THD% for Current		
	R	Y	B	R	Y	B	R	Y	B
8.00	0.88	0.87	0.88	2.1	2.2	2.1	4.5	5.5	4.5
9.00	0.86	0.86	0.87	2.3	2.3	2.2	6.5	6.5	5.3
10.00	0.87	0.88	0.87	2.2	2.1	2.2	4.7	4.4	5.6
11.00	0.88	0.86	0.87	2.1	2.3	2.2	4.6	6.3	5.4
12.00	0.85	0.85	0.86	2.4	2.4	2.3	6.8	6.8	6.3
13.00	0.86	0.87	0.85	2.3	2.2	2.4	6.4	5.3	6.8
14.00	0.89	0.88	0.87	2.0	2.1	2.2	4.1	4.5	5.6
15.00	0.88	0.87	0.88	2.1	2.2	2.1	4.4	5.6	4.7
16.00	0.86	0.86	0.85	2.3	2.3	2.4	6.5	6.4	6.8
17.00	0.85	0.86	0.85	2.4	2.3	2.4	6.7	6.5	6.8

3.4. Power Factor vs THD% of Voltage Red, Yellow, and Blue Phase

The combined plots show an inverse relationship between power factor and THD% voltage across all three phases. As the power factor increases, the THD% decreases, indicating improved voltage waveform quality and reduced harmonic distortion. Figure 8 specifically illustrates this trend for the red phase, where higher power factor values correspond to lower THD%, confirming that the voltage waveform becomes more stable as reactive losses are minimized. The consistent trend among the red, yellow, and blue phases demonstrates balanced operation and stable power quality throughout the system. It is shown in Figure 8.

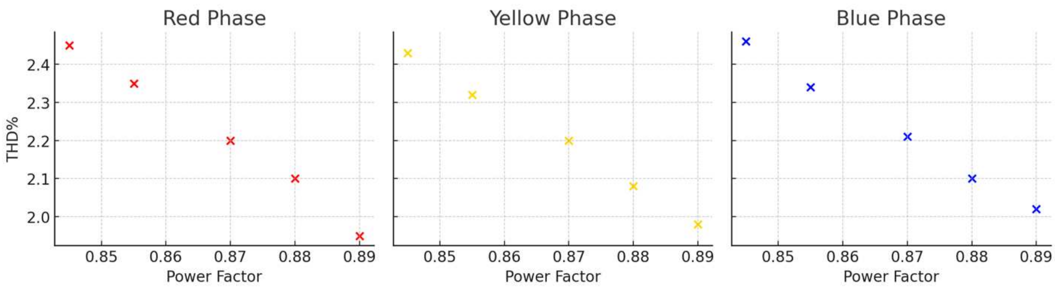

Figure 8. Relationship between power factor and THD% voltage for red, yellow, and blue phases

3.5. Power Factor vs THD% of Current Red Phase

The combined plots indicate a clear inverse correlation between power factor and THD% current across all three phases, highlighting that higher power efficiency corresponds to lower current distortion. This finding demonstrates that the proposed IoT-based PQNA system can effectively maintain power quality and load balance in real-time monitoring. Specifically, Figure 9 shows that for the yellow phase, an increase in power factor leads to a noticeable reduction in THD% current, resulting in smoother current waveforms and improved motor performance. Compared with previous studies, this research provides an enhanced understanding of the dynamic relationship between power factor and harmonic distortion by integrating IoT-enabled data acquisition and analysis. The system offers a more practical and scalable approach for optimizing three-phase induction motor performance and improving overall industrial power quality management. These results are consistent with the study conducted by Esen and Ciancetta [14], [15], which indicated that developing a low-cost IoT-based monitoring system can indirectly measure the mechanical power of three-phase induction motors to support real-time condition and efficiency monitoring.

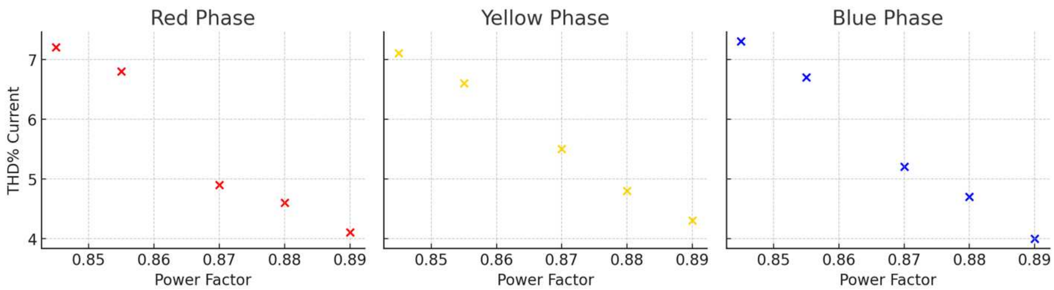

Figure 9. Relationship between power factor and THD% current for red, yellow, and blue phases

4. CONCLUSION

The study successfully demonstrates the implementation of an IoT-based Power Quality Network Analyzer (PQNA) for three-phase induction motor control applications. The key findings reveal that the proposed system can accurately measure voltage, current, power factor, and total harmonic distortion (THD%) in real time while maintaining stable system performance. The integration of the Thinger.io platform enhances remote monitoring and data accessibility, allowing users to analyze power quality parameters efficiently. Compared with previous research, this study improves monitoring flexibility and data accuracy through seamless IoT connectivity, reducing manual data collection and enhancing system responsiveness. Furthermore, the correlation analysis between power factor and THD% provides a deeper understanding of motor performance under varying loads. Overall, the developed PQNA-IoT framework offers a more reliable and intelligent solution for optimizing energy efficiency and maintaining operational stability in industrial motor control systems.

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