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RESEARCH ARTICLE

Experimental Analysis Using IoT-Based Smart Power Quality Analyzer System With Remote Data Access and GSM Alerting Mechanism

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ABSTRACT Power Quality Analyzers (PQA) play an important role in monitoring and controlling health of the electrical systems. They can report the fluctuations in the field measurements with different power quality issues as well as due to load variations. Internet of Things (IoT) is a potential technology to design Smart PQAs for remote monitoring and easy integration of the field information on the cloud platform using gateway units. This paper focuses on the development of a Smart PQA system using low-cost IoT hardware and software design solutions. The hardware development is completed using Arduino Mega 2560 microcontroller in combination with ESP32 Wroom Wi-Fi gateway and SIM900A GSM gateway. The real-time field data is gathered at the ThingSpeak platform for future analysis, while GSM-based design ensures timely alerts to the end users for any major fluctuation in the power supply. The performance of the proposed low-cost system has been compared with the readings obtained from FPGA-based conventional PQA and standard Fluke Meter when connected to different loads. The proposed system output values are tabulated and compared using graphs. The proposed system is expected to be useful for the critical assessment, monitoring, and control of power quality parameters in various commercial and residential premises.

INDEX TERMS Electrical systems, GSM, Internet of Things, smart, power quality analyzer.

I. INTRODUCTION

Power quality (PQ) is a crucial aspect of electrical engineering that regulates voltage, current, and frequency within specified boundaries in power systems. A deviation from these standards can result in equipment malfunctions, data loss, shorter component lifespans, and higher operational costs. The Power Quality Analyzer (PQA) plays a critical role in observing, identifying, and evaluating the quality of power in electrical networks. The PQA monitors real-time voltage, current, frequency, and power factor and identifies power disturbances such as voltage sags, swells, transients, harmonics, flickers, and interruptions. It records data on power quality events for analysis. By integrating the Internet of Things (IoT) with PQAs, traditional monitoring and analysis systems are revolutionized through enhanced capabilities. IoT-enabled PQAs offer improved data accessibility, advanced analytics, and automation, providing comprehensive insights into power systems. An IoT-based smart power quality analyzer (SPQA) is a sophisticated system designed to monitor, analyze, and report on the quality of electrical power in a given system using IoT technologies. IoT with PQAs enables

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monitoring and addressing power quality issues remotely, facilitates data collection and cloud storage, and enhances sophisticated analytics. IoT systems automatically generate alerts and enable interaction among various devices, improving the overall system performance. As a result of the IoT, various fields have been transformed through the effortless sharing of data between devices. The quality of power in electrical grids is monitored, analyzed, and managed using IoT devices. In order to evaluate the performance of electrical power systems, PQAs are crucial tools. In addition to voltage, current, frequency, harmonics, and transients, they measure a range of other key parameters as well. High power quality is crucial for electrical equipment to operate efficiently and to prevent damage from power disturbances.

Sensors, communication modules, data processing units, and cloud platforms are used in PQAs to enable IoT functionality [1]. These analyzers must measure various electrical parameters and display the gathered information locally or remotely [2]. IoT-based power quality analyzers use edge computing to perform initial data analysis locally before sending critical information to the cloud [3]. They are also integrating ML algorithms for predictive maintenance and anomaly detection [4]. However, the substantial amount of data transmitted by IoT-based PQAs presents significant challenges in terms of security, privacy, interoperability, and scalability [5]. Additionally, IoT-based monitoring and control systems are being used in smart grids [6] and surveillance systems for electric meters using the Android platform [7]. An IoT-based electric meter surveillance system utilizing an Android platform has been developed to reduce human efforts in monitoring power units and increase users' knowledge of excessive electricity usage [8]. IoT edge cloud computing modules and smart microgrid architectures are used for energy management in VANETs [9]. IoT-based energy management systems are important in research and practical industrial practices involving various stakeholders [10].

SPQA systems leverage advanced data analytics, Artificial Intelligence (AI), and machine learning (ML) to offer numerous benefits across various industries. SPQAs can reduce defects in production processes by 30-50%, thereby improving product quality and reducing waste. Companies that implement SPQAs have reported cost savings of 10-20% in manufacturing processes due to reduced rework and scrap rates. Manufacturing operations that use SPQA systems have noted productivity improvements of 15-25% owing to optimized production processes and reduced downtime. SPQAs enhance decision-making speed by 40-50% by providing real-time insights and predictive analytics, allowing for quicker responses to production issues. These systems can predict equipment failures with an accuracy of 85-90%, leading to a 20% reduction in maintenance costs and a 50% decrease in unplanned downtime. Companies have reported a Return on Investment (ROI) of 300-500% within the first 2-3 years of implementing SPQA systems due to enhanced efficiency and reduced operational costs. When SPQAs are utilized, there is a 20-30% improvement in quality assurance metrics, including adherence to regulatory standards and customer satisfaction ratings. Effective use of data collected from SPQA systems can lead to a 10-15% increase in the utilization of manufacturing data for continuous improvement initiatives.

Integrating IoT systems with PQA applications can bring significant benefits to both society and industry. Industry benefits include real-time monitoring and data collection, predictive maintenance, energy efficiency, improved decision-making, and enhanced reliability and quality control. Society benefits include energy conservation, grid stability, enhanced public safety, support for renewable energy integration, and economic benefits.

II. RELATED WORK

Over the years, several researchers put emphasis on the potential of IoT and AI to build efficient and reliable SPQA systems. Researchers in [11] proposed an IoT-based system for real-time monitoring of power quality in industrial environments to enhance detection and response capabilities. It introduces an IoT-enabled power quality analyzer for smart grids, which integrates advanced sensing and analytics for better grid management [12]. The researchers in [13] presented an IoT and machine learning framework for real-time power quality monitoring, with a focus on anomaly detection and predictive maintenance. An IoT-based system was implemented in [14] for monitoring and managing power quality in renewable energy systems to ensure stability and reliability. The study published in [15] introduced an IoT-driven approach for monitoring power quality in microgrids, emphasizing continuous monitoring and analysis for improved reliability. Additionally, authors in [16] provided a cloud-based IoT system for power quality monitoring, leveraging cloud computing for real-time data processing and analysis. An IoT-based power quality analyzer was specifically implemented in [17] for electric vehicle charging stations to ensure a stable and efficient power supply. The research introduced an IoT-driven approach for power quality monitoring in smart homes, integrating fault detection mechanisms for enhanced management [18]. Researchers in [19] analyzed power quality in smart cities using IoT-based methodologies, aiming for efficient power distribution and utilization. Authors in [20] developed an IoT framework for managing power quality in smart grids, integrating real-time monitoring and adaptive control strategies. Findings in [21] show the integration of IoT with predictive maintenance for power quality monitoring, enhancing system reliability and performance. Moreover, researchers in [22] applied IoT and edge computing for real-time monitoring of power quality in industrial settings, reducing latency and improving responsiveness. IoT-enabled power quality monitoring solution published in [23] was tailored for healthcare facilities while ensuring reliable operations. A distributed IoT-based system was proposed in [24] for monitoring power quality in rural electrification projects, aiming to provide a reliable electricity supply. Lastly, the study [25] enhances power quality monitoring in smart buildings through IoT technologies, focusing on improving energy efficiency and reliability.

This analysis covers the use of IoT for monitoring power quality in smart grids, involving real-time data acquisition, ML algorithms, and predictive and descriptive analytics. The equipment used includes voltage and current sensors, IoT gateways, and microcontrollers. Research into IoT applications for power quality monitoring in renewable energy systems entails continuous monitoring and data analytics, including descriptive and predictive analytics [26]. Addressing integration challenges with existing systems ultimately leads to improved energy efficiency and reliability [27]. When it comes to using IoT for power quality analysis at EV charging stations, continuous monitoring and data analytics involving descriptive and predictive analytics are employed. Despite the high initial investment, the goal is to improve user satisfaction and operational efficiency [28]. The study utilizes sensor networks, IoT gateways, and microcontrollers to monitor power quality in distribution networks, aiming to improve grid reliability and efficiency [29]. This study explores IoT-based solutions for monitoring power quality in smart homes, addressing concerns related to data privacy and security [30]. The concerns about high deployment costs are outweighed by the benefits of enhanced grid reliability and performance [31].

Research on IoT for monitoring power quality in healthcare facilities involves continuous monitoring and data analysis using power quality meters, IoT gateways, and environmental sensors. Table 1 provides quick highlights on types of microcontrollers, sensors, gateways, and communication technologies used by existing studies. The main challenge while designing these smart monitoring systems is to improve system safety and operational efficiency [32]. IoT-enhanced power quality assurance in data centers can decrease downtime and enhance power quality, ultimately improving data center reliability and efficiency [33]. IoT-based power quality monitoring solutions can be implemented in smart cities to improve urban power quality management and address interoperability issues. In [34], IoT is employed for power quality monitoring in commercial buildings, utilizing smart meters, power quality meters, and IoT gateways. Although there are scalability challenges, the potential benefits include improved operational efficiency and cost savings [35]. IoT is also used for predictive maintenance and predictive analytics in industrial automation to reduce downtime and maintenance costs while improving production efficiency and quality [36], [37]. The IoT initiative focuses on power quality monitoring in smart manufacturing using power quality meters, IoT gateways, and cloud platforms, while also addressing integration challenges with existing systems to enhance manufacturing quality and reliability [38]. IoT-based power quality assurance is being explored for electric utility providers, involving continuous monitoring, real-time data analysis, and predictive and descriptive analytics. However, there are high deployment costs associated with this approach [39].

TABLE 1. Contribution of Existing Studies of IoT-Based Power Quality Analyzer Development.

Ref	Year	Microcontrollers	Sensors/Type of PT or CT Sensors	Gateways	Communication Technologies	Other Highlights
[39]	2020	Arduino Uno	ACS712 (CT)	Raspberry Pi	WiFi, GSM	Real-time monitoring, cloud integration
[40]	2019	ESP8266	ZMPT101B (PT), SCT-013-000 (CT)	ESP 8266	WiFi	Low-cost, mobile app for monitoring
[41]	2021	NodeMCU	SCT-013 (CT)	Raspberry Pi	WiFi, Bluetooth	Energy consumption analysis, anomaly detection
[42]	2018	Arduino Mega	Rogowski coil (CT), ZMPT101B (PT)	BeagleBone Black	Xbee, GSM	Remote monitoring, SMS alerts
[43]	2020	ESP32	LEM HX 10-P (CT)	ESP 32	WiFi, LoRa	Wide area monitoring, long-range communication
[44]	2019	STM32	HLW8012 (PT/CT combo)	Raspberry Pi	WiFi, Ethernet	High precision, real-time data logging
[45]	2021	Arduino Nano	ACS758 (CT)	ESP 8266	WiFi, Bluetooth	Compact design, cost-effective solution
[46]	2020	Raspberry Pi	Split-core CT, Voltage divider	Raspberry Pi	WiFi, GSM, LTE	Scalability, integration with smart grid systems
[47]	2018	ESP8266	SCT-013-030 (CT)	ESP 8266	WiFi, ZigBee	Home automation, integration with smart home devices
[48]	2021	Arduino Uno	Current transformer (CT), PT100	Arduino MKR GSM 1400	GSM, 4G LTE	Real-time alerts, robust communication in remote areas

Literature shows that IoT-based systems play an essential role in sensing, calculating, and measuring electrical parameters from the field environments. Due to the compact system design and user-friendly operation, they are ideal solutions for monitoring and controlling the efficiency of energy management systems. Furthermore, IoT also provides the ability to deal with universal and sophisticated applications by communicating field data to the cloud without requiring any human intervention. Therefore, critical failures, downtimes, and sudden fluctuations in the supply can be reported easily to the end users. The cloud-based data storage with advanced gateways also leads to better data analysis and forecasting opportunities. Based on the insights obtained from the literature, an IoT-based SPQA system has been deployed and analyzed in this study. The goal is to have a live track of all power quality fluctuations by using a low-cost IoT hardware and software solution. This PQA system has been installed in the institute building, in Hyderabad, India. The main contributions of this study are highlighted below:

- Development of an SPQA system with a compact IoT-based design.
- Generating GSM-based alerts for the end users for any critical fluctuations in the power supply.
- Implementing Wi-Fi gateway for real-time data transfer to the cloud platform.
- Gathering essential field parameters on ThingSpeak for data analysis and forecasting applications.

The paper is further divided into various sections as below: Section II provides detailed information about materials & methods used in the development of IoT-based SPQA system. This section explains the hardware components, system architecture, circuit diagrams, and the focus parameters for field measurements. Furthermore, Section III focuses on the results and discussions associated with the designed IoT-based SPQA system. It highlights the tabulated results from the conducted laboratory experiments and the graphical analysis of the parameter values. Section IV indicates the conclusion with limitations and the future scope of this work.

III. MATERIALS AND METHODS

This research study focuses on the development of IoT-based smart power quality analyzer for a three-phase system. The smart IoT systems are expected to provide a quick alerting mechanism for field data so that prompt actions can be taken for any critical change in the observations. Continuous monitoring can help end users in timely decision-making. The parameter reading from the power supply can be obtained by using an adequate integration of hardware and software systems. These boards are expected to provide adequate measurements for voltage deviations, power fluctuations, flickering issues, harmonics analysis, voltage and current distortions along with load variations across different phases of supply.

At the initial level, the real-time field measurements were conducted using an FPGA board; the results and detailed performance analysis of this design have been already published in [49]. The current sensors, voltage sensors, and FPGA boards are used to create a PQA system that can analyze output coming from a transmission line, transformer, or alternator. The current and voltage sensors take up the relevant signals from the main source and transfer them further to the FPGA board. A suitable load or utility is attached to the system which helps the analyzer to detect the corresponding impact of the load on the input system. The results available from the FPGA board were displayed on the PC screen through a USB cable. The FPGA board was also equipped with on-chip analog to digital-converters to sense the analog signals as approximate digital values. Detailed information on the design of the FPGA system for PQA can be found in [49]. However, it was not enough to bring the outcomes to the PC screen only; another essential objective of the project was to enable remote access to the field data. In this study, the system is further connected to IoT-based mechanism for live remote monitoring and smart decision-making. The proposed system has been designed using an Arduino Mega 2560 microcontroller connected with two different gateway units – GSM Gateway and Wi-Fi Gateway. GSM gateway helps end users to get quick SMS updates on their mobile phones on a pre-specified sampling period whereas the Wi-Fi gateway is used to send data online for real-time graphical analysis. The general connection diagram of the hardware system is provided in Fig 1. A detailed description of all hardware modules is provided further.

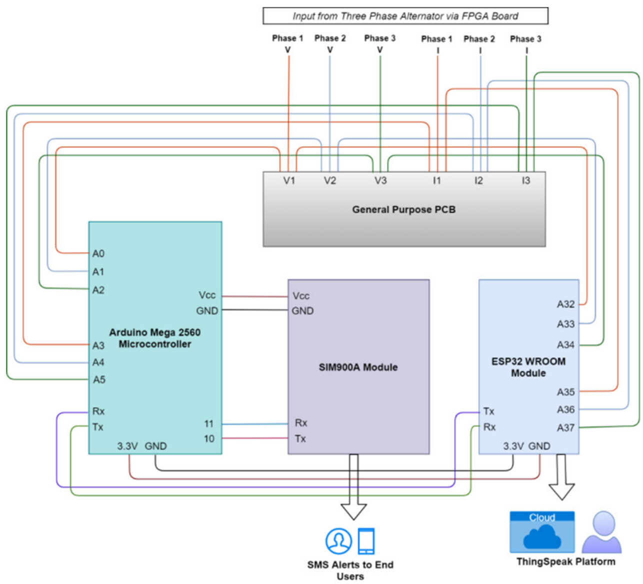

FIGURE 1. General connection diagram of hardware system.

A. ARDUINO MEGA 2560

Arduino Mega has been selected as the main microcontroller board for this experimental analysis. The chip contains ATmega2560 as a core controller on board and it can be programmed using the Arduino IDE software platform. This board is essentially designed to handle complicated projects with its 16 analog input pins and 54 digital input/output pins. Moreover, this board has a bigger memory capacity of 8KB SRAM and 4KB EEPROM in comparison to other Arduino boards. The SPQA system requires reading input from an FPGA board with three lines of Voltage and three lines of Current from three different phases. The input signals were further used to calculate essential parameters from SPQA including root mean square (RMS) voltage, RMS current, real power, apparent power, reactive power, frequency, and power factor. The current and voltage total harmonic distortion from the SPQA was calculated with the help of Fast Fourier Transform (FFT); however, since it requires massive calculation over a large number of samples, the memory capacity of Arduino Mega was not enough to handle all FFT calculations for three phases along with the pre-listed 7 important parameters. Therefore, the ESP32 module was further used to handle all the FFT calculations to measure voltage and current harmonics distortion as an independent node while working as a Wi-Fi gateway side by side. The parameters calculated from the phase supply were further sent to end users via two different gateways: Wi-Fi gateway (ESP32) and GSM gateway (SIM900A).

B. ESP32 WROOM

The ESP32 chip is one of the most renowned and powerful microcontrollers designed by Espressif. Its strong processing speed, accessibility, and ability to have on-chip Bluetooth and Wi-Fi connectivity make it a relevant choice for IoT system design. The ESP32 is designed with an Xtensa single-core or dual-core 32-bit microprocessor that operates on 160-240 MHz frequency. The chip comes with 448 KiB ROM and 520 KiB RAM. The wireless connectivity comes with 802.11 b/g/n and the Bluetooth (BLE and v4.2 BR/EDR) also shares radio with Wi-Fi. The main reason to select the ESP32-WROOM chip for designing a smart power quality system was its enhanced memory capacity, 18 analog-enabled pins with two 12-bit SAR Analog to Digital (ADC) converters. The ESP32 co-processor is designed to measure signal voltage even while it is in the sleep mode which leads to reduced power consumption during operation. As mentioned earlier, the ESP32 board in this project handled two main tasks – working as an independent node to measure harmonic distortions and sending all measured data variables to the ThingSpeak platform for cloud storage and remote data analysis.

C. SIM900A MODULE

TheSPQAsystem was expected to provide quick SMS alerts to the end users and this objective was achieved with the help of SIM900A. This board is a compact solution for using data, SMS, voice, and fax over GPRS/GSM networks. This tiny chip makes use of dual frequency bands including DCS1800 and EGSM900 that it can automatically search or the programmer can set by using AT commands. The maximum download and upload speeds of this chip are 85.6 Kbps and 42.8 Kbps, respectively.

The hardware system received input from conventional PQA in the form of voltage and current. The input was taken from the dedicated tap points available on the FPGA board and they were applied to the analog input ports of Arduino Mega and ESP32 for the real-time calculations as per the input signal variations. Since ESP32 Wroom works on 3.3V logic, therefore, a voltage divider network was added to the circuit to drop down input signals to the levels acceptable by the ESP32 module. Although the addition of a voltage divider network led to some alternations in the resolution level of the measurement, the rigorous calibration process was followed to achieve desired accuracy with the system. The image of the hardware system designed using the above approach is provided in Fig. 2.

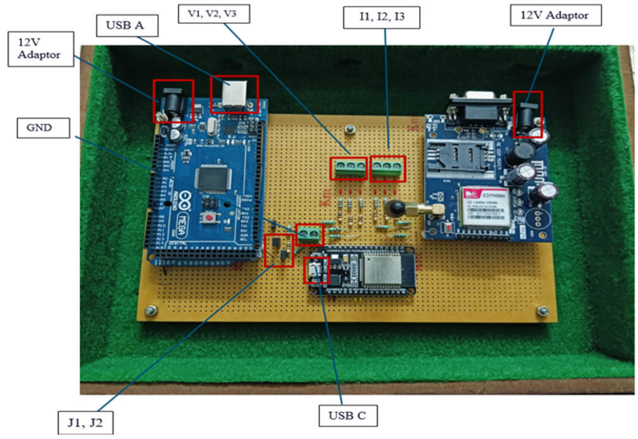

FIGURE 2. Hardware designed for IoT-based SPQA system.

The V1, V2, and V3 terminals are dedicated to Phase 1, Phase 2, & Phase 3 Voltage input; however, I1, I2, and I3 terminals are used for Phase 1, Phase 2, and Phase 3 currents, respectively. The ground terminal will be used to connect the ground wire of the 3-phase input coming from the FPGA board. J1 and J2 are jumpers used for the make & break connection of Tx and Rx lines between Arduino Mega 2560 and ESP32 Wroom module. The system was designed to calculate several important parameters from individual phases along with the average and total component values from a three-phase system. The total 30 parameters measured and calculated using this IoT-based SPQA system are provided in Table 2.

The FPGA board makes use of various hardware elements to collect signals from the three-phase alternator and to process them for real-time monitoring and analysis. Along with several ADCs and DACs, the main sections of the unit are the voltage sensing board and current sensing board. The already designed FPGA board contained a HE055T01 closed loop current sensor for measuring current in the system. This sensor is desired to measure a steady-state current of 55A with a range of up to 70A. On the other side, the IC7840 isolation amplifier was used for voltage measurements. It works by measuring small voltage drops across the shunt resistors on high-voltage rails that are deployed for current sensing. Both of these sensors can work well in the operating range of -45 to +85 C. The FPGA board itself utilized an 8-bit USB FIFO mode for operation with a 100MHz oscillator. Detailed information about this development can be found in [49]. In the current study, the main focus is to retrieve the parameters of interest from the three-phase supply using an IoT system so that a smart monitoring solution can be developed. This is achieved by using the hardware arrangement mentioned above. The voltage and current tap points from

TABLE 2. Parameters measured by IoT-based SPQA system.

Sr. No.	*Parameters*	Phase 1	Phase 2	Phase 3	Total/Avg.
1	*RMS Voltage*	$Vrms_1$	$Vrms_2$	$Vrms_3$	Average Vrms
2	*RMS Current*	$Irms_1$	$Irms_2$	$Irms_3$	Average Irms
3	*Real Power*	kW_1	kW_2	kW_3	Total kW
4	*Apparent Power*	kVA_1	kVA_2	kVA_3	Total kVA
5	*Reactive Power*	$kVAr_1$	$kVAr_2$	$kVAr_3$	Total kVAr
6	*Power Factor*	--	--	--	Average PF
7	*Frequency*	--	--	--	Average Hz
8	*Current Harmonics*	$iTHD_1$	$iTHD_2$	$iTHD_3$	Total iTHD
9	*Voltage Harmonics*	$vTHD_1$	$vTHD_2$	$vTHD_3$	Total vTHD

the FPGA board are further connected to the analog port of the Arduino Mega 2560 microcontroller and ESP32 Wroom chip for collecting field data. These field parameters can help end users get a quick idea about the power quality which can further assist in quick decision making. A total of 30 different parameters (Table 2) were measured using the SPQA system and they were further sent to end users for real-time analysis via Wi-Fi gateway and GSM gateway.

IV. RESULTS AND DISCUSSIONS

Power quality fluctuations lead to a detrimental impact on residential, commercial & industrial drives. Fortunately, the PQA systems are capable enough to measure those disturbances with live monitoring. In this study, the hardware and software solutions designed using IoT helped authors to deploy live, real-time monitoring solutions for the SPQA system. The performance of the proposed hardware system was tested by conducting multiple experiments on varying loads. The outcomes were compared against FPGA-based conventional PQA and standard Fluke Meter to verify the accuracy of the proposed system. Tables 3 and 4 represent a comparative analysis of all three measuring devices including FPGA based conventional PQA system, IoT-based SPQA, and Fluke Meter with varying loads. Fig 3 displays the experimental setup in the laboratory environment for the IoT-based SPQA system. This image from laboratory settings displays the MG Set with three phase input behind the work bench and a resistive load bank with adjustable switches in front of the work bench. On the work bench, the fluke meter, FPGA based PQA meter, IoT based PQA meter and laptop (right to left), respectively, are placed for displaying IoT system readings on the cloud and Arduino IDE coding platform.

FIGURE 3. Experimental setup for power quality analyzer.

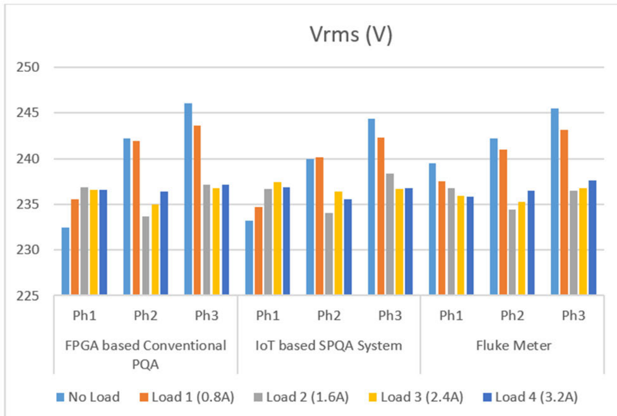

FIGURE 4. Comparison of Vrms values from Conventional PQA, IoT-based SPQA, and Fluke Meter.

The IoT based hardware system input is connected to the dedicated tap points on FPGA based PQA system which helps to measure the main three phase supply with the 5V resolution as required by the Arduino Mega microcontroller.

The parameters of interest including Vrms, Irms, Real Power, Reactive Power, Apparent Power, Voltage Harmonics, and Current Harmonics were measured from all three phases. The measuring devices also provided updates about the average and total values of these parameters as listed in Table 2.Furthermore, the Power Factor and Frequency component were also measured as the average of all three phases for comparison with varying load values. The first measurement was conducted under no load condition for all parameters (Table 3 & Table 4). The remaining four readings were taken with varying load conditions with values of 0.8A 1.6A, 2.4A, and 3.2A. The variations in the Vrms and Irms for all these load conditions can be also observed in Fig 4 and Fig 5.

It is observed that IoT based SPQA system provided comparable readings for both Vrms and Irms values. However,

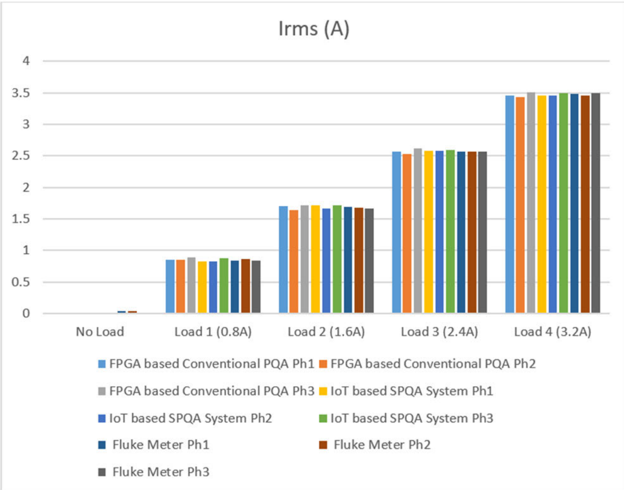

FIGURE 5. Comparison of Irms values from Conventional PQA, IoT-based SPQA, and Fluke Meter.

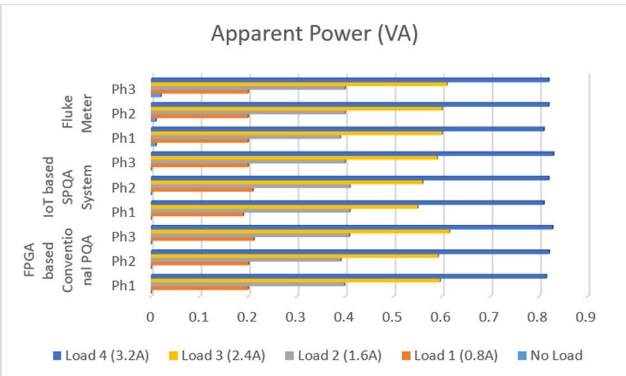

FIGURE 6. Comparison of apparent power values from conventional PQA, IoT based SPQA and Fluke Meter.

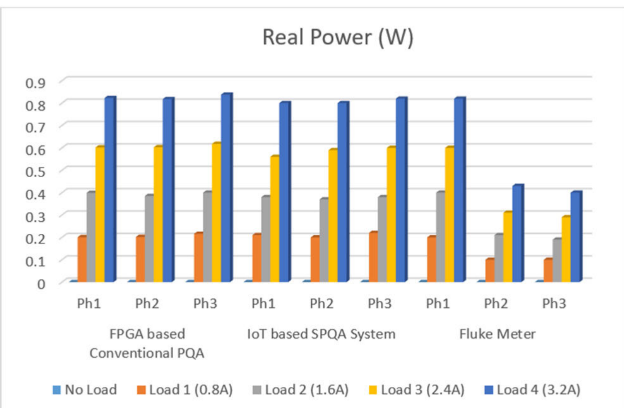

FIGURE 7. Comparison of real power values from conventional PQA, IoT-based SPQA, and Fluke Meter.

in order to achieve this accuracy, the system was calibrated multiple times under unique test conditions. The calibration process was completed using specific values of voltage

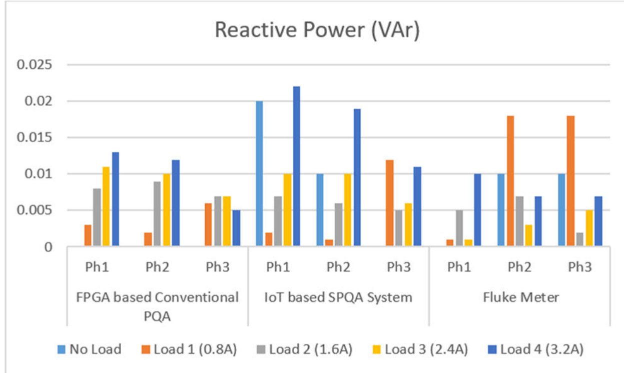

FIGURE 8. Comparison of reactive power values from conventional PQA, IoT-based SPQA, and Fluke Meter.

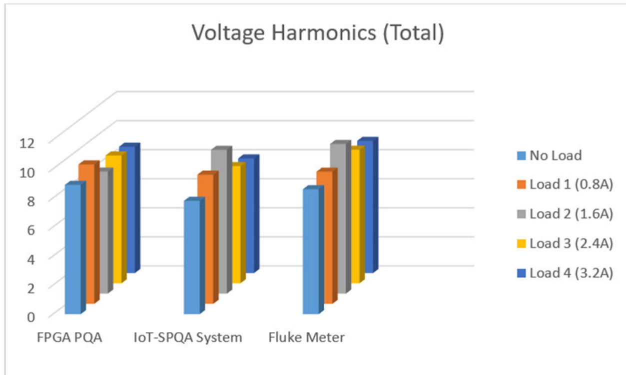

FIGURE 9. Comparison of total voltage harmonics values from conventional PQA, IoT-based SPQA, and Fluke Meter.

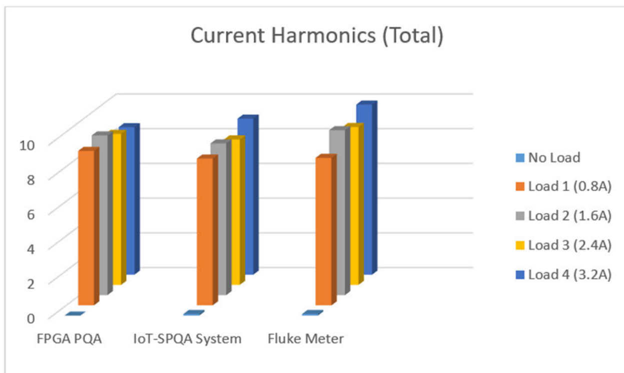

FIGURE 10. Comparison of total current harmonics values from conventional PQA, IoT-based SPQA, and Fluke Meter.

calibration constant, current calibration constant and phase calibration constant in Emon Library used on Arduino IDE platform. During the calibration process, the reliability tests were conducted against standard equipment (Fluke Meter) to ensure enhanced accuracy in the system. Due to the voltage divider network added to the circuit, there was a slight current drop issue during measurements. Therefore, multiple reliability tests were conducted to reach the enhanced level of

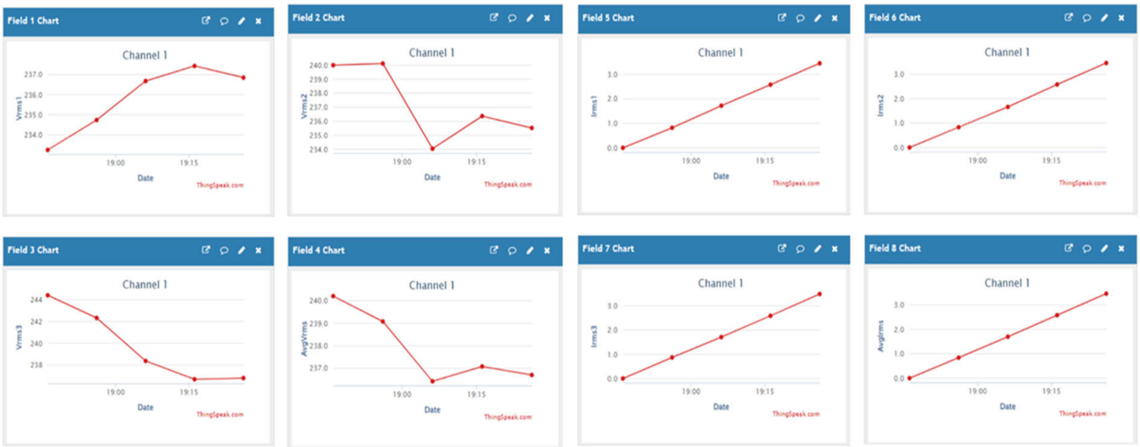

FIGURE 11. Channel 1 Readings on ThingSpeak Platform (Vrms1, Vrms2, Vrms3, Avg Vrms, Irms1, Irms2, Irms3, Avg Irms).

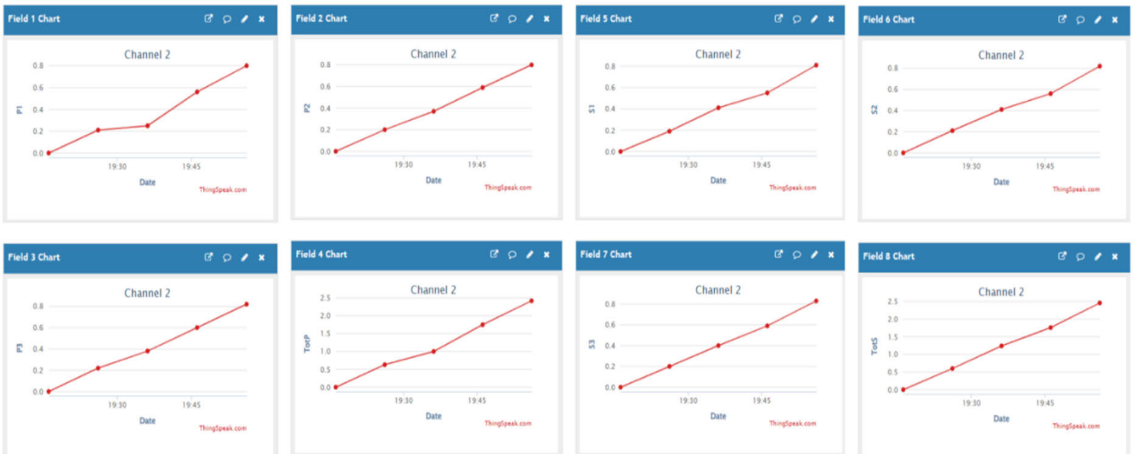

FIGURE 12. Channel 2 Readings on ThingSpeak Platform (P1, P2, P3, Total P, S1, S2, S3, Total S).

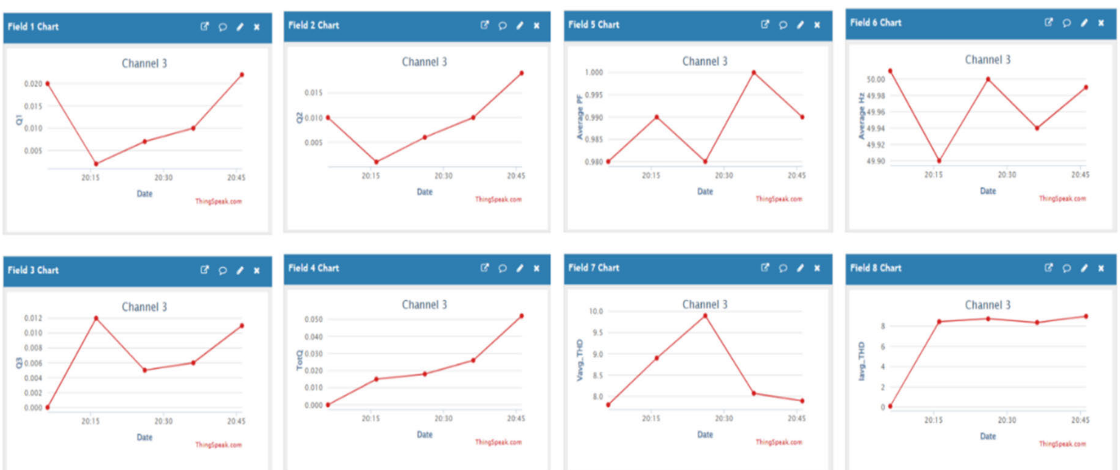

FIGURE 13. Channel 3 Readings on ThingSpeak Platform (Q1, Q2, Q3, Total Q, Avg PF, Avg Hz, Total V_{THD}, Total I_{THD}).

accuracy with the proposed system. The main limitation of the proposed system was the voltage divider network added to drop the voltage level to 3.3V to meet ESP32 Wroom specifications since it leads to difficulty in tracking fast changes

TABLE 3. Comparison between parameters values obtained from FPGA-based Conventional PQA, IoT-based SPQA System & Fluke Meter.

Parameters	Load	Values Obtained from FPGA-based Conventional PQA			Values Obtained from IoT-based SPQA System			Values Obtained from Fluke Meter		
		Ph1	Ph1	Ph2	Ph1	Ph2	Ph3	Ph1	Ph2	Ph3
Vrms (V)	*No Load*	232.5	242.2	246.1	233.25	240.0	244.4	239.5	242.2	245.5
	Load 1 (0.8A)	235.6	241.9	243.6	234.74	240.12	242.32	237.5	241.0	243.2
	Load 2 (1.6A)	236.9	233.7	237.2	236.68	234.04	238.38	236.8	234.4	236.5
	Load 3 (2.4A)	236.6	235.0	236.8	237.43	236.37	236.70	235.9	235.3	236.8
	Load 4 (3.2A)	236.6	236.4	237.2	236.85	235.52	236.81	235.8	236.5	237.6
Irms (A)	*No Load*	0	0	0	0.001	0	0	0.03	0.03	0.003
	Load 1 (0.8A)	0.851	0.844	0.890	0.82	0.83	0.83	0.87	0.86	0.84
	Load 2 (1.6A)	1.696	1.642	1.719	1.72	1.66	1.72	1.71	1.67	1.66
	Load 3 (2.4A)	2.568	2.534	2.613	2.58	2.58	2.58	2.57	2.57	2.57
	Load 4 (3.2A)	3.452	3.433	3.512	3.45	3.46	3.45	3.48	3.46	3.50
Real Power (W)	*No Load*	0	0	0	0	0	0	0	0	0
	Load 1 (0.8A)	0.201	0.202	0.216	0.21	0.20	0.21	0.20	0.22	0.10
	Load 2 (1.6A)	0.399	0.385	0.400	0.25	0.37	0.38	0.37	0.38	0.19
	Load 3 (2.4A)	0.602	0.603	0.618	0.56	0.56	0.59	0.60	0.61	0.59
	Load 4 (3.2A)	0.823	0.818	0.838	0.80	0.80	0.80	0.82	0.43	0.40
Apparent Power (VA)	*No Load*	0	0	0	0	0	0	0.01	0.01	0.02
	Load 1 (0.8A)	0.200	0.201	0.212	0.19	0.21	0.20	0.20	0.20	0.20
	Load 2 (1.6A)	0.399	0.391	0.409	0.41	0.41	0.41	0.40	0.40	0.40
	Load 3 (2.4A)	0.596	0.592	0.615	0.55	0.55	0.56	0.59	0.60	0.61
	Load 4 (3.2A)	0.815	0.821	0.828	0.81	0.81	0.82	0.83	0.82	0.82
Reactive Power (VAr)	*No Load*	0	0	0	0.02	0.01	0	0	0.01	0.01
	Load 1 (0.8A)	0.003	0.002	0.006	0.002	0.002	0.001	0.012	0.18	0.18
	Load 2 (1.6A)	0.008	0.009	0.007	0.007	0.007	0.006	0.005	0.34	0.34
	Load 3 (2.4A)	0.011	0.010	0.007	0.010	0.010	0.01	0.006	0.51	0.53
	Load 4 (3.2A)	0.013	0.012	0.005	0.022	0.019	0.011	0.01	0.70	0.72
vTHD (%)	*No Load*	2.6	2.8	3.5	2.5	2.10	3.2	2.7	2.8	3.1
	Load 1 (0.8A)	2.7	3.2	3.7	2.9	2.8	3.3	3.2	2.5	3.4
	Load 2 (1.6A)	2.9	2.4	3.1	2.7	2.2	3.0	3.4	3.5	3.4
	Load 3	2.8	2.7	3.3	2.5	2.17	3.1	3.0	3.1	3.1

TABLE 3. ***(Continued.)*** **Comparison between parameters values obtained from FPGA-based Conventional PQA, IoT-based SPQA System & Fluke Meter.**

	(2.4A)									
	Load 4 (3.2A)	2.9	2.7	3.1	2.51	2.40	2.98	3.1	2.9	3.1
iTHD (%)	*No Load*	0	0	0	0.06	0.03	0	0.03	0.03	0.03
	Load 1 (0.8A)	2.8	1.8	4.3	2.84	1.92	3.70	2.83	1.84	3.83
	Load 2 (1.6A)	3.1	2.7	3.4	3.05	2.60	3.09	3.2	3.2	3.1
	Load 3 (2.4A)	2.9	2.8	3.0	2.30	2.65	3.43	3.1	3.0	3.0
	Load 4 (3.2A)	2.9	2.8	2.8	2.67	2.42	2.90	2.9	3.0	3.9

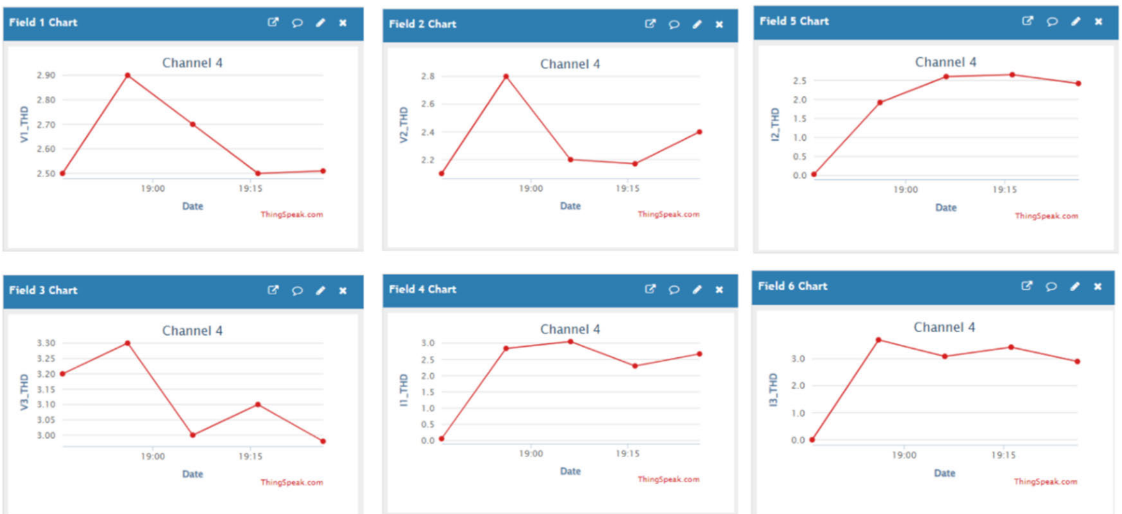

FIGURE 14. **Channel 4 Readings on ThingSpeak Platform ($V1_{THD}$, $V2_{THD}$, $V3_{THD}$, $I1_{THD}$, $I2_{THD}$, $I3_{THD}$).**

in voltage and current measurements with load variations. However, the system was able to track the updated values with a time delay of 90 seconds. Therefore, the initial readings with load change were dropped and the accurate ones after a specified time delay were transmitted to the ThingSpeak platform for cloud data storage. As a more reliable solution to this current drop issue, the authors plan to replace the voltage divider network with a level shifter in future works. The main goal is to meet the higher level of accuracy with this low-cost system.

The Vrms and Irms values were further utilized to calculate Apparent Power. The Arduino IDE-based code was further designed to measure the phase angle difference between current and voltage waveform to calculate angleφ. This angle information was further utilized to calculate Real and Reactive Power. The comparison between experimental observations for Apparent, Real, & Reactive Power using conventional, IoT, and standard measuring devices are provided in Table 3 and Fig 6, 7 & 8, respectively.

The calculation for the Power Factor was done for every phase. However, instead of storing values for every phase on the cloud, only average values from all the phases were sent to the ThingSpeak platform. Furthermore, the time period for signal was estimated by calculating the signal high and signal low time. This signal duration information was further used to calculate signal frequency. The frequency component was also stored with the average value obtained from all three phases. The comparison between power factor and frequency values obtained from all three measuring devices is provided in Table 4.

Another important measurement conducted using the ESP32 Wroom chip available with IoT SPQA was signal harmonics. The voltage and current harmonics for all three phases were measured independently for all different load conditions (Table 3). The measurement was done using FFT calculation on the Arduino Mega platform. The system was set using sampling frequency of 800 Hz with 128 number of samples. The base frequency for harmonics calculation was 50 Hz and odd components

TABLE 4. Average and Total Values obtained for different field parameters from FPGA-based Conventional PQA, IoT-based SPQA System & Fluke Meter.

Parameters	Load	Values Obtained from FPGA-based Conventional PQA	Values Obtained from IoT-based SPQA System	Values Obtained from Fluke Meter
Avg Vrms	*No Load*	243.3	240.21	242.40
	Load 1 (0.8A)	240.8	239.08	240.56
	Load 2 (1.6A)	235.8	236.42	235.90
	Load 3 (2.4A)	237.1	237.08	236.00
	Load 4 (3.2A)	237.5	236.70	236.63
Avg Irms	*No Load*	0	0	0.021
	Load 1 (0.8A)	0.86	0.84	0.843
	Load 2 (1.6A)	1.685	1.698	1.673
	Load 3 (2.4A)	2.577	2.580	2.57
	Load 4 (3.2A)	3.465	3.461	3.48
Total Real Power	*No Load*	0	0	0
	Load 1 (0.8A)	0.612	0.63	0.64
	Load 2 (1.6A)	1.18	1.0	1.01
	Load 3 (2.4A)	1.80	1.75	1.74
	Load 4 (3.2A)	2.48	2.42	2.43
Total Apparent Power	*No Load*	0	0	0
	Load 1 (0.8A)	0.612	0.60	0.60
	Load 2 (1.6A)	1.19	1.24	1.19
	Load 3 (2.4A)	1.81	1.76	1.81
	Load 4 (3.2A)	2.46	2.46	2.46
Total Reactive Power	*No Load*	0	0	0.02
	Load 1 (0.8A)	0.010	0.015	0.016
	Load 2 (1.6A)	0.020	0.018	0.017
	Load 3 (2.4A)	0.026	0.026	0.027
	Load 4 (3.2A)	0.035	0.052	0.053
Average PF	*No Load*	1	0.98	0.99
	Load 1 (0.8A)	1	0.99	0.98

TABLE 4. *(Continued.)* **Average and Total Values obtained for different field parameters from FPGA-based Conventional PQA, IoT-based SPQA System & Fluke Meter.**

	Load 2 (1.6A)	1	0.98	0.99
	Load 3 (2.4A)	1	1	1
	Load 4 (3.2A)	1	0.99	1
Average Hz	*No Load*	50.04	50.01	50.03
	Load 1 (0.8A)	49.98	49.90	50.01
	Load 2 (1.6A)	49.96	50.00	49.97
	Load 3 (2.4A)	49.96	49.94	49.97
	Load 4 (3.2A)	50.12	49.99	50.11
V_{total}_THD	*No Load*	8.9	7.8	8.6
	Load 1 (0.8A)	9.6	8.9	9.1
	Load 2 (1.6A)	8.4	7.9	10.3
	Load 3 (2.4A)	8.8	7.77	9.2
	Load 4 (3.2A)	8.7	7.89	9.1
I_{total}_THD	*No Load*	0	0.09	0.09
	Load 1 (0.8A)	8.9	8.46	8.5
	Load 2 (1.6A)	9.2	8.74	9.5
	Load 3 (2.4A)	8.7	8.38	9.1
	Load 4 (3.2A)	8.5	7.99	9.8

(3^{rd}, 5^{th}, $7^{th,}$ and 9^{th}) with frequency range of 150Hz, 250Hz, 350Hz and 450Hz from FFT evaluation were considered for obtaining the final harmonic component. The field values for Total Harmonics components for voltage and current are displayed in Table 4 and Fig 9 & 10, respectively.

The field values obtained from the IoT-based SPQA system are comparatively close enough to the standard and conventional measuring devices. The field observations for all different experiments conducted in the no-load and with load conditions were transmitted to the ThingSpeak platform for cloud data storage. The 30 field parameters were easily stored in the four channels of the ThingSpeak platform with a sampling rate of 30 samples per hour. The idea was to ensure quick tracking of any change in the field values due to disturbances in the electrical system. The graphs obtained from each channel for the field experiments as listed in Tables 3 & 4 are provided in Fig 11, 12, 13, and 14.

The ThingSpeak-based readings can help end users check field measurements remotely in real time. Moreover, the stored data can be extracted in the form of CSV files in the future to conduct pattern analysis and forecasting tasks. Since PQA fluctuations are critical to the performance of commercial and residential power units, alternators, and laboratory setups, it is important to generate quick alerts to the end user whenever field parameters cross certain thresholds. The SIM900A gateway was added into the system to generate SMS based alerts for the end users. During the testing phase, the Vrms limit was kept around 225 Volt to 245 Volt for field measurement. Considering this threshold limit, the GSM module sent a quick alert on a dedicated mobile number as soon as Vrms for Phase 2 crossed the lower limit with a value of 222.10 volts (Fig 15).

Different threshold levels were added to the software with reference to critical field parameters such as Vrms, Irms, Real Power, Reactive Power, and Apparent Power for creating

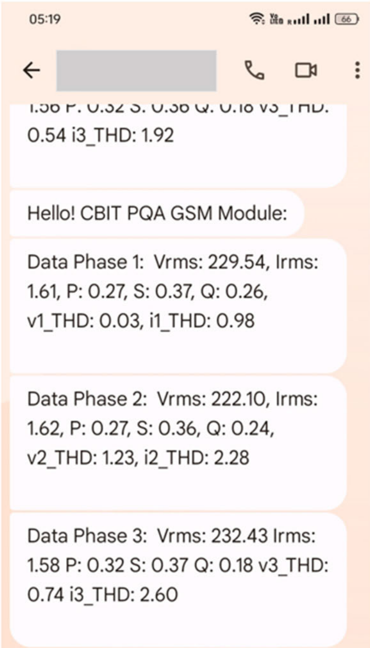

FIGURE 15. SMS alerts received on mobile for fluctuations in the field measurements.

timely alerts to enable quick decision-making. This system was expected to present a reliable, user-friendly, and portable solution for measuring disturbances in the power quality. However, in order to meet the accuracy of a conventional PQA and standard fluke meter, it is important to update the system with advanced circuit design. While designing a low-cost solution with IoT, the biggest challenge to deal with is the accuracy of the system. The Arduino Mega 2560 and ESP32 Wroom follow ADC different resolution levels with 10-bit and 12-bit specifications, respectively. Moreover, they have different operating voltages such as Arduino Mega following 5V design therefore, 10-bit resolution of 0 to 1023 different values is mapped to 0 to 5V range. Whereas, in the case of ESP32 Wroom, the 12-bit resolution with 0 to 4095 discrete analog levels mapped to 0 to 3.3V range. The resolution of ADC affects the accuracy of analog readings while making it difficult to track frequent & minute changes in the field parameter measurements. Moreover, while designing this IoT-based SPQA system, the input was taken from conventional FPGA board tap points which consist of an internal current transformer and potential transformer. It is usually difficult to calibrate the IoT SPQA observations without knowing the internal transformer ratio and sensitivity levels. This is one of the potential reasons behind reduced precision, and delay in tracking change in the field parameter value. With a known sensitivity level of voltage and current transformers, it gets easier to calibrate the system with the burden resistance to follow linear behavior with the change in input signal. In the future, authors plan to use independent voltage and current sensors to receive input from mains directly on the Arduino Mega 2560 and ESP32 Wroom board. With precisely defined hardware configurations, it will be easier to calibrate the SPQA system to deliver accurate readings even with minute changes in the signal levels. Furthermore, the voltage divider circuit in the future will be also replaced with a level shifter to enhance system accuracy without suffering any current loss in the circuit. With the improved design, the proposed system is expected to provide more reliable and accurate monitoring of power quality disturbances. Such portable units can be easily installed in residential, commercial, and industrial environments to avoid any trouble associated with fluctuations in the power supply. Furthermore, the real-time remote data access and SMS-based alerting mechanism make such IoT-based SPQA systems more useful for the end users.

V. CONCLUSION

Power quality disturbances are always a matter of concern for residential, commercial, and industrial environments. Sudden fluctuations in the supply can sometimes cause difficulty in handling loads within the building premises, laboratories, or industrial operations. Power quality management is a complex problem that has a direct association with several industrial issues. Early identification of disruptions is essential to enhance service efficiency while boosting the productivity of the system. IoT-based SPQA system opens new opportunities for real-time monitoring of power quality fluctuations to ensure continuity of operations. This paper proposes an IoT-based SPQA system with a real-time monitoring and alerting mechanism using Arduino Mega 2560, ESP32 Wroom, and SIM900A module. The main contribution of this experimental study is to develop a low-cost, portable, and user-friendly monitoring system for power quality disruptions. The performance analysis of the proposed system was conducted against a conventional PQA and standard fluke meter. The tests were conducted in no load condition as well as with four different load values including 0.8 amp, 1.6 amp, 2.4 amp, and 3.2 amp load. The experimental results were tabulated for all load combinations and graphical analysis for outputs recorded from all measuring devices was also provided in this study. The IoT-based system provided reliable outcomes with parameter readings close to the conventional and standard measuring units. Furthermore, the data was stored on the ThingSpeak cloud interface for future needs and timely alerts for critical variations were provided using the GSM module.

Nevertheless, the proposed system also had several limitations that can be improved with modifications in the future design. The main problem observed during experimental analysis was the unavailability of internal circuit specifications available inside FPGA based PQA system. Since the input to the IoT-based SPQA system was provided from dedicated tap points available on conventional PQA systems, calibrating the system without knowing the sensitivity level of the internal transformers was a challenge. Furthermore, the ADC resolution of Arduino Mega and ESP32 also made it difficult to track minor changes in the signal parameters.

In order to deal with this problem, the authors plan to use dedicated voltage and current sensors with IoT-based SPQA to get direct access to the main supply from the proposed hardware system. Furthermore, the use of a voltage divider circuit to create a low-cost system design also leads to losses in current during circuit operation that further lead to reduced accuracy in the system. This challenge in the future will be solved using a high-quality level shifter in association with the ESP32 development board. The system design will be further improved with a compact and portable chip design so that an easy-to-use solution can be achieved for field monitoring. The data collected on the ThingSpeak platform will be utilized for pattern analysis and forecasting in the near future.

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