Edge-Driven Linux Platform for Power Quality Solutions

Jeevan Chandra C, Sandhya S, Bhaskar Reddy N

***Abstract**: In the modern landscape of data centers, ensuring optimal power quality and efficiency is paramount. This paper describes designing and implementing an edge-driven Linux platform for power quality solutions for real-time measurement, analysis, and conformity with IEC 61000-4-30, IEEE 519, and EN 50160 standards. It employs an AM6442xx processor and has a web interface with the backing of an efficient embedded web server, a NodeJS, and a Nginx server. It supports industrial communication protocols like Modbus TCP to simplify integration into existing systems. In addition, it involves risk assessment, threat modeling, and enhanced ability of the platform to withstand tests that threaten the confidentiality and integrity of data. Thus, the proposed solution increases the efficiency of data center operations and provides reliable power quality metering that meets current international standards.*

Keywords: Power Quality, Edge Computing, Linux Platform, Data Centers, NodeJS, ARM64, Modbus TCP, Real-time Monitoring, Embedded Web Server.

I. INTRODUCTION

A continuous, high-quality power supply in modern data centers is critical to maintaining operational efficiency and preventing costly downtimes. Power quality disturbances, such as voltage sags, swells, harmonics, and transients, can severely impact the performance of sensitive equipment, leading to failures and increased operational costs. Traditional power quality monitoring systems often fall short of the real-time capabilities and seamless integration required for modern data centers, especially in environments with high energy demands and complex infrastructures. These limitations highlight the need for advanced monitoring solutions that offer real-time data acquisition, detailed analysis, and robust reporting mechanisms while adhering to stringent international power quality standards. An edge-driven solution based on the AM6442xx computing platform has been formulated to meet these challenges adequately.

This system architecture effectively supports data acquisition, power quality analysis, waveform capture, report generation, and a high-performance SQLite3 database. All components are deployable over the web and secured with advanced protection systems. The built-in web server, created using NodeJS and Nginx servers, helps smooth interaction with the system, enabling proper management and dissemination of data acquired. A vital characteristic of the platform is its adherence to global power quality standards such as IEC 61000-4-30, IEEE 519, and EN 50160. These standards help to guarantee the accuracy of measuring and reporting a wide range of power quality parameters within the platform, offering data center operators crucial actionable insights necessary for optimal performance. Support for industrial communication protocols, including Modbus TCP, that makes integration with existing data center infrastructure easy, enhances interoperability, and facilitates smoother information interchange. The platform incorporates risk assessment, threat modeling, and thorough durability testing for the web server and database to prevent unauthorized access to power-quality data in terms of risk management and security. These include real-time monitoring of the data center and the swift identification of issues that need resolution, ultimately enhancing the efficiency and capacity of the facility to provide services.

This paper emphasizes the importance of edge-driven solutions in improving power quality management and maintaining the resilience and efficiency of modern data center operations. The developed platform is a pivotal improvement in the field as it provides a comprehensive and standard-compliant power quality metering system that deals with technical and integration issues to improve the quality of data center operations.

II. LITERATURE SURVEY

The rapid evolution of data centers has necessitated advancements in power quality monitoring and management to ensure operational efficiency and minimize downtime. Scholars have presented numerous works on diversified technologies and methodologies for improving the performances and interconnectivity of PQ monitoring systems. This section includes a quick review of the literature on significant advancements and accomplishments in this field of research.

In the context of PQ problems in microgrids [1], significant attention is directed toward supra harmonics, with methods proposed for their effective reduction and compliance with existing standards.

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Similarly, regarding power consumption and quality in public buildings [2], the analysis focuses on how power consumption profiles adhere to the IEEE 1459 standard, highlighting the importance of monitoring systems for power efficiency and cost.

Another study [3] assesses the techniques employed for identifying and classifying events that impact PQ in advanced grids, emphasizing the necessity for ongoing enhancement of detection systems. It is also evident from the evolution of a Linux web server designed for embedded devices [4] that PQ monitoring procedures can be improved through embedded servers, making data storage and retrieval essential. The interface of the embedded systems with a remote Graphical User Interface [5] also helps by improving the monitoring outcome and enhancing the user interaction and data visualization in real-time. According to [6], some security techniques to avoid in Modbus/TCP-based industrial systems include message authentication codes, which present an understanding of security and communication protocol in PQ monitoring.

Moreover, the difficulties provoked by the design of smart microgrids with superior communicating layers [7] and the employment of edge computing to provide specific connections in the microgrid networks are explained and solved. The application of load-balancing algorithms in the context of Nginx web servers [8] is examined to improve the utility of the web-based monitoring interfaces. Additionally, the architecture of the more effective API gateway applying the heterogeneous hardware accelerators [9] is evaluated to enhance PQ monitoring systems for multiple large data transactions. Also, the usage of software-defined networks realized based on APIs [10] points to the flexibility and scalability of PQ monitoring systems.

An overview of PQ disturbances and their classification is provided [11], the effects of these disturbances on data centers are summarized, and several intelligent techniques for PQ disturbance monitoring are detailed. To enhance PQ monitoring, real-time data processing is recommended [12]. Nonetheless, a new method can improve PQ data analysis in edge computing by lowering latency. Data interface and delivery [13] examines the integration of PQ monitoring systems with industrial automation systems. The escalator architectural approach for meeting more extensive demands is also discussed, along with other methods utilized in PQ monitoring in data centers [14]. PQ monitoring analytical techniques used in communication protocols [15] are examined, along with suggestions for enhancing system interactions and data transfer rates.

Specific online aspects of PQ surveillance systems are analyzed, particularly regarding easily understandable, timely updated graphic interfaces [16]. Various applications of artificial intelligence in PQ analysis [17] are also examined, demonstrating its ability to predict certain disturbances. The elements of information security in PQ monitoring systems [18] are explored, focusing on efficient data storage solutions. Finally, contemporary approaches to PQ monitoring are evaluated based on current guidelines for this process [19]. The extended use of the technology [20][21][22][23][24][25] is analyzed, presenting a view of extending the PQ data storing process to become decentralized to enhance the PQ information reliability.

Altogether, these studies contribute to the continuous development of power quality monitoring systems so that data centers can have reliable power quality in their operations.

III. PROBLEM STATEMENT

The current approaches to monitoring PQ components in data centers present several significant challenges. One key issue is the lack of web interfaces crafted to effectively display power quality metrics, making it difficult for operators to interpret and work with the collected data. Additionally, previous methods have struggled to handle the demands of real-time data monitoring and high-load processing in environments using NodeJS and Nginx on ARM64 processors. Furthermore, there is insufficient research and testing focused on implementing advanced security measures for specialized PQ monitoring systems integrated into smart grids. These limitations underscore the need for an efficient solution that contains a robust data processing mechanism, reliable web interfaces, and strong security protocols to improve the dependability and usability of PQ monitoring in data centers.

IV. OVERALL ARCHITECTURE

The overall architecture of the edge-driven Linux platform, particularly tailored for power quality monitoring in data centers, is a robust integration of hardware and software components designed to deliver high efficiency, scalability, and real-time data processing. The architecture uses the AM6442xx processor, which is very popular among the embedded systems community due to its balance between power efficiency and computational performance.

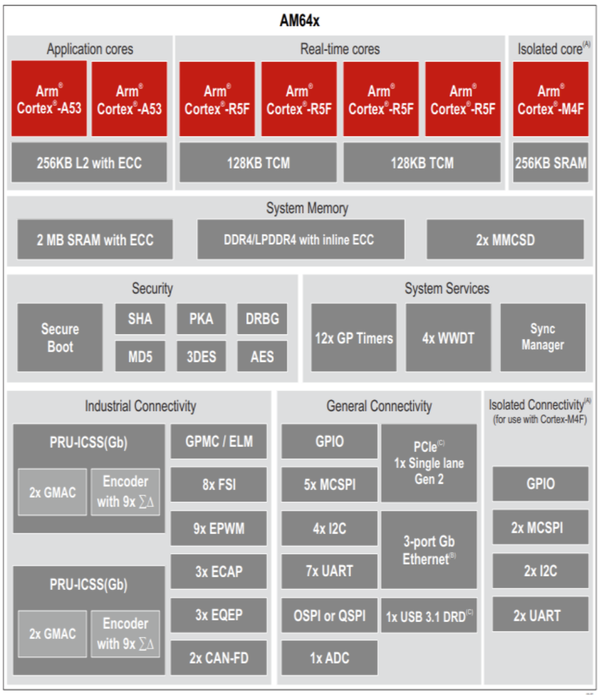

Fig. 1: Functional Block Diagram of AM6442xx

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The AM6442xx microprocessor, as depicted in Fig. 1, is meticulously designed to meet the needs of industrial applications that demand high efficiency, real-time processing, and secure operations. This architecture features a streamlined use of multiple specialized cores for different tasks. The dual Cortex-A53 cores, acting as application cores, handle both the main functions of the operating system and user-level applications. These ARMv8-A CPU cores are known for providing a balance between computational performance and energy efficiency, making them well-suited for handling complex data processing tasks in industrial environments. Additionally, the Cortex-R5F real-time cores are designed for low-latency tasks, such as sensor data sampling and managing industrial protocols, ensuring the system can respond quickly to external signals. Moreover, an isolated Cortex-M4F core is incorporated into the architecture to handle critical low-power operations. This core works parallel with the others, ensuring functions can continue even during power constraints, further enhancing the system's overall reliability and efficiency.

The core is designed for system health monitoring or safety-critical functions, thereby enhancing reliability by providing a backup mode that ensures critical functions continue to operate even in the event of a system failure. The general structure of the microprocessor memory, as shown in Fig. 1, incorporates elements such as L2 cache and Tightly Coupled Memory (TCM) with Error Correction Code (ECC). This design improves data reliability and facilitates quick access to frequently used data, as cache memory offers faster access times than main memory, thereby boosting processing speeds. Additionally, various I/O interfaces like Universal Asynchronous Receiver-Transmitter (UART), Serial Peripheral Interface (SPI), and Inter-Integrated Circuit (I2C) are crucial for interfacing with sensors and devices necessary for Power Quality Monitoring (PQM) applications. These interfaces enable the microprocessor to receive and efficiently analyze data. The AM6442xx is a versatile and highly effective microprocessor engineered to meet the demands of modern industrial systems.

Fig 2: Hardware Component of AM6442xx

Moving beyond the processor's internals, the hardware components of the AM6442xx, Fig. 2, illustrate the essential physical elements that form the backbone of the edge-driven platform. While serving as the central processing unit, the processor, RAM, provides the necessary volatile memory for application execution, with the firmware stored in ROM. These components are interconnected with other critical hardware parts at the device level, Along with network modules such as Ethernet or Wi-Fi, which are crucial for reliable data transmission to a centralized server or cloud platform. General Purpose Input/Output (GPIO) pins and other I/O interfaces extend the system, allowing connections to various sensors and external devices. These components are vital for obtaining real-time power quality information.

The broader system integration is thorough in Fig. 3, which presents a comprehensive view of how these hardware components are orchestrated with software layers to achieve the platform's objectives. At the core of the software stack is the Linux operating system, which is stable, secure, and versatile enough for industrial embedded systems. The inbuilt web server, which employs NodeJS and Nginx servers, will cater to the significant data traffic in power quality monitoring.

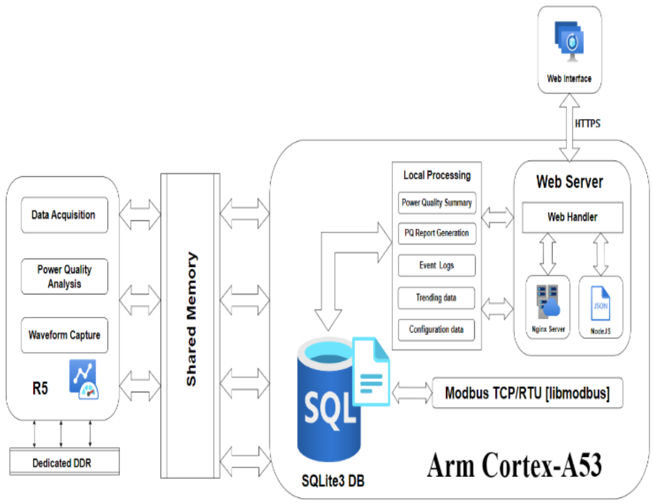

Fig 3: System Architecture of an Edge-Driven Linux Platform for Power Quality Solutions

NodeJS provides asynchronous capability, allowing the system to handle multiple requests simultaneously, while Nginx acts as a high-performing reverse proxy server that balances the incoming load. SQLite3 is used as the database system to manage standalone PQ data on the device, making the data quickly accessible for processing, especially in areas with restricted or intermittent network connectivity. The platform also leverages shared memory to enable smooth and efficient communication between the software and hardware units, particularly during real-time activities. The HMI operates solely with Modbus TCP, while the unit includes R5 processors to gather PQ data and waveform captures, which are essential for monitoring electrical parameters. Using the shared memory interface, these processors allow the platform to perform high-speed data transfers, vital for efficiently processing PQ data with minimal delay. Although these cybersecurity measures focus on simple tasks such as table validation, they are crucial in securing processed data from platform probes, given the sensitive nature of power-quality data in data center operations.

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V. METHODOLOGY

The development of the edge-driven Linux platform for power quality monitoring in data centers follows a structured approach, starting with requirements gathering and system design. The hardware implementation involves connecting the AM6442xx processor to other interfaces, such as UART, SPI, and I2C, to monitor and process power-quality data. The integration of Nginx, SQLite3, and NodeJS plays a pivotal role in enhancing the overall performance of the power quality monitoring platform. Nginx is configured strategically to manage API processing with an emphasis on speed and data security, as illustrated in Fig. 4. Utilizing load balancing and SSL/TLS encryption at its core, Nginx ensures that data transfer across the network is both efficient and secure—an essential feature given that power-quality data is very delicate. The platform's ability to quickly secure data processing is central to its support for real-time analytics, ensuring data integrity is never compromised.

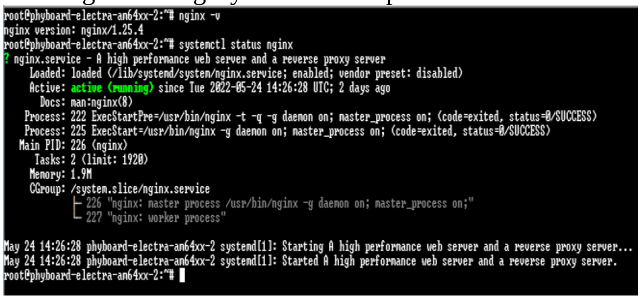

Fig 4: Nginx Server Integration

Fig. 5 depicts SQLite3 as the primary database engine, chosen for its simplicity, speed, and reliability blend. It handles real-time and historical data optimally, with speed in retrieval and seamless integration with NodeJS, as depicted in Fig. 6.

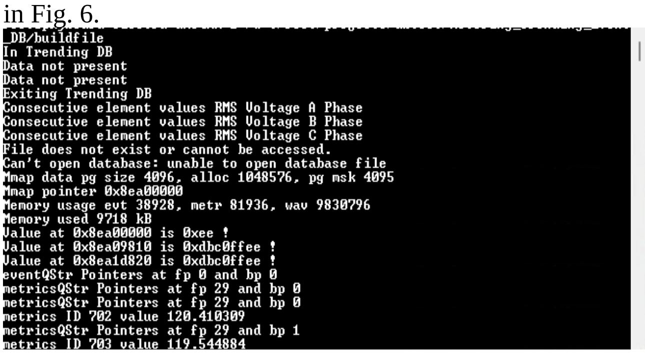

Fig. 5: SQLite3 Integration

NodeJS provides the backbone for the platform's backend operations and controls the flow of data from the first point of capture to its last visualization on the dashboard. With SQLite3 integrated into NodeJS, latency is reduced to nearly instantaneous when accessing power quality metrics, allowing users to depend on the platform for timely insights and informed decision-making.

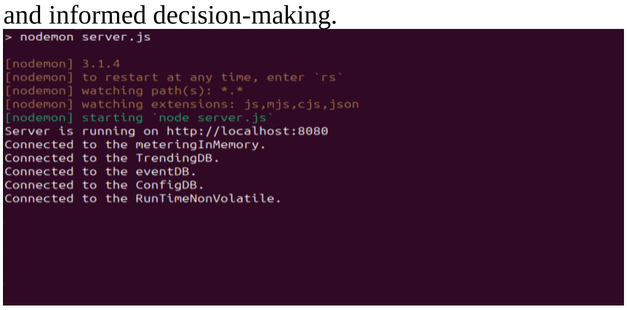

Fig. 6: Node JS Integration

The software integration phase focuses on the Linux OS, which supports an integrated web server built with NodeJS and Nginx. This server is optimized to handle multiple data requests simultaneously, balance system load, and enable real-time monitoring. SQLite3 functions as the database management system, storing power-quality data locally to ensure quick access regardless of network conditions. Shared memory allows software and hardware components to communicate efficiently, sending and receiving data in real-time. Additionally, Modbus TCP is designed for communication with the HMI, and R5 processors manage waveform data acquisition and high-speed transactions. These components work together to make the platform efficient, scalable, and reliable, fully meeting the user's needs and capacity requirements.

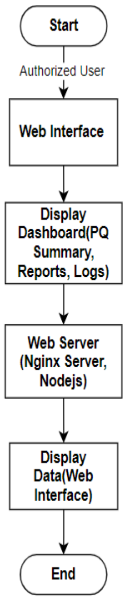

Fig 7: Flow Chart of an Edge-Driven Linux Platform for Power Quality Solutions

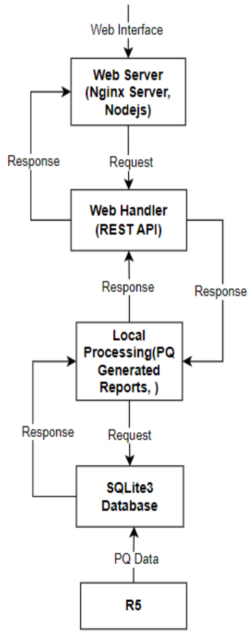

Fig 8: Flow Chart of Embedded Web Server

To illustrate the logical flow of these core operations, the flow chart in Fig. 7 depicts the linear process of the platform's core functionalities. It visualizes the initialization process, data capture, processing mechanisms, and communication between the system and external devices or networks. This flowchart is vital for understanding the logical progression of tasks and ensuring the platform's reliability and operational efficiency.

Also, Fig. 8 provides a focused view of the web server component, detailing how it handles incoming data requests, processes the information, and delivers appropriate responses. This flowchart emphasizes the web server's role in managing substantial data traffic, ensuring efficient communication between the platform and its users, and maintaining performance even under multiple concurrent requests. This aspect is critical for ensuring the platform's robustness and real-time data accessibility, which is fundamental for effective power quality monitoring.

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A. Architecture Workflow Overview

In addition to the flowcharts, the use-case diagram, as shown in Fig. 9, provides a comprehensive visualization of the platform's development process.

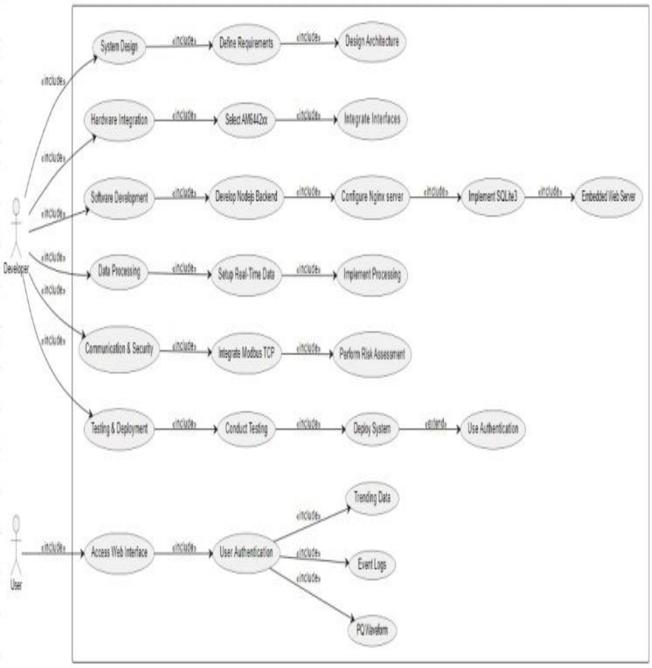


Fig. 9: Architectural Workflow Overview of an Edge-Driven Linux Platform for Power Quality Solutions

The developer initially works on system design and then continues to include hardware modules, such as the AM6442xx processors with UART, SPI, and I2C interfaces. Next, software development occurs, where a Linux-based operating system hosts an integrated web server built with NodeJS and Nginx to process data in real-time and manage the load. The diagram also highlights the implementation of SQLite3 for local data storage, ensuring network availability for data storage and retrieval. The details about the communication setup using Modbus TCP and the configuration of R5 processors for high-speed data acquisition are significant steps in this process. Next is the testing and deployment phase, where the platform undergoes thorough testing to ensure it is fully functional and secure. This well-coordinated workflow enables the seamless integration of each unit into the overall system, maintaining stability and scalability for power quality monitoring.

VI. RESULTS AND ANALYSIS

The overall consistency of the developed power quality monitoring platform permits the integration of real-time data capture and processing of all the vital characteristics of power quality. The real-time voltage, current, power quality indices, and waveform captures are easily understandable with the help of the dashboard. These metrics are shown in a manner that is understandable and usable for further analysis and are compliant with IEC 61000-4-30, IEEE 519, and EN 50160.This results in a strong integration of the two components that enables the platform to provide the accurate and timely information needed for managing power quality as formulated by the recommended quality standards.

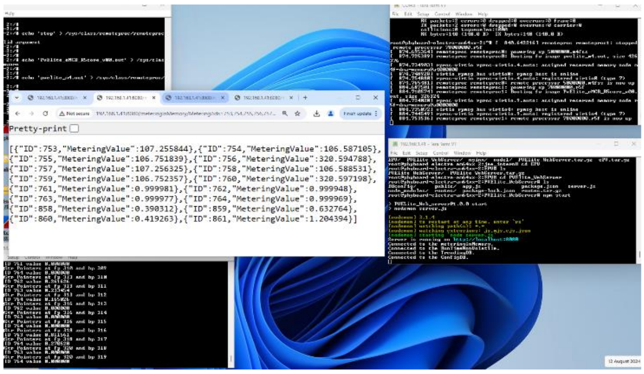


Fig. 10: Power Quality Integration

The power quality integration aspect of the platform, illustrated in Fig. 10, plays a crucial role in its operation, facilitating the acquisition of signals and their immediate analysis for critical power quality parameters like voltage and current. These metrics are easily managed and monitored within the dashboard, offering a clear view of system status while ensuring adherence to compliance standards. Performing real-time power quality analysis is essential to identify fluctuations from the standard level and restore reliable operation.

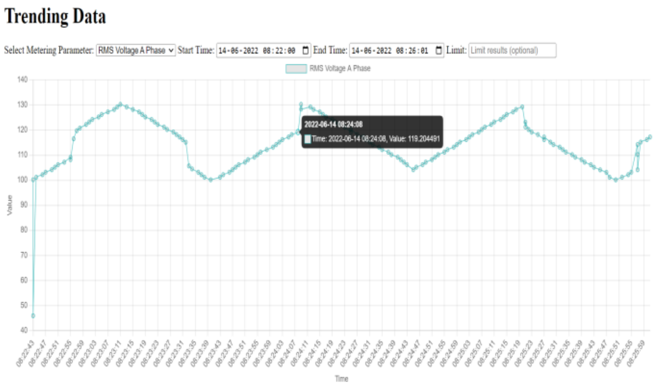
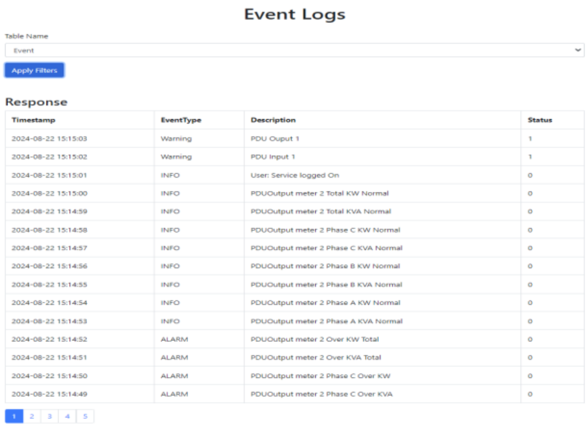


Fig. 11: Trending Data Chart of Power Quality Solutions

The trending data chart shown in Fig. 11 is crucial in handling and analyzing vast amounts of data, especially from previous session operations. For instance, it allows users to observe temporal fluctuations of some parameters, such as RMS voltage or harmonic distortion, and find abnormal changes or trends. With this capability, users can make decisions on power management, forecast power problems, and enhance power quality. Thus, it also presents a significant benefit of the platform, as it can process vast amounts of data and deliver vital analytical information promptly and accurately. The event logs shown in Fig. 12 are essential for documenting and organizing significant power-quality events. It systematically captures anomalies and interruptions, providing users with a detailed log for effective management and troubleshooting. This comprehensive event logging supports a thorough understanding of the system's performance and facilitates prompt issue resolution, thereby maintaining high standards in power quality management.



Timestamp	EventType	Description	Status
2024-08-22 15:15:03	Warning	PDU Ouput 1	1
2024-08-22 15:15:02	Warning	PDU Input 1	1
2024-08-22 15:15:01	INFO	User: Service logged On	0
2024-08-22 15:15:00	INFO	PDUOutput meter 2 Total KW Normal	0
2024-08-22 15:14:59	INFO	PDUOutput meter 2 Total KVA Normal	0
2024-08-22 15:14:58	INFO	PDUOutput meter 2 Phase C KW Normal	0
2024-08-22 15:14:57	INFO	PDUOutput meter 2 Phase C KVA Normal	0
2024-08-22 15:14:56	INFO	PDUOutput meter 2 Phase B KW Normal	0
2024-08-22 15:14:55	INFO	PDUOutput meter 2 Phase B KVA Normal	0
2024-08-22 15:14:54	INFO	PDUOutput meter 2 Phase A KW Normal	0
2024-08-22 15:14:53	INFO	PDUOutput meter 2 Phase A KVA Normal	0
2024-08-22 15:14:52	ALARM	PDUOutput meter 2 Over KW Total	0
2024-08-22 15:14:51	ALARM	PDUOutput meter 2 Over KVA Total	0
2024-08-22 15:14:50	ALARM	PDUOutput meter 2 Phase C Over KW	0
2024-08-22 15:14:49	ALARM	PDUOutput meter 2 Phase C Over KVA	0

Fig. 12: Event Logs of Power Quality Solutions

A. Performance Analysis

The performance analysis assesses how efficiently the platform manages different functionalities under varying demand levels. This assessment is crucial for understanding the system's ability to handle real-time and historical data processing, which impacts overall power quality management.

Table 1: Performance Metrics for Power Quality Solutions

Functionality	Concurrency Level	Total Requests	Time Taken (seconds)	Requests per Second	Time per Request (ms)	Transfer Rate (Kbytes/sec)
Power Quality Integration	50	1000	3.911	255.66	195.568	285.13
Trending Data	25	100000	253.23	394.9	63.308	2950.55
Event Logs	25	100000	311.959	320.56	77.99	831.13

The performance metrics in Table 1 underscore the platform's proficiency in managing diverse functionalities with varying degrees of efficiency, demonstrating its robustness in real-time and historical data management. The Power Quality Integration feature efficiently processes 1,000 requests in 3.911 seconds, indicating its capability to handle moderate data loads crucial for maintaining power quality. The Trending Data feature excels by processing 100,000 requests in just 253.230 seconds, showcasing its speed in handling historical data for predictive analysis and decision-making. Although the Event Log takes 311.959 seconds to manage 100,000 requests, reflecting a slightly higher time per request due to the complexity and volume of event data, it still demonstrates reliable performance in maintaining extensive logs over time.

B. Evaluation Metric

The evaluation metrics for Table 1 align with industry standards, underscoring the platform's compliance and efficiency. The Power Quality Integration feature processes 1,000 requests in 3.911 seconds with a concurrency level of 50, meeting the IEC 61000-4-30 standards for timely power quality management. The Trending Data feature, handling 100,000 requests in 253.230 seconds with a concurrency level of 25, aligns with IEEE 519 standards for efficient historical data sampling, ensuring stability and reliable predictive maintenance. Additionally, the Event Logs manage 100,000 requests in 311.959 seconds with a concurrency level of 25, adhering to EN 50160 standards for maintaining comprehensive event records, which ensures high dependability despite the higher time per request.

VII. CONCLUSION

The platform developed in this study offers a comprehensive and efficient solution for real-time data capture and analysis in complex electrical environments. By integrating advanced technologies like Nginx, SQLite3, and NodeJS, the platform can efficiently manage large volumes of high-quality data while monitoring them in real-time with precision. The system architecture is structured to process and store critical parameters such as voltage, current, and power quality in compliance with IEC 61000-4-30, IEEE 519, and EN 50160 standards. Additionally, the platform generates structured JSON-formatted data, simplifying integration with other applications and further processing. This capability makes the platform ideal for industrial environments requiring power quality control. The combination of NodeJS for dynamic updates, SQLite3 for data management, and Nginx for secure API processing ensures high performance and reliability. Its ability to function as a cross-platform web server enhances both versatility and security. Ultimately, the platform addresses the challenge of accurately assessing power quality in real-time and determining key parameters, fulfilling the requirements of modern industrial facilities. It also provides a solid foundation for future platform designs.

VIII. FUTURE SCOPE

The further development of the Advanced Power Quality Monitoring platform will focus on expanding functions beyond data acquisition. Novelties include more sophisticated waveform analysis and extended PQ reports on multimedia power quality trends. The platform's scalability and performance will increase to ensure more reliable operation under larger data loads and higher processing speeds. Testing will incorporate stress testing, vulnerability assessments, and new automated frameworks for bug troubleshooting and system stability. User experience improvements include homepage dashboards, Event logs, and visualization elements. The platform will maintain compliance with regulatory standards and integrate next-generation security with enhanced authentications and continuous threat detection.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted with objectivity and without any external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

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