Assistive tool of energy metering system for power utility companies

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Article Info

Article history:

Received Sep 9, 2024
Revised Nov 27, 2025
Accepted Jan 15, 2026

Keywords:

Assistive tool
Energy consumption
Fog cloud computing
Power quality
Smart meter

ABSTRACT

The growing demand for electricity and the complexity of power quality management highlight the need for advanced energy monitoring systems. Existing solutions often could not provide the real-time, detailed data necessary for smart grids, smart cities, and Industrial 4.0. They also fail to monitor power quality effectively, avoid equipment damage and ensure safety. To address this, we developed an internet of things (IoT)-based tool that leverages standard energy meters. The system monitors and analyzes electrical energy consumption and its power quality in real-time. The system adopts a multi-layered IoT architecture, where fog computing handles immediate data processing and the cloud computing supports machine learning for power quality detection. In this work, measurement accuracy is validated against a commercial power multimeter, achieving mean absolute percentage error (MAPE) values below 1.0% across different appliances. A companion web portal allows for real-time data visualization, time-series analysis, remote control of appliances and power quality detection that comply with IEC and IEEE standards. The proposed system is scalable and user-friendly, offering a practical smart metering solution for modern energy management. It aligns with the needs of smart grids and smart cities, contributing to efficient and intelligent energy consumption in the context of Industry 4.0.

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1. INTRODUCTION

Electricity is a fundamental and essential resource in modern society for daily life, economic development, technological advancement, and improving quality of life. It powers industries, homes, and infrastructure, making it indispensable to daily living. However, the growing demand for electricity and concerns about power quality (PQ) present significant challenges to humanity and global sustainability. Currently, a large portion of the world's energy consumption is supplied by fossil fuels, amounting to 62% of global energy use in 2022 [1]. The extensive reliance on non-renewable energy resources leads to rapid depletion and environmental degradation. It ultimately pushes the need for smart energy metering for more effective energy management solutions [2].

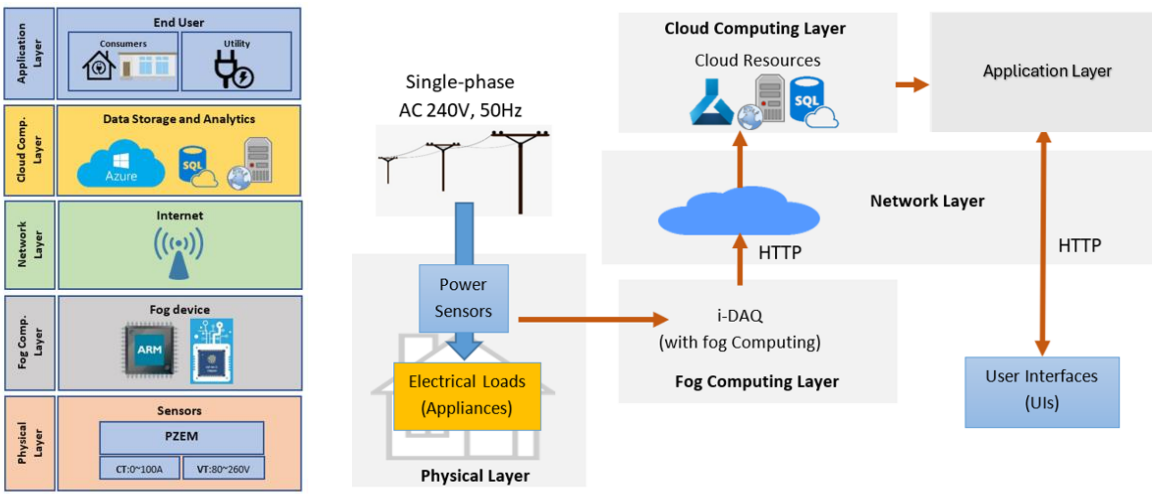
Power quality, which refers to the stability and reliability of electrical supply, is crucial for maintaining the efficiency and safety of electrical systems. Poor PQ can lead to a range of issues, including deviations in supply voltage and system frequency, harmonics, and waveform distortion, which can damage electrical equipment, disrupt operations, and even pose safety hazards. For example, improper or accidental use of electricity with over-current, short-circuit, and malfunctioning of electrical appliances can result in fire incidents [3], [4]. The widespread use of non-linear (NL) loads, such as power converters, rectifiers, induction ovens, and battery chargers, has degraded the PQ of low voltage (LV) distribution networks. These NL loads generate harmonics that distort the sinusoidal waveforms of current and voltage [5], [6]. The presence of harmonic currents in electrical systems can increase root mean square (RMS) current and degrade the quality of the power supply. Signs of problematic harmonic levels include overheating transformers, motors, and cables, tripping protective devices, and logic faults of digital devices. Moreover, elevated operating temperatures can significantly reduce the lifespan of various devices [5].

Despite advancements in energy metering technology, current metering systems face considerable limitations. Although traditional analog meters have largely been replaced by digital smart meters which offer improved data collection and remote monitoring capabilities, these systems are often inadequate to address specific challenges related to PQ and detailed energy consumption monitoring [7]–[11]. Many smart meters lack the ability to provide real-time and granular data for advanced energy management strategies at the consumer level in supporting smart grid (SG), smart cities (SC) and IR 4.0 environment. Furthermore, these smart meters frequently fail to monitor and detect electrical faults or anomalies which are crucial for preventing equipment damage and ensuring safety. These shortcomings highlight the need for a more comprehensive solution that enhances existing metering systems' capabilities and integrates advanced technologies like machine learning, fog computing and cloud computing to create a robust, scalable, and user-friendly platform [12].

The proposed assistive tool for energy metering system (ATEMS) is a non-intrusive, user-friendly, real-time monitoring system for PQ and electricity consumption. ATEMS can measure energy consumption and a range of other PQ parameters, providing a more comprehensive understanding of electricity usage at the consumer level. By implementing ATEMS, it becomes possible to monitor and control consumption and PQ in real-time, in compliance with IEC-61000-4-30 (Testing and measurement techniques - power quality measurements methods) and IEEE 1159-2009 (IEEE recommended practice for monitoring electric power quality) standards. Ultimately, the system can reduce energy waste and enhance the safety and reliability of the power grid [13]–[15], contributing to the specific environment of smart grid and smart city initiatives by providing feedback through cloud applications to end-users [16].

2. MULTI-LAYERED IOT ARCHITECTURE

The proposed model of ATEMS is based on multi-layer internet of things (IoT) architecture as depicted in Figure 1. The conceptual architecture model consists of physical layer, fog computing layer, network layer, cloud computing layer, and application layer [17], [18], as depicted in Figure 1(a). Its system implementation is illustrated in Figure 1(b).



(a) (b)

Figure 1. The design of the ATEM system, (a) conceptual layered architecture and (b) implementation diagram

The physical layer comprises several sensors responsible for acquiring data from power sensors. The fog computing layer, positioned at the second layer, handles lightweight data storage and computation of the power data collected by the physical layer. The cloud computing layer offers extensive data storage and advanced computing capabilities. The network layer bridges the fog computing and cloud computing layers, ensuring secure and seamless data communication. The final layer is the application layer, which manages all application processes using the information from the cloud computing layer. This layer includes user interfaces, data visualization of electrical energy information, and real-time support of load monitoring.

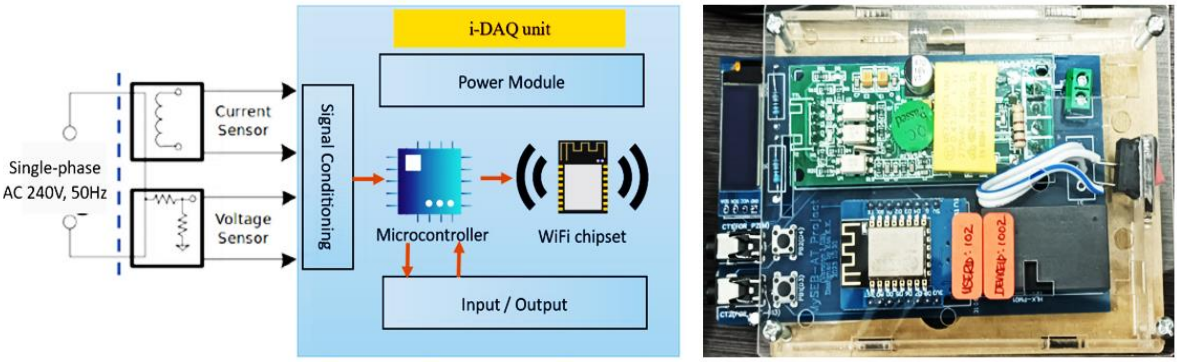
The system integration is achieved using standard internet transfer protocols, i.e., hypertext transfer protocol (HTTP) and application program interface (API), to facilitate real-time monitoring and visualization of electrical parameters. The proposed model enhances the existing smart metering system by supporting real-time monitoring of PQ and consumption within defined limits [14], [15]. It incorporates cloud computing and machine learning algorithms for the detection of electrical risks and faults. Consequently, delivering an electricity supply that meets quality standards is crucial for protecting customers and their sensitive devices within LV distribution networks [19].

3. METHOD

The practical model consists of three components: i) power sensors and intelligent data acquisition (i-DAQ) unit, ii) cloud server platform, and iii) graphical user interface (GUI) and mobile application. A cost-effective and Wi-Fi enabled i-DAQ unit has been developed to connect to a local Wi-Fi access point (AP) for internet connectivity. This unit collects electrical data from the incoming power supply point (near the kWh meter) using non-intrusive sensors (CT/VT). The acquired data is uploaded and stored on a cloud platform that includes several cloud servers for web portal, database storage, web hosting and computation. This data is then processed for advanced machine learning (ML) applications, such as energy consumption modeling and power quality analysis. Finally, GUIs are deployed to access the ATEMS system through a web browser (such as Google Chrome and Microsoft Edge) or mobile app (Android).

3.1. Intelligent data acquisition (i-DAQ)

The primary function of the i-DAQ unit is to acquire electrical quantities measured by a calibrated power meter, specifically the Peacefair PZEM module. In addition, the ARM-based processor in i-DAQ performs fog computing by handling data pre-processing of current signals from the current transformer (CT) sensor to calculate harmonics and total harmonic distortion (THD) parameters. The recorded data with timestamp (UTC) is compiled, including voltage (V), current (A), power (W), energy (kWh), power factor (%), frequency (Hz), harmonics, and THD. The i-DAQ unit also acts as a communication gateway, connecting fog and cloud systems. The acquired and streamlined electrical data is then uploaded to the cloud platform for storage, analysis, and computation for machine learning modeling. Figure 2 shows the design of i-DAQ unit for ATEMS system with Figure 2(a) depicting the block diagram, and the prototype of the i-DAQ unit in Figure 2(b).



(a) (b)

Figure 2. i-DAQ unit of ATEMS system, (a) block diagram and (b) prototype

3.2. Peacefair PZEM module

The PZEM power meter is commonly known for its efficiency in operating as a single-phase alternating current (AC) power meter which is supported by Modbus serial communication protocol. Widely adopted in IoT projects, the PZEM power meter has a high measurement accuracy, with a measurement error of less than 0.5% for the electrical parameters it monitors [20]. It exhibits the capability to measure various fundamental electrical parameters, encompassing the RMS values of voltage and current, real power, energy consumption, system frequency, and power factor. The device can measure current up to 100 A. The power measurement process starts with a non-invasive split-core current transformer (CT) securely clipped around the phase current-carrying cable. Additionally, the PZEM power meter has a built-in voltage sensor (VT) that accurately measures RMS voltage and other critical electrical parameters. The PZEM-004T model is manufactured by Ningbo Peacefair Electronic in China, and its technical specifications are listed in Table 1.

Table 1. Peacefair PZEM-016 technical specifications and accuracy

Parameter	Unit	Range	Resolution	Accuracy
Voltage	V	80-260	0.1 V	±0.5%
Current	A	0-100	0.001 A	±0.5%
Active Power	W	0-23000	0.1 W	±0.5%
Energy	kWh	0-9999.99	1 Wh	±0.5%
Frequency	Hz	45-65	0.1 Hz	±0.5%
Power factor	-	0-1	0.01	±1%

3.3. Fog computing for harmonics parameters

The Fourier series allows any periodic signal function *f(t)* to be represented as a sum of a DC term, along with the amplitudes and frequencies of its sinusoidal components, as shown in (1):

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n cos\, n\omega_0 t + b_n sin\, n\omega_0 t \qquad (1)$$

where a_0 represents the DC component or average value of *f(t)*, *n* is a non-zero integer, a_n and b_n are amplitude terms for the harmonic components of cosine and sine waves, respectively [21]. These coefficients indicate that the periodic signal *f(t)* can be reconstructed from sine and cosine waves with frequencies that are multiples of fundamental frequency $f_n = n\, f_0$.

In this work, an ARM-based processor is embedded within the i-DAQ unit to perform various fog computing tasks, minimizing data transmission latency and reducing the load on cloud servers [22]. The process begins by acquiring the aggregated CT current signal at the point of common coupling (PCC) where the incoming power supply line interfaces. The analog input signal is converted into a digital format through a sampling and quantization process. The fast Fourier transform (FFT) is then applied to compute additional parameters such as system frequency, harmonics, and total harmonic distortion (THD) [23]. Due to the symmetrical nature of sinusoidal wave distortion around the average center line of the waveform, odd harmonics (3^{rd}, 5^{th}, 7^{th}) tend to be dominant in the distortion waveform, in contrast to even harmonics [24]. THD is a measure of harmonic distortion present in the signal. It is defined as the ratio of the sum of all amplitudes of harmonic components to its fundamental frequency [25], as expressed in (2).

$$THD = \frac{\sqrt{\sum_{h=2}^{n} (I_h)^2}}{I_1} \times 100\% \qquad (2)$$

3.4. Web-based ATEMS portal

As a fundamental component of the ATEMS system, the web-based ATEMS portal equips users with a full set of tools for system management. Its capabilities form a core pillar of functionality, encompassing everything from data storage and retrieval to the remote control of electrical devices and advanced data trending and visualization. Technically, the portal is built on a PHP and MySQL foundation and is enhanced with APIs that bridge the ATEMS system with its backend and third-party clouds, including Microsoft Azure. Authorized users entering the portal first encounter the main menu, a central dashboard that summarizes the system's capabilities. This gateway provides access to vital areas such as site and user administration, a comprehensive overview of live site information, analytical tools, and automation controls for appliances, which are depicted in Figure 3.

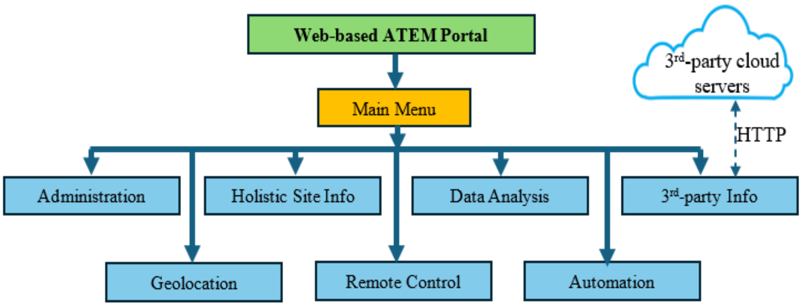
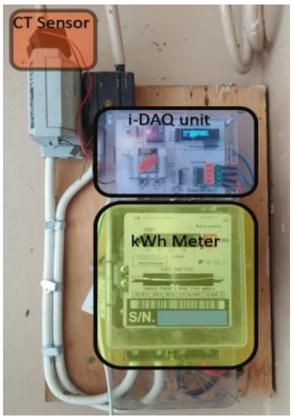


Figure 3. Web-based ATEMS portal structure

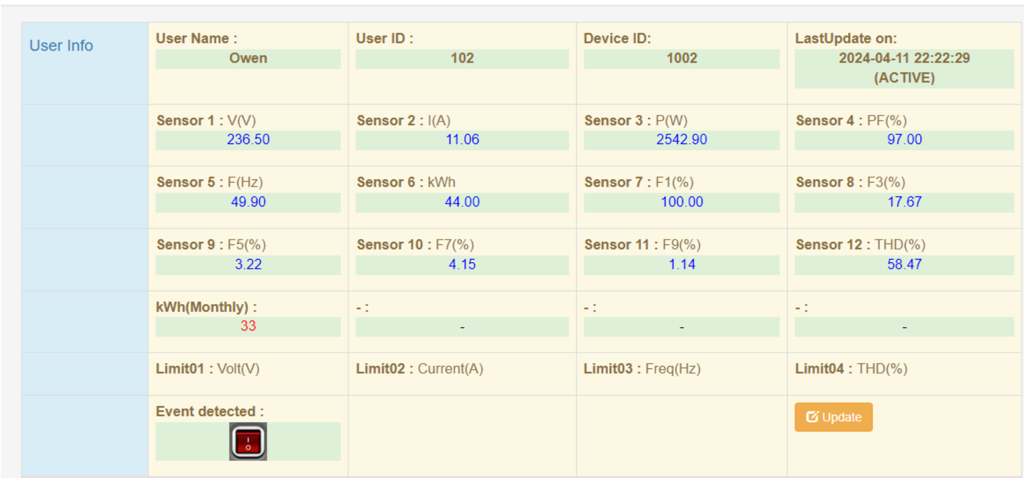
4. RESULTS AND DISCUSSION

4.1. Web-based ATEMS portal

The real-world implementation of the ATEMS system is captured in Figure 4. In this setup, the i-DAQ serves as the critical link from the physical site to the cloud, responsible for acquiring, streamlining, and uploading all data to the web portal for analysis, as depicted in Figure 4(a). On the software side, the web portal and its application programming interface (API) are coded in PHP and HTML. We host these APIs on robust cloud computing platforms to access scalable storage and computational resources. The result of this deployment is shown in Figure 4(b), which provides a holistic view of the ATEMS data within the web portal interface.



(a)



(b)

Figure 4. The real-world implementation of the ATEMS system: (a) deployment of ATEMS system and (b) holistic view of ATEMS data on the web portal

4.2. Verification of acquired data for electrical parameters

To thoroughly validate the measurement accuracy of the ATEMS i-DAQ unit and address the need for cross-verification, we conducted a comparative analysis against a calibrated reference instrument, i.e., the Lovato DMG800 power multimeter [26]. DMG800 is a high-precision instrument widely recognized in industry, which is highly comparable in measurement accuracy to others for advanced power quality analysis. Figure 5 illustrates the measurement setup of Lovato DMG800 power multimeter.

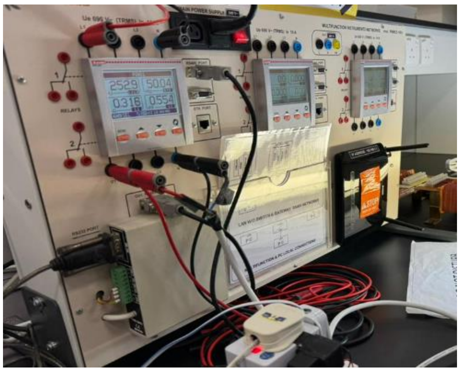


Figure 5. Measurement setup showing ATEMS validation against Lovato DMG800 power multimeter

In this section, the measurement accuracy of the electrical parameters acquired by the ATEM system is evaluated by comparing it with a calibrated Lovato DMG800 power multimeter [26]. The metric used for this evaluation is the mean absolute percentage error (MAPE). Three electrical appliances, namely LED light, microwave oven, LED TV, and electric kettle, are selected to assess measurement accuracy, with their respective MAPE values calculated. The measurement results for these electrical appliances using the DMG800 and ATEMS units are presented in Table 2. The measured MAPE values for 11 parameters average below 1.0%, specifically 0.62% for LED light, 0.94% for the microwave oven, 0.99% for LED TV, and 0.82% for electric kettle.

Table 2. Measurement results of selected electrical appliances with DMG800 and ATEMS unit

Features	LED Light			Microwave Oven			LED TV			Electric Kettle		
	DMG800	ATEMS	Error (%)	DMG800	ATEMS	Error (%)	DMG800	ATEMS	Error (%)	DMG800	ATEMS	Error (%)
Vrms	240.1	240.3	0.08	237.9	238.6	0.29	241.7	242.9	0.50	240.5	241.2	0.29
Irms	0.14	0.14	0.00	6.01	6.03	0.33	0.35	0.34	2.86	4.67	4.63	0.86
P	17.2	17.3	0.58	1338.1	1341.8	0.28	73.8	74	0.27	1076.8	1077.0	0.02
PF	49.90%	50.00%	0.20	92.88%	93.00%	0.13	91.50%	91.00%	0.55	100.00%	100.00%	0.00
F	49.9	50.0	0.20	49.9	50.0	0.20	50.0	50.0	0.00	49.9	50	0.20
THD	94.90%	94.30%	0.63	36.11%	36.68%	1.58	5.90%	5.86%	0.68	2.10%	2.14%	1.90
f_3	60.10%	60.50%	0.67	33.12%	33.96%	2.54	5.41%	5.38%	0.55	1.61%	1.64%	1.86
f_5	44.41%	44.30%	0.25	12.49%	12.52%	0.24	2.29%	2.30%	0.44	1.12%	1.13%	0.89
f_7	35.50%	36.10%	1.69	5.23%	5.31%	1.53	0.21%	0.21%	0.00	0.68%	0.70%	2.94
f_9	24.12%	23.60%	2.16	2.49%	2.42%	2.81	0.69%	0.71%	2.90	0.29%	0.29%	0.00
	MAPE (in %)		0.62%	MAPE (in %)		0.94%	MAPE (in %)		0.99	MAPE (in %)		0.82%

The result also highlights the issue of low power factor (49.9%) in LED light. A low power factor can reduce energy efficiency and impact PQ. To address this issue, power factor correction techniques using filters and converters can mitigate this issue and enhance PQ [27], [28]. These results indicate that the ATEMS system achieves measurement accuracy comparable to the commercial DMG800 power multimeter. Furthermore, the cost-effective ATEMS system can provide accurate power monitoring at a lower cost (USD30.00) as compared to commercial DMG800 power multimeters (USD250.00) [26], and making it a more affordable solution for widespread deployment.

4.3. Various functions of ATEMS

The web platform extends its functionality to include real-time data listing and visualization of time-series feature data, as shown in Figure 6. This includes the real-time display of electrical load conditions and

PQ parameters, along with robust tools for analyzing energy consumption through time-series data trending. The platform also allows for benchmarking electricity consumption to provide insights into usage patterns and identify peak demand periods. Real-time monitoring with graphical representation enhances user understanding for conscious electricity consumption. Furthermore, the system's ability to alert users to abnormal patterns and PQ issues makes ATEMS an invaluable tool for optimizing energy efficiency and promoting sustainable practices, as depicted in Figure 6. Typical ATEMS demonstration model and installation in smart grid, smart home, and IR 4.0 applications are illustrated in Figure 7. ATEMS incorporates machine learning algorithms for enhanced functionalities such as anomaly detection, fault classification, predictive maintenance (PdM), and participation in demand side management (DSM) and demand response (DR) of smart grid initiatives [29].

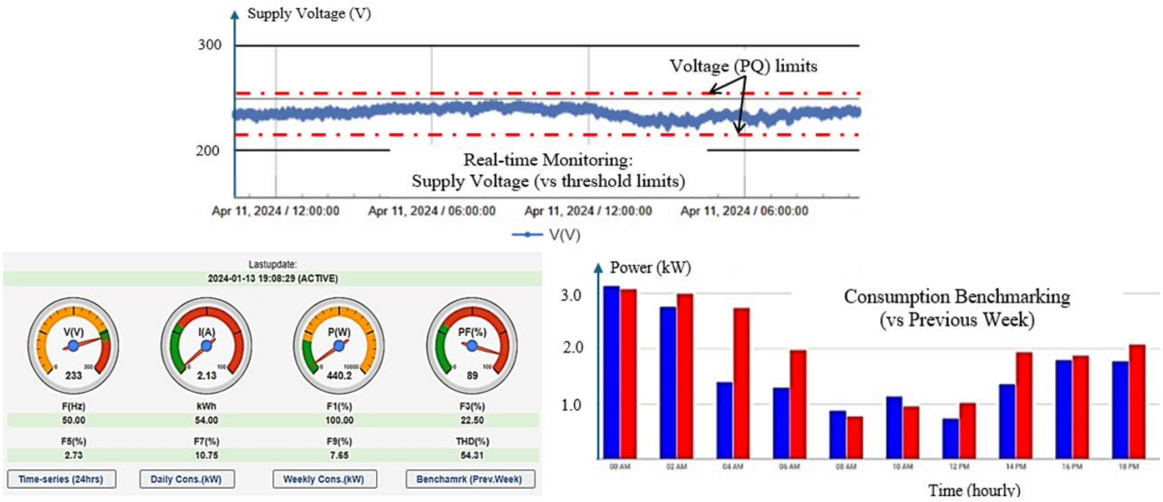


Figure 6. Various functions of the ATEMS web-based platform

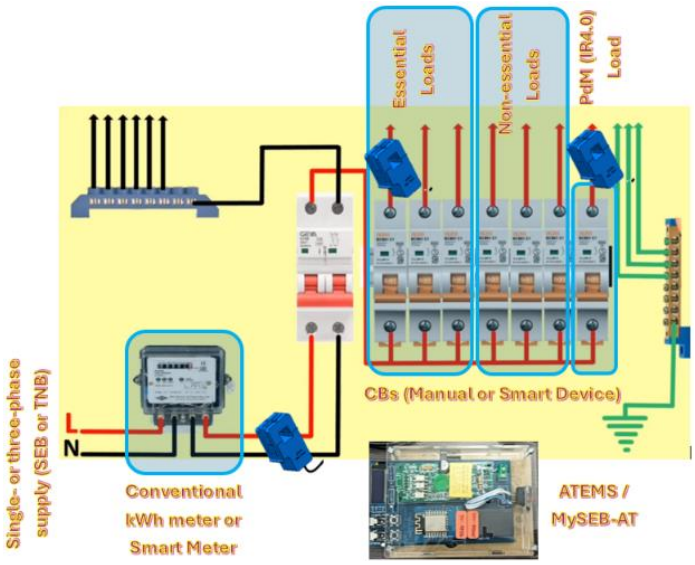


Figure 7. ATEMS demonstration model for smart grid, smart home, and IR4.0 applications

5. CONCLUSION

This paper presents the development and implementation of the ATEMS, designed to enhance the monitoring and management of electrical energy consumption and power quality. Through the integration of IoT-based architecture, fog computing, and cloud services, the ATEMS system offers real-time data acquisition, analysis, and visualization, providing users with a comprehensive understanding of their energy usage patterns and ensuring power quality in compliance with industry standards. The system's capability to measure key electrical parameters with high accuracy, which is comparable to commercial power meters, highlights its reliability and effectiveness. Its real-time alerting features and robust data analysis capabilities make it a valuable tool, contributing to smarter energy management and sustainable practices. In conclusion, the ATEMS system demonstrates significant potential in addressing the challenges of modern energy management, offering a scalable, user-friendly, and technologically advanced solution that aligns with the needs of smart grids, smart cities, and the broader goals of Industry 4.0. Further development and integration of advanced machine learning models could enhance its functionality, making it an even more powerful tool for future energy management initiatives.

FUNDING INFORMATION

This work is funded by the UTS Research Grant (Project ID: UTS/RESEARCH/<3/2023/07>(01)) of the University of Technology Sarawak. The authors would like to thank the Centre of Research and Development (CRD) of UTS for its support. Special thanks to Sarawak Energy Berhad (SEB) for the sponsorship of the Powering Ideas Program in this project.

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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