A Cloud-Enabled IoT Smart Energy Metering System for Smart Grid Applications

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Abstract

The existing energy metering systems lack real-time monitoring capabilities as well as cloud-based access. Smart grid technology helps in increasing energy efficiency and reliability of electrical power systems. This research work intends to design and develop an IoT-based smart energy metering system for real-time monitoring and visualization. The proposed system encompasses ESP32 microcontroller integrated with ZMPT101B voltage sensor and SCT-013 current sensors. However, the collected data is then processed using the EmonLib library in order to evaluate voltage, current, power, power factor, and energy consumption. The processed information is later sent to the Blynk cloud using Wi-Fi technology. As a result of the performed experimental tests, voltage, current, power, and energy consumption measurement errors has not exceeded 0.80%, 4.55%, 4.00%, and 2.06%, respectively.

Keywords: ESP32 Microcontroller, Smart Grid Infrastructure, IoT-Based Energy Metering, Cloud-Based Energy Monitoring, Real-Time Power Measurement, Wireless Energy Management.

1. Introduction

The rapid growth in electricity, urbanization, and increased use of renewable sources of energy has led to the evolution of energy systems from traditional power grids to intelligent

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smart grids. While the traditional power grid involves one-way power transmission and manual meter reading, smart grid systems are made possible through the use of advanced communications, sensing, and information technology, which helps in providing an efficient and sustainable way of energy usage. These technologies include the Internet of Things (IoT), which mainly contributes to smart energy metering through real-time monitoring, two-way communication and data collection. The IoT-enabled smart meters offer precise measurement of electrical parameters, remote monitoring facility, clear billing, participation in the demand response program and assist in the incorporation of distributed renewable energy resources into the power grid. The IoT-enabled smart meters improve reliability of the grid, cut down the cost of operations, reduce the energy losses and help users to manage the energy consumption. However, challenges like communication interoperability, security threats, data privacy issues, scalability, and integration with the existing utilities' infrastructure pose challenges in implementing such systems. This research work proposes the design and implementation of an IoT-enabled smart energy metering system for smart grids based on smart meter architecture, communication technologies, cloud computing data management, mathematical analysis, application scenarios and experimentations.

2. Literature Review

Recent advancements in IoT-based smart energy metering has greatly increased the efficiency of modern smart grid systems in terms of monitoring and management. Smart energy metering using ESP32 has successfully achieved a reliable collection of electrical measurements with the capability of connecting to the cloud for the purpose of continuous energy monitoring [1]. IoT based smart electricity meters have further helped to achieve more efficient energy management through precise measurement, remote accessibility, and increased operational efficiency [2]. The energy-aware IoT framework has also been used to make intelligent decisions on energy consumption and smart grid communication [3]. Moreover, the performance evaluation of smart meters has revealed their role in dynamic pricing, user engagement, and energy efficiency [4].

Emerging research has explored the IoT application in the form of smart microgrids, incorporating intelligent energy management and electric vehicle and distributed energy resource support [5]. The use of blockchain technology in IoT has increased the security and privacy of smart home energy systems, making them more sustainable [6]. Wireless communication has made significant contributions in establishing the connectivity and interoperability of IoT-powered smart grids [7]. In addition to this, Power Internet of Things (PIoT) has enhanced the energy management and communication on the demand side of smart grids [8]. Smart energy meters have used power quality monitoring and cloud computing in order to improve the reliability of the grid [9], and finally, AI-based energy management systems have provided intelligent monitoring and energy optimization of the grid [10].

2.1 Research Gap

Although, existing research is limited to only one aspect among real-time monitoring, cloud communication, smart micro-grid, wireless communication, security, or intelligent energy management. There is no integrated model where the exact measurement of energy consumption, embedded computing, cloud monitoring, and IoT communication have been considered. This research work proposes an IoT-based smart energy metering system with real-time electrical parameters monitoring, secure wireless communication, and cloud monitoring to facilitate the deployment of intelligent applications in smart grid networks.

3. Proposed Framework

3.1 System Architecture

The proposed system aims to measure, process, transmit and visualize the electrical parameters by using an IoT-based framework. This architecture includes sensors, ESP32 microcontroller, wireless module, cloud computing service, and user interface for monitoring. The ZMPT101B (voltage sensor) and SCT-013(current sensor) measure the electrical energy parameters from the connected load. The signals obtained from the source are processed and sent to the ESP32 microcontroller, wherein the built-in EmonLib library performs the calculation of RMS voltage, current, and other parameters. The information is presented visually on the LCD screen while being transferred via the Wi-Fi module to the cloud-based Blynk application. The cloud-based platform provides the real-time monitoring of the measured parameters as well as remote energy consumption monitoring by users through the web and mobile interface. Figure 1 shows the general architecture of the proposed system.

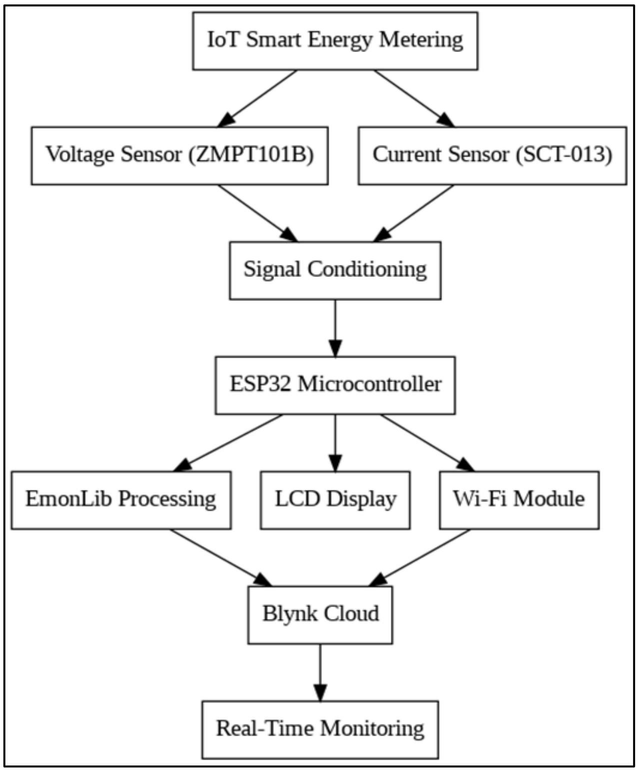

Figure 1. Proposed IoT-Based smart energy metering system architecture

3.2 Data Processing and Cloud-Based Monitoring

The proposed intelligent energy metering system continuously monitors electrical parameters through the ZMPT101B voltage sensor and the SCT-013 current sensor, which are attached to the electric load. The two sensors measure the real-time voltage and current, and these measurements are then processed to filter out noise before they are digitized through the 12-bit ADC in the ESP32 microcontroller.

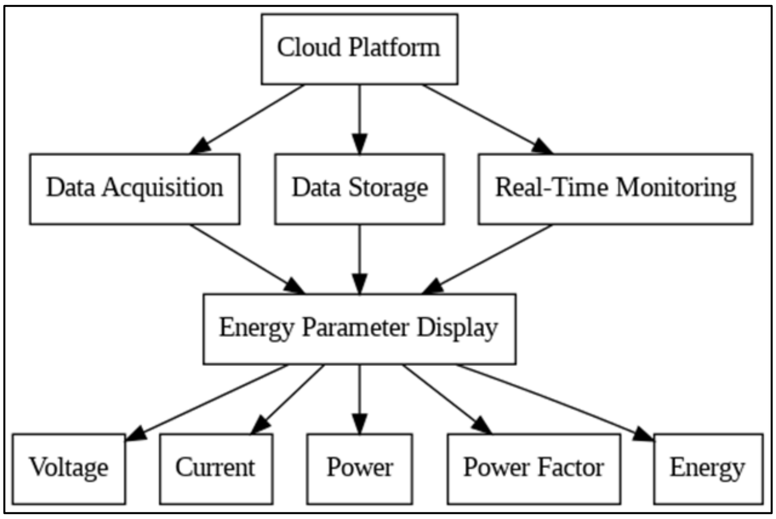

Figure 2. Blynk cloud platform for real-time energy monitoring

The processed electrical parameters are transferred to the Blynk cloud system via the embedded Wi-Fi communication system as shown in Figure 2. The cloud system captures the recorded data and stores it while enabling real-time visualization of the recorded data by using the interactive dashboard. The cloud system assists in enabling a continuous monitoring of the energy consumption levels, centralized management of the collected data, and remote access to the measured data without interfering with the recording process.

3.3 Mathematical Analysis

The IoT based smart metering of electricity system uses mathematical equations that are used to estimate electrical parameter measurements for the sample voltage and current obtained by the ESP32 microcontroller.

The instantaneous voltage and current of the single-phase alternating current source can be expressed as

$$v(t) = V_m \sin(2\pi f t + \phi_v) \tag{1}$$

$$i(t) = I_m \sin(2\pi f t + \phi_i) \tag{2}$$

where V_m and I_m denote the peak voltage and peak current, respectively, f represents the supply frequency, and ϕ_v and ϕ_i are the phase angles of the voltage and current signals.

The voltages and currents are measured and the RMS (Root Mean Square) values are calculated.

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} v_n^2} \tag{3}$$

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} i_n^2} \tag{4}$$

where N denotes the total number of sampled data points collected during one or more AC cycles.

The active power dissipated by the electrical load is found as a function of the RMS voltage, the RMS current, and the phase difference between voltage and current.

$$P = V_{rms} I_{rms} \cos\theta \tag{5}$$

where θ represents the phase angle between the voltage and current signals.

The power factor shows how effectively the electrical power is utilized and can be found as

$$PF = \frac{P}{V_{rms} I_{rms}} \tag{6}$$

where P is the active power and $V_{rms} I_{rms}$ represents the apparent power of the connected load.

The total amount of the electrical energy dissipated within a specified period of time is calculated as

$$E(kWh) = \frac{P \times t}{1000} \tag{7}$$

where P is the active power in watts and t denotes the operating time in hours. The computed energy reading will be dynamically changed and sent to the cloud server Blynk by the ESP32 processor.

4. Results and Discussion

The proposed system was experimentally analyzed in order to assess its accuracy of measurement, the reliability of communication and real-time monitoring capabilities when operating in practical conditions. The validation process was based on the assessment of the performance of the sensing devices, data processing in embedded systems and cloud-based monitoring through the comparison of electrical parameters with the help of standard measuring devices. The results of the experimental analysis prove the applicability of the developed IoT-based smart energy metering system.

4.1 Experimental Setup

The experimental verification process was carried out in order to test the practical performance of the developed system for various loadings. The developed prototype combines the capabilities of sensing, embedded computing, wireless connectivity, and cloud monitoring in one solution for continuous measuring of electrical parameters. In the process of experimentations, the collected sensor readings have been processed using the ESP32 microcontroller while being sent simultaneously to the Blynk cloud platform for visualization purposes. In order to check the accuracy of the designed system, the obtained results have been validated with respect to calibrated reference devices. The configuration used for the experimental testing is presented in Table 1.

Table 1. System configurations used in the proposed system

Parameter	Specification
Microcontroller	ESP32
Voltage Sensor	ZMPT101B
Current Sensor	SCT-013
Display Module	16×2 LCD
Communication	Wi-Fi
Cloud Platform	Blynk
Processing Library	EmonLib
Measured Parameters	Voltage, Current, Power, Power Factor, Energy
Test Environment	Residential Electrical Loads

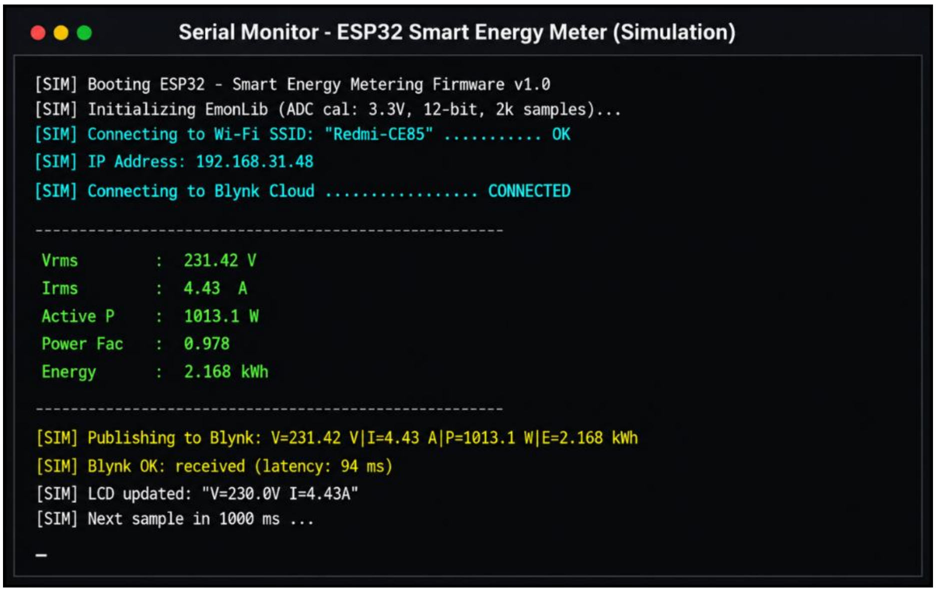

Figure 3. Serial monitor output of the proposed smart energy metering system

Figure 3 illustrates the results of the serial monitor when implementing the proposed system. The output indicates the success of the initialization process of the ESP32 microcontroller, successful establishment of the connection to Wi-Fi network, the communication between the microcontroller and Blynk cloud platform.

Figure 4. Blynk dashboard for real-time smart energy monitoring

The Blynk dashboard shown in Figure 4 provides real-time visualization of the measured electrical parameters from the ESP32 via Wi-Fi. It also displays device and network connectivity status, enabling continuous remote monitoring and cloud-based energy management for the proposed smart energy metering system.

4.2 Voltage Measurement Performance

The voltage measurement accuracy of the smart energy metering system was assessed by comparing the recorded readings with those obtained from a calibrated reference system under various operating conditions. This process tests the accuracy and reliability of the voltage sensing module as it provides readings required in energy metering. Comparison readings are provided in Table 2.

Table 2. Experimental evaluation of voltage measurement accuracy

Reference (V)	Measured (V)	Error (V)	Error (%)
180.0	181.4	+1.4	+0.78%

200.0	201.2	+1.2	+0.60%
220.0	221.0	+1.0	+0.45%
230.0	230.4	+0.4	+0.17%
240.0	241.5	+1.5	+0.63%

From the results shown in Table 2, it is evident that there was a high degree of agreement between the proposed system and the standard device under various tested conditions. The voltage readings showed very small variations, showing how effective the ZMPT101B voltage sensor and the calibration process of the ESP32 processing unit are. This implies that the proposed system can effectively measure the supply voltage in real-time with the necessary level of accuracy.

4.3 Current Measurement Performance

Accuracy of the current measurement module within the proposed smart metering system was evaluated by conducting tests on the current measurement capability of the proposed smart energy metering system. Current values from the SCT-013 current transformer was compared with the readings of a calibrated reference instrument to validate the efficiency of the sensing and processing architecture.

Table 3. Experimental evaluation of current measurement accuracy

Reference (A)	Measured (A)	Error (A)	Error (%)	Status
0.44 (Light Load)	0.46	+0.02	+4.55%	NOTE
1.00	1.02	+0.02	+2.00%	PASS
2.17 (50W)	2.21	+0.04	+1.84%	PASS
4.35 (1kW Load)	4.43	+0.08	+1.84%	PASS
10.00	10.21	+0.21	+2.10%	PASS

The comparison results presented in Table 3 shows that the current readings provided by the proposed system can be considered reliable, with the least difference between readings and those from the reference device. The calibration of the SCT-013 current sensor, along with the signal processing implemented by the ESP32 microcontroller and the EmonLib library helped to maintain a stable reading accuracy. The measurement error is small enough to justify the use of the system for achieving constant current measurement and both energy and power calculations.

4.4 Power and Energy Measurement

The accuracy of power and energy calculation using the proposed energy metering system was investigated to confirm the correctness of power and energy calculations performed in various loads. on the data calculated from the ESP32 integrated processor module were compared with the actual measured values using reference devices to check the accuracy of the proposed measurement technique.

Table 4. Experimental evaluation of power measurement accuracy

Load	Reference Power (W)	Measured Power (W)	Error (%)
100 W Lamp	100.0	104.0	+4.00%
500 W Iron	500.0	511.4	+2.28%
1000 W Heater	1000.0	1018.1	+1.81%
Fan Motor (Inductive)	350.0	358.2	+2.34%
Lamp + Iron (Mixed Load)	600.0	615.7	+2.62%

Table 4 results shows that the proposed system can provide an accurate calculation of active power for various loads. It can be seen from the comparison that the values calculated using this system are in good agreement with the actual measured values. This proves the reliability of the proposed system for power estimation purposes.

Table 5. Experimental evaluation of energy consumption

Monitoring Duration	Expected Energy (kWh)	Measured Energy (kWh)
1 Hour (500 W)	0.500	0.511 (+2.2%)
4 Hours (500 W)	2.000	2.040 (+2.0%)
8 Hours (500 W)	4.000	4.081 (+2.0%)
24 Hours (500 W)	12.000	12.247 (+2.06%)

Table 5 results indicate that the proposed system is capable of properly tracking the cumulative energy usage through time. The measured energy readings have been able to match those of the reference energy readings, showing stable and reliable energy computations. With such a capability, continuous energy consumption monitoring becomes possible.

4.5 Discussion

The experimental evaluation proves that the proposed IoT-based intelligent electrical metering system is capable of measuring the electrical parameters accurately and reliably under different conditions. The use of the ESP32 microcontroller and EmonLib processing library ensured fast calculations of the electrical parameters.

The cloud-based communication architecture provided additional functionality of the proposed system in the form of the ability to transfer measurement results continuously to the Blynk application and monitor the measurements remotely. Synchronization of operations performed locally and the cloud, provided consistent availability of real-time energy data through the monitoring dashboard. This feature provides convenience for accessing and monitoring energy consumption without the need for manual metering.

Overall, the experimental results show that the proposed system is effective in incorporating sensing, embedded computing, wireless communication, and cloud computing in one IoT architecture. The accuracy of electrical parameters measurement and data transfer together with real-time visualizations prove the feasibility of the proposed implementation of the system in the case of smart energy metering applications.

5. Conclusion and Future Work

This research presented the design and implementation of an IoT-based smart energy metering system used to monitor and manage electrical energy continuously in smart grid networks. Using voltage and current sensors together with the ESP32 microcontroller and communication through the cloud, the designed system provides reliable and efficient acquisition and processing of various electrical parameters. This implementation showcases the successful integration of embedded sensing, wireless, and cloud communication technology under one platform, making it easy to access the energy data. This proposed system provides a feasible and scalable approach for improving energy monitoring, making users more aware, and efficient energy use. Moreover, due to its modular structure, this system can be incorporated into modern smart grid networks and future energy management systems. The future research will be focus on development of the system to monitor three-phase energy usage and use advanced communication techniques, improve data security and privacy, as well as perform intelligent analysis for forecasting energy usage and demand management.

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