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IoT based Smart Energy Meter using ESP32 with Real-Time Cloud Monitoring

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***Abstract*— This work demonstrates the development and deployment of an IoT-enabled smart energy metering system built around the ESP32 microcontroller. The proposed system captures real-time electrical parameters by utilizing a ZMPT101B sensor for voltage measurement and an SCT-013-030 current transformer for current sensing. Power consumption is calculated using the EmonLib library, and the processed data is transmitted to the Blynk 2.0 cloud platform, enabling users to monitor energy usage remotely through a mobile application. Additionally, a 16×2 LCD screen is incorporated to display instantaneous values of voltage, current, power, and total energy consumption locally. Experimental evaluation conducted using a 9W LED load indicates that the system delivers consistent performance, with measurement deviations remaining within 5% when compared to standard reference meters.**

***Index Terms*— IoT-based energy metering, ESP32 microcontroller, real-time power monitoring, cloud-based data transmission, smart energy management.**

I. INTRODUCTION

The growing demand for electrical energy, driven by rapid urbanization and technological expansion, has emphasized the need for efficient energy monitoring and management systems. Conventional energy meters are limited in functionality, as they provide only cumulative readings without enabling real-time monitoring or remote accessibility. In contrast, modern smart energy meters utilize Internet of Things (IoT) technologies to support continuous monitoring, improved accuracy, and intelligent analytics, thereby contributing to sustainable energy usage and smart grid development [1], [2].

IoT-based energy metering systems integrate sensing, communication, and cloud computing technologies to measure electrical parameters such as voltage, current, and power consumption in real time. These systems allow users to remotely access energy usage data through mobile or web applications, promoting energy awareness and efficient consumption practices. Recent studies highlight that IoT-enabled smart meters significantly improve transparency, reduce manual intervention, and enhance overall system efficiency [3], [4].

Among various hardware platforms, the ESP32 microcontroller has emerged as a preferred choice due to its built-in Wi-Fi capability, low power consumption, and high processing performance. Its compatibility with multiple sensors enables accurate data acquisition, while cloud platforms facilitate seamless data transmission and visualization. Several recent implementations demonstrate that ESP32-based smart energy meters can reliably monitor and transmit real-time energy data in both residential and industrial environments [5][6] using connectivity [20].

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In addition, advancements in sensing technologies [21], IoT [16][17] along with AI [18][19] including non-invasive current transformers and voltage sensors, have improved the safety and accuracy of measurement systems. When combined with efficient computational libraries, these systems can deliver precise energy calculations while maintaining cost-effectiveness. Recent research also emphasizes the integration of advanced features such as power quality analysis, predictive analytics, and secure communication mechanisms, further enhancing the capabilities of smart metering systems [7], [8].

In this context, the present work focuses on the design and implementation of an IoT-based smart energy meter using the ESP32 microcontroller. The system measures real-time electrical parameters, processes them locally, and transmits the data to a cloud platform for remote monitoring, while also providing a local display interface. This dual functionality improves accessibility and user engagement while encouraging energy-efficient practices. The proposed system offers a cost-effective, scalable, and efficient solution suitable for next-generation smart energy management applications [9], [10].

II. Literature Survey

Recent developments in IoT-based smart energy metering systems have primarily focused on enhancing real-time monitoring, improving measurement accuracy, and enabling efficient energy management. Alarga et al. [11] designed an IoT-enabled smart energy meter using the ESP32 platform, capable of tracking key electrical parameters such as voltage, current, and energy consumption. Their study demonstrated that integrating IoT technology with smart meters allows users to monitor energy usage remotely, thereby promoting better awareness and control over electricity consumption.

In a similar direction, Reddy et al. [12] proposed a smart home energy monitoring system that utilizes IoT connectivity to provide real-time updates through cloud-based platforms. Their work emphasized the importance of user interaction and accessibility, showing that continuous feedback can encourage more efficient energy usage patterns. Additionally, Masali et al. [13] explored the application of ESP32-based systems in renewable energy environments, particularly for solar-powered homes. Their findings highlighted that IoT integration can significantly improve energy utilization and support sustainable energy practices.

Further contributions include the work of Nursalim et al. [14], who developed a smart kWh meter capable of real-time monitoring and control of household energy consumption. The system was designed to be cost-effective while maintaining reliable performance, making it suitable for practical deployment. Moreover, Hannan et al. [15] presented an advanced smart energy metering framework with additional features such as power quality monitoring and cloud-based analytics. Their study demonstrated the potential of combining multiple functionalities within a single system to enhance overall efficiency and reliability.

III. Problem Statement

Despite the widespread deployment of conventional energy meters, their functionality remains limited to basic energy consumption recording, offering little to no insight into real-time usage patterns. This lack of instantaneous feedback prevents consumers from understanding their energy behavior, often leading to inefficient usage and higher electricity costs. Moreover, traditional systems require manual reading and billing, which can introduce human errors, delays, and operational inefficiencies. In the context of increasing energy demand and the transition toward smarter infrastructure, the absence of remote monitoring and intelligent analysis capabilities in existing metering systems poses a significant limitation.

In addition, modern energy management requires systems that are not only accurate but also capable of integrating with digital platforms for real-time data access and control. Many existing smart metering solutions are either expensive or complex, making them less accessible for widespread adoption, particularly in residential settings. Challenges such as data reliability, scalability, and secure transmission further complicate the implementation of advanced energy monitoring systems. Therefore, there is a clear need for a cost-effective, reliable, and IoT-enabled smart energy metering solution that can provide real-time monitoring, remote accessibility, and improved user interaction while maintaining accuracy and ease of deployment.

IV. Proposed Method

The proposed system is structured into four main subsystems: sensing, processing, local display, and cloud communication, each contributing to efficient energy monitoring. The sensing unit consists of a ZMPT101B voltage sensor and an SCT-013-030 current transformer, which measures real-time voltage and current from a single-phase AC supply. These signals are conditioned through filtering and amplification before being fed into the ESP32 microcontroller. The ESP32 serves as the core processing unit, performing analog-to-digital conversion, calculating electrical parameters such as voltage, current, power, and energy using the EmonLib library, and managing wireless data transmission via its built-in Wi-Fi module. The processed data is displayed locally on a 16×2 LCD using an I2C interface, minimizing wiring complexity, while also being transmitted to the Blynk 2.0 cloud platform for remote monitoring through mobile and web dashboards. The hardware setup includes essential components such as biasing resistors, decoupling capacitors, and a stable mounting platform to ensure reliable operation. On the software side, EmonLib enables accurate computation of electrical parameters using techniques like zero-crossing detection, while Blynk 2.0 provides an intuitive interface for real-time visualization and data management. Together, these integrated hardware and software components form a compact, cost-effective, and efficient IoT-based smart energy metering system. Figure 1 shows the block diagram of the proposed system.

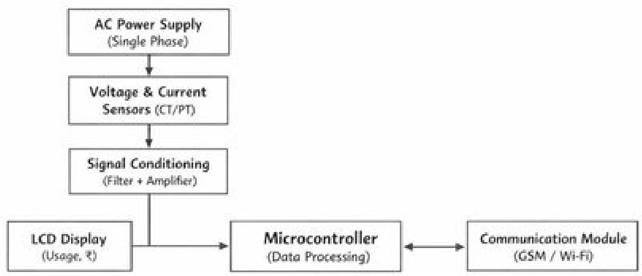

Figure 1. Block Diagram of the Proposed System

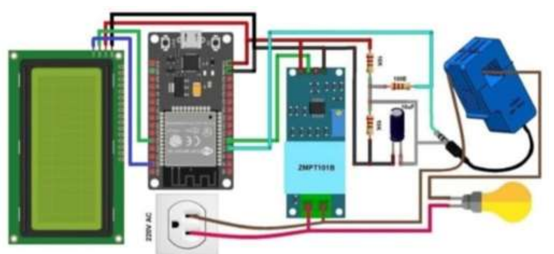

Figure 2. Circuit diagram of the IoT smart energy meter system

Fig. 2 presents the circuit diagram of the system. The ZMPT101B voltage sensor is connected to ESP32 GPIO 35 through an ADC biasing network, while the SCT-013-030 current transformer is interfaced with GPIO 34 using a burden resistor and a voltage divider (two 10 kΩ resistors) to maintain a 1.65 V reference, along with a 10 µF capacitor for noise reduction. The 16×2 LCD is connected via I2C, with SDA and SCL linked to GPIO 21 and GPIO 22. The 220 V AC supply feeds both the voltage sensor and the load, with current measured through the CT clamp. A compact PCB is used to ensure stable and reliable connections.

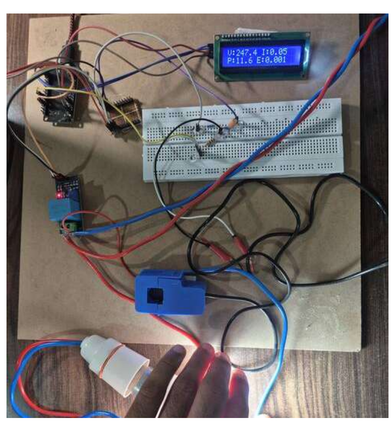

Figure 3. Hardware prototype: ESP32, ZMPT101B, SCT-013-030 CT, breadboard, 16×2 LCD

The prototype was assembled on a breadboard mounted on an MDF board. The ZMPT101B was connected to mains supply with output to ESP32 GPIO 35. The SCT-013-030 was clamped around the live wire to GPIO 34. The LCD was connected via I2C (GPIO 21/22). Fig. 3 shows the prototype assembly.
The system was tested with a 9W LED bulb. Fig. 4 and Fig. 5 show the system during testing with the LCD displaying real-time measurements.

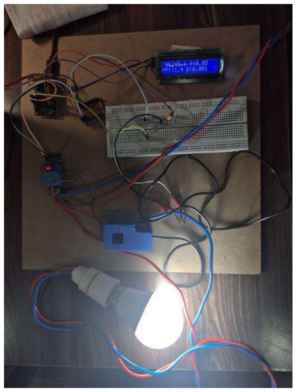

Figure 4. System under test with 9W LED bulb, LCD showing V: 248.1, I: 0.05, P: 11.4

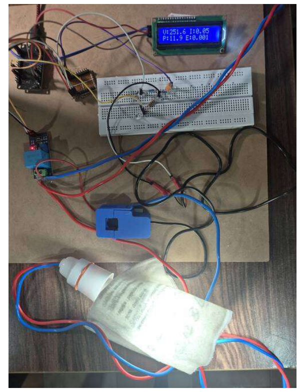

Figure 5. Alternate view, LCD readout: V: 251.6, I: 0.05, P: 11.9, E: 0.001

V. Results and Discussion

The Blynk 2.0 web console was configured with gauge widgets for instantaneous readings and time-series charts for historical trends. Fig. 6 shows the current and voltage gauges, and Fig. 7 shows the power and energy gauges.

Figure 6. Blynk gauges: Current (0.05A, range 0–30A) and Voltage (248.17V, range 0–300V)

Figure 7. Blynk gauges: Power (11.19W, range 0–1000W) and Energy (0.002 kWh, range 0–1)

Fig. 8 shows the current and power charts. Current was stable at 0.04–0.05A with clear on/off transitions. Power ranged 10–15W, consistent with a 9W LED bulb (apparent power > rated due to power factor ~0.8). Fig. 9 shows energy accumulation (linear growth, 0.008 kWh over 45 min) and stable voltage around 200–250V.

Figure 8. Current (left) and power (right) monitoring charts

Figure 9. Energy accumulation (left) and voltage stability (right) charts

TABLE I. SMART METER VS. REFERENCE DMM

Parameter	DMM	LCD	Blynk	Err(LCD)	Err(Blynk)
Voltage(V)	245.8	247.4	248.17	0.65%	0.96%
Voltage(V)	249.1	251.6	252.75	1.00%	1.47%
Current(A)	0.048	0.05	0.05	4.17%	4.17%
Current(A)	0.046	0.04	0.04	3.26%	3.26%
Power(W)	11.80	11.60	11.19	1.69%	5.17%
Power(W)	11.46	11.90	11.31	3.84%	1.31%

TABLE II. ACCURACY SUMMARY

Parameter	Mean Err(%)	Max Err(%)
Voltage	1.02%	1.47%
Current	3.72%	4.17%
Power	3.00%	5.17%
Energy	6.43%	6.43%

Table I compares smart meter readings against the reference DMM. Table II shows accuracy summary. Voltage: 1.02% mean error. Current: 3.72% (low current near SCT-013 sensitivity floor). Power: 3.00% (cumulative V+I errors). Energy: 6.43% (time-integrated). System achieves ±5% accuracy, suitable for residential monitoring.

VI. ADVANTAGES AND LIMITATIONS

The proposed IoT-based smart energy meter offers several practical advantages. It enables real-time monitoring of electrical parameters such as voltage, current, and power, allowing users to better understand and manage their energy consumption.

The integration of cloud connectivity provides remote access through mobile or web applications, improving convenience and user engagement. The use of the ESP32 microcontroller ensures low cost, compact design, and built-in Wi-Fi capability, reducing the need for additional communication modules.

Moreover, the system is relatively easy to install due to the use of non-invasive current sensing, and the local LCD display ensures that essential data can still be accessed without internet connectivity. The overall design is scalable and can be extended with additional features such as alerts, data logging, or integration with smart home systems.

However, the system also has certain limitations. The accuracy of measurements may be affected by sensor calibration and external noise, especially in low-cost implementations. Dependence on Wi-Fi connectivity can impact real-time data transmission in areas with unstable networks. Additionally, the system may require regular maintenance and calibration to ensure consistent performance over time. Security concerns related to cloud-based data transmission also need to be considered, as unauthorized access or data breaches could compromise user information. Despite these challenges, the system provides a cost-effective and efficient solution for basic smart energy monitoring applications.

VII. CONCLUSION AND FUTURE WORK

The developed IoT-based smart energy meter demonstrates an effective approach for monitoring electrical parameters in real time using a compact and low-cost design. By integrating voltage and current sensing with the ESP32 microcontroller, the system is capable of accurately measuring and processing energy consumption data. The inclusion of both local display and cloud-based monitoring ensures that users can access information conveniently, either directly from the device or remotely through a mobile interface. This dual-mode functionality improves usability and makes the system suitable for practical applications in residential and small-scale environments.

The experimental results indicate that the system provides reliable performance with acceptable accuracy, making it a viable alternative to conventional energy meters for basic monitoring purposes. In addition to enhancing user awareness, the system encourages more efficient energy usage by providing continuous feedback.

Although certain challenges such as network dependency and measurement precision exist, the overall design remains simple, scalable, and adaptable. With further improvements in calibration, security, and data analytics, the proposed system can be extended to support advanced smart grid and energy management applications in the future.

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