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Integrating IoT Systems for Real-Time Energy Monitoring and Efficiency in Smart Buildings

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Abstract: The fusion of the Internet of Things (IoT) into an electrical energy meter modernizes energy monitoring in homes and businesses. This innovative metering system allows remote oversight and control of energy usage through an IoT platform. The need for affordable and efficient energy management solutions, particularly in a context where power fluctuations, energy loss are common in major cities and localities within developing country. These challenges were addressed with providing real-time insights into energy consumption within the household. The system utilizes microcontrollers, communication modules, and sensors, this enhanced model collect and processes data, enabling seamless communication among the device's components. Voltage and current sensors provide crucial input for the microcontroller, undergoing analog to digital conversion (ADC) as programmed. User-friendly interfaces, featuring liquid crystal display (LCD), empower users to monitor energy usage remotely. The device connects wirelessly to the Internet, transmitting data to the cloud for storage and analysis. With a maximum relative error of -6.4725%, the negative value of the relative error suggests that the measured energy consumed is slightly lower than the actual energy consumed. The highest relative error is observed in Case 3 with a rated power of 40W and an absolute current of 0.06A, while the minimum relative error is -0.8696 in Case 5 with a power rated of 140W and an absolute current of 0.02A. The actual energy consumed ranges from 0.00329kWh to 0.01668kWh. The designed energy meter prototype leverages IoT advancements for remote monitoring and efficient management of energy consumption, marking a transformative step toward smarter and sustainable energy practices.

1. Introduction

The growing demand for energy in homes, industries, and organizations necessitates the consistent need to develop new solutions that meet this demand while being environmentally responsible and economically sustainable. Many countries face difficulties in managing their electrical energy consumption especially developing nations (Akinyele *et al.*, 2019; Ogbonnaya *et al.*, 2019; Fayomi *et al.*, 2021; Obar *et al.*, 2022). Effective monitoring and control of energy usage would solve traditional energy metering problem which provide limited real-time data and insights, hindering intelligent energy management. In developing countries, power fluctuations and high energy costs are common, yet there is often a lack of understanding of how and where energy is being used (Haddiya & Ramdani

(2024); Purwania *et al*., 2020; Oultiligh *et al.*, 2020; Elkari *et al.*, 2014). Smart metering and monitoring systems offer a new approach to energy management, providing granular real-time data on energy consumption. By installing smart meters in homes, businesses, and industries, valuable insights into energy consumption patterns can be gained. Smart meters not only record overall energy usage but also break it down by appliance, time of day, and usage patterns (Zhou *et al*., 2019; Manic *et al*., 2021). This level of detail allows for the identification of energy-intensive devices and informed decisions to reduce consumption during peak pricing periods. Smart meters empower users to proactively manage their energy consumption, resulting in significant cost savings (Ma *et al*., 2015; Birendrakumar, *et al*., 2017; Aneesh, *et al*. 2017; Mehta *et al*., 2021; Munoz *et al*., 2022). In addition to cost savings, smart meters can also facilitate the adoption of sustainable practices and the more effective use of renewable energy sources. By recognizing peak energy demand periods, energy consumption can be aligned with the availability of renewable energy sources, reducing dependence on fossil fuels and environmental impact (Qiang & Wang 2015; Obulesu *et al*., 2019). The adoption of smart meters and energy monitoring systems can foster a culture of energy efficiency that benefits individuals and the nation as a whole. Energy companies can better plan and allocate resources, reducing energy waste and ensuring a more stable power supply. Additionally, a greater sense of environmental responsibility is promoted as individuals and organizations can actively contribute to reducing greenhouse gas emissions and addressing climate change (Selvam *et al*., 2022; Dass *et al*., 2023). While the challenges in developing countries energy sector are significant, the adoption of smart meters for energy conservation represents a transformative path forward. Smart meters enable the bridging of the gap between energy demand and supply, ensuring sustainable energy usage and paving the way for a more energy-efficient future (Varma & Sushil, 2019; Rodrigues *et al*., 2019; Avancini *et al*., 2021; Qureshi, *et al*., 2022). This research focus on designing a user-friendly, cost-effective, and IoT-integrated power control and monitoring system. Thus, dependable and precise metering system capable of delivering real-time information on energy usage, effectiveness in reducing energy wastage and enabling sustainable energy management practices in households. The rest of the article is organized as follows: Sections 2 discuss the materials and methods showcasing the hardware and software components used, as well as how they are linked in the work; Section 3 presents the results obtained from the system testing and the discussion about the impact and accuracy of the results generated from the system; and Section 4 concludes the finding of the work and propose framework for further studies, with emphasizes on the long-term stability, diverse testing environment and possible cyber treats to the system.

2. Materials and Methods

Materials are chosen for their durability, affordability, highest level of efficiency, and compatibility with the proposed design. In this study, the design of an IoT-based electric energy meter is divided into hardware and software components. The device's hardware contains the entire physical makeup of the design prototype. The software portion of the design is made up of programs that are uploaded into the design's processing component and simplify how the entire device works.

2.1 Hardware Components

The following hardware component were selected for optimal integration of the design system

- ESP – WROOM-32 development board
- ASC712 current sensor 30A
- ZMPT101B AC voltage sensor
- LCD 1602

- Relay module 1 channel

The power unit powers both the sensing unit (voltage and current sensor) and the processing unit (ESP-32 microcontroller). A 230-volt AC power supply powers both the current and voltage sensors. A rectification circuit will provide a 5V DC supply to the microcontroller. The voltage and current sensors on the sensing unit send an input signal to the ESP-32 microcontroller, which processes it using specially created instructions required for the microcontroller It uploads the data to the cloud, where it can be accessed via a smartphone app, In addition to processing the voltage and current signals collected by the sensing unit and sending the output to the LCD display and buzzer, it uploads the data to the cloud, where it can be accessed via a smartphone app. The mobile app also shows the associated current, voltage, and total energy consumption in kWh, which can be accessed via the internet from anywhere in the world.

When the mobile application is unavailable for an extended period of time, the LCD display shows the current, voltage, and total energy used in kilowatt-hours. When the system is operational, the audio unit (buzzer) will provide an audio signal to the user. In the event of a temporary fault, the switching component (relay) protects the load. Figure (1) below depicts the block diagram of the hardware integration of the developed system.

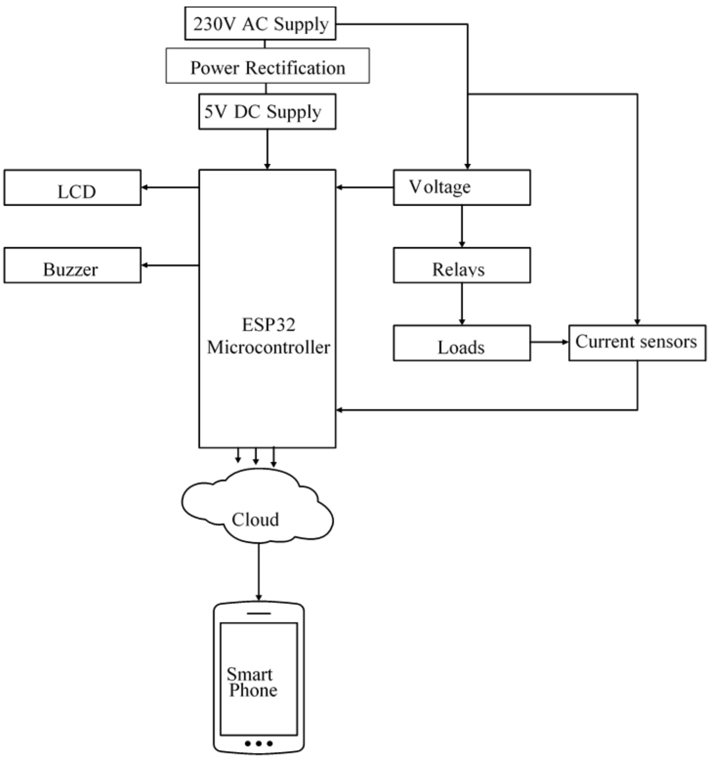

Figure 1: Shows hardware components linked

2.2 Software Components

The software components of the system are a collection of operational guidelines and applications that are used to control the hardware element of the design and carry out the desired task. This component consists of three functional elements: Android application software, the Arduino IDE programming environment, and the Proteus simulation software.

The Android mobile application, built using MIT App Inventor, acts as a user interface. This app enables users to interact with the energy meter, such as monitoring energy consumption and controlling connected loads.

The core functionality of the system is driven by a microcontroller. Arduino IDE was used to program this microcontroller, instructing it on how to manage energy readings, respond to user commands, and control the connected loads.

To validate the design before physical implementation, the electrical circuitry of the proposed smart meter is simulated using Proteus software, this Provides a visual, block-based programming environment, making it relatively easy to create the user interface and define the app's interactions with the microcontroller (through a communication protocol like Bluetooth or Wi-Fi). This simulation helps identify potential design flaws and optimize the circuit's performance.

2.3 Flowchart of IoT-Based Energy Meter Functionality

A flowchart is a visual representation of an algorithm, which is a method for problem solving or process creation.

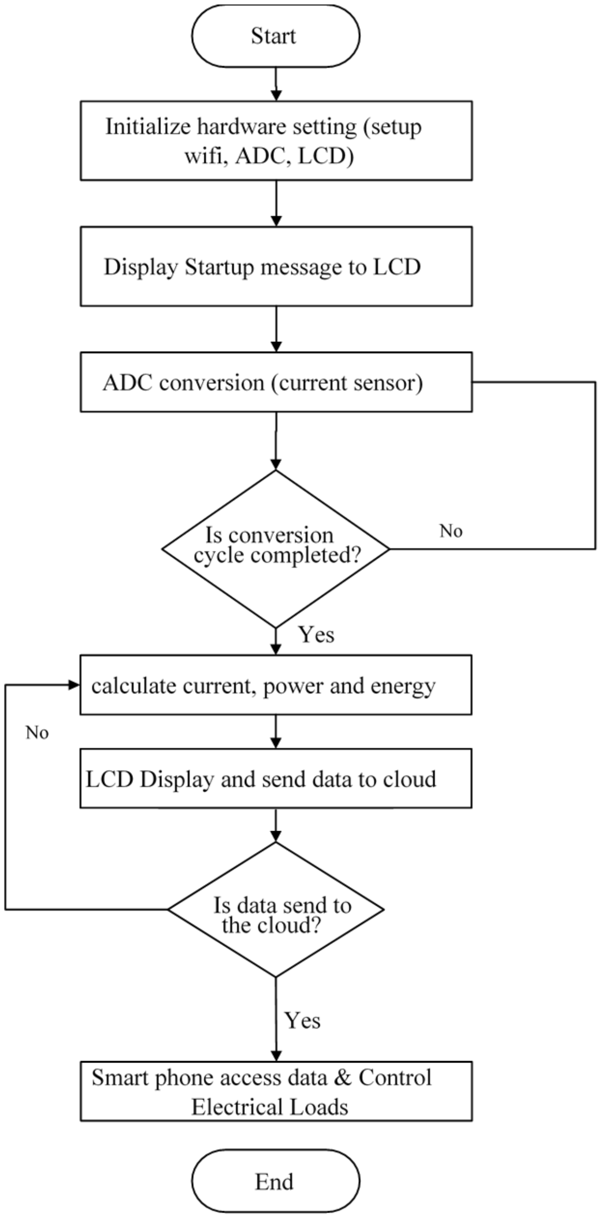

Figure 2: Energy Meter Flowchart functionality

1) Start: The process begins here.
2) Initialize Hardware Settings:

- Setup Wi-Fi: This step involves configuring the Wi-Fi module on the microcontroller to enable communication with the cloud or other devices. This might include setting up the SSID (network name) and password.
- ADC (Analog-to-Digital Converter): The ADC is initialized to convert the analog current signal from the sensor into a digital value that the microcontroller can understand and process.
- LCD: The Liquid Crystal Display (LCD) is initialized to display information to the user.

3) Display Startup Message to LCD: A welcome message or system status information is displayed on the LCD to indicate that the system has started.
4) ADC Conversion (Current Sensor):

- The microcontroller triggers the ADC to start converting the analog current signal from the sensor.
- The conversion process takes a certain amount of time.

5) Is Conversion Cycle Completed?

- The microcontroller checks if the ADC conversion process has finished.
- If No, it waits for the conversion to complete.
- If Yes, it proceeds to the next step.

6) Calculate Current, Power, and Energy:

- The microcontroller uses the digital value from the ADC to calculate the current flowing through the circuit.
- Based on the current, it calculates the power consumption using the formula: Power = Voltage × Current (assuming a constant voltage).
- The energy consumption is calculated by integrating the power over time.

7) LCD Display and Send Data to Cloud:

- The calculated current, power, and energy values are displayed on the LCD for the user to view.
- The data is also sent to a cloud server for storage and further analysis. This could be done using protocols like MQTT, HTTP, or others.

8) Is Data Send to the Cloud?

- The microcontroller verifies if the data has been successfully sent to the cloud.
- If No, it attempts to resend the data.
- If Yes, it proceeds to the next step.

9) Smart Phone Access Data & Control Electrical Loads:

- The user can now access the energy data from the cloud using a smartphone app.
- The app allows the user to control connected electrical loads, such as turning appliances on or off remotely.

10) End: The process ends here.

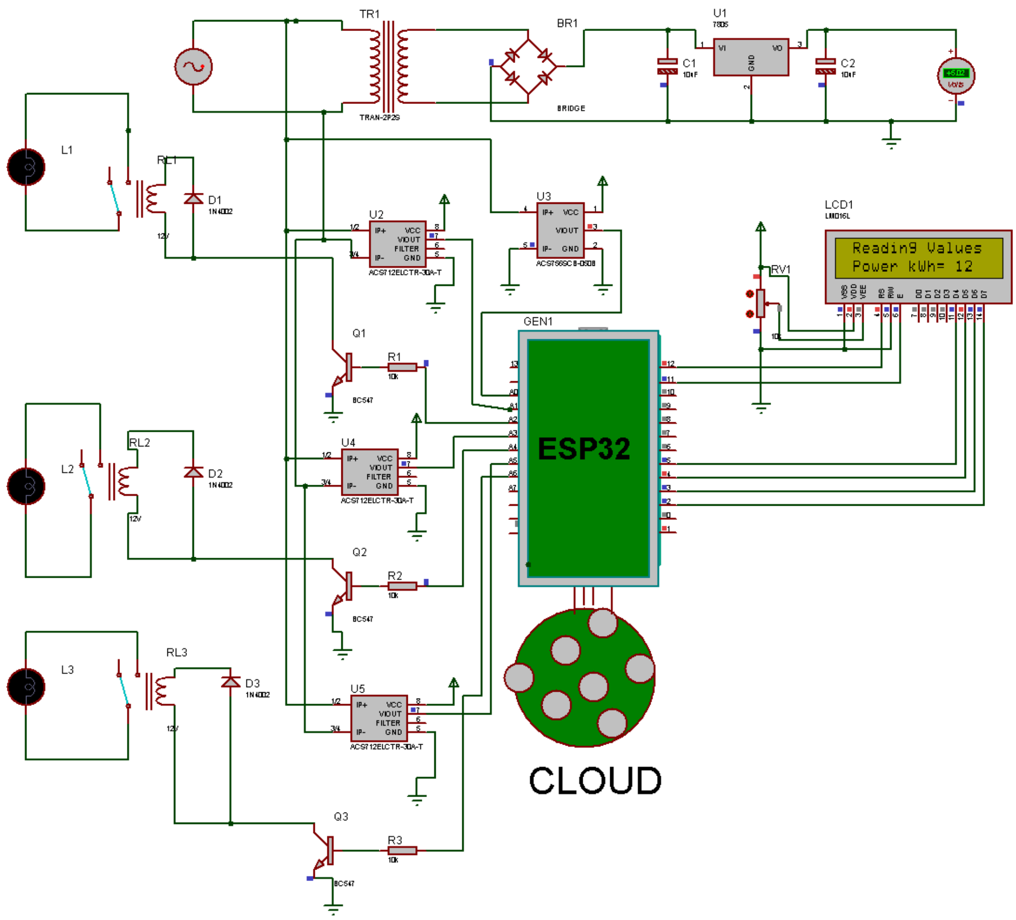

Figure 3: Circuit Diagram of the Design

3. Results and Discussion

3.1 Testing

A number of tests was carried out. Each of the energy meter modules was first tested individually to verify their functionality and responsiveness. The modules were then assembled together and tested as a complete unit. A number of loads with different power ratings as given in Table 1 were used. For Experimental studies, loads are connected in different combinations as given in Table 2, the readings were recorded and compared against the real time data sent to the cloud (firebase) which is accessible on a mobile phone.

Table 1: Capacity of Loads

Loads Rated	Power Rating	Current
Load 1	100W	0.41A
Load 2	60W	0.23A

Table 2: Different types of Load combinations

Cases	Description
1	Load 1
2	Load 2
3	Load 1 + load 2

Figure (4), shows the complete assembly of the system while figure (5) depicts the link between the Android application and the load to be monitored and controlled. The application was installed on a Techno WX3 Android phone and initialized. After initialization and connection between the energy meter and Android phone was established, the real-time current and energy consumed by loads were also displayed on the phone accordingly. The controlling mechanism of loads was done remotely from the Android application which triggered the relay to trip either off or on by clicking the buttons which were immediately followed by the lighting of the bulbs and socket outlet connected as load. The process was carried out a number of times to ensure the process was functioning correctly and properly. The figure (4) below shows the complete hardware developed.

Figure 4: Complete Assemble of the System

Figure 5: Android Application Interface and the Load

3.2 Discussion

The energy meter was tested for accuracy in measurement and ability to transfer real-time data to database. A rated voltage of 230V and frequency of 50Hz was recorded during the experimental setup. To validate the readings against theoretical estimates, the energy consumed (E) is calculated as the product of power (P) and time (t) for an interval of 5 minutes (300 seconds).

This theoretical estimation is compared with the measured energy consumed by loads as displayed by the developed energy meter. The relative error (%) determine the accuracy of the IoT-based energy meter. The corresponding values of load study is given in Table 3.

Table 3: Energy consumption measurement, accuracy result of the developed Energy Meter

Case	Voltage (V)	Rated current (A)	Measured current (A)	Absolute current (A)	Rated power (W)	Actual energy consumed (kWh)	Measured energy consumed (kWh)	Relative error (%)
1	230	0.41	0.40	0.02	100	0.00840	0.0082	-2.4390.
2	230	0.23	0.22	0.03	60	0.00500	0.0048	-4.1667.
3	230	0.64	0.62	0.06	40	0.00329	0.0031	-6.4725.
4	230	0.67	0.61	0.06	160	0.01330	0.0131	-1.5267.
5	230	0.63	0.64	0.02	140	0.01160	0.0115	-0.8696.
6	230	0.45	0.40	0.03	100	0.00831	0.0081	-2.5926.
7	230	0.85	0.83	0.01	200	0.01668	0.0165	-1.0909.

The results indicate that the developed Energy Meter has good accuracy in measuring energy consumption with a maximum relative error of -6.4725%. The negative value of the relative error suggests that the measured energy consumed is slightly lower than the actual energy consumed. The highest relative error is observed in Case 3 with a rated power of 40W and an absolute current of 0.06A, while the minimum relative error is -0.8696 in Case 5 with a power rated of 140 W and an absolute current of 0.02A. The actual energy consumed ranges from 0.00329kWh to 0.01668kWh. Therefore, further analysis and testing are necessary to determine the meter's performance under different conditions and its long-term stability.

The experimental results suggest that the developed Energy Meter has good accuracy in measuring energy consumption. However, more extensive testing under different conditions is necessary to validate its performance and stability over the long term.

Conclusion

The innovation and accomplishment of energy consumers metering system with the integration of smart users' management model is a major achievement in the field of energy monitoring and management. With the capability to send real-time current and power consumption in kWh to online database, users can now access information about their energy consumption and control appliances from anywhere in the world through a mobile application at their convenient time. This design offers a lot of vivid benefits, including the ability to accurately monitor energy consumption, identify patterns in energy usage, and make plausible decisions about energy conservation.

More so, the integration of the ESP32 development board with the online database and mobile application enables uninterrupted and efficient data transfer, making it easier and quicker for users to access and manage their energy consumption information. With the increasing focus on energy efficiency and conservation, the development of this electric energy meter provides an invaluable solution to help individuals and organizations reduce their energy consumption and eventually contribute to a more sustainable future. With IoT integration, this research presents a step towards modernizing our homes, making them smarter, more energy-efficient, and better aligned with the challenges faced in the current energy needs of households

The following recommendations were made after the successful testing of the system, to further enhance the system;

1. When appraising the accuracy of energy meters for electricity, it is recommended that an electrical load that draws electrical current at a uniform rate be used. This will help to ensure that the measurement of electrical energy is accurate even when there are changes in temperature.
2. The reliability of electric energy meters should be tested before use, and this can be done by testing the reliability of the communication achieved by the meter. This will help to ensure that the meter is functioning properly and can be trusted to provide accurate readings.
3. Further research is needed around IoT-based energy meters to enhance data security and network security around energy meters. This will help to prevent unauthorized access and ensure that data is protected from potential cyber threats. Special attention should be given to Implementing a strong encryption and authentication mechanisms to protect data transmitted over networks, ensured the meter's firmware and software are updated regularly to patch security vulnerabilities and Implement security measures to detect and prevent unauthorized access or malicious activities.

Generally, the recommendations aim to improve the accuracy and reliability of energy meters, as well as enhance the security of energy consumption data. By implementing these recommendations, we can ensure that energy meters are providing accurate data, which is essential for proper energy management and planning.

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