Development of A Real-Time Energy Metering System Using ZMPT101B and ACS712 Sensors with Blynk-Based Cloud Visualization

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Abstract: - This paper discusses the limitations associated with traditional energy meters, which include delayed data collection, the inability to provide real-time data, and inefficient billing systems. This paper also discusses the impact of these limitations on user experience. A cost-effective Internet of Things (IoT)-based smart energy meter is proposed, and the proposed system includes the accurate collection and processing of data by utilizing NodeMCU ESP8266 and ZMPT101B and ACS712 current and voltage sensors. The proposed system also includes the ability to display data locally and to monitor data remotely by utilizing the Blynk mobile application. The proposed system also includes the ability to compute data and to control the load remotely. The proposed system includes a custom-designed printed circuit board to make the system compact and efficient. The proposed system also includes empirical results, and the proposed system can be considered efficient for real-world applications.

Key-Words: - IoT, Smart Meter, NodeMCU, ZMPT101B, ACS712, Real-Time Energy Monitoring, Blynk Cloud Platform.

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1 Introduction

The resurgent of Internet of Things (IoT) has revolutionized energy metering systems by transforming the traditional metering system into more dynamic, automation, responsive and exchange of real-time data to the user. Traditional metering system is entirely depended on manual collection of data for billing which causes delayed billing cycle, limits the transparency leading to the data error and meter tempering, [1], [2]. With the integration of smart sensors, advance microcontrollers, communication modules, real-time data collection through cloud IoT facilities, the conventional meters can be transformed into more starter meter with data-driven energy management capabilities, [3], [4].

Previous studies have integrated a variety of methods, such as GSM-based smart meters build on android platforms [5], occupancy-responsive automation via motion detection [6], and Bluetooth-integrated solutions for automated meter reading [7]. Other models offered Wi-Fi and duplex communication that's shows real-time tracking and cloud support [8], [9]. A web-based ARM-enabled system for power monitoring was developed in [10] whereas a bluetooth-based polling mechanism for wireless data retrieval was proposed in [7].

Despite of these developments, few limitations remained in the system like poor scalability, lack of mobile interface for consumer and lack of data security, [5], [11]. These issues create obstacle in large-scale deployment of smart meter and limits the feasibilities in integration with the traditional infrastructure. The rapid rise in the global smart meter market, now over a billion, there is an increasing need for solution that are secure, user focused, [12]. This project addresses these challenges by proposing a low cost and IoT based smart meter that is more consumer oriented. The system is built around a NodeMCU ESP8266 microcontroller which uses ZMPT101B voltage and ACS712 current sensors for precise real- time measurement. The data can be found uninterruptedly on the mobile phone though Blynk mobile application for remotely energy management.

The objectives of this project are to (i) develop a real-time IoT-enabled energy metering system; (ii) implement a smart billing interface with mobile access; and (iii) enable remote load monitoring and control. The key contributions of this project area fully integrated and modular system, real-time communication, low cost module and suitable for scalable deployment and improved user interaction.

2 Literature Review

Incorporating Internet of Things (IoT) with the metering system has considerably enhanced the real-time monitoring, consumer engagement and efficient use of energy, [1], [2]. Adding cloud base Blynk app has also improved the continuous tracking of power consumption and enabled dynamic feedback for both consumer and utility operators, [3], [4].

A GSM-enabled Arduino ESP8266 system was used for transmitting data and alarms with remote control functionality [5]. A smart monitoring system combining Wi-Fi, SMS communication, and motion sensing was implemented to improve energy efficiency, [6]. The importance of real-time sensor feedback in distributed grid optimization was highlighted in [11]. An ESP8266-driven smart metering approach enabling bidirectional data exchange and cloud support was proposed in [8]. A NodeMCU-based architecture supporting real-time monitoring and wireless control was proposed in [10]. Real-time monitoring was achieved by integrating a web-based server into an ARM-based energy management system, [13]. A Bluetooth-enabled ARM system was implemented for wireless data acquisition, [7]. In addition to these research, AMR integrated with PLC was used to support long-range communication in energy distribution systems, [9].

Regardless of so many research and achievement, these smart meters face challenges at the used end such as seeming monitoring, data management, user friendly interface/app and large scalable system. This project addresses the gaps and limitations to some extent by proposing a low-cost and secure smart metering design using NodeMCU ESP8266 and Blynk.

3 Methodology

The proposed smart meter system was designed using NodeMCU ESP8266, ZMP101B and ACS712 sensors, LCD interface, regulated power supply and a double-layer PCB. Firmware was developed in Arduino IDE, EasyEDA aided circuit for PCB design and Blynk for real time data along with mobile monitoring.

The system was experimentally tested with residential load (bulb), with real time data displayed synchronously both in LCD display and mobile platform, establishing the framework as a scalable solution for smart grid integration.

3.1 Hardware Development

The hardware design proposed in the Figure 1 (Appendix) is focused on the reliability of the energy management system, sensing, and wireless communication through the cloud. In the proposed hardware, the NodeMCU ESP8266 is the main core unit of the hardware, which provides support for the communication of the data acquisition system. The crystal oscillator is also added to the hardware for the reliability of the hardware. The SPI flash memory is also added to the hardware.

The system uses a robust SMPS circuit system that used TNY267 IC to convert AC input into a regulated 5V supply shown in Figure 2 (Appendix). surge protection was given through a fuse and MOV, followed by filtering and rectification process. the flyback transformer provides the required DC output. on the other hand, optocoupler-based feedback ensures consistent voltage under changing load conditions.

Figure 3 (Appendix) explains the simple operation of SMPS system. the MOSFET switching stores energy in the inductor and delivered through a diode and the further smoothen by a capacitor. the feedback loop ensues stable output voltage by adjusting the duty cycle.

Figure 4 represents the conventional AC to DC conversion process, where supply AC voltage is stepped down and then rectified, filtered and regulated into usable DC supply.

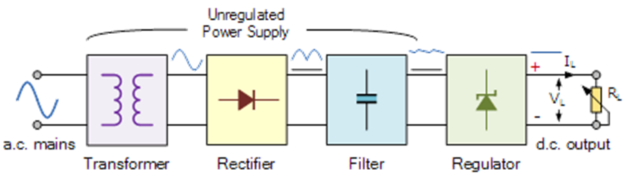

Fig. 4: Block diagram of AC to DC power conversion using transformer, rectifier, filter, and regulator.
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The line voltage and load current are sensed and read by the ZMPT101B and ACS712 sensor, which computes the power, energy consumption and billing data in real time. These allow the user to track the energy more accurately and response accordingly. Data also can be seen in the installed 16x2 LCD modules.

The performance of the TNY267-based SMPS was analytically evaluated to justify design choices. Let Vin, Iin denote the input voltage and current, and Vout, Iout the regulated output voltage and load current. From the input and output Powers, the conversion efficiency is computed using equation (1)

$$\eta = \frac{Pout}{Pin} x100\% \quad (1)$$

Load regulation can be evaluated using equation (2) as shown below

$$load\ Regulations(\%) = \frac{Vno\_load - Vfull\_load}{Vfull\_load}\ x\ 100 \quad (2)$$

These expressions confirm that the designed SMPS provides sufficient efficiency, low ripple, and stable regulation for reliable operation of the smart energy metering system.

Hardware sturdiness, thermal stability, and electromagnetic compatibility were ensured by a customized, two-layer printed circuit board to provide where all the hardware parts were placed on. Hardware design, which encompasses designing involving high and low-voltage areas, grounding, decoupling, and isolation to promote signal integrity and noise robustness, among other factors, were treated with great caution. The proposed hardware system is responsible for integrating sensing, processing, display, and wireless transmission of electrical energy data. Consequently, the modular design supports scalability and adaptability for residential or industrial deployment. Employing high-efficiency power conversion, accurate analog sensing, and reliable embedded computing, this platform is an ideal candidate for real-time smart energy monitoring and IoT-based automation.

3.2 Software Development

The embedded programming environment plays a pivotal role in the real-time acquisition, processing, and wireless transmission of data. The software tools, platforms, and implementation techniques used in the development of the IoT-Based Smart Energy Meter are described thoroughly in this section. The software was selected based the ease of integration in to cloud.

The coding and uploading code files to the NodeMCU ESP8266 microcontroller were done by the Arduino Integrated Development Environment (IDE) software, shown in Figure 5, which is very user friendly where programming in C/C++ code was done. Typically, the code contains `setup()` or `loop()` functions for continuous monitoring which can be verified, compiled, or simply monitored. There also exist internal libraries for communication supporting UART communication, I2C communication, or SPI communication with sensor modules.

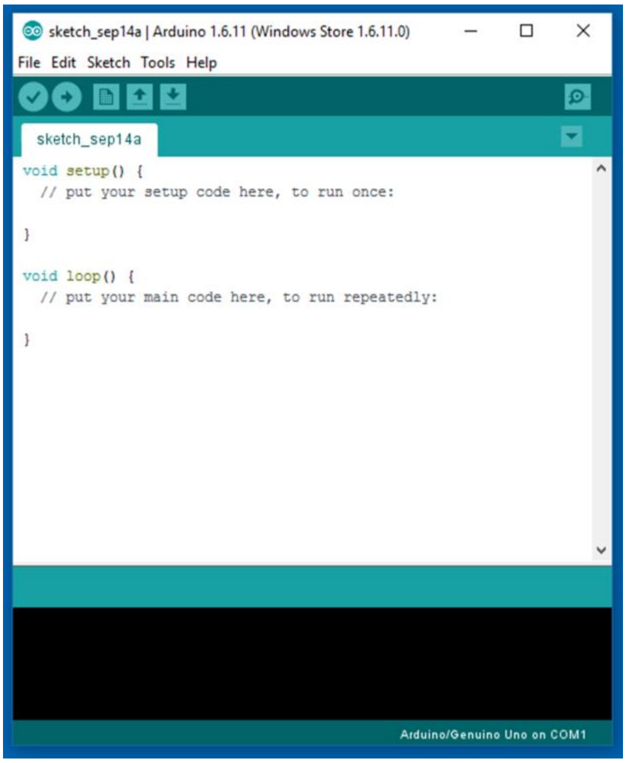

Fig. 5: Arduino Software Interface IDE.
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The software employed for the purpose of carrying out the EDA task described in the statement is the EasyEDA (Figure 5). This is online software employed for the purpose of designing schematics and PCB layouts, as well as simulations. This software made it feasible to design and verify the hardware components without requiring the development of the hardware. Moreover, it allows simulation at the component level.

For cloud-based monitoring and remote visualization, there was interfacing of Blynk app and NodeMCU using Wi-Fi connectivity. From Figure 6, it can be noted that it supports real-time visualization of sensor readings for current, voltage, power, and billing information. The app contains graphical plots, numerical gauges, and LCD widgets, all of which support refreshing of values by making use of Blynk library functions available within the firmware of the microcontroller. This remote-control system via mobile apps holds a very prominent place for consumer interaction and smart billing purposes.

Fig. 6: IoT Device Control and Monitoring in Blynk Application.
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Overall, the integration of three key platforms was developed in the software development process. These include the Arduino Integrated Development Environment, EasyEDA, and Blynk. The three platforms created a strong, modular, and scalable platform that helped develop the fully functional IoT solution for the energy monitoring and billing system.

3.3 Mathematical Modeling and Measurement Equations

The precise measurement of energy, on the other hand, requires implementation on hardware platforms using IoT networks as well as Models of signal conversion, sampling, and computation have a sound mathematical basis. Some recent papers emphasize the importance of these ideas in signal processing, which, in the absence of explicit mathematical expressions, weakens the reproducibility and scientific validity in the studies of smart metering, [11], [13]. In consideration of the aforementioned, the entire mathematical model encompassing voltage and current sensing, RMS value calculation, active power, energy, etc. estimation in the proposed system. The formulations are applicable to single-phase residential loads and are consistent with established measurement practices in smart energy meters, [7], [10], [14].

3.3.1 Sensor Signal Conversion

The proposed system employs a ZMPT101B voltage sensor and an ACS712 current sensor to obtain scaled analog representations of line voltage and load current. These analog signals are digitized using the built-in analog-to-digital converter (ADC) of the ESP8266 microcontroller.

Let the ADC resolution be denoted as NNN bits and the reference voltage as $Vref$. For the ESP8266, $N = 10$ bits and $Vref = 1.0V$. The ADC output count DDD therefore lies in the range $0 \leq D \leq 2^N - 1$. The corresponding analog input voltage V_{ADC} is given in equation (3),

$$V_{ADC} = \frac{D}{2^N - 1} x\, V_{ref} \tag{3}$$

Voltage Conversion (ZMPT101B)
The ZMPT101B provides an analog output proportional to the AC voltage, with a sensitivity $S_v(V/V)$ and a DC offset V_{0v} due to mid-scale biasing. The instantaneous line voltage $v(t)$ is obtained as

$$v(t) = \frac{V_{ADC}(t) - V_{0v}}{S_v} \tag{4}$$

where S_v and V_{0v} are experimentally determined during calibration using a reference meter in equation (4).

Current Conversion (ACS712)
Similarly, the ACS712 current sensor produces an output voltage proportional to load current, with sensitivity $S_i\,(V/A)$ and offset V_{0i}. The instantaneous current $i(t)$ is expressed in equation (5) as

$$i(t) = \frac{V_{ADC}(t) - V_{0i}}{S_i} \tag{5}$$

This linear sensor model is widely adopted in smart metering literature and offers acceptable accuracy for low- to medium-power residential applications, [6], [11].

3.3.2 RMS Voltage and Current Calculation

To obtain meaningful electrical quantities, root mean square (RMS) values of voltage and current are computed over a discrete sampling window. For a sampling frequency f_s and window length T_w, the number of samples is $N = f_s \times T_w$.

The equation (6) and (7) calculates the discrete RMS voltage and current as

$$V_{RMS} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} v^2\,(k)} \tag{6}$$

$$I_{RMS} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} i^2\,(k)} \tag{7}$$

This formulation remains valid for both sinusoidal and non-sinusoidal waveforms, provided that the sampling window spans an integer number of fundamental cycles. Such discrete RMS computation methods are standard in digital energy meters and are particularly suitable for microcontroller-based implementations, [7], [13].

3.3.3 Instantaneous Power and Energy (kWh) Calculation

The instantaneous power $p(k)$ at each sampling instant is calculated in equation (8) as the product of the instantaneous voltage and current samples:

$$p\,(k) = v(k) \times i\,(k) \tag{8}$$

The Electrical energy consumption is obtained by numerically integrating the instantaneous power over time. In discrete form, the accumulated energy E over N samples is given by

$$E = \sum_{k=1}^{N} p(k)\ \Delta t \tag{9}$$

The accuracy obtained from this numerical integration procedure can be improved using a higher rate of sampling and equally accurate time steps through equation (9). For practical embedded systems, this discrete summation helps to strike an optimal balance between the processing rate and accuracy, [10], [14].

In the current implementation, the power factor is assumed to be unity, $(PF = \frac{P}{S})$ because the load is residential. This is explained and clarified to avoid any obscurities, which was recommended in previous studies concerning smart metering in [11] and [14].

4 Analysis and Simulation

In this section, the proposed smart energy metering system based on the IoT will be evaluated rigorously. Although the mathematical models for the sensing and calculation part were proven in Section 3, in this section, the emphasis will be on the measurement accuracy, uncertainty, and comparison with the standard measuring instrument. In this case, the aim is to validate the proposed method and confirm its reliability.

Let X_{means} represent the electrical parameter measured by the proposed system and x_{ref} denote the corresponding value obtained from a reference meter.

The equation (10) shows the root mean square error (R_{MSE}), which captures both systematic and random components, can be calculated from the above parameters, is defined as

$$R_{MSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_{mean,i} - X_{ref,i})^2} \tag{10}$$

These metrics form the basis for evaluating the accuracy of voltage, current, power, and energy measurements produced by the proposed system.

4.1 Measurement Accuracy and Error Analysis

The accuracy of measurement was tested by interposing the proposed smart energy meter with a calibrated single phase digital energy meter of accuracy class 1.0, which was taken as the standard of measurement of accuracy of the energy meters. All experiments were performed in the steady state domestic load condition, including the resistive and composite load conditions, simulating practical loads.

For each operating condition, 30 trials were conducted independently to obtain recordings of a satisfactory level of statistical significance. The voltage, the current, the instantaneous power, and the accumulated values of energy were measured separately for both the meters. The previously defined values for errors were calculated for each variable.

The results indicate low mean error and limited dispersion across repeated trials, demonstrating stable and repeatable performance suitable for residential energy monitoring applications.

4.2 Uncertainty and Quantization Analysis

In addition to experimental error, uncertainty arising from analog-to-digital conversion and sensor tolerances was analytically evaluated to establish a complete error budget.

For an N-bit ADC with reference voltage V_{ref}, the quantization step size (Δ) is given in the below equation (11)

$$\Delta = \frac{V_{ref}}{2^N} \tag{11}$$

The maximum ADC quantization error is therefore $E_q = \pm\frac{\Delta}{2}$

Separate uncertainty contributions were considered for the ZMPT101B voltage sensor and the ACS712 current sensor based on manufacturer specifications.

Assuming independent uncertainty sources, the combined standard uncertainty (u_c) is calculated using the root-sum-of – squares (RSS) method,

$$u_c = \sqrt{u_q^2 + u_S^2 + u_{noise}^2} \tag{12}$$

where in equation 12, u_q represents ADC quantization uncertainty, u_s represents sensor tolerance uncertainty, and u_{noise} accounts for residual electrical noise. This uncertainty analysis strengthens measurement traceability and supports the reported accuracy claims.

4.3 Validation using Reference Meter

To further validate the proposed system, regression-based comparison was performed between measured values and reference meter readings.

The linear regression model is defined as $X_{mean} = aX_{ref} + b$

Where a is the slope and b is the intercept. Additionally, the mean absolute error (MAE) is calculated in equation (13) as

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|X_{menas,i} - X_{ref,i}\right| \qquad (13)$$

Regression results and error metrics confirm strong linear agreement between the proposed system and the reference meter.

4.4 Simulation and Experimental Verification

Figure 7 (Appendix) depicts the overall architecture of the system that has been utilized for analysis and simulation purposes. It is represented in a clear block diagram of the IoT-based smart energy meter system. It explains how the modules of the system are integrated during the experimental evaluation process.

The hardware setup used in the experiments is shown in Figure 8 (Appendix). It presents the full circuit diagram, including the NodeMCU ESP8266, the voltage and current sensors, the power supply, and the display. This diagram gives clear, practical detail that backs up the analysis and test results shared earlier.

Tests were made under real conditions of operation, showing the readings simultaneously on the local LCD display and on the Blynk cloud. It monitored voltage, current, power, and total energy consumed over a period of time. These tests confirmed the correct operation of the device and matched the expected results from our analysis.

5 Conclusion and Cost Analysis

The proposed system is a cost-effective solution that offers scalability in real-time energy monitoring. This is achieved through the integration of the ESP8266 NodeMCU, the ZMPT101B, and the ACS712 sensors, which provide real-time voltage, current, power, and energy measurements. These measurements can be read on the 16×2 I2C LCD display, which is connected through the system, while the data is also sent through the Wi-Fi connection to the Blynk app. This is facilitated by the 5V, 7A SMPS.

The circuit was built over a custom board having small form factor, which lines the microcontroller, sensors, display and power board. Building the circuit this way allowed modularity while testing the components, assembling it as well as demonstrating it for teaching purposes. The completed prototype is shown below in Figure 9 (Appendix).

A detailed cost analysis was completed based on the components used. The total cost of the materials of the system was 3,330 Taka. The cost-effective configuration makes it possible for the system to be deployed in large numbers in residential areas, academic institutions, and rural electrification. Table 1 indicates the cost of the materials, specification, and the price of the project.

Table 1. Bill of Materials and Cost Summary

No.	Particulars	Specification	Qty	Price (Tk.)
01	Node MCU	ESP-8266	1	650
02	SMPS	5V, 7Amp	1	380
03	Voltage Sensor	ZMPT101B	1	350
04	Current Sensor	ACS712	1	320
05	LCD Display	16*2	1	580
06	Others	-	-	1050

Source: created by the authors

6 Future Scope

The Internet of Things technology-based smart energy metering system allows for the monitoring, remote access, and control of the system using the aid of technological advancements, along with the use of interdisciplinary approaches for the efficient working of the system. In addition, the future scope of the system will include the various possible uses of the system. How does the system work? The provisions for future improvements of the system involve the integrated use of machine learning for anomaly detection, real-time tariffs, remote updates, and intelligent management, [15]. Bi-directional system updates to enable DSM, tariff updates, firmware upgrades, and load balancing, ultimately turning the device into an active grid participant, [14]. Smart IoT systems could benefit from the integration of secure standards for TLS/SSL pseudonymic untraceable access controls coupled with blockchain-based audit trails to secure data from eavesdropping, spoofing, and unauthorized access, [16]. The integration of sensitive-context smart home technologies with voice assistants and automation systems like Amazon Alexa and Google Home could improve user experience and accessibility, [17]. Smart systems with user-friendly, intelligent, and self-monitoring energy systems are anticipated to improve the consumer experience.

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APPENDIX

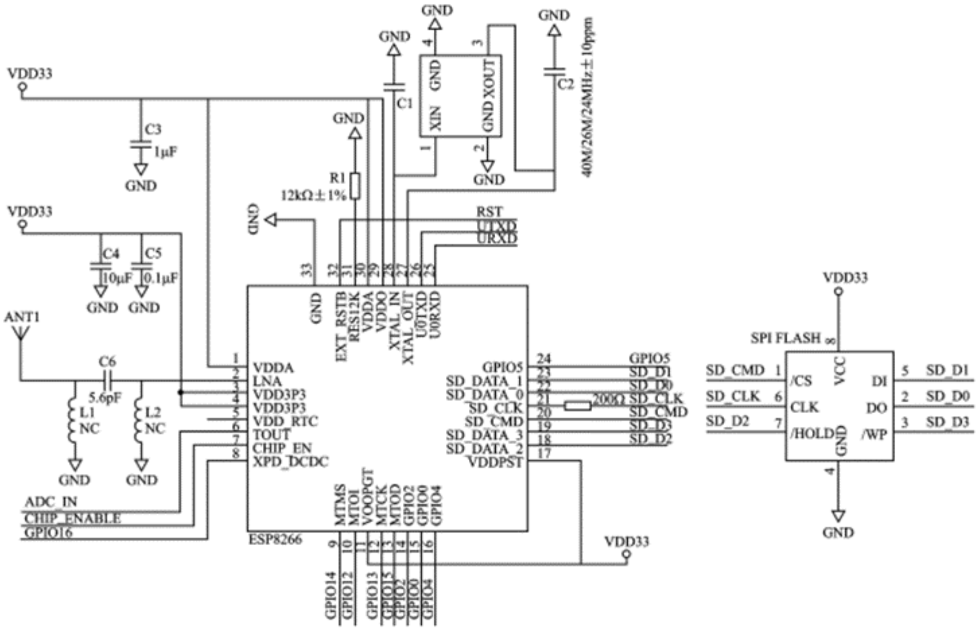

Fig. 1: ESP8266-based microcontroller system schematic with crystal oscillator and SPI Flash memory
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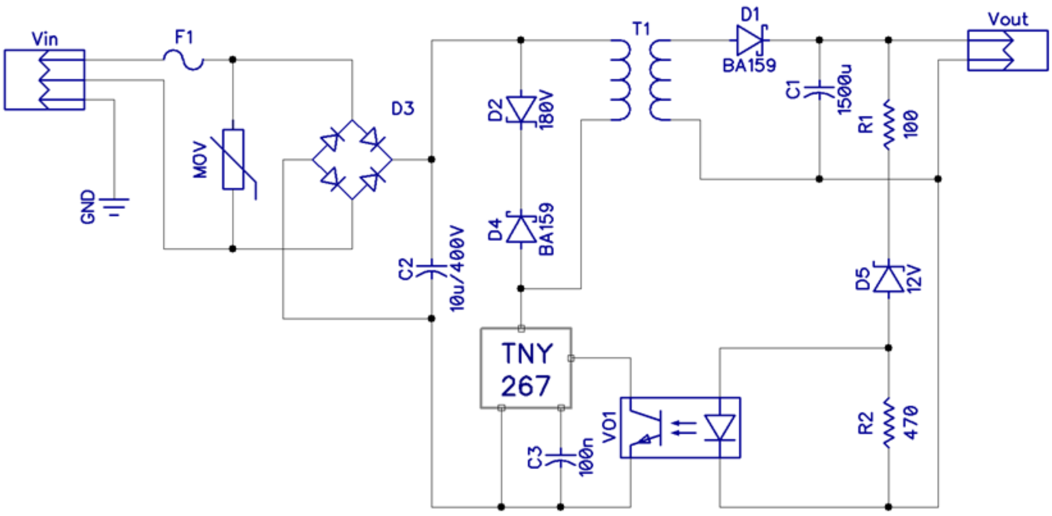

Fig. 2: SMPS power supply circuit using TNY267 IC for regulated 5V output
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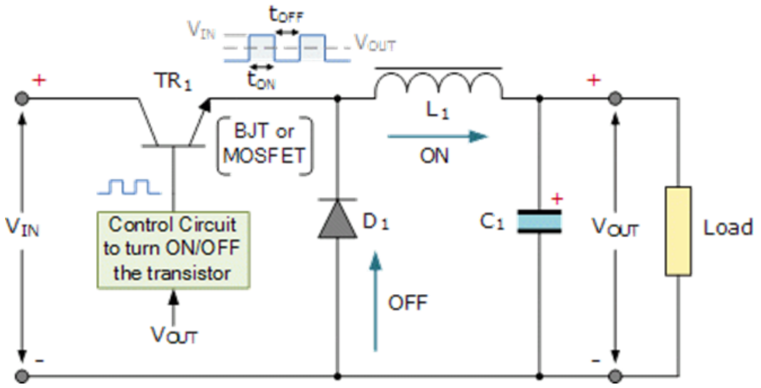

Fig. 3: Buck converter topology representing the working principle of SMPS
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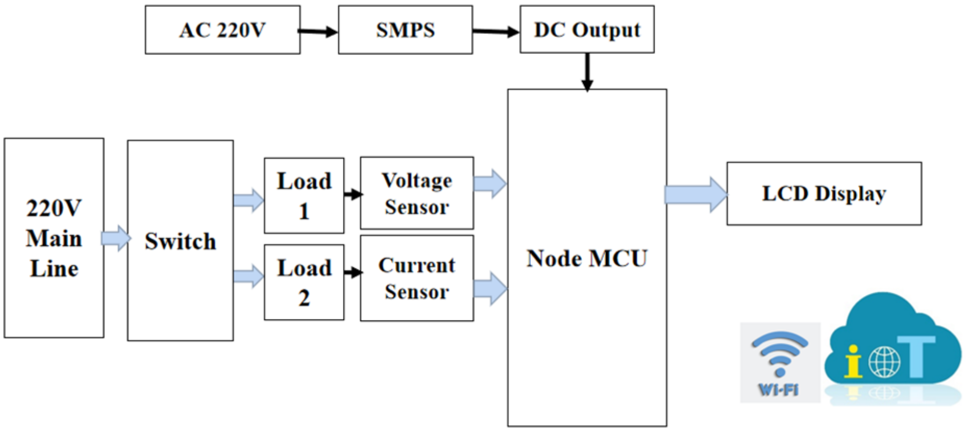

Fig. 7: Block Diagram of the IoT-Based Smart Energy Metering System
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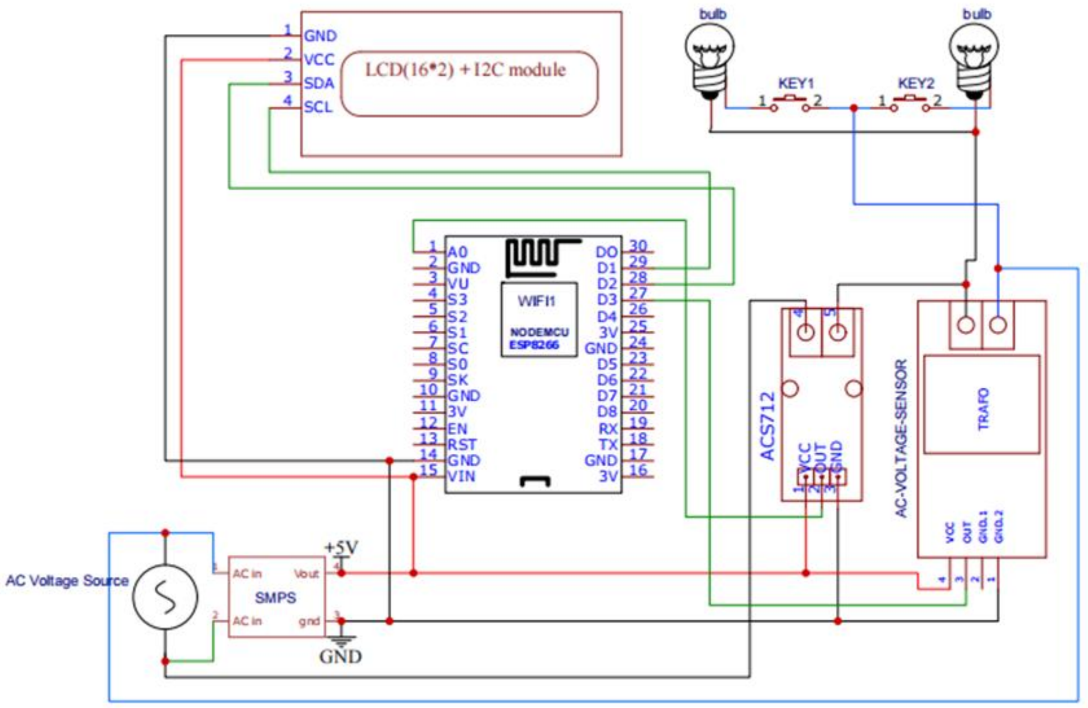

Fig 8: Circuit Diagram of the IoT-Based Smart Energy Meter
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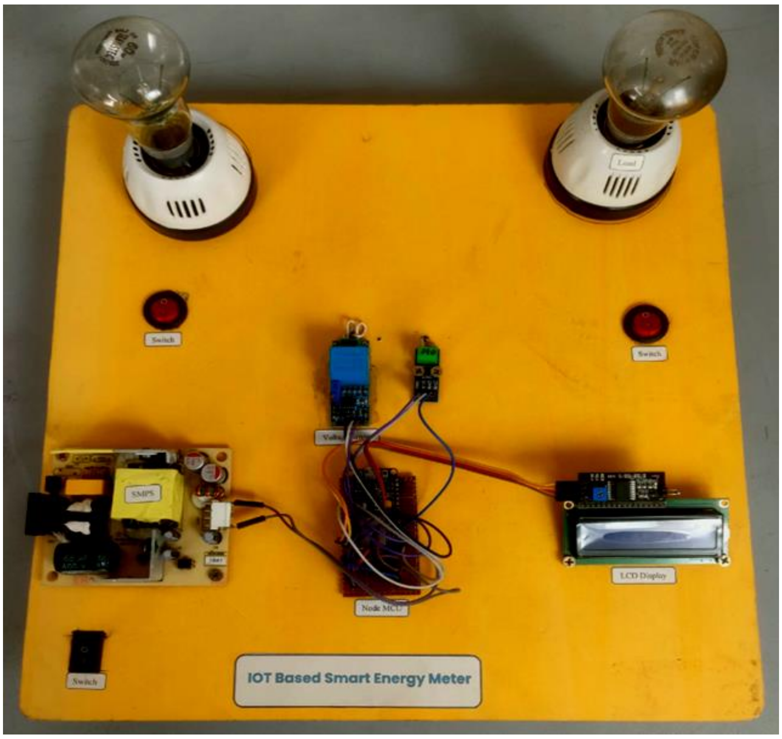

Fig. 9: Hardware Design (Prototype) of an IoT-Based Energy Monitoring Device
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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)
The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest
The authors have no conflicts of interest to declare that are relevant to the content of this article.