DESIGN AND FABRICATION OF REAL TIME ENERGY CONSUMPTION TRACKING SYSTEM IN A MICROGRID

A PROJECT REPORT

Submitted by

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BACHELOR OF ENGINEERING

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SRI KRISHNA COLLEGE OF ENGINEERING AND TECHNOLOGY

An Autonomous Institution | Approved by AICTE | Affiliated to Anna University | Accredited by NAAC with A++ Grade

Kuniamuthur, Coimbatore – 641008.

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SUSTAINABLE DEVELOPMENT GOALS

The Sustainable Development Goals are a collection of 17 global goals designed to blue print to achieve a better and more sustainable future for all. The SDGs, set in 2015 by the United Nations General Assembly and intended to be achieved by the year 2030, In 2015, 195 nations agreed as a blue print that they can change the world for the better. The project is based on one of the 17 goals.

Questions	Answer Samples
Which SDGs does the project directly address?	SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation & Infrastructure), SDG 12 (Responsible Consumption & Production), SDG 13 (Climate Action).
What strategies or actions are being implemented to achieve these goals?	Using ESP32 with CT & voltage sensors for real-time monitoring, web dashboard for reporting, and cost calculation for awareness.
How is progress measured and reported in relation to the SDGs?	Through real-time data logging, web dashboard reports, cost analysis, and comparison of energy use before vs. after implementation.
How were these goals identified as relevant to the project's objectives?	They align with the project's aim of affordable, efficient, and sustainable energy monitoring and management.
Are there any partnerships or collaborations in place to enhance this impact?	Yes, academic guidance from faculty and team collaboration; future scope for industry and government partnerships.

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BONAFIDE CERTIFICATE

Certified that this project report “**DESIGN AND FABRICATION OF REAL TIME ENERGY CONSUMPTION TRACKING SYSTEM IN A MICROGRID**” is the bonafide work of “**AKSHAY KRISHNAN SURESH (727722EUMT012), HARIHARAN S (727722EUMT047), KANISHK S (727722EUMT060), KAVIBHARATHI B (727722EUMT065)**” who carried out the project work under my supervision.

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INTERNAL EXAMINER EXTERNAL EXAMINER

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At this juncture, we take the opportunity to convey our sincere thanks and gratitude to the management of the college for providing all the facilities to us.

We wish to convey our gratitude to our college Principal **Dr. K. Porkumaran**, for supporting us to do our project and offering adequate duration to complete our project.

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ABSTRACT

The increasing demand for electricity and the integration of distributed energy resources highlight the need for accurate and transparent energy monitoring in microgrids. Conventional billing systems provide only aggregated data, offering little insight into appliance-wise consumption and limiting the ability to manage loads effectively. This project presents the design and implementation of a real-time energy consumption tracking system using an ESP32 microcontroller, current transformers (CT), and voltage sensors.

The system measures current and voltage at different nodes, calculates power and energy usage, and displays the results on both an LCD module and a web-based dashboard for remote access. By enabling real-time monitoring and cost calculation, the system provides users with greater visibility of their electricity usage, helping them to identify high-consumption appliances and optimize load distribution. Circuit design and simulation were carried out to ensure measurement accuracy, system stability, and efficiency.

The proposed solution is low-cost, scalable, and user-friendly, making it suitable for households and small-scale microgrid applications. By promoting energy awareness and cost efficiency, it contributes to sustainable and intelligent power management.

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S.NO	Symbol	Description	Unit
1	V	Voltage	Volts (V)
2	I	Current	Amperes (A)
3	P	Power	Watts (W)
4	E	Energy	Watt-hour (Wh) / Kilowatt-hour (kWh)
5	t	Time	Seconds (s) / Hours (h)
6	V_{rms}	Root Mean Square Voltage	Volts (V)
7	I_{rms}	Root Mean Square Current	Amperes (A)
8	V_{peak}	Peak Voltage	Volts (V)
9	V_{DC}	Direct Current Voltage	Volts (V)
10	C	Capacitance	Farads (F)
11	T	Torque	Newton-meter (Nm)
12	m	Mass	Kilogram (kg)
13	g	Acceleration due to Gravity	Meter per Second Squared (m/s^2)
14	d	Distance / Lever Arm	Meter (m)
15	Rs	Burden Resistor	Ohm (Ω)
16	$T_{elevation}$	Torque about Elevation Axis	Newton-meter (Nm)
17	$T_{azimuth}$	Torque about Azimuth Axis	Newton-meter (Nm)
18	Δt	Time Interval	Seconds (s)
19	η	Efficiency	Percentage (%)
20	R	Resistance	Ohm (Ω)
21	f	Frequency	Hertz (Hz)
22	V_{out}	Output Voltage	Volts (V)
23	V_{in}	Input Voltage	Volts (V)
24	E(kWh)	Energy Consumed	Kilowatt-hour (kWh)
25	P_{avg}	Average Power	Watts (W)

CHAPTER 1: INTRODUCTION

1.1 MOTIVATION

The growing demand for electricity, combined with the rapid integration of renewable energy sources, has made efficient energy management a crucial requirement in modern power systems. Traditional billing methods only provide total consumption values, which fail to give insights into appliance-wise usage or load distribution. This lack of transparency makes it difficult for users to identify high-consumption devices, manage electricity costs effectively, or take steps toward energy conservation.

Furthermore, with rising concerns about sustainable energy usage and environmental impacts, there is a strong need for **low-cost, real-time, and user-friendly monitoring systems**. The development of such a system can empower households and microgrid users to monitor consumption patterns, reduce wastage, and contribute to responsible energy usage aligned with global sustainability goals.

In addition, the rapid growth of Internet of Things (IoT) technologies has opened opportunities for smarter energy management. Devices like ESP32 enable seamless data collection, wireless communication, and remote monitoring at an affordable cost. Leveraging these technologies in microgrids not only improves efficiency but also supports the vision of smart cities and sustainable infrastructure, motivating the development of this project.

1.2 INTRODUCTION

Energy management plays a vital role in ensuring the reliability and efficiency of microgrids. However, existing real-time monitoring solutions are often expensive and technically complex, which restricts their adoption in smaller applications. To address these challenges, this project focuses on the **design and implementation of a real-time energy consumption tracking system** using **ESP32, CT sensors, and voltage sensors**.

The ESP32 microcontroller acts as the central unit for acquiring, processing, and transmitting real-time data. Measured values of voltage and current are used to calculate power and energy, which are then displayed on both a **local LCD module** and a **web-based dashboard** for remote monitoring. The system also provides a cost breakdown, enabling users to understand usage patterns and optimize load management.

By providing accurate and accessible information, the proposed system encourages energy awareness and efficiency, making it suitable for **households, academic institutions, and small-scale microgrids**. Its simplicity, scalability, and affordability distinguish it from conventional monitoring systems.

Moreover, the integration of IoT features through the ESP32 enhances the practicality of the system by enabling wireless data transmission and remote accessibility. Unlike conventional meters that only record cumulative usage, this project delivers real-time insights into consumption trends, helping users identify high-demand periods and take preventive actions to avoid overloading. The system is also designed with flexibility in mind, allowing easy expansion to monitor multiple nodes or appliances, which makes it a future-ready solution for smart homes and microgrid applications.

1.3 SCOPE OF THE PROJECT

The scope of this project includes the design, development, and validation real-time monitoring system for energy consumption. The major aspects are:

- **Hardware Design**: Integration of ESP32 with CT sensors and voltage sensors for data acquisition.
- **Software Development**: Programming of ESP32 for data processing, storage, and wireless transmission.
- **User Interface**: Display of real-time data on an LCD and web dashboard for easy interpretation.
- **Energy Cost Calculation**: Appliance-wise consumption and cost breakdown to promote responsible usage.
- **Testing and Validation**: Circuit design verification using simulations and hardware implementation for real-time results.

The system is designed to be **modular, scalable, and cost-effective**, making it adaptable for residential and institutional applications. Its emphasis on transparency and efficiency contributes to sustainable energy management practices.

1.4 PROBLEM STATEMENT

Efficient monitoring of electricity usage has become increasingly important in modern households and microgrids due to rising energy demands, fluctuating tariffs, and the global emphasis on sustainability. However, most existing energy billing systems only provide cumulative monthly consumption values. This traditional approach fails to identify which appliances consume more energy, when peak usage occurs, or how consumption patterns can be optimized. As a result, users are left with limited awareness of their actual usage behavior and little scope for making informed decisions to reduce wastage.

Without real-time and appliance-level insights, consumers are unable to manage loads effectively, detect anomalies, or adopt energy-saving practices. Although commercial energy monitoring systems exist, they are often expensive, complex to install, and therefore inaccessible for small-scale users such as households or microgrids. The lack of integration with modern IoT technologies also restricts features such as remote access and data-driven analysis, which are crucial for efficient energy management in today's context.

Therefore, there is a clear need for a **low-cost, accurate, and user-friendly monitoring system** that can measure current and voltage in real time, calculate power and energy consumption, and present the results in an easily understandable format. By using an **ESP32 microcontroller with CT and voltage sensors**, such a system can be developed to not only log consumption but also calculate energy costs and display them both locally on an LCD and remotely through a web dashboard. This would empower users to better understand their consumption patterns, optimize usage, and save on electricity bills.

1.5 OBJECTIVES

The primary objective of this project is to **design and implement a real-time energy consumption tracking system** for household and microgrid applications using **ESP32, CT sensors, and voltage sensors**. The system aims to provide users with detailed insights into their energy usage and encourage responsible consumption.

The specific objectives are as follows:

- To develop a **low-cost and scalable system** capable of monitoring real-time voltage, current, and power consumption.

- To implement **appliance-level tracking** of energy usage using CT and voltage sensors for improved visibility.

- To design a **user interface** that displays real-time data on an LCD screen and a **web dashboard** for remote monitoring.

- To incorporate **energy cost calculation** features that provide users with a clear breakdown of consumption and expenses.

- To validate the system through **circuit simulations and hardware implementation**, ensuring accuracy, stability, and reliability.

- To promote **energy efficiency and awareness** by enabling users to identify high-consumption appliances and optimize load management.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

A review of past literature is essential to understand the advancements made in the field of energy monitoring and management, as well as to identify the limitations of existing systems. Researchers across the globe have proposed various approaches to improve efficiency, ranging from **solar tracking mechanisms** that enhance energy generation to **IoT-enabled smart meters** that provide real-time monitoring of consumption. Each of these contributions has addressed specific challenges, such as reducing costs, improving accuracy, or enabling remote accessibility.

While some studies have focused on the **supply side of energy systems**, such as maximizing the output of solar panels through automated tracking, others have concentrated on the **demand side**, developing monitoring systems that give users visibility into their consumption patterns. IoT platforms, microcontrollers like Arduino, ESP8266, and ESP32, and communication technologies such as GSM and Firebase have all been employed to create monitoring solutions. These systems have demonstrated the potential of modern technology to transform energy awareness and efficiency.

However, despite these advances, literature shows that many solutions remain either **technically complex, expensive, or limited in scalability**. Commercial e-monitors, while offering advanced analytics, are often inaccessible to average households due to cost. By reviewing these works, it becomes possible to pinpoint the research gaps and justify the development of the present project: a **low-cost, ESP32-based energy consumption tracking system with CT and voltage sensors** designed to be accurate, scalable, and user-friendly.

2.2 LITERATURE SURVEY

In recent years, several researchers have contributed significantly to the fields of energy monitoring, microgrid management, and IoT-based smart metering. Their works provide valuable insights into both renewable energy generation optimization and consumption-side monitoring, though each comes with its own set of strengths and limitations.

Naskar and Das (2025) designed a dual-axis solar tracker using an AVR microcontroller and four LDRs. Their work demonstrated that simple, low-cost solar tracking solutions can improve responsiveness and accuracy under varying light conditions, making them suitable for seasonal adaptation. Similarly, **Muthukumar (2023)** introduced an IoT-based dual-axis solar tracking system, which showed significant efficiency gains in photovoltaic generation. His system confirmed that integrating IoT enhances automation and reliability in renewable applications. Extending this line of work, **Kale and Adak (2022)** developed an LDR + servo-controlled dual-axis solar tracker that achieved **31.3% higher power output** compared to static solar panels, proving the effectiveness of automated positioning.

On the consumption side, **Hariharan (2021)** presented a smart home energy consumption monitoring system via IoT. The system provided **real-time appliance-level data**, along with predictive analysis for monthly bills and alerts for threshold exceedance. This work emphasized the role of IoT in reducing household energy wastage and empowering users with detailed consumption insights. **Vasanth and Kumar (2020)** focused on wireless real-time load monitoring using ESP8266 and Firebase. Their prototype successfully demonstrated that **low-cost wireless modules** can track and transmit energy usage to cloud platforms effectively, highlighting affordability as a key driver for scalability. Similarly, **Patel and Zinzuvadia (2020)** developed an IoT-based smart energy meter that monitored real-time parameters and allowed **remote access through a web interface**, proving flexible solutions in modern power systems.

Other approaches explored communication technologies to enhance accessibility. **Shinde and Baviskar (2019)** proposed a GSM-based real-time monitoring system using Arduino. Their system measured voltage, current, and power, and transmitted data to users via SMS, making it particularly useful for rural or remote microgrids where internet access is limited. **Alam, St-Hilaire, and Kunz (2019)** conducted a comprehensive survey on real-time energy management in microgrids, published in *IEEE Access*. They concluded that systems combining communication technologies with monitoring significantly improved grid efficiency, enabling better fault detection, demand response, and load balancing. These findings underscore the necessity of communication integration in modern energy monitoring solutions.

In addition to prototypes and field implementations, commercial monitoring tools have also been examined. **Haq and Jacobsen (2018)** carried out a technical review of off-the-shelf electronic monitors for appliance-level load monitoring. They found that while many consumer-owned e-monitors supported advanced features like load disaggregation and analytics, they were generally **too costly and technically complex for ordinary users**. Their review highlighted a critical gap between advanced capabilities and everyday accessibility, reinforcing the need for simpler, low-cost systems.

Taken together, these studies reveal the broad spectrum of energy monitoring research—from improving renewable generation efficiency through solar tracking to developing IoT-enabled systems for consumption-side transparency. The common theme across all works is the importance of real-time data and communication in improving efficiency, reliability, and user engagement. However, the literature also consistently points to key challenges: **high cost, technical complexity, and lack of scalability for small-scale users**. These limitations provide the foundation and justification for the present project, which proposes a **low-cost ESP32-based system using CT and voltage sensors** to deliver real-time monitoring, appliance-level insights, and cost calculation in a simple and scalable design.

CHAPTER 3: SYSTEM DESIGN AND METHODOLOGY

3.1 INTRODUCTION

The design and methodology of a system form the foundation for its successful implementation. In the case of an energy consumption tracking system, careful planning is required to ensure that the sensing, processing, and display units work seamlessly together to provide accurate and real-time results. This chapter focuses on the system design and methodology adopted in the project, covering the block diagram, flow diagram, and detailed explanation of each functional unit. By combining both hardware and software perspectives, the design aims to create a reliable, scalable, and cost-effective solution for real-time monitoring.

The proposed system is built around the ESP32 microcontroller, which serves as the central processing unit. Current and voltage values are captured using CT sensors and a voltage sensor module (ZMPT101B). These signals are conditioned and fed into the ESP32, where calculations for power and energy are performed. The results are then displayed on a 20x4 LCD module for local access and transmitted via Wi-Fi to a web dashboard for remote monitoring. This dual-mode display ensures that the system is accessible to users both at the site and from remote locations.

To organize the functioning of the system, a block diagram and flow diagram are prepared. The block diagram illustrates the relationship between the sensing, processing, and output units, while the flow diagram provides a logical representation of the program execution inside the ESP32.

The methodology emphasizes **simplicity, scalability, and affordability** by using low-cost, widely available components without compromising accuracy.

3.2 DESIGN PARAMETERS

Sensitivity of for power source:

The sensitivity of the power source is a vital parameter in the design of an energy monitoring system, as it directly affects accuracy and efficiency. Sensitivity refers to the system's ability to detect small changes in voltage and current and respond in real time. To achieve this, two different sensors are used in this project: a **CT sensor** for measuring current and a **ZMPT101B module** for voltage measurement. These sensors were chosen for their affordability, safety, and ability to detect variations at both low and high consumption levels.

Data processing for values generated:

The raw values generated by the sensors are analog and cannot be directly understood by digital systems. The **ESP32 microcontroller** converts these signals into digital values using its ADC (Analog-to-Digital Converter). Once digitized, the ESP32 performs essential calculations such as $\boldsymbol{P}=\boldsymbol{V} \times \boldsymbol{I}$ for power and $\boldsymbol{E}=\boldsymbol{P} \times \boldsymbol{t}$ for energy consumption. Filtering and scaling techniques are also applied to reduce noise and improve accuracy. This processing ensures that the values displayed or transmitted are not just raw readings but reliable, real-time consumption data.

High level data interface:

For the system to be practical, processed data must be accessible to the user in an understandable format. This is achieved through a dual-interface approach. Locally, a 20x4 LCD module displays real-time voltage, current, power, and energy values. Remotely, the ESP32 uses Wi-Fi to transmit the data to a web-based dashboard, following IoT communication principles. This dashboard not only shows the usage values but also provides trends and cost analysis, helping users identify peak usage and optimize loads. By combining local display with IoT-enabled remote monitoring, the system ensures both accessibility and scalability, making it suitable for households, institutions, and small-scale microgrids.

3.3 SYSTEM DESIGN

The system is designed to monitor and manage energy consumption in real time by integrating sensors, a microcontroller, and IoT-enabled communication. The block diagram illustrates the flow of energy and information, beginning from the source and extending up to the end-user interface.

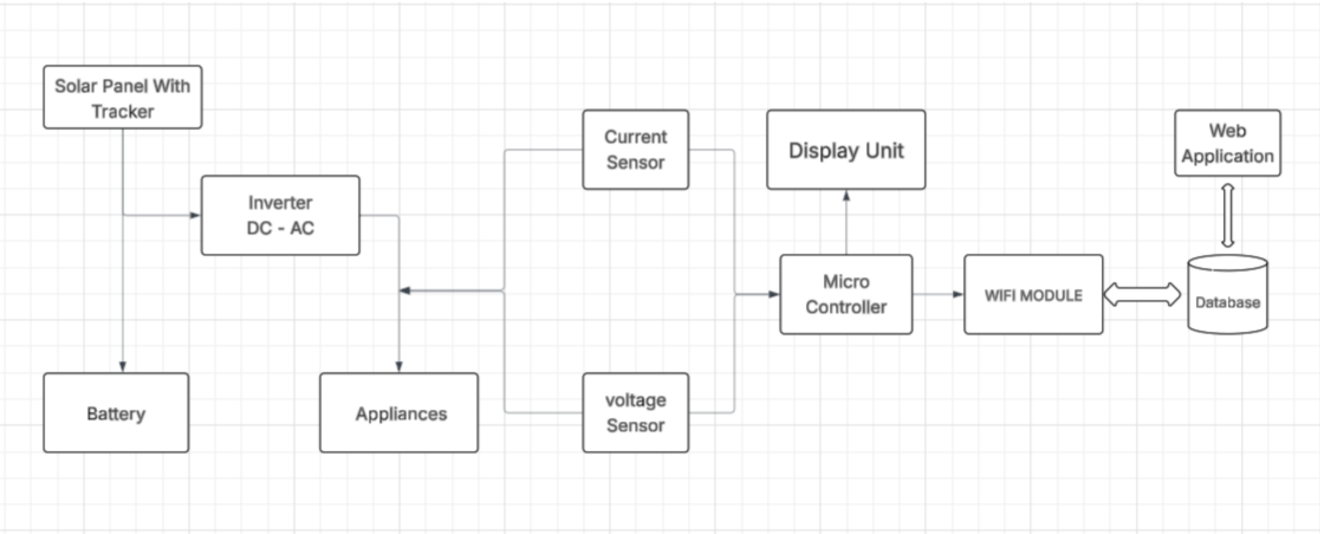

Fig no. 3.3.1 Design Diagram

The **Solar Panel with Tracker** acts as the primary source of energy, generating DC power from sunlight. To ensure uninterrupted supply, the panel is supported by a **Battery unit**, which stores excess energy and provides backup during low sunlight conditions. The **DC output** from the solar panel and battery is converted into usable AC power by the **Inverter**, making it suitable for household **Appliances**.

To measure power consumption, the system employs two sensing modules: a **Current Sensor** and a **Voltage Sensor**. The current sensor detects the load current drawn by appliances, while the voltage sensor measures the AC line voltage. These sensor signals are then fed into the **Microcontroller (ESP32)**, which processes the inputs, calculates power and energy consumption, and prepares the data for display and transmission.

The processed data is first sent to the **Display Unit (LCD)**, which shows real-time values of voltage, current, power, and energy. At the same time, the ESP32 uses its **Wi-Fi Module** to transmit the data wirelessly to a **Database**. This database stores all usage records and communicates with a **Web Application** that allows remote monitoring by the user. The web interface presents consumption trends, cost breakdowns, and appliance-level insights, making it possible for users to track their energy usage from anywhere.

This design ensures that users have access to **both local and remote monitoring**, creating a transparent and user-friendly system. The integration of IoT not only enhances accessibility but also provides opportunities for scalability, such as adding more sensors or enabling advanced features like anomaly detection and predictive energy analysis in the future.

In addition to accurate sensing and processing, the design also focuses on **reliability and user convenience**. Safety isolation is ensured by using CT and voltage sensors, which allow indirect measurement without exposing the microcontroller to high voltages or currents. The use of the ESP32 further enhances the system by combining high processing power with built-in Wi-Fi, reducing the need for external modules. The modular nature of the design makes it easy to expand the system for multiple appliances or future integration with renewable energy sources. Thus, the proposed system is not only efficient and cost-effective but also adaptable to the growing needs of smart grid and IoT-based energy management applications.

3.4 FUNCTIONAL BLOCK REPRESENTATION

While the overall architecture explains the interaction of energy sources, sensors, and IoT modules, it is equally important to analyze the **functional representation of the monitoring system**. The functional block diagram provides a simplified view of how the microcontroller interacts with different modules to achieve real-time monitoring and reporting.

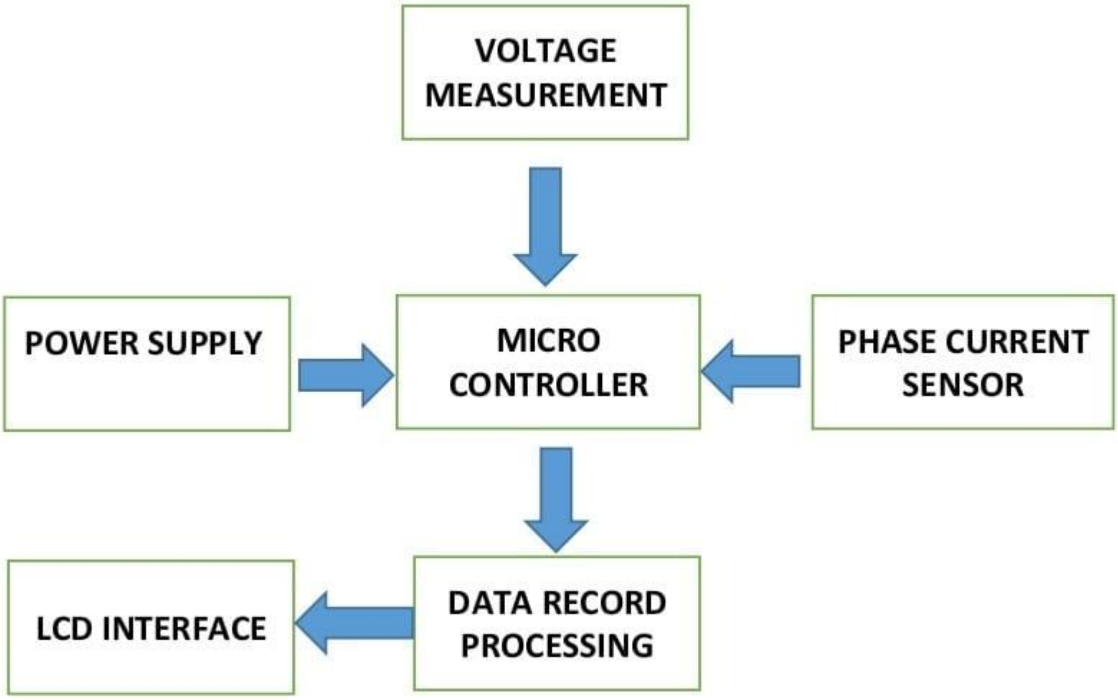

Fig no. 3.4.1 Functional Block diagram of monitoring system

Within the **microcontroller**, the conditioned analog signals from the sensors are first sampled and converted into digital values using the inbuilt **Analog-to-Digital Converter (ADC)** of the ESP32. This step is crucial because it allows the raw sensor data to be represented in a format that the microcontroller can process accurately. The digitized signals form the basis for all further calculations, ensuring that the measured parameters such as voltage and current reflect real-time operating conditions

Once the data is digitized, the ESP32 executes programmed algorithms to compute essential parameters of the system. These include **instantaneous power ($P = V \times I$)**, which represents the real-time load on the system, and **energy consumption ($E = P \times t$)**, which accumulates usage over time. In addition, the system is programmed to perform **cost estimation** by mapping consumption values to tariff rates defined in the software. This feature directly translates technical energy usage into monetary values, making the system more meaningful and user-oriented.

The processed information is then passed to the **Data Record Processing Unit**, which handles local storage and organizes the readings for further use. This ensures that data is not only available for immediate display but also stored for later analysis. The integration of IoT features in this stage allows the data to be packaged and transmitted to remote servers or cloud databases. This capability ensures that the system goes beyond simple monitoring to enable advanced features like trend analysis, usage comparison, and long-term energy management.

Finally, the results are communicated to the user through both local and remote interfaces. Locally, a **20x4 LCD module** displays real-time values of voltage, current, power, energy, and estimated cost, ensuring on-site visibility of the data. Simultaneously, the ESP32 transmits the processed information wirelessly to an **IoT-based web dashboard**, where users can access historical records, visualize consumption trends, and even track appliance-level insights. By combining immediate display with remote accessibility, the system ensures transparency, convenience, and user empowerment, making it highly effective for both **daily monitoring** and **long-term sustainable energy management**.

3.5 DESIGN CALCULATION

The design calculations form the foundation for ensuring the accuracy, stability, and efficiency of the system. They cover power supply design, current transformer with burden resistor, LCD interfacing, energy monitoring, and solar tracker torque requirements. Each calculation validates the suitability of chosen components and the overall feasibility of the project.

3.5.1 Power Supply Design

The system requires a regulated DC power supply for the ESP32 microcontroller, sensors, and display module. The input is standard **220V AC mains**, stepped down through a transformer (**TR1**) rated at 220V/12V.

- **Input:** 220V AC
- **Output (RMS):** 12V AC
- **Peak voltage:**

$$V_{peak} = V_{RMS} \times \sqrt{2} = 12 \times 1.414 = 16.97 \text{ V}$$

- **Rectified voltage:** Accounting for the diode drops in a bridge rectifier (≈0.7V per diode, 2 in conduction),

$$V_{DC(peak)} = V_{peak} - 1.4 = 16.97 - 1.4 = 15.57 \text{ V}$$

A **filter capacitor (C1 = 1000µF)** is used to reduce ripple. The required capacitance is given by:

$$C = \frac{I}{f \; X \; \mathrm{Vr}}$$

For load current of 100 mA and ripple voltage of 1V,

$$C = \frac{0.1}{50 \; X \; 1} = 2000 \; \mu\text{F}$$

In practice, a 1000µF capacitor is used, which provides acceptable ripple for the given current load. Voltage regulators are then used to produce 5V and 3.3V required by ESP32 and peripherals.

3.5.2 CT Circuit and Burden Resistor Design

A Current Transformer (CT) is used for safe measurement of load current.

- **CT Ratio:** 5A : 5mA
- **At maximum load (5A):**

$$I_{secondary} = 5mA$$

- **With a 10Ω burden resistor:**

$$V = I \times R = 5mA \times 10 = 0.05V = 50mV$$

Since 50mV is too small for the ADC input range of ESP32 (0–3.3V), a **signal conditioning circuit** is introduced. Using a non-inverting amplifier, the voltage is scaled up. The required scaling factor is:

$$\text{Gain} = \frac{\text{VADCmax}}{\text{Vinput}} = \frac{5}{0.05} = 100$$

This ensures that the CT output is mapped effectively within the ADC's operating range.

3.5.3 LCD Backlight and Contrast Control

The LCD requires a backlight resistor to limit current and for contrast adjustment.

- **Supply Voltage:** 5V
- **Resistor chosen:** 220Ω
- **Backlight current:**

$$I = \frac{V}{R} = \frac{5}{220} = 22.7 \text{ mA}$$

This value is within the safe operating range (<30mA).

3.5.4 Energy Monitoring Calculations

The system calculates real-time power and energy consumption using the following formulas:

- **Power:**

$$P = V \times I$$

- **Energy:**

$$E = P \times t$$

Example:

If a load draws 3A at 230V,

$$P = 230 \times 3 = 690W$$

If the load operates for 2 hours,

$$E = 690 \times 2 = 1380Wh = 1.38kWh$$

The energy consumption is then multiplied by the tariff rate to estimate cost.

3.5.5 Solar Tracker Calculations

The solar tracker requires torque calculations to size motors for both elevation (tilt) and azimuth (yaw) axes.

A) Elevation Axis (Tilt – Up/Down)

- Panel weight: $m=2$ kg
- Distance from axis to center of gravity: $d=0.125$ m
- Torque required:

$$T=m \times g \times d=2 \times 9.81 \times 0.125=2.45 \text{ Nm}$$

B) Azimuth Axis (Yaw – Left/Right)

- Structure weight: $m=2.5$ kg
- Distance from axis: $d=0.15$ m
- Torque required:

$$T=2.5 \times 9.81 \times 0.15=3.67 \text{ Nm}$$

C) Motor Selection

A standard servo motor (model **MG995/MG996R**) with a rated stall torque of **0.92 Nm** has been selected for the system. In order to meet the torque requirements of the two primary axes of motion—**Elevation** and **Azimuth**—the motors are integrated with gear reduction mechanisms. The use of gears increases the effective output torque according to the selected gear ratios.

- **Elevation Axis**:

  The gear ratio chosen for the elevation axis is **4:1**, meaning the motor torque is amplified by a factor of four. Thus, the effective torque available at the output shaft is:

  $$T_{elevation} = 0.92\ \text{Nm} \times 4 = 3.68\ \text{Nm}$$

- **Azimuth Axis**:

  For the azimuth axis, a gear ratio of **5:1** is implemented. This results in an effective output torque of:

  $$T_{azimuth} = 0.92\ \text{Nm} \times 5 = 4.6\ \text{Nm}$$

When compared against the calculated torque requirements for the system, which are **2.45 Nm for the elevation axis** and **3.67 Nm for the azimuth axis**, it is clear that the geared servomotors provide more than sufficient torque capacity.

Required vs. Available Torque:

- Elevation: 2.45 Nm (required) vs. 3.68 Nm (available)
- Azimuth: 3.67 Nm (required) vs. 4.6 Nm (available)

This margin ensures reliable operation under normal loading conditions, while also providing additional tolerance to account for unforeseen loads, mechanical friction, or minor misalignments. Therefore, the chosen servomotors, when paired with the specified gear reductions, are **well-suited for the intended application**.

CHAPTER 4: SYSTEM ARCHITECTURE

4.1 DESIGN AND FABRICATION

4.1.1 SIDE VIEW

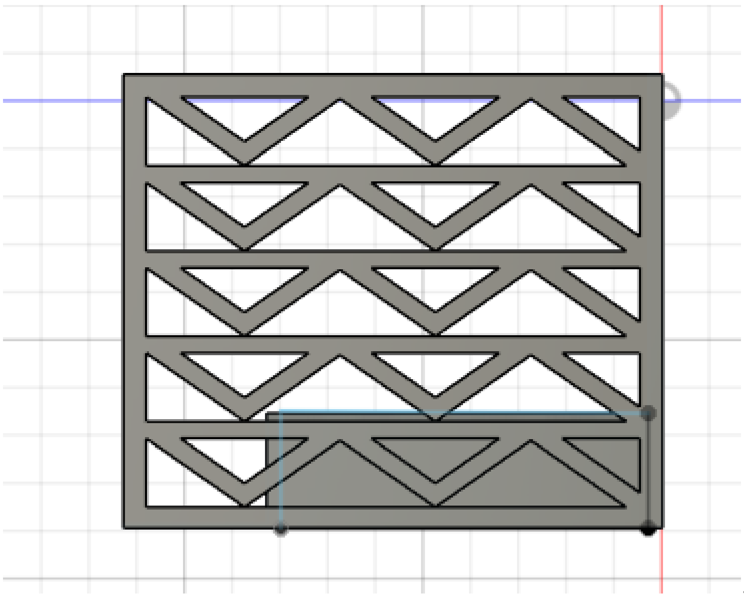

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Fig no. 4.1.1 Side view

4.1.2 FRONT VIEW

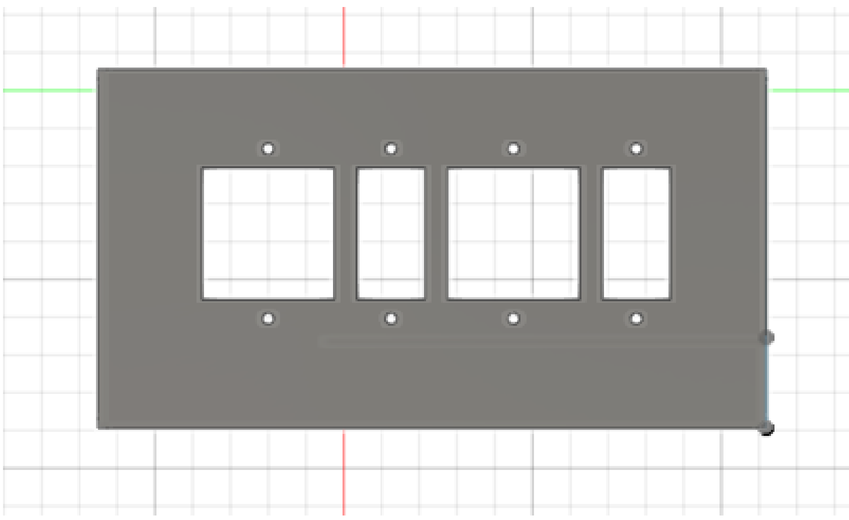

Fig no. 4.1.2 Front view

4.1.3 TOP VIEW

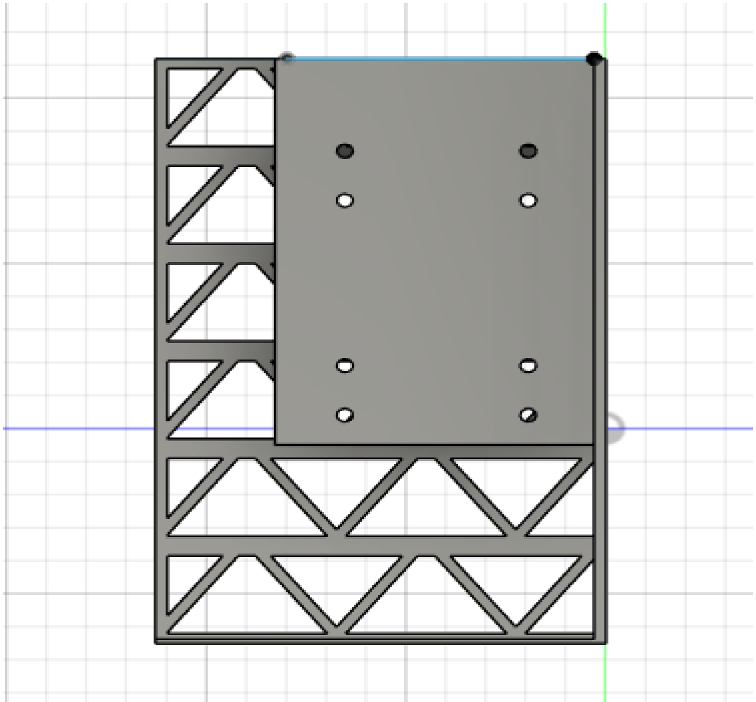

Fig no. 4.1.3 Top view

4.1.4 ISOMETRIC VIEW

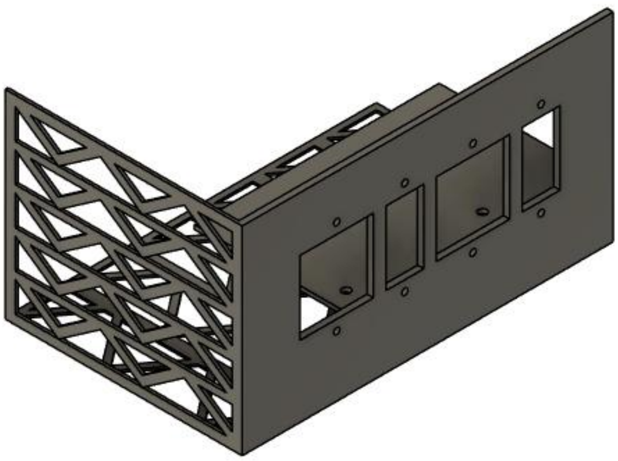

Fig no. 4.1.4 Isometric view

4.1.5 DIMENSIONS

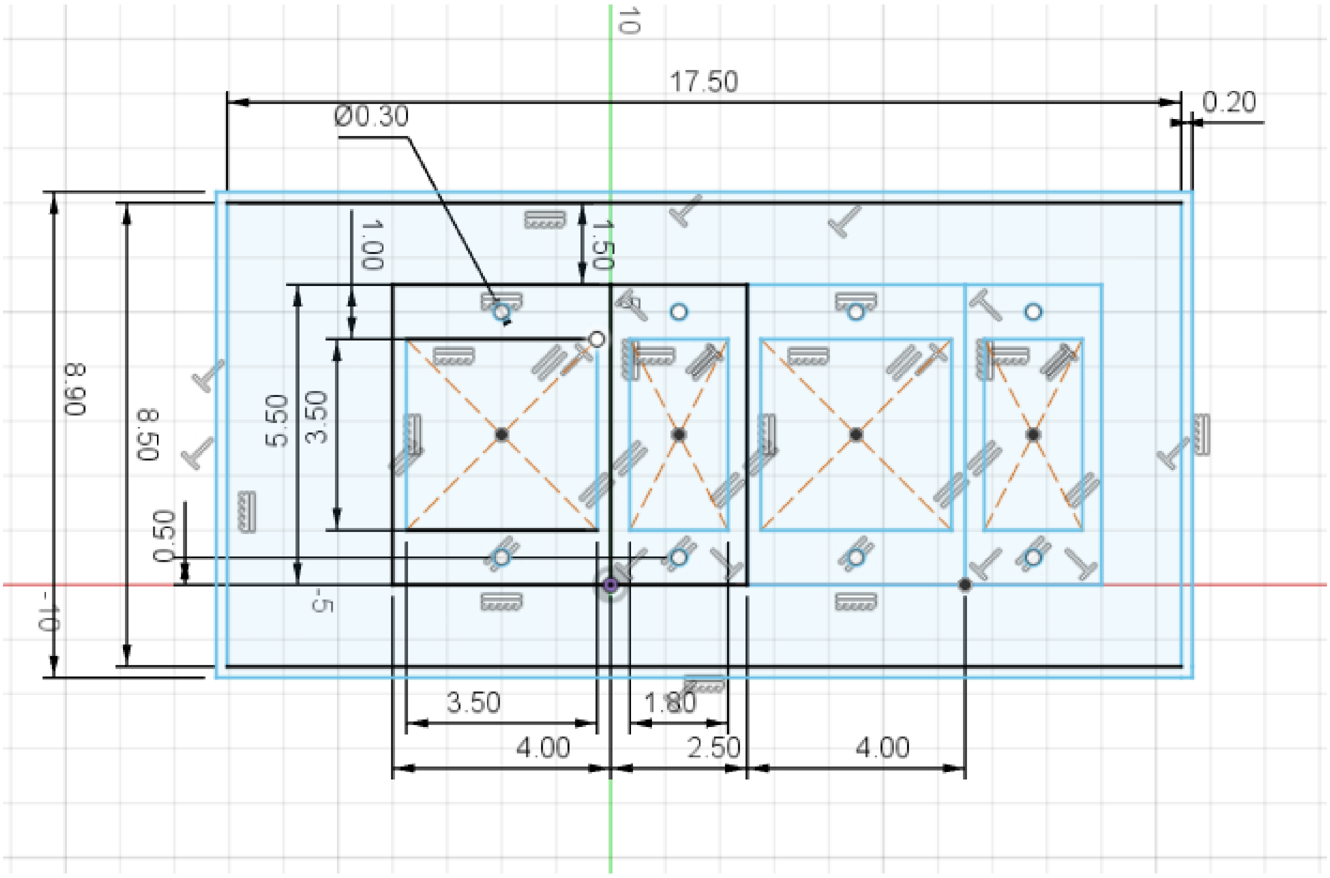

Fig no. 4.1.5 Dimensions

4.2 SCHEMATIC DIAGRAMS AND CIRCUIT DIAGRAM

4.2.1 SCHEMATIC DIAGRAM OF ESP32 MICROCONTROLLER

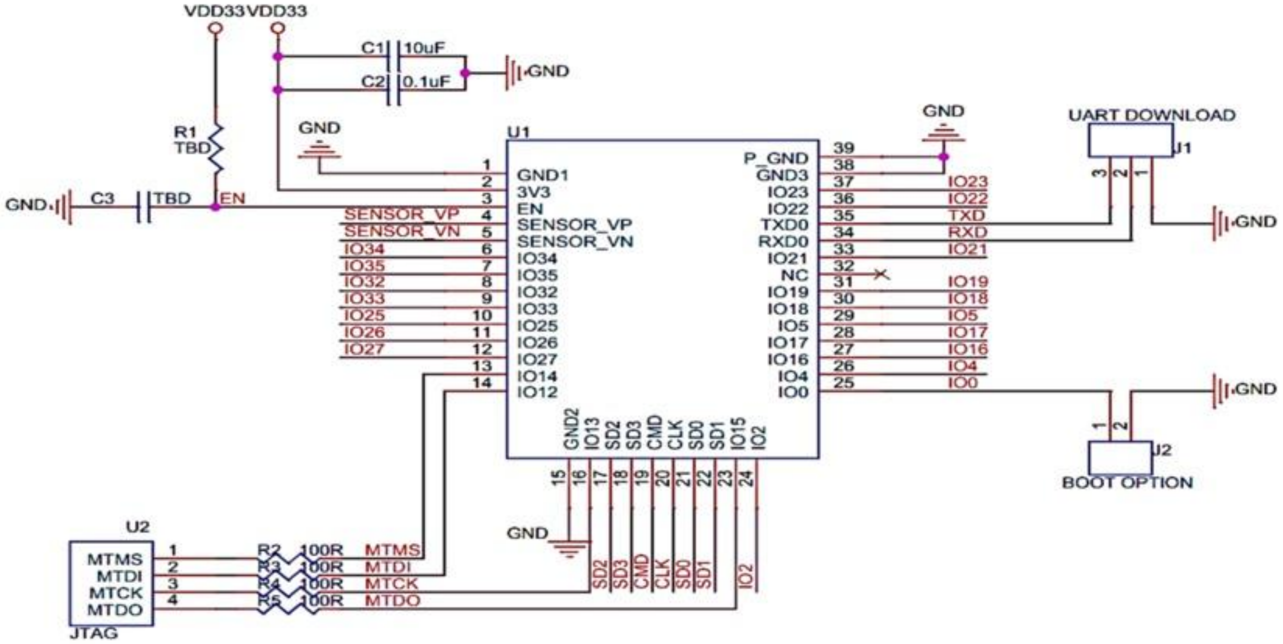

Fig no. 4.2.1 ESP32 – Schematic Diagram

4.2.2 SCHEMATIC DIAGRAM OF VOLTAGE SENSOR ZMPT101B

Structural parameters:

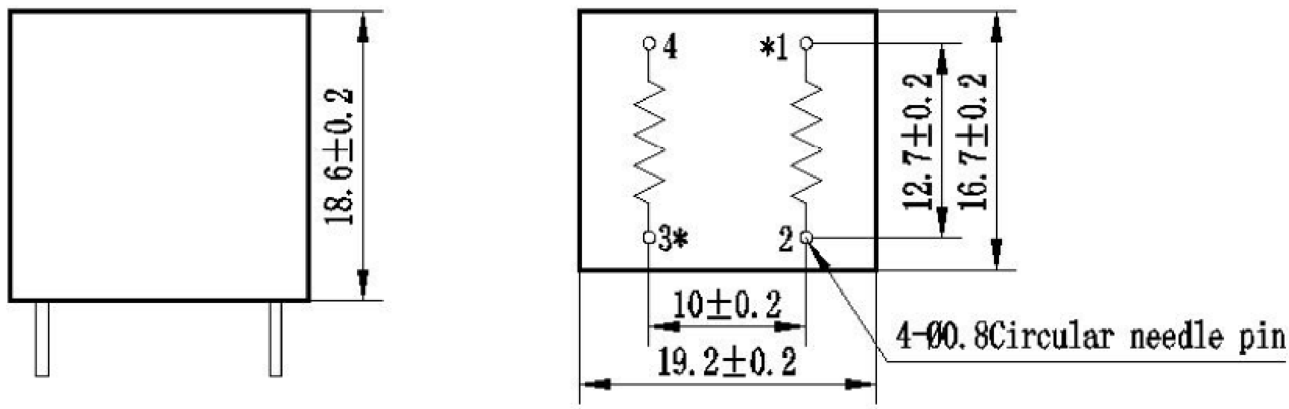

Fig no. 4.2.2 Voltage Sensor – Schematic Diagram

4.2.3 SCHEMATIC DIAGRAM OF CURRENT TRANSFORMER

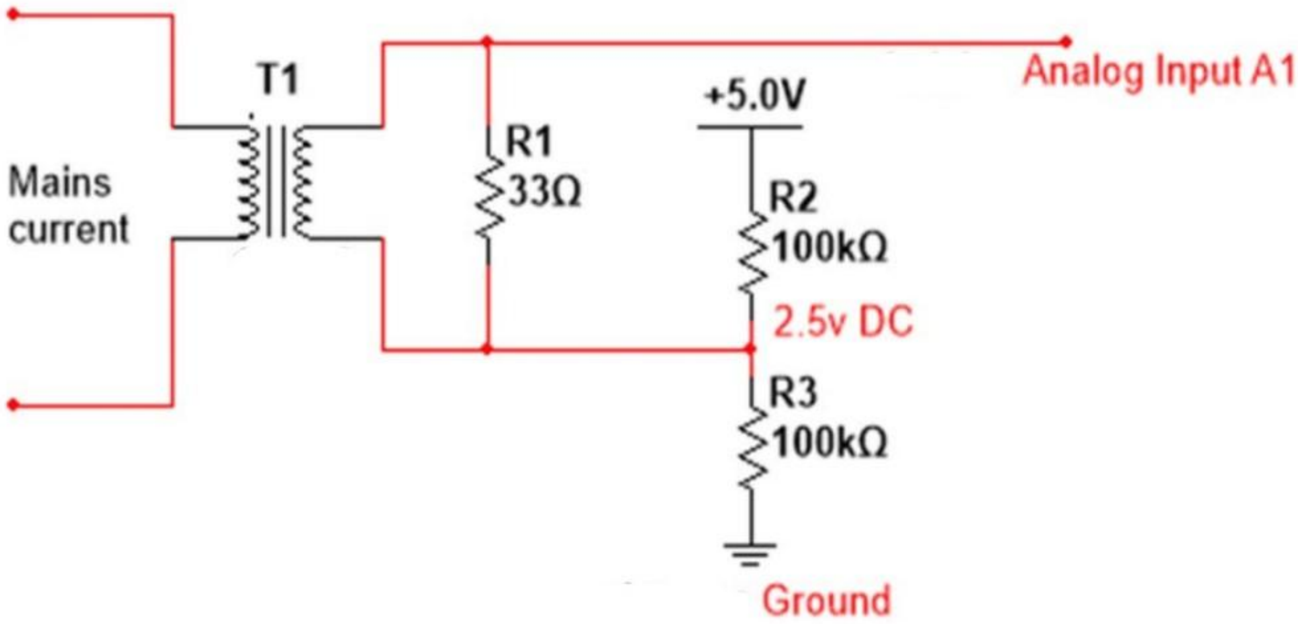

Fig no. 4.2.3 Current Transformer - Schematic Diagram

4.2.4 CIRCUIT DIAGRAM

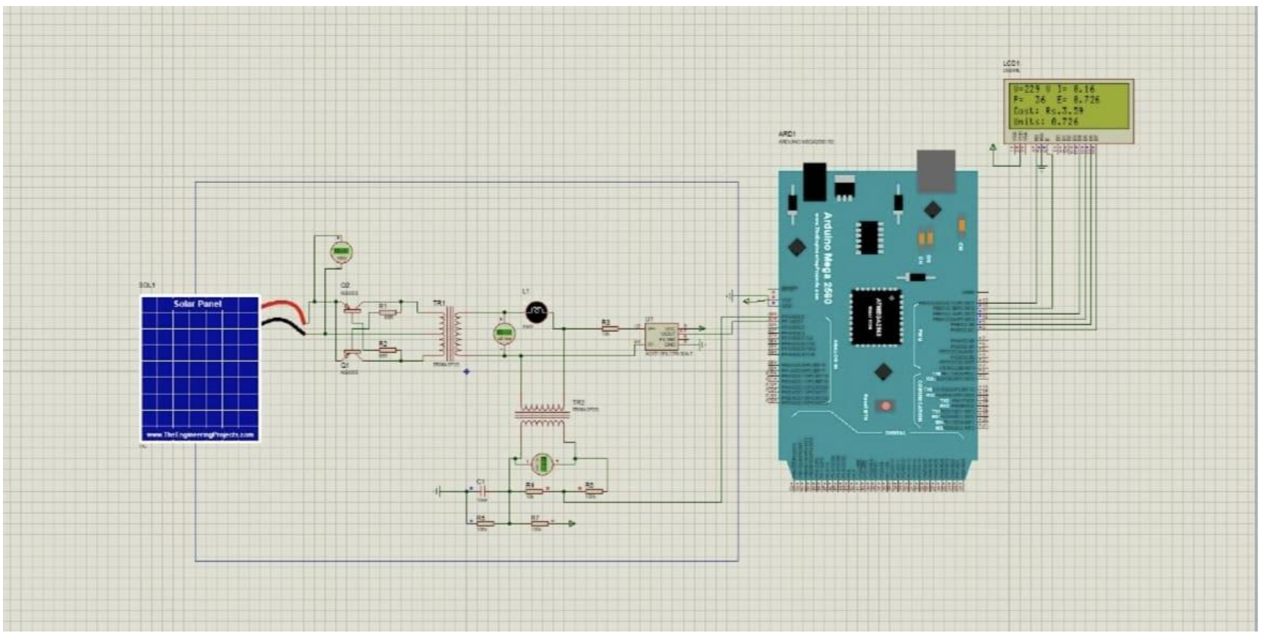

Fig no. 4.2.4 Circuit Diagram

CHAPTER 5: HARDWARE AND SOFTWARE IMPLEMENTATION

5.1 INTRODUCTION

This chapter presents the practical implementation of the proposed real-time energy consumption tracking system in a microgrid. It details the hardware components used, their integration, and the software developed for real-time measurement, processing, and visualization of energy data. The combination of hardware and software ensures the system’s ability to accurately monitor consumption, track solar energy generation, and provide both local and remote accessibility.

5.2 HARDWARE IMPLEMENTATION

The hardware forms the backbone of the system, comprising sensors, microcontrollers, display units, and actuation mechanisms. Each component was carefully selected to achieve accuracy, reliability, and affordability.

The main hardware components used are:

- ESP32 Microcontroller
- Current Transformer (CT) Sensor
- Voltage Sensor (ZMPT101B)
- LCD Display (20×4 with I2C)

5.2.1 ESP32 MICROCONTROLLER

The ESP32 is a low-cost, high-performance microcontroller with built-in Wi-Fi and Bluetooth, making it ideal for IoT applications. In this project, it acquires real-time data from CT and voltage sensors, processes it to calculate power, energy, and cost, and displays results locally on an LCD and remotely via a web dashboard. With efficient processing, scalability, and low power consumption, the ESP32 ensures reliable monitoring and serves as an excellent choice for smart energy tracking in microgrid applications.

Fig no. 5.2.1 ESP32

Fig no. 5.2.2 ESP32

5.2.2 CURRENT TRANSFORMER(CT) SENSOR

The Current Transformer (CT) is used to safely measure AC by stepping it down to a manageable value. In this project, it monitors appliance current without direct contact with high-voltage lines, ensuring safety and isolation. The CT output is converted into a measurable voltage using a burden resistor and conditioning circuit, which is then fed to the ESP32 for real-time power and energy calculations. Its accuracy, safety, and low cost make it essential for appliance-level energy monitoring.

Fig no. 5.2.3 Current Transformer

5.2.3 VOLTAGE SENSOR (ZMPT101B)

The Voltage Sensor (ZMPT101B module) is used to measure AC voltage in the system with high accuracy and safety. It provides galvanic isolation, ensuring that the ESP32 is protected from high voltages while still receiving accurate readings. In this project, the voltage sensor continuously monitors the supply voltage, and its output is fed into the ESP32 for calculating real-time power and energy consumption along with the CT readings. Its compact size, reliability, and precision make it well-suited for household and microgrid energy monitoring applications.

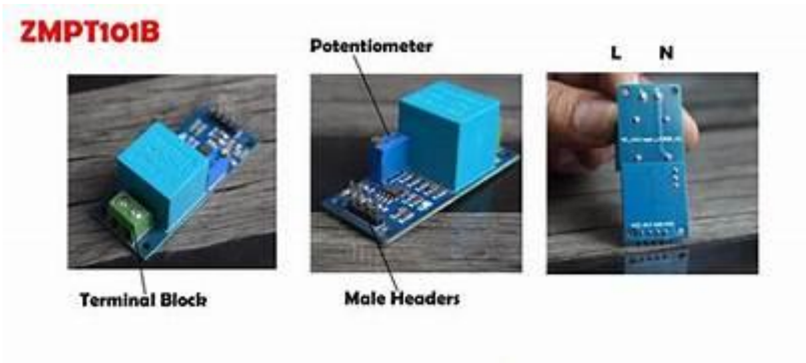

Fig no. 5.2.4 Voltage Sensor

5.2.4 LCD DISPLAY (20×4 WITH I2C)

The **20×4 LCD display with I2C interface** is used to show real-time outputs such as voltage, current, power, energy, and cost in a clear format. The I2C module reduces wiring complexity and saves ESP32 GPIO pins, making integration easier. With four rows and twenty columns, the display can present multiple parameters simultaneously, allowing users to conveniently monitor energy usage on-site. Its low power consumption, simplicity, and cost-effectiveness make it well-suited for embedded energy monitoring applications.

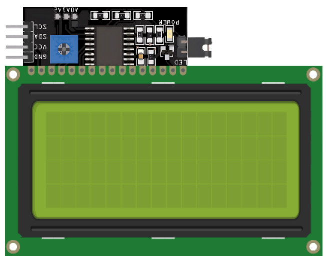

Fig no. 5.2.5 LCD Display20x4

5.3 SOFTWARE IMPLEMENTATION

5.3.1 PROGRAMMING ENVIRONMENT

The software was developed using the **Arduino IDE**, which provides a simple and effective environment for coding, compiling, and uploading programs to the ESP32 microcontroller. The programming was carried out in **Embedded C++**, with supporting libraries for I2C communication, Wi-Fi connectivity, and LCD interfacing. Simulation and preliminary validation of the program logic were performed in Proteus, ensuring that the design met the requirements before hardware implementation.

5.3.2 ALGORITHM

The software follows a structured algorithm to ensure real-time operation. First, the sensors are initialized, and calibration constants are set. The ESP32 then continuously samples analog signals from the CT and voltage sensors through its ADC. These raw values are converted into meaningful electrical parameters by applying scaling factors. Once current and voltage are determined, the program calculates power and energy consumption, followed by cost estimation. The processed values are displayed on the LCD and transmitted wirelessly to the web dashboard. The program also runs in a loop, ensuring uninterrupted monitoring. A flowchart was developed to visualize this process, showing data acquisition, computation, display, and transmission steps.

5.3.3 SENSOR DATA PROCESSING

The raw outputs of the **CT sensor** and **ZMPT101B voltage sensor** are analog signals. The ESP32 uses its inbuilt **Analog-to-Digital Converter (ADC)** to digitize these values. To improve accuracy, the program applies calibration constants derived during testing. The data is filtered using averaging techniques to minimize noise and fluctuations. These processed values provide the basis for calculating real-time power and energy.

5.3.4 PROGRAM

```
#include <WiFi.h>
#include <HTTPClient.h>
#include <ArduinoJson.h>

// WiFi
const char* ssid = "";
const char* password = "";

// Backend API
const char* serverUrl = "";
// Sensor pins
const int PIN_V1 = 34;   // ZMPT101 for Load 1
const int PIN_I1 = 35;    // CT for Load 1
const int PIN_V2 = 32;  // ZMPT101 for Load 2
const int PIN_I2 = 33;   // CT for Load 2

// Calibration constants
const float VOLTS_CAL = 230.0 / 1000.0;
const float AMPS_CAL  = 5.0 / 1000.0;
float energy1_Wh = 0.0, energy2_Wh = 0.0;
unsigned long lastPost = 0;
void connectWiFi() {
  WiFi.begin(ssid, password);
}
int readADC(int pin) {
  int s = 0;
  for (int i = 0; i < 8; i++) s += analogRead(pin);
  return s / 8;
```

```
}
void setup() {
  Serial.begin(115200);
  connectWiFi();
}
void loop() {
  const int N = 200;
  float sumV1=0, sumI1=0, sumP1=0;
  float sumV2=0, sumI2=0, sumP2=0;

  int vOffset1 = readADC(PIN_V1);
  int iOffset1 = readADC(PIN_I1);
  int vOffset2 = readADC(PIN_V2);
  int iOffset2 = readADC(PIN_I2);

  unsigned long start = micros();
  for (int n=0; n<N; n++) {
    int rawV1 = analogRead(PIN_V1);
    int rawI1 = analogRead(PIN_I1);
    int rawV2 = analogRead(PIN_V2);
    int rawI2 = analogRead(PIN_I2);

    float v1 = (rawV1 - vOffset1) * VOLTS_CAL;
    float i1 = (rawI1 - iOffset1) * AMPS_CAL;
    float v2 = (rawV2 - vOffset2) * VOLTS_CAL;
    float i2 = (rawI2 - iOffset2) * AMPS_CAL;

    sumV1 += v1*v1; sumI1 += i1*i1; sumP1 += v1*i1;
    sumV2 += v2*v2; sumI2 += i2*i2; sumP2 += v2*i2;
```

```
  delayMicroseconds(1000); // ~1kHz
 }
 unsigned long duration = micros() - start;
 float seconds = duration / 1e6;
 float Vrms1 = sqrt(sumV1/N);
 float Irms1 = sqrt(sumI1/N);
 float P1 = sumP1/N;
 energy1_Wh += P1 * (seconds/3600.0);
 float Vrms2 = sqrt(sumV2/N);
 float Irms2 = sqrt(sumI2/N);
 float P2 = sumP2/N;
 energy2_Wh += P2 * (seconds/3600.0);
 if (millis() - lastPost > 5000) {
  lastPost = millis();
  if (WiFi.status() == WL_CONNECTED) {
   HTTPClient http;
   http.begin(serverUrl);
   http.addHeader("Content-Type", "application/json");
   StaticJsonDocument<400> doc;
   doc["deviceId"] = "ESP32_1";  // Change for 2nd ESP32
   JsonArray loads = doc.createNestedArray("loads");

   JsonObject l1 = loads.createNestedObject();
   l1["loadId"] = 1;
   l1["voltage"] = Vrms1;
   l1["current"] = Irms1;
   l1["power"] = P1;
   l1["energy_wh"] = energy1_Wh;

   JsonObject l2 = loads.createNestedObject();
```

```
      l2["loadId"] = 2;
      l2["voltage"] = Vrms2;
      l2["current"] = Irms2;
      l2["power"] = P2;
      l2["energy_wh"] = energy2_Wh;

      String json;
      serializeJson(doc, json);
      int httpResponseCode = http.POST(json);
      Serial.printf("POST -> %d, data: %s\n", httpResponseCode, json.c_str());
      http.end();
    }
  }
}

// Function to calculate cost based on kWh
float calculateCost(float kWh) {
  if (kWh <= 100) return 0.00;
  else if (kWh <= 200) return (kWh - 100) * 2.35;
  else if (kWh <= 400) return (100 * 2.35) + ((kWh - 200) * 4.70);
  else if (kWh <= 500) return (100 * 2.35) + (200 * 4.70) + ((kWh - 400) * 6.30);
  else if (kWh <= 600) return (100 * 2.35) + (200 * 4.70) + (100 * 6.30) + ((kWh - 500) * 8.40);
  else if (kWh <= 800) return (100 * 2.35) + (200 * 4.70) + (100 * 6.30) + (100 * 8.40) + ((kWh - 600) * 9.45);
  else if (kWh <= 1000) return (100 * 2.35) + (200 * 4.70) + (100 * 6.30) + (100 * 8.40) + (200 * 9.45) + ((kWh - 800) * 10.50);
  else return (100 * 2.35) + (200 * 4.70);
}
```

5.3.5 POWER, ENERGY, AND COST CALCULATION

The system measures RMS voltage using the ZMPT101B voltage sensor and RMS current using the current transformer (CT) sensor. These values are processed by the ESP32, and the apparent power (P) is calculated as:

$$\mathbf{P = V_{rms} \times I_{rms}\ (Watts)}$$

The energy consumption (E) is then obtained by integrating power with respect to time. Since the ESP32 operates in milliseconds, the elapsed time is converted into hours, and energy is calculated in kilowatt-hours (kWh) as:

$$\mathbf{E(kWh) = \frac{P(W) \times \Delta t(ms)}{3.6 \times 10\text{^}9}}$$

The calculated energy values are accumulated continuously, providing both instantaneous and cumulative consumption data.

For cost estimation, a slab-based tariff structure is implemented to simulate real-world billing. The first 100 units are free of cost, while subsequent slabs are charged at increasing rates: ₹2.35/unit for 101–200 units, ₹4.70/unit for 201–400 units, ₹6.30/unit for 401–500 units, ₹8.40/unit for 501–600 units, ₹9.45/unit for 601–800 units, and ₹10.50/unit for 801–1000 units. This structure translates technical energy readings into meaningful monetary cost, thereby improving user awareness.

Example:

Consider a load drawing 3 A at 230 V.

$$P = 230 \times 3 = 690 \text{ W}$$

If this load operates for 2 hours:

$$E = 690 \times 2 = 1380 \text{ Wh} = 1.38 \text{ kWh}$$

Since the consumption is below 100 units, the cost = ₹0.00 (free slab).

If the same load runs for 120 hours, total energy consumed will be:

$$E = 690 \times 120 = 82{,}800 \text{ Wh} = 82.8 \text{ kWh}$$

Here, the cost is still ₹0.00 (within the free first 100 units).

If extended to 350 hours:

$$E = 690 \times 350 = 241{,}500 \text{ Wh} = 241.5 \text{ kWh}$$

Now, the cost will be:

- First 100 units → Free
- Next 100 units (101–200) → 100 × ₹2.35 = ₹235
- Remaining 41.5 units (201–241.5) → 41.5 × ₹4.70 ≈ ₹195.05

Total Cost ≈ ₹430.05

This example illustrates how the system calculates power, energy, and electricity cost in real time, giving users both technical and financial insights into their energy consumption.

5.3.6 Display and IoT Integration

For local monitoring, the results are shown on a 20×4 LCD display through I2C communication, reducing wiring complexity and conserving ESP32 GPIO pins. Simultaneously, the ESP32's inbuilt Wi-Fi module enables IoT integration by transmitting data to a web-based dashboard. The dashboard provides real-time access to voltage, current, power, energy, and cost values from remote locations. It also supports graphical visualization of usage trends, allowing users to better understand consumption patterns.

5.3.7 Error Handling and Filtering

To maintain accuracy, the software implements noise filtering techniques such as averaging multiple ADC samples before processing. Error-handling routines were added to manage situations like missing sensor inputs, unstable Wi-Fi connections, or sudden fluctuations in readings. This ensures the system continues to provide stable and reliable output under varying conditions.

5.3.8 Simulation and Testing

Before hardware implementation, the software logic was tested using Proteus simulation to verify circuit behavior and output accuracy. The Arduino IDE's Serial Monitor was used extensively for debugging, helping validate sensor readings and computational results. After successful simulation, the program was uploaded to the ESP32 and tested with actual hardware. The system produced stable readings, confirming the accuracy of calculations and the effectiveness of data display on both LCD and the web dashboard.

CHAPTER 6: COST ESTIMATION

6.1 ESTMATION TABLE

In this project, the Bill of Materials (BOM) outlines the electronic components and modules required for the design and implementation of the real-time energy consumption tracking system. It includes the ESP32 microcontroller, CT and voltage sensors for data acquisition, LCD display for local monitoring, servo motors and solar panel for renewable integration, along with supporting elements such as power supply units, connectors, and wiring. The BOM not only helps estimate the overall project cost but also ensures transparency, proper resource planning, and easy replication of the system.

S.No.	Components	Quantity	Price (₹)	Amount (₹)
1	CT SENSOR	2	465.00	930.00
2	M-F JUMPER	10	1.50	15.00
3	M-M JUMPER	10	1.50	15.00
4	F-F JUMPER	10	1.50	15.00
5	MB 102 BREAD BOARD	1	67.00	67.00
6	DOUBLE SIDE TAPE	1	10.00	10.00
7	ZMPT101B AC VOLTAGE SENSOR MODULE	2	135.00	270.00
8	2004-LCD-BLUE (20X4)	1	255.00	255.00
9	I2C FOR 16^2 LCD MODULE	1	95.00	95.00
10	10 MICRO FARAD CAPACITOR	2	2.00	4.00
11	1K OHM RESISTOR	4	0.25	1.00
12	4.7K RESISTOR	4	0.25	1.00
13	ESP CABLE	1	30.00	30.00
14	ESP32 MICROCONTROLLER	1	350.00	350.00
15	SWITCH AND PLUG POINT	2	70.00	140.00
TOTAL		52		2,198

CHAPTER 7: FUTURE SCOPE

7.1 Applications of Real-Time Energy Consumption System in a Microgrid

Real-Time Energy Monitoring

- Provides instant measurement of energy consumption across all microgrid components, helping operators understand usage patterns and trends.

Load Management

- Identifies peak demand periods and enables dynamic load balancing, preventing overloads and ensuring stable power supply.

Integration with Renewable Energy Sources

- Tracks energy generation from solar panels, wind turbines, and battery storage systems, enabling efficient usage of renewable resources.

Energy Billing and Auditing

- Facilitates accurate billing based on actual consumption and provides data for detailed energy audits in residential, commercial, and industrial setups.

Smart Grid Control

- Supports demand response mechanisms, automated switching, and grid optimization to enhance the reliability and efficiency of the microgrid.

Fault Detection and Maintenance

- Detects abnormal consumption patterns, equipment faults, or short circuits in real time, allowing for preventive maintenance and minimizing downtime.

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7.2 Advantages of Real-time Energy Consumption System in a Microgrid

1. Real-Time Data Availability

   Provides instant information about energy consumption, allowing immediate corrective action and enhanced operational control.

2. Cost Savings

   Reduces energy wastage and lowers electricity bills by optimizing load management and consumption patterns.

3. Improved Reliability

   Continuous monitoring ensures stable and uninterrupted energy supply by detecting issues before they escalate.

4. Supports Renewable Energy Integration

   Optimizes the use of solar, wind, or other renewable sources by tracking generation and matching it with consumption in real time.

5. Scalability

   Can easily be scaled to accommodate additional buildings, loads, or microgrids without significant infrastructure changes.

6. Environmental Benefits

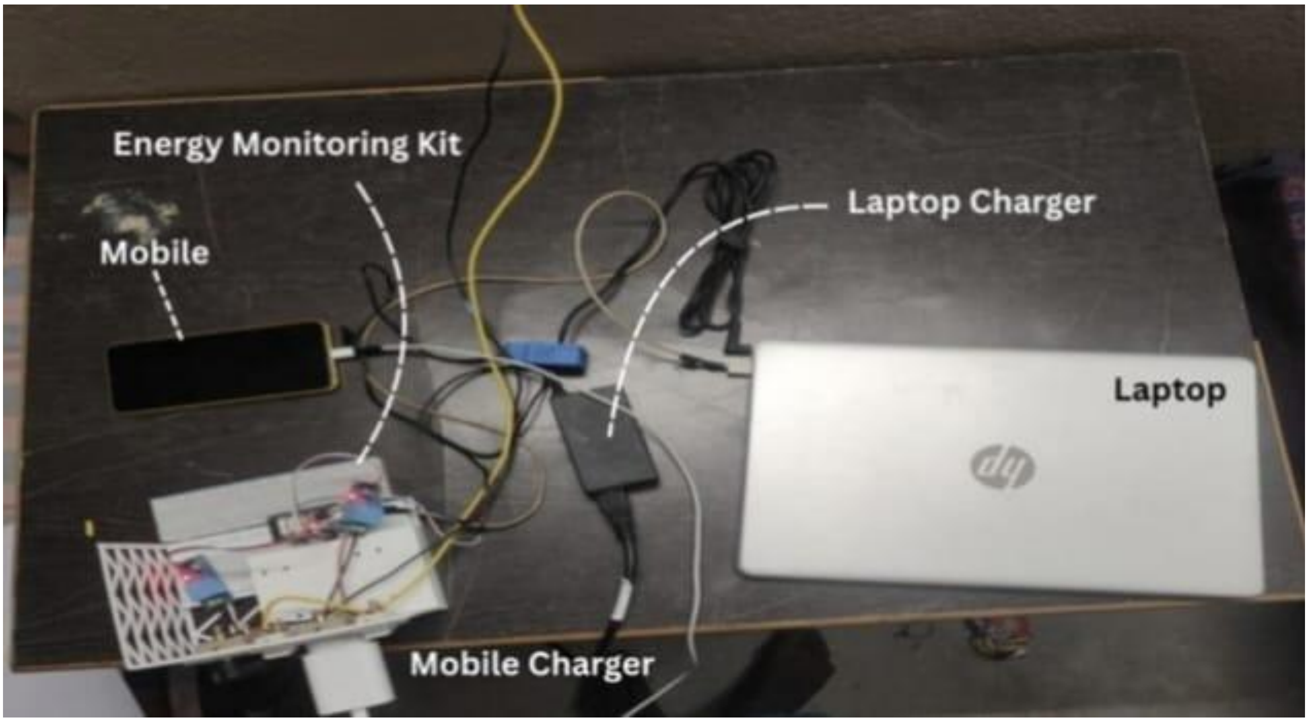
   Promotes energy conservation and reduces greenhouse gas emissions by minimizing unnecessary consumption.

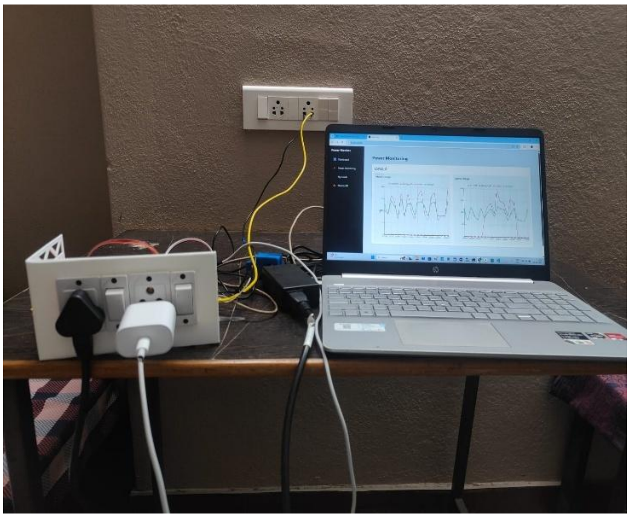
7. Predictive Maintenance

   Early detection of system anomalies allows for proactive maintenance, reducing downtime and repair costs

CHAPTER 8: EXPERIMENT SETUP

8.1 HARDWARE SETUP





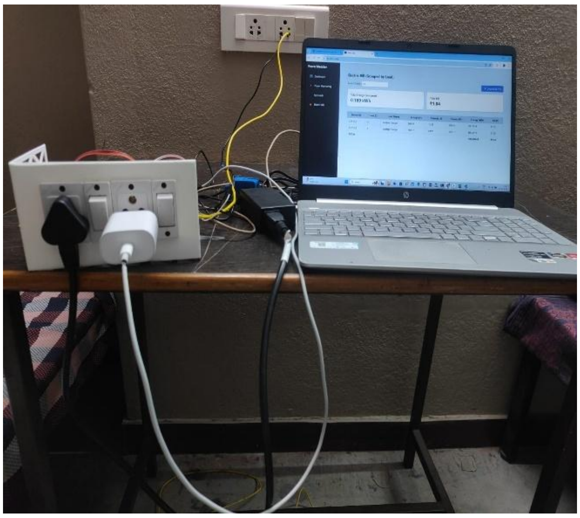


Fig no. 8.1.4 Final prototype setup

8.2 Visual overview of our website

Fig no 8.2.1 Power Monitoring Dashboard

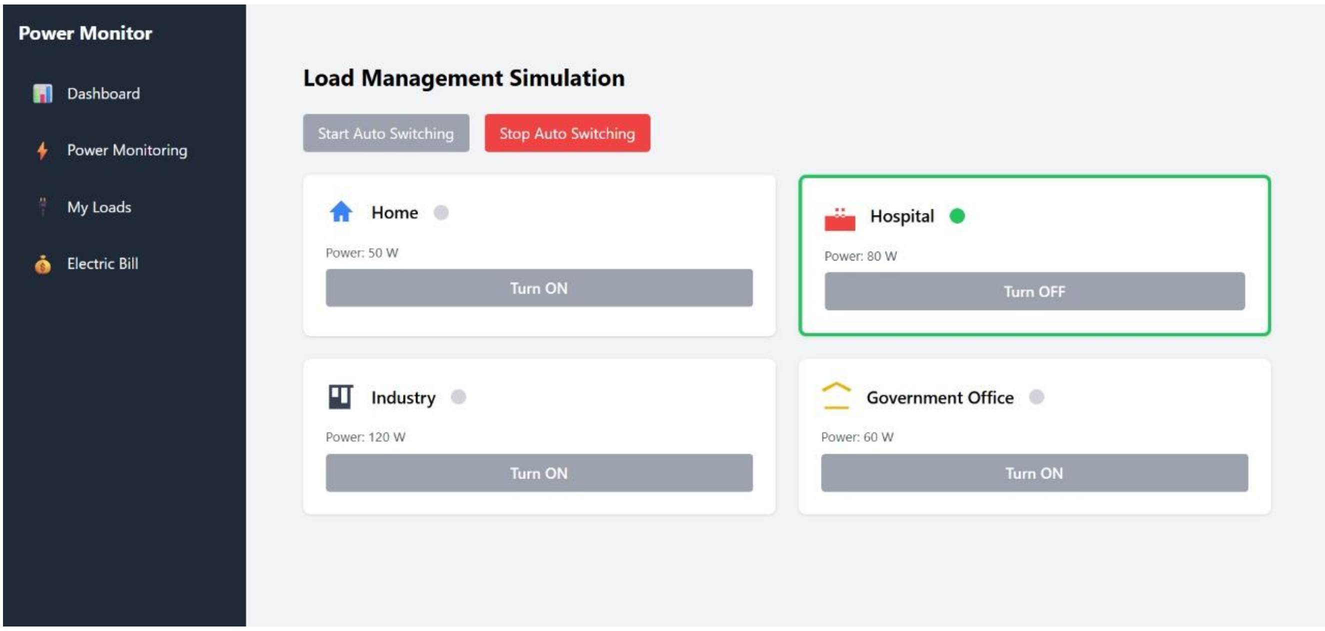


Fig no. 8.2.2 Load Management Simulation

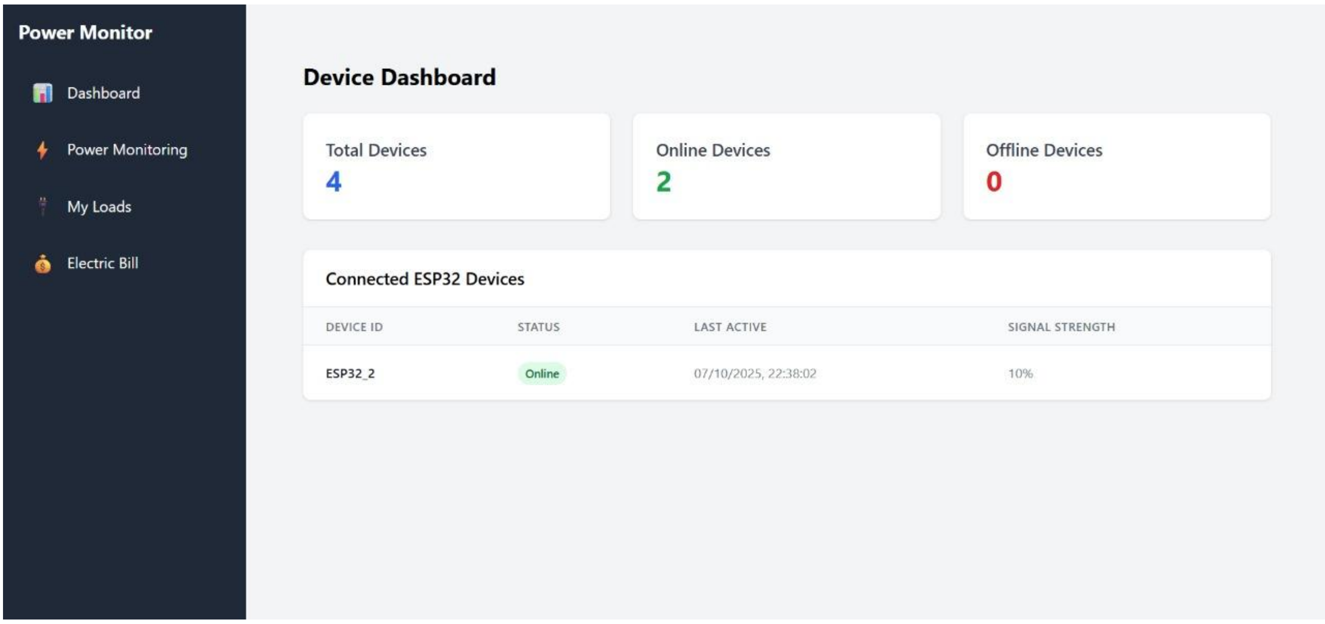


Fig no. 8.2.3 Dashboard Showing Devices Connected

Device ID	Load ID	Load Name	Voltage (V)	Current (A)	Power (W)	Energy (Wh)	Bill (Rs)
ESP32_2	3	Mobile Charger	145.48	0.853	124.12	33.27943	0.18
ESP32_2	4	Laptop Charger	160.72	0	0	20.36034	0.11
TOTAL	-	-	-	-	-	53.63977	0.3

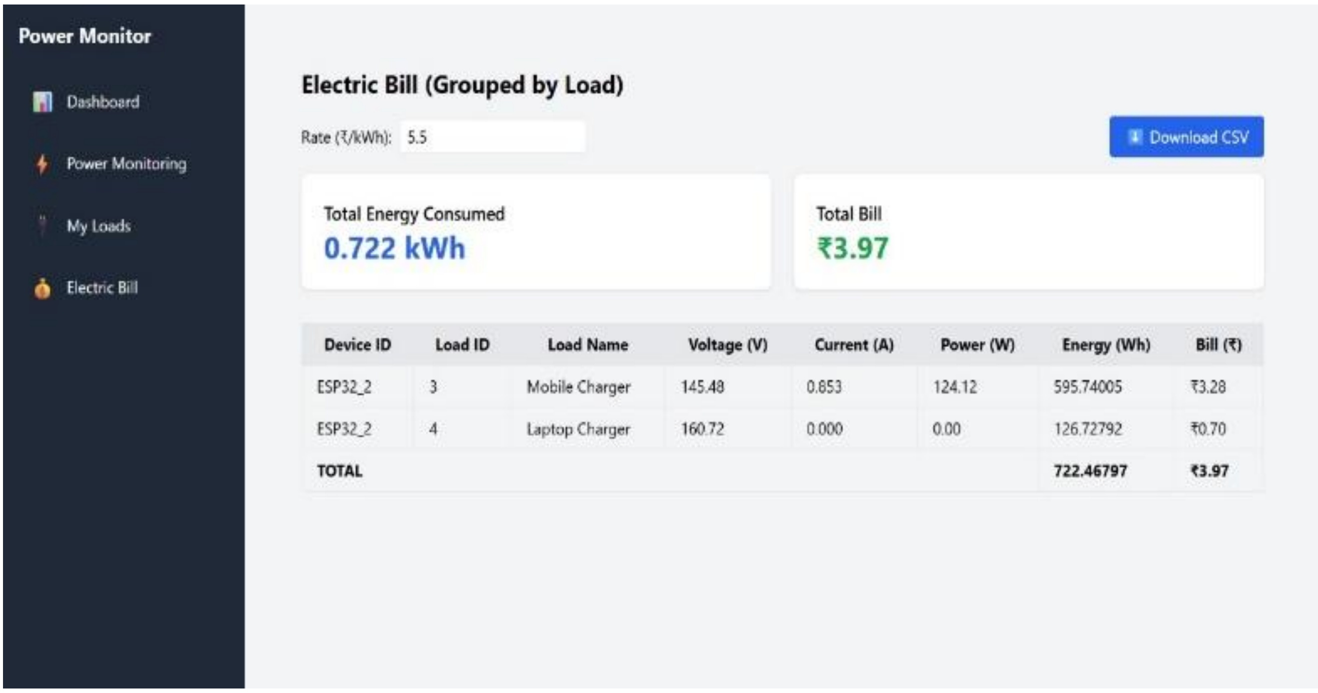


Fig no. 8.2.4 Electric Bill (Grouped by Load)

- Representation in Web Page and CSV File

8.2.1 Explanation of Energy Billing and Consumption Analysis Interface

Fig 8.2.1: Power Monitoring Dashboard

This page displays real-time graphical representations of key electrical parameters such as voltage, current, power, and energy (in watt-hours) for multiple connected loads. The dashboard continuously updates readings from the sensors interfaced with the ESP32 microcontroller. In this example, the *Mobile Charger* and *Laptop Charger* loads are monitored simultaneously. The plotted graphs help visualize variations in voltage, power, and current, enabling users to analyze consumption patterns, identify peak loads, and detect abnormalities efficiently.

Fig 8.2.2: Load Management Simulation

This interface demonstrates both automated and manual control of different loads within the simulated microgrid environment. Loads such as *Home*, *Hospital*, *Industry*, and *Government Office* are displayed with their respective power ratings. The "Start Auto Switching" feature activates an intelligent load management mechanism based on priority levels and available power, whereas manual control options ("Turn ON" / "Turn OFF") allow the user to override automatic operations when necessary. This setup enhances energy distribution efficiency and supports demand-side management, ensuring reliable and optimized microgrid performance.

Fig 8.2.3: Electric Bill (Grouped by Load)

This page provides a detailed analysis of energy consumption and cost estimation as per *TNEB (Tamil Nadu Electricity Board)* tariff standards. It calculates real-time voltage, current, power, and energy values (in Wh and kWh) for each connected load. The system computes the total bill amount dynamically using the user-defined tariff rate (₹/kWh), ensuring accurate and regionally compliant billing. Additionally, the dashboard enables users to download consumption and billing data in CSV format, facilitating verification, reporting, and record maintenance.

CONCLUSION

The project titled *"Design and Fabrication of Real-Time Energy Consumption Tracking System in a Microgrid"* was successfully conceptualized, designed, and implemented with the objective of addressing the limitations of conventional energy billing systems. Traditional electricity meters only provide cumulative readings, which fail to give insights into appliance-wise usage, peak demand periods, or cost distribution. By developing a low-cost and scalable IoT-based solution, this work has demonstrated how real-time monitoring and cost analysis can empower users to make informed decisions, reduce energy wastage, and promote sustainable practices.

The hardware implementation integrated an ESP32 microcontroller, current transformer (CT) sensor, and voltage sensor module (ZMPT101B) to acquire real-time parameters. The ESP32 was chosen for its inbuilt Wi-Fi capabilities, low power consumption, and scalability, which make it particularly suitable for IoT-based energy monitoring applications. The acquired data was processed to compute voltage, current, instantaneous power, cumulative energy usage, and cost estimation. For local monitoring, results were displayed on a 20×4 LCD with I2C interface, while the built-in Wi-Fi enabled data transmission to a web dashboard for remote access. A solar tracker using LDR sensors and servo motors was also implemented to optimize renewable energy capture, thereby increasing efficiency in microgrid applications.

The software implementation was carried out using the Arduino IDE, with coding in Embedded C++. Algorithms were developed for sensor calibration, data filtering, and accurate computation of electrical parameters. Power and energy calculations were validated through simulations in Proteus before being tested on hardware. The system successfully combined local display and remote web visualization, ensuring user-friendly accessibility. Error handling techniques and filtering methods were integrated to reduce sensor noise, making the readings reliable and stable.

Through experimental testing, the system proved capable of providing appliance-level monitoring with sufficient accuracy. Users could view detailed breakdowns of consumption, cost estimations, and identify high-power appliances contributing to higher bills. This enhanced transparency allows users to adopt better load management practices, such as shifting non-essential loads to off-peak hours or replacing inefficient devices. Additionally, the integration of the solar tracker further highlights the project's contribution to sustainable energy utilization, aligning it with global energy conservation goals.

The project supports several Sustainable Development Goals (SDGs), including SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). By providing a low-cost, scalable, and user-friendly solution, it addresses rising energy demands while promoting responsible consumption, making it suitable for households, institutions, and small-scale microgrids. Some limitations include sensor resolution affecting accuracy, ripple voltage from the 1000 µF capacitor, reliance on stable internet for remote monitoring, and limited load capacity. Future enhancements could involve cloud integration, mobile applications, predictive analysis, load forecasting, and smart grid features such as automated demand response and fault detection. Overall, the project demonstrates an innovative approach to energy monitoring by combining real-time data acquisition, IoT-based accessibility, and solar tracking, thereby improving transparency, efficiency, and energy awareness while laying a foundation for future smart energy management solutions.

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