IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.414 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 14, Issue 11, November 2026

DOI: 10.17148/IJIREEICE.2026.141109

IoT Smart Energy Meter with AI-Based Theft Detection and Power Analytics

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Abstract: With increasing demands in electrical energy, intelligent monitoring systems should be implemented to manage energy usage and identify abnormal energy consumption in domestic applications. This report presents an IoT smart energy meter which can detect energy theft, monitor leakage issues and provide power analytics using artificial intelligence (AI). The system uses a ESP32 microcontroller with PZEM-004T energy measurement module and ZMPT101B voltage sensor to monitor key electrical parameters such as voltage current power and energy. Data is transferred through Wi-Fi to the Firebase Realtime Database, providing real time monitoring capability along with historical data storage. An interactive user-friendly web dashboard provides live data, consumption analytics, remote relay control, estimated energy bills and downloadable reports with user login/logoff option. An alert system is produced if abnormal load conditions are detected, using a buzzer, dashboard alerts and a Telegram bot. The relay module gives the ability of remote operation for proposed system. Linear Regression algorithm is used to predict future energy consumption from historical data that is recorded. The system also contains an energy bill estimator which will take into account the user defined Gruha Jyothi unit allowances. Results have demonstrated that the system has successfully incorporated real time electrical monitoring, data management on the cloud, alerting capability, remote control and prediction of energy consumption into one system. This system therefore provides a way to monitor energy consumption within the home in a practical manner and encourages more informed energy consumption. Further technical advancements in future are required to make the system more efficient and reliable.

Keywords: Internet of Things (IoT), Smart Energy Meter, Electricity Theft Detection, Leakage Monitoring, ESP32, PZEM-004T, Firebase, Linear Regression, Energy Prediction.

I. INTRODUCTION

Electrical energy is an essential resource in domestic environments and hence managing and monitoring energy consumption effectively has become increasingly important. The combination of IoT, cloud computing, and AI can be used to provide real time monitoring, remote access, anomaly detection, and future energy consumption predictions. This project outlines a smart energy meter using the IoT technology with electricity theft detection, leakage monitoring, and power analysis using AI. The system uses the ESP32 microcontroller with PZEM-004T energy metering module and ZMPT101B voltage detection system to monitor essential electrical parameters. Data is stored on the cloud using the Firebase Realtime Database. Monitoring and notifications can be provided using the web dashboard and Telegram bot. Future energy consumption can be predicted using linear regression to aid in improving energy management in domestic environments using historical data.

1.1 Motivation of Work

There is increasing demand for electrical power in household applications. Conventional and regular meters only measure energy consumption. However, they may lack features such as real time monitoring, remote monitoring, alarm if there is an anomaly and prediction of future energy needs. IoT technology can be used to monitor electrical parameters and remotely view data using the cloud and web-based dashboards.

Further features include alarm functionality to inform the user if there are anomalies set up and remote relay control to easily switch the monitored supply. This could increase awareness of the user. AI can be used for analysation of past energy consumption and prediction of future consumption requirements. Using Linear Regression the system can predict future energy consumption. The system also takes into account of configurable allowances for Gruha Jyothi scheme of

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Karnataka, India which can help estimate bills based on the scheme. This project has been motivated by the desire to create an integrated system that can monitor electrical consumption in households. Alarms can be set if there are anomalies, the system can be monitored using the cloud and remotely controlled. The system can also monitor and undergo prediction for energy needs using AI.

1.2 Problem Statement and Challenges

Standard domestic energy meters will typically just measure and record the amount of electricity that has been consumed. They may well lack any kind of integrated capability for real time remote monitoring, detection of abnormal loads and the ability to forecast future consumption. Without a single integrated monitoring system in place, users will be at a disadvantage in terms of their ability to spot any unusual consumption, to be alerted to such events and to understand their own consumption. An integrated system is therefore required to provide monitoring of the electrical parameters, alerting on abnormal conditions, cloud based data access, remote control and energy analytics. The first of these is the accurate measurement of voltage, current, power and energy which will require appropriate sensors and suitable interfacing to the microcontroller. The detection of abnormal load conditions (i. e. those associated with electricity theft) will require appropriate detection logic and will need to be tested under a variety of different operating conditions. Similarly the monitoring of leakage will require appropriate sensing and will need to be validated in order to be able to distinguish actual leakage from normal load. Reliable communication between the ESP 32, the Firebase Realtime Database and the web dashboard is also required to ensure that the data is updated and notifications are received in a timely fashion. The ability to predict future consumption from historical data will also be required. This will be achieved using a Linear Regression model which will require consistent input data and appropriate evaluation to determine the level of reliability of the prediction. The system will also need to be capable of integrating all of these functions into a single platform, with the ability to operate the relay reliably, to provide monitoring that is responsive and to provide a user interface that is accessible.

1.3 Objective of Work

- Real Time Energy Monitoring and Detecting Electricity Theft: To design a smart energy meter that can monitor electrical parameters in real-time such as, voltage, current, consumption; detect abnormal load scenarios indicative of electricity theft and alert the user.
- Leakage Monitoring and Alert: To implement a Leakage monitor that can detect set leakage test conditions and trigger sound and remote alerts.
- AI Based Energy Prediction: To integrate an AI model with IoT connected energy data. The model will use Linear Regression as AI algorithm to determine future electricity consumption based on past consumption data.
- Monitoring using Cloud: To create a web-based dashboard to monitor data in real time using the Firebase Realtime Database. Historical data can also be viewed and analysed.
- Remote Switch and Notification: To allow remote switching of the monitored supply using the dashboard. A telegram bot will be used to notify about abnormal conditions of electricity happening in the residential areas.
- Electricity Bill Estimation: To create an Electricity Bill Estimation feature. This will include user configurable Gruha Jyothi Unit allowances. Reports can be generated and downloaded as PDF and CSV files.

II. LITERATURE REVIEW

1. “IoT-Based Smart Energy Meter with Real-Time Monitoring and Theft Detection Using Arduino and PZEM004T”
Authors: S. L. Nalbalwar, D. P. Jayaswal, S. M. Fule, and U. D. Meshram (IJERT, 2025)
With the increase in demand of electrical energy, there is a need for smart metering systems which can monitor the consumption and detect anomalies in the electricity usage. Traditional energy meters often do not provide much information and cannot provide constant remote monitoring. This paper discusses an IoT based Smart Energy Meter using Microcontroller and PZEM-004T Energy Measurement Module. This system measures the electrical parameters and provides access to this data. By connecting the Energy Measuring device with the communication device it makes it easier for the consumer to see their usage and can identify any suspicious changes in their load behavioural pattern. This project is also applicable to domestic scenarios as it uses simple hardware and real time electrical measurements. However, to ensure accurate detection of theft in this project the system must be able to identify any suspicious activity. This project aims to build upon this principle by using an ESP32, PZEM-004T, Firebase Realtime Database, Responsive Dashboard, Telegram Notifications, Remote Relay Control and Energy Prediction using Linear Regression.

2. “IoT Based Smart Energy Meter with Theft Detection”
Authors: Aniket Babar, Sujan Babaji, Somesh Pujeri, Vittal Kabburi, and Nirupad Nandanawad (*International Journal of Research Publication and Reviews*, Vol. 6, Issue 11, pp. 7170–7176, November 2025).

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This paper proposes the design of an IoT based smart energy meter to monitor the usage of electricity in real time. Linear Regression is used to analyze the consumer and distribution end smart meter readings to detect any electricity theft such as meter tampering, meter bypassing and direct line tapping. The prototype design includes an ATmega328P microcontroller and NodeMCU Wi-Fi module. The android application displays the amount of electricity consumed and bill amount. The system can also allow the user to control the electricity supply to each consumer remotely. This study highlights how IoT based communication can be implemented into a smart energy meter for theft detection and remote control. The concept has been expanded on by including the ESP32, Firebase Realtime Database, interactive web dashboard, Telegram notification, threshold-based detection of theft test and Linear Regression to predict energy consumption.

3. "An Efficient Electricity Theft Detection Based on Deep Learning"
Authors: Nada M. Elshennawy, Dina M. Ibrahim, and Ahmed M. Gab Allah (Scientific Reports, 2025)
This paper focuses on deep learning techniques that can be used to detect electricity theft using consumption data. Using techniques such as Convolutional Neural Networks (CNN) with Long Short-Term Memory (LSTM), abnormal graphical patterns in the electricity consumption can be recognised. Basic thresholds can never understand the complex relationships of the model. The study demonstrates the benefits of using intelligent algorithms to increase the accuracy of detecting electricity theft. The proposed project currently has alerts for electricity theft using controlled abnormal loads but in the future it can be trained as a classification model to identify whether the electricity consumption is suspicious.

4. "A Global Probabilistic Approach for Short-Term Forecasting of Individual Households Electricity Consumption"
Authors: Lola Botman, Jesus Lago, Thijs Becker, Koen Vanthournout, and Bart De Moor (Applied Energy, 2025)
This paper depicts accuracy of electricity monitoring can help with energy planning and cost estimation in residential and industrial regions. It presents a generic probabilistic forecasting methodology based on historical data to predict short term household electricity demand. A uniform forecasting method is used across several consumers rather than forecasting each individually. It accounts for varying demand patterns and allows uncertainty in forecasting. This study will be relevant to our proposed project as historical energy data is used to forecast future demand using Linear Regression. This study will allow us to make improvements in the future by comparing Linear Regression against advanced forecasting methods and seeing how accurate our forecasts are across different periods of time.

5. "A Smart Energy Monitoring System Using ESP32 Microcontroller"
Authors: Hala Jarallah El-Khozondar, Shady Y. Mtair, Khaled O. Qoffa, Omer I. Qasem, Ahmad H. Munyarawi, Yasser F. Nassar, Ehab H. E. Bayoumi, and Ahmed Abd El Baset Abd El Halim (e-Prime – Advances in Electrical Engineering, Electronics and Energy, 2024; Elsevier)
This paper proposes an IoT based energy monitoring system. The system makes use of an ESP32 microcontroller to monitor and measure various electrical parameters. With the aid of Wi-Fi connection, the system sends this data to allow users to easily view energy consumption. This shows that a cheap microcontroller can be used to monitor energy in real time and improve energy management in the home. The study shows the importance of having electrical measuring devices connected to communication systems. This research is relevant due to the fact that the proposed project also uses an ESP32 to monitor voltage, current, power and energy consumption. The proposed system also includes additional features such as Firebase integration, an interactive web dashboard, alerting via telegram, remote control of relays, alerting for theft and leakage tests, estimating bills and predicting energy with the use of Linear Regression.

6. "Artificial Intelligence for Energy Theft Detection in Distribution Networks"
Authors: Mileta Žarković and Goran Dobrić (Energies, 2024; MDPI)
This paper depicts the use of artificial intelligence to detect electricity theft and non-technical losses within distribution networks. Analysation using these techniques the electrical data and pinpoint any unusual consumption patterns. This paper shows that how intelligent analysis can help detect electricity theft and improve monitoring within distribution networks. The findings from this research are relevant to the project as it will be used to detect abnormal electricity usage. The proposed prototype would then alert the user using an OLED screen, web dashboard and Telegram notifications. However, this prototype does not use an AI classification model to detect electricity theft but rather uses controlled testing using load tests. This paper will provide the basis for future improvements in detection through machine learning and analysing real-life electricity consumption data.

7. "Leakage Current Detector and Warning System Integrated with Electric Meter"
Authors: Tsung-Hui Cheng, Chien-Hao Chen, Chien-Hung Lin, Bor-Horng Sheu, Chia-Hung Lin, and Wen-Ping Chen (Electronics, 2023; MDPI)

IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

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In this paper, a leakage-current detection and warning system integrated with an electric meter is introduced. It uses current transformer based sensing to detect the leakage current and evaluates the measurements under different testing conditions. The study emphasizes the requirement for strong sensation and warning systems for a much better electrical safety. This is relevant to the proposed project's leakage-monitoring feature that produces OLED warnings, buzzer alerts and Telegram notifications. However, the prototype needs to be further validated under the leakage-test condition using an appropriate sensing arrangement to confirm the actual detection of electrical leakage.

8. Electricity-Theft Detection for Smart Grid Security Using Smart Meter Data: A Deep-CNN Based Approach
Authors: Ejaz Ul Haq, Can Pei, Ruihong Zhang, Huang Jianjun, and Fiaz Ahmad (Energy Reports, 2023; Elsevier).
This paper presents a deep convolutional neural network (Deep-CNN) approach for detecting fraud. This works by analysation of electricity usage patterns to detect abnormal usage. The key benefit of this method is that it uses data driven techniques to identify non-technical losses in the electricity distribution system. This is relevant to our proposed project as it looks at detecting anomalous electricity usage. We have not used the trained Deep-CNN model to detect fraud but demonstrated how we can detect fraud within our project. This has given us a basis for future improvements as the paper looks at using Machine Learning techniques to evaluate how well fraud can be detected based on real electricity usage data.

III. PROPOSED DESIGN AND METHODOLOGY

This system can be used to measure electrical factors whilst being monitored through the Internet of Things. Once any abnormal situations are detected it can send alerts, control relays and give forecasts for Energy Consumption. Multiple factors can be measured such as Voltage, Current, Power and Energy Consumption using an energy monitoring board called the PZEM-004T. Another voltage can be measured using the ZMPT101B sensor. The ESP32 will process this data and show it on the OLED display. The ESP32 has Wi-Fi connectivity which connects to the Firebase Realtime Database. A Linear Regression model was used to analyse the past consumption data and forecast future Energy Consumption.

3.1 Proposed System Architecture

The currently proposed system can monitor various electrical parameters, identify any issues or anomalies, and triggers the buzzer for local alarms. It allows us to store data on the cloud, and control remotely. The system comprises an ESP32 DevKit as the main controller. This receives data from the PZEM-004T Energy Meter and Voltage Sensor ZMPT101B. This data is sent to the Firebase Realtime Database using Wi-Fi and HTTPS. This allows us to store and retrieve real-time data, historical data, and alarm and control information. A web dashboard has been designed to show the electrical parameters, energy usage trends, estimated bills, reports and predictions. An OLED screen, buzzer and relay module have been used to display locally, raise an alarm and switch the connected supply/load.

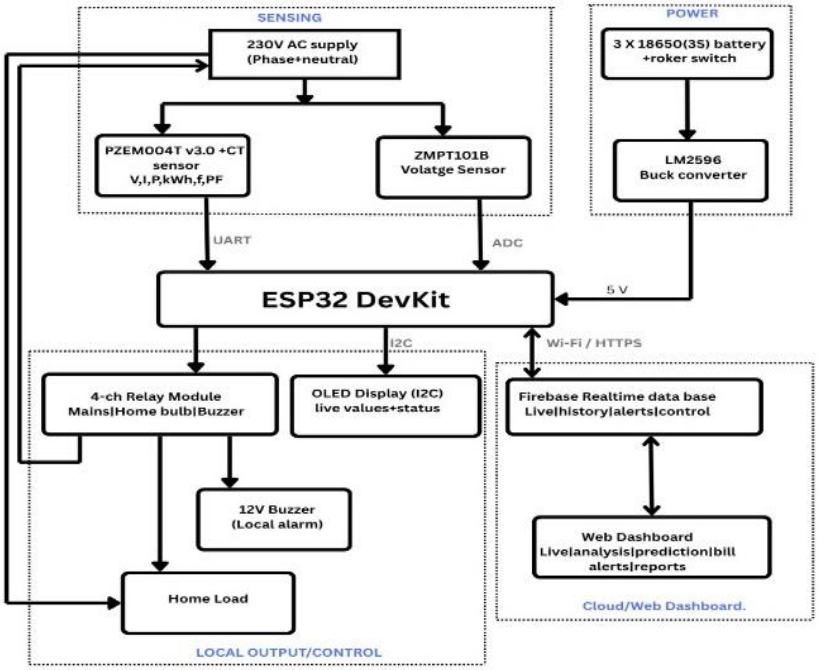


Fig. 3.1 System Block Diagram

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3.2 System Working Methodology

When the ESP32 Devkit, sensors, OLED, Wi-Fi and Cloud services are initialised, the ESP32 will read the electrical data from both the PZEM-004T Energy Meter and ZMPT101B Voltage Sensor. Depending on which module is used the ESP32 will capture voltage, current, power, energy usage, frequency and power factor. The data will be processed and analysed depending on how it has been detected based on the criteria set within the controller. Whilst the system is operating the OLED will display real-time data and status. The data is then transmitted using the Wi-Fi connection to the Firebase Realtime Database. This will allow the user to see real-time electrical data and historical energy usage data on the web dashboard. If the theft/leakage test has been configured and triggered, the OLED will update to show the appropriate warning. The Buzzer will activate depending on the alert mode that has been set. Alerts will be sent to the web dashboard. The Relay Module allows the user to turn the connected supply/load off/on. Commands can be sent to the relay module using the web dashboard. The relevant data will be stored in Firebase. The dashboard displays real-time data, graphs, predicted electricity bill and downloadable reports. Within the dashboard there is a Linear Regression model that predicts the energy usage based on the historical energy usage data. This will help the user understand their consumption trends. There is also a configurable allowance for the Gruha Jyothi unit. This process will be repeated continuously whilst the system is operational. This methodology includes monitoring, alerts, cloud, remote relay control and predicting the energy usage.

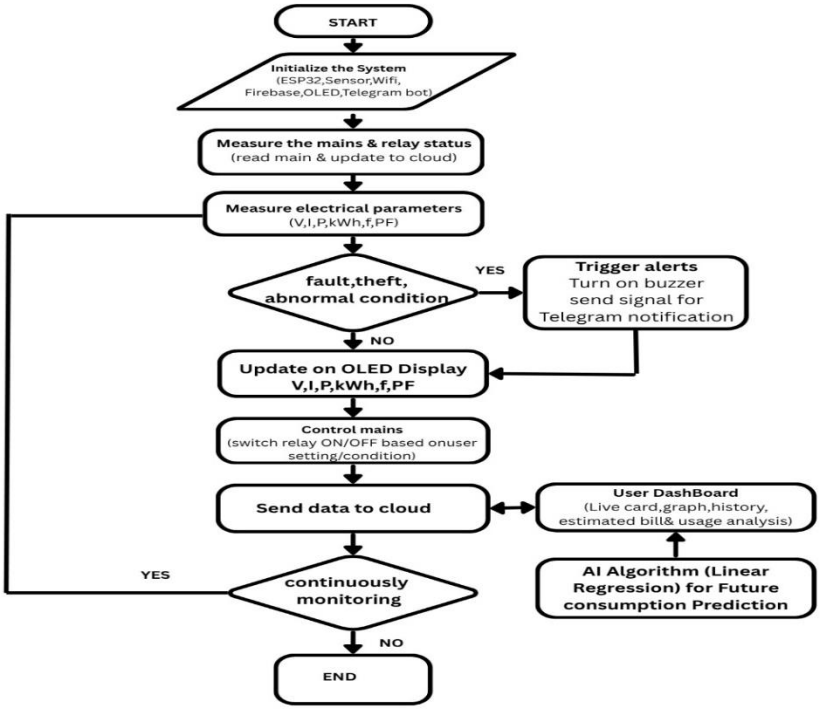


Fig. 3.2 System Work Flow

3.3 Electrical Parameter Monitoring

The PZEM-004T energy measuring module is used to monitor different electrical parameters. The module provides information such as voltage, current, apparent power, energy use, frequency and power factor. The ZMPT101B sensor provides another input to the ESP32 board that measures voltage that helps for verification. This allows the system to gather different electrical measurement, this can be used to monitor how much energy is being used in the home and observe any changes in the load. The ESP32 collects and gathers available measurements and displays the verified electrical values and status on the OLED screen. The values are sent to Firebase so they can be accessed from anywhere by the user. This allows the user to monitor real time electrical values from anywhere. The data can be analysed, graphed, reports created and predictions made based on the recorded values. Comparing values between different times can help the user see how much energy is being used in their home.

3.4 Theft Detection and Alert Mechanism

The THEFT detection feature involves monitoring an electrical parameter. If it meets the set threshold then it is deemed that there is a THEFT. In the prototype the 9W LED light is turned on along with the 60W tungsten light that simulates a THEFT load. If the electrical parameter meets the thresholds then the ESP32 will display a message on the OLED

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screen saying 'THEFT DETECTED' and will make the buzzer continuously sound. The THEFT alert will be logged onto Firebase and the web dashboard so it can be seen by the user. A Telegram Bot will send an alert to the user. The system can also be controlled from different places through UI dashboard when the alerts are sent to the user. On the dashboard the user can control the main supply relay to cut off the power supply of the prototype. This will cause the lights to turn off and the buzzer to stop. The THEFT detection feature has been demonstrated with the control load test setup. The extra 60W bulb represents the THEFT load.

3.5 Leakage Monitoring and Alert Mechanism

The leakage mode will monitor the state of the leakage test. When the prototype is in this state (the 2W orange bulb will light up), the ESP32 will show a message on the OLED saying "LEAKAGE DETECTED" and the buzzer will be turned on to beep in a stop start manner. The system will also log onto Firebase to let the user know about what has happened. This will be shown on the web dashboard along with a Telegram Bot notification being sent to notify the user that there has been a leakage detected. During testing, it showed a power reading of around 1W in the leakage section of the dashboard. This means that the user can monitor what is happening with the system from afar. The OLED will flash to let the user know straight away what has happened and the buzzer will beep to make them aware. The leakage mode has been shown by using a test setup. As the bulb was used to show that there was a leakage, it did not confirm that there was electrical leakage but instead shows that the system will notify the user and monitor what is happening.

3.6 IoT Cloud Monitoring and Remote Control

The IoT cloud monitoring feature stores and updates the electrical data and alerts coming from the ESP32 within Firebase Realtime Database. A responsive web dashboard is used which can be accessed on either a desktop or mobile device. This will display the live electricity data along with charts showing how much energy and other parameters are getting consumed. This also shows any past data along with any alerts that have been triggered from any theft or leakage. Electricity bill estimates, energy usage predictions, report creation and energy saving suggestions are also provided. Users can also be notified of any alerts using the Telegram Bot notifications. The remote control feature allows users to control the relay from the web dashboard even through their mobile. When a command is given to the relay the connected supply will change according to how the relay has been set up. During the demonstration of the prototype, the main supply relay was operated to turn off the power supply going into the prototype. This would then turn off the complete electric supply and stop the buzzer.

3.7 Linear Regression-Based Energy Consumption Prediction

This section predicts the energy consumption using the Linear Regression model written in Python. The energy consumption data is captured by the model and is used to predict the future energy consumption using the Linear Regression model. The electrical data captured is stored in the Firebase database. The Linear Regression model will find the relation between the historical data and will provide us with an estimate of the future value. This predicted consumption is shown to the user in the web dashboard. The predicted consumption section is connected to the cloud monitoring system. This allows the user to see the estimated energy consumption. The dashboard shows the user the consumption so that they can understand how much energy they will be consuming and can prepare accordingly. The accuracy of the predictions depend on how much data we have, how good the data is, and how varied the data is. There is also an option to calculate the estimated bill of electricity units as per the tariff of Karnataka state. This is done by using the correct tariffs and the estimated consumption. The estimated bill can be seen by the user to understand how much they might be charged. The dashboard has an option to set the allowed units for the Gruha Jyothi scheme. If the scheme is activated and the allowed units are set, then the dashboard will show the user an estimated bill of ₹0. If the scheme is not activated then the dashboard will show the standard estimated bill. These values are just for guidance to the user and may not be the same as the bill provided by the electricity company.

IV. HARDWARE AND SOFTWARE IMPLEMENTATION

4.1 Hardware Implementation:

1. ESP32 Microcontroller:

ESP32 acts as a central controller. It receives the electrical data from PZEM-004T using UART. Further, it interacts with ZMPT101B voltage sensor. Based on the logic written, control the OLED, buzzer, and relay module. The ESP32 has inbuilt Wi-Fi to interact with the Firebase Realtime Database. This helps in storing the measuring electrical data, sending alerts, and controlling the relay from a remote location with turning on the loads.

IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

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Fig. 4.1.1 EPS32

2. PZEM-004T Energy Meter Module

PZEM-004T is an energy module which helps in measuring electrical parameters like voltage current power energy consumed frequency and power factor. This module is used in our project to measure the electrical attributes of the connected load. It shares this data with the ESP32 using UART serial protocol. The data received by the controller is processed and sent to the Firebase Realtime Database. This helps us in real-time monitoring storing historical data estimating electricity bill and predicting energy consumed.



Fig. 4.1.2 PZEM-004T

3. ZMPT101B Voltage Sensor

The ZMPT101B also known as Single Phase AC voltage sensor was used to allow checking of the voltage from the loads attached to the system. This was connected to the ESP32 so it can measure the voltage using the ADC pin. This voltage was used to confirm the voltage measurements from the PZEM-004T energy meter module.



Fig. 4.1.3 ZMPT101B

4. Four-Channel Relay Module

The four channel relay module was used to control turning on/off the electrical load. It was connected to the ESP32 to allow it to send signals to the relay. This will turn on/off the relay according to the logic programmed into the ESP32. This allows the relay module to be used to remotely control the power supply in the prototype. Turning off the bulbs that are connected to the relay. The 4th channel of the relay was left as a reserve in-case there was any expansion in the future.



Fig. 4.1.4 4-Channel Relay

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5. Buzzer

The buzzer will notify the user audibly with an alert if there are any anomalies in the system. It can be controlled by the ESP32. There are two types of buzzer alerts that have been implemented, one will constantly beep when the system detects there is a theft test being performed and the other will beep intermittently when there is a leakage test being performed. This helps in indicating the difference between the two conditions when testing the prototype. The buzzer notifies the user immediately with an alert locally and also notifies them through the OLED and web dashboard.



Fig. 4.1.5 Buzzer

6. DC–DC Buck Converter

The DC-DC Buck Converter has been used to convert the 12V DC input into 5V DC. This provides the correct voltage to power the ESP32 Development Board. The output voltage has been changed to 5V and connected to the 5V/VIN pin on the ESP32. This permits the prototype to be powered using a 12V power source while still providing the correct voltage to the controller without causing damage.

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Fig. 4.1.6 Buck Converter

7. OLED Display Module

The OLED display will be used to provide the user with real time data and information regarding the system. This will be used to inform the user about key parameters such as Voltage, Current, Power and Energy usage by connecting it to the ESP32. The OLED display will also provide information about the current state of the system. This will include information like Normal Operation, Theft Detection and Leak Test Detection. This will give the user local information about the working of prototype and help them identify if any issues have occurred during testing.

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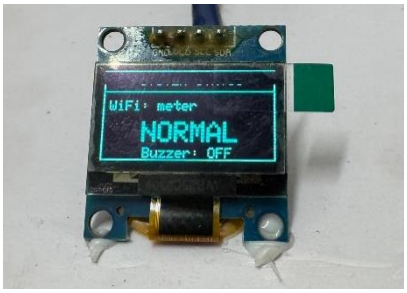


Fig. 4.1.7 OLED Display

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8. Battery Pack and Rocker Switch

The battery pack will provide the prototype with a DC power supply, and the Rocker Switch can be used to enable/disable the power supply. The battery pack consists of three 18650 lithium ion cells. The rocker switch gives a convenient way to manually enable/disable the power supply.



Fig. 4.1.8 DC Power

9. Electrical Test Loads

The three electric bulbs were used as test loads to show the operation. These were a 9W LED bulb (representing a typical domestic load), a 60W tungsten bulb (to represent a theft scenario) and a 2W bulb (to represent a leakage scenario). These were used to demonstrate how the system would operate according to its programmed logic. This was done by showing the OLED displays, buzzer alerts and relay control. The leakage scenario setup does not test for real electrical leakage.



Fig. 4.1.9 Electrical Bulbs

4.2 Circuit and Prototype Assembly

The required prototype was constructed on a mounting board with the ESP32 microcontroller, PZEM-004T energy meter module, ZMPT101B voltage sensor, 4 channel relay, an OLED display, buzzer, DC -DC buck converter, battery pack and electrical test loads connected. The connections allow for monitoring of electrical parameters and identifying any abnormal circumstances through the display of alerts on site. The OLED displays the actual real time data that is coming as output from the cloud database. In Fig 4.2.2 the prototype has been connected directly to a 230V AC domestic supply. This allows us to test the prototype with actual load of 230V voltage. The PZEM-004T component monitors the test loads that are connected. The ESP32 will take the values from the electrical measurement module, and control the OLED, buzzer and relay. Due to the 12V DC input, the DC-DC buck converter was added to lower the voltage to 5V for the ESP32 Dev Board. A battery pack was added to the prototype along with a rock switch. The prototype was tested with three electrical loads; a 9W LED Bulb (normal), a 60W Tungsten Bulb (theft) and a 2W Bulb (leakage). This allowed the prototype to be tested with the programmed statuses, audio alert and switching capabilities. The prototype was also able to communicate with the cloud dashboard.

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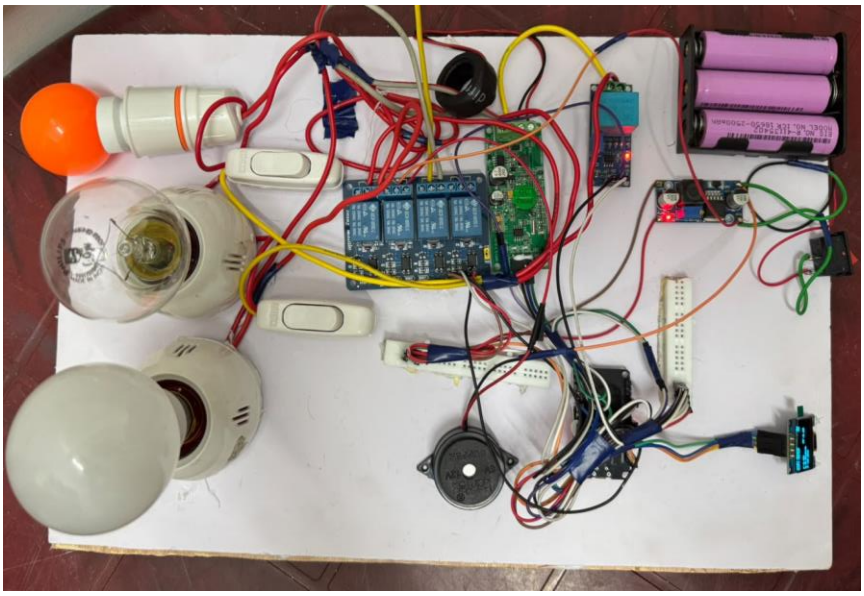


Fig. 4.2.1 Prototype Setup

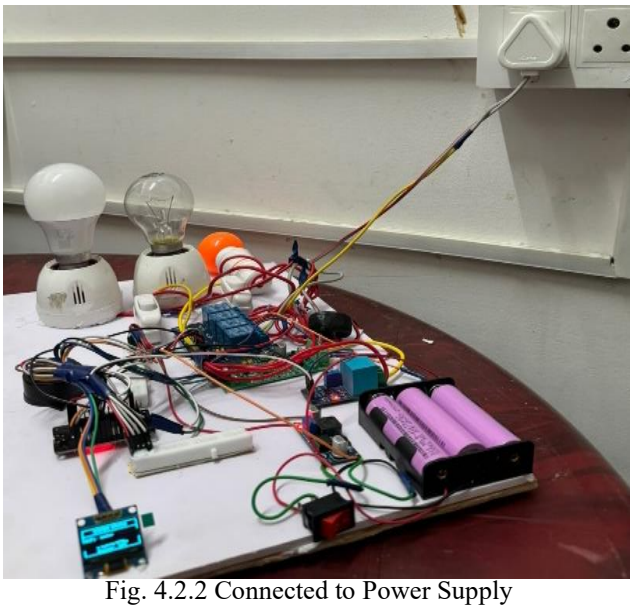


Fig. 4.2.2 Connected to Power Supply

4.3 Software Implementation

This section explains the software components of the smart energy meter system. The code consists of the ESP32 microcontroller capturing the electrical data and detecting specific conditions and updating the display also sending messages through the buzzer and controlling the relays. The Realtime database allows information to be stored and communicated with the hardware and web application. The dashboard can be used to monitor the device remotely and view past data and estimate electricity bills. Finally a Linear Regression model has been integrated using Python to predict future energy usage based on past data.

4.3.1 IoT Cloud and Dashboard Implementation

The Firebase Realtime Database is used to store the electrical values and system status information gathered from the ESP32. This information can be accessed using the user interface web dashboard. The dashboard provides information including voltage current power and electricity usage. It has features for visualising historical data and detecting theft and leakage tests with controlling supply remotely and estimating electricity costs and generating reports in PDF and CSV format. The Telegram Bot integration provides alerts through notifications when any abnormal situations like theft or leakage may occur. Overall this means that the prototype can be monitored and used through an internet enabled device.

IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering

Impact Factor 8.414 ⁜ Peer-reviewed & Refereed journal ⁜ Vol. 14, Issue 11, November 2026

DOI: 10.17148/IJIREEICE.2026.141109

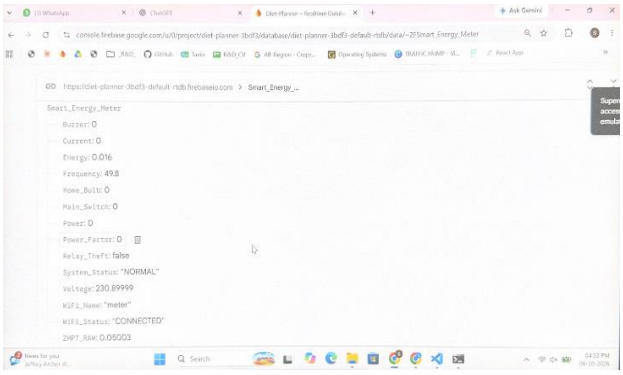


Fig. 4.3.1a IoT Cloud Firebase

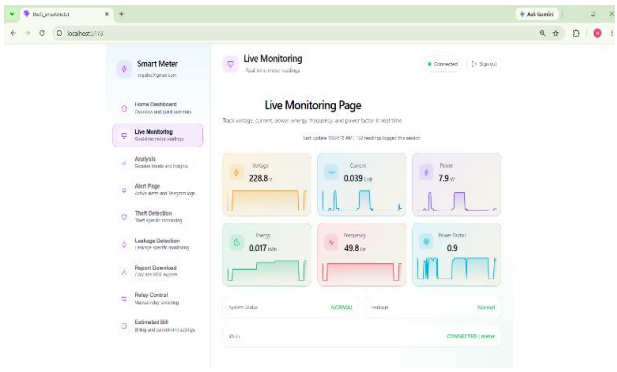


Fig 4.3.1b UI Dashboard

4.3.2 AI-Based Prediction and Electricity Bill Estimation

The Prediction of Energy Consumption module uses a Linear Regression Model written in Python, which will predict the electricity consumption based on past energy data. This will be shown on the web dashboard for the user to understand their predicted usage. The electricity bills are predicted based on predicted consumption and the selected tariff. There is an option to set the unit limit under the Gruha Jyothi scheme. If the scheme is enabled then once the unit limit is set the dashboard shows a estimated bill of ₹0 based on the unit limit however if it's disabled then it shows the normal estimated bill.

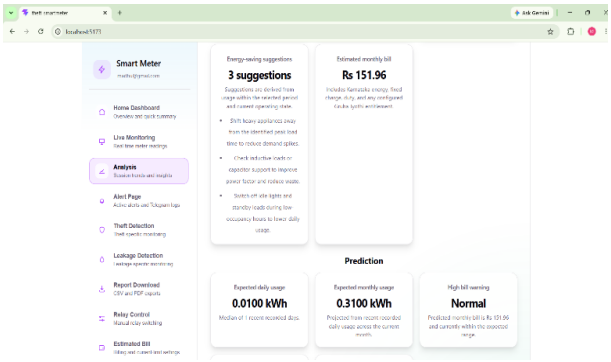


Fig. 4.3.2a Power Consumption Prediction

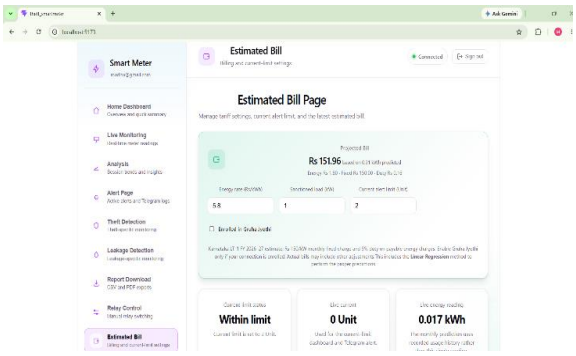


Fig. 4.3.2b Estimated Bill Calculation

4.4Mobile Monitoring and Remote Control

The system will allow the user to monitor their system via a mobile responsive web dashboard. The interface uses the Firebase Realtime Database to monitor various features such as live monitoring, data analysis, theft detection, leakage detection, alerts log, report downloads, relay control and estimated electric bill. Figure 4.4 shows the navigation bar of the mobile dashboard, live monitoring interface and relay control interface. The live monitoring interface has various cards showing the different electrical values including voltage, current and power. There is also a graph to show the trend of the values. At the bottom there is information about the connection status and updates. The relay control interface shows separate operable buttons for the home bulb and main power supply. This allows the user to control the relays to switch them on/off from a distance. By having this interface the user can monitor the electrical values, see the information about the system and control the prototype loads connected to the system from a distance. All the other parameters that can be viewed on the web dashboard can be viewed using the mobile user interface dashboard.

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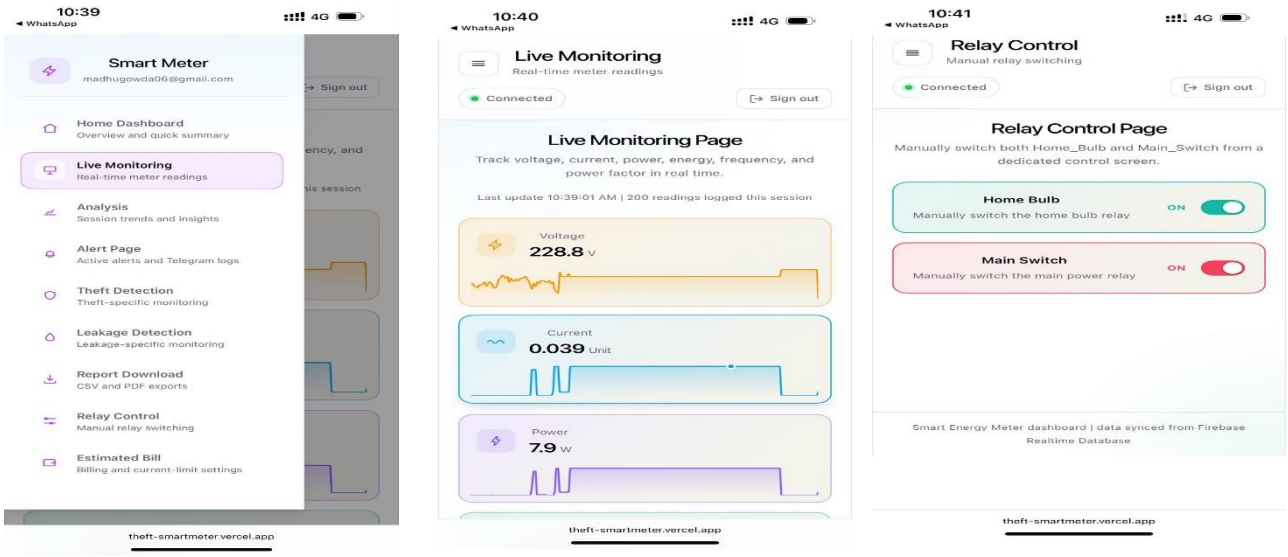


Fig. 4.4 Mobile monitoring interface showing (a) Dashboard navigation menu, (b) Real-time electrical parameter monitoring, and (c) Remote relay control.

V. RESULTS

5.1 Normal Load Monitoring

In this section the designed smart energy meter solution has been tested with normal conditions. A 9W LED lightbulb was connected and turned on. The PZEM-004T module measured the electrical parameters of the connected load, which have been processed within the ESP32 device. These values were then displayed on the OLED screen and sent to the Firebase Realtime Database in order to be visualized within the web dashboard. This information is also available to view via the mobile platform. The dashboard was showing a normal condition for the system with no alerts being raised for theft or leakage, no notification messages sent to telegram and no suggestions of any abnormal conditions. This shows that the system was running normally when under this load condition. This demonstrates that the prototype can monitor the electrical parameters, send the data to the cloud, and make the information available to view via a mobile phone.

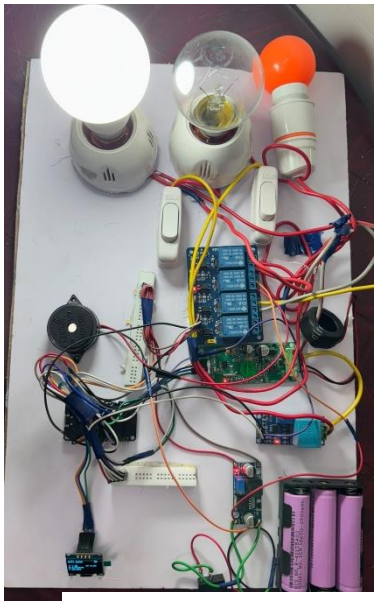


Fig. 5.1.1 Normal user load condition with the 9W LED bulb switched ON.

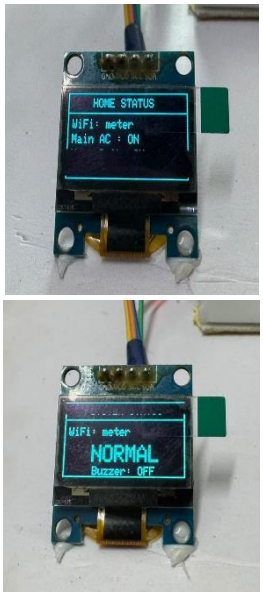


Fig. 5.1.2 OLED Display Indicating Normal System Status

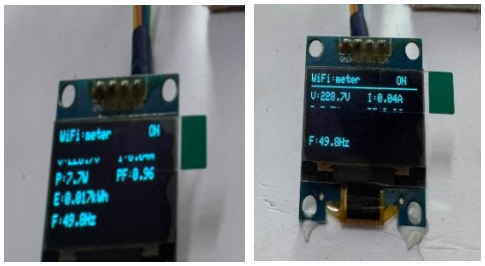


Fig. 5.1.3 OLED display showing the measured electrical parameters under normal load

IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

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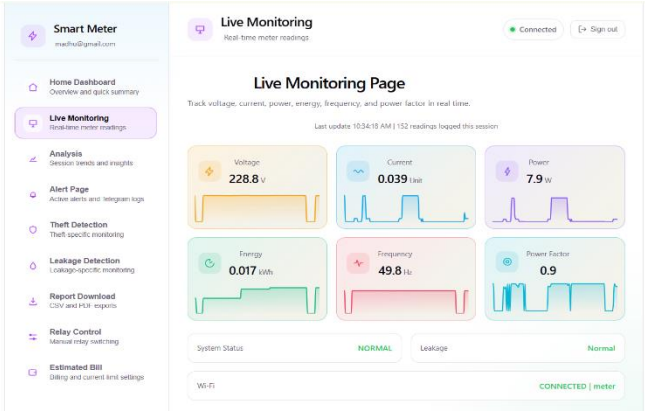


Fig. 5.1.4 Web dashboard displaying live electrical readings and normal system status.

5.2 Theft Detection and Alert Generation

The Theft Detection and alert generation were tested by simulating a THEFT scenario. The 9W household LED bulb and the 60W tungsten bulb (for simulating THEFT) were turned on. The PZEM-004T module was used to obtain the electrical parameters. Then, the values were processed by the ESP32 based on the set threshold for detection. If the conditions were met, then it was detected that there was a potential THEFT scenario. The OLED screen would display "THEFT DETECTED" and "BUZZER: CONSTANT," to inform the user that there had been a THEFT. A BUZZER was activated to give an audible alert locally. The detected event would also be shown in the web dashboard. The Theft Detection page would show the status of the THEFT and an alert saying that there was suspected unauthorised use of electricity or tampering. The Alert Page would log the event so the user can see what the alert is. The system successfully sent a THEFT alert using the Telegram Bot. The alert contained the electrical parameters, detection status, BUZZER status and time stamp of the event. This meant the user could receive information about a THEFT remotely using their phone.

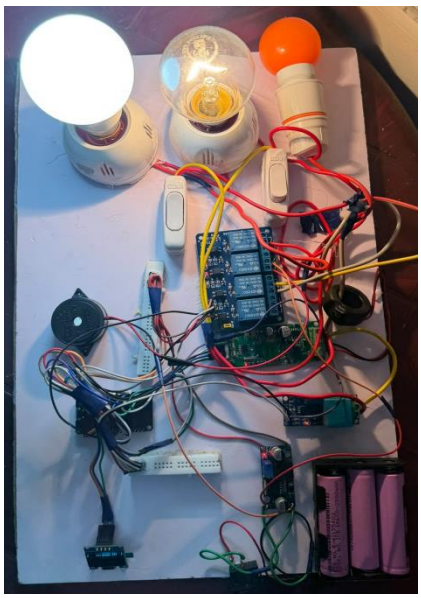


Fig. 5.2.1 Theft Load Condition where 60W tungsten bulb is ON

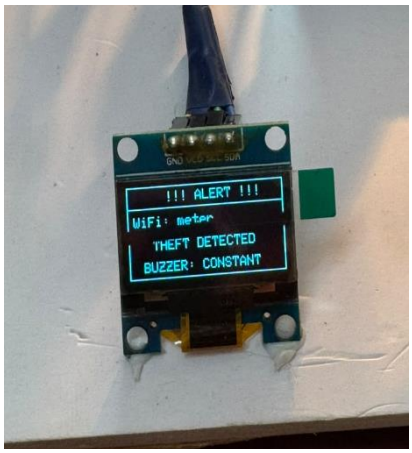


Fig. 5.2.2 OLED indication of theft detection with continuous buzzer activation.

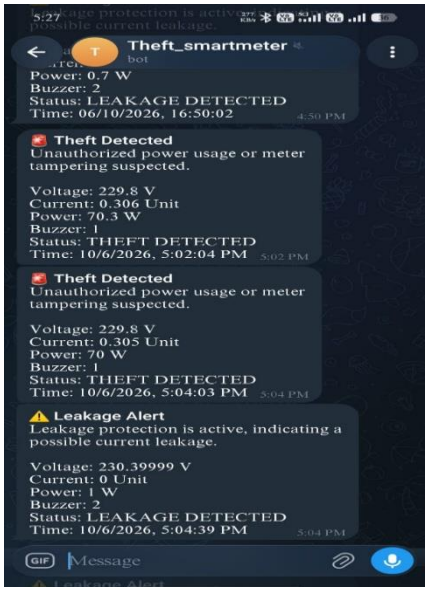


Fig. 5.2.3 Telegram Bot notifications generated for theft event.

IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

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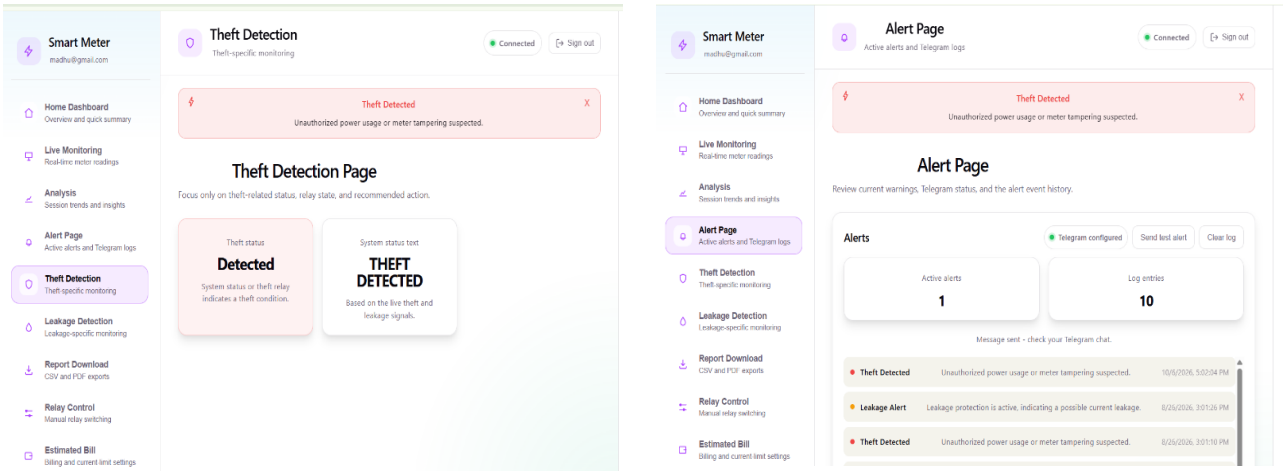


Fig. 5.2.4 Web dashboard displaying the detected theft condition.

5.3 Leakage-Test Detection and Alert Generation

The leakage testing feature of the smart energy metering system was tested by turning on a 2 W orange bulb. When the leakage test was implemented the ESP32 microcontroller updated the system status and displayed "LEAKAGE DETECTED" on the OLED screen through Google Firebase. The buzzer was making an intermittent beeping sound to alert the user locally. The alert was shown on the web dashboard too. A notification was also sent via Telegram showing the alert status as well as the electrical values. The system gave a power value of around 1 W for the leakage. This is because during testing the system was giving a live reading of the system. The dashboard and alert page showed the event had occurred. This lets the user look back at the alert on their computer or smartphone. It was observed that the prototype was able to show the status of the leakage test, trigger an alert sound, update the monitoring page and send a message with the alert details via Telegram.

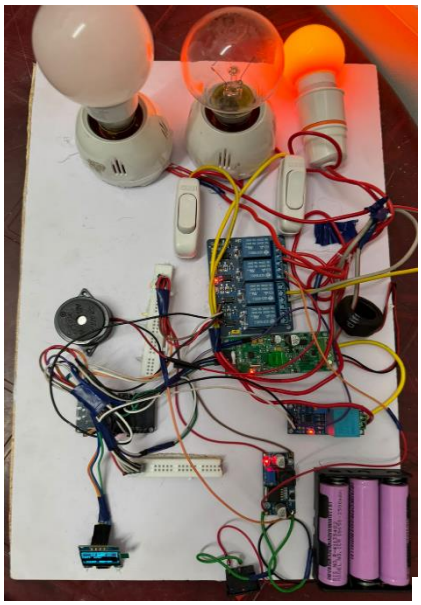


Fig. 5.3.1 Leakage Load Condition where 2W bulb is ON

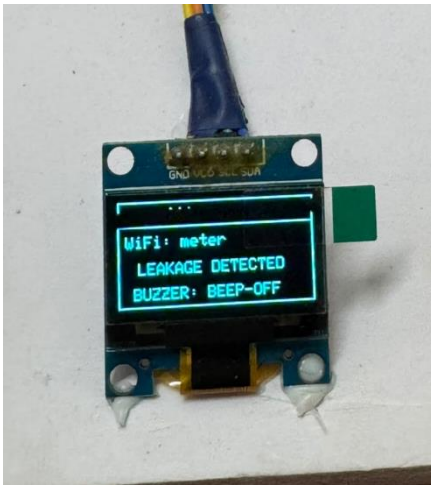


Fig. 5.3.2 OLED indication of Leakage detection with intermittent buzzer activation.

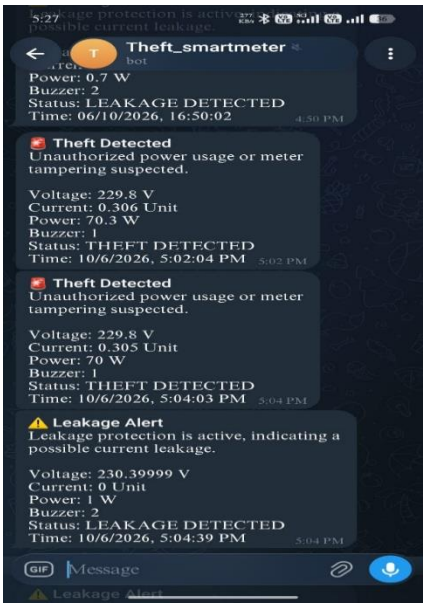


Fig. 5.3.3 Telegram Bot notifications generated for Leakage event.

IJIREEICE ISSN (O) 2321-2004, ISSN (P) 2321-5526

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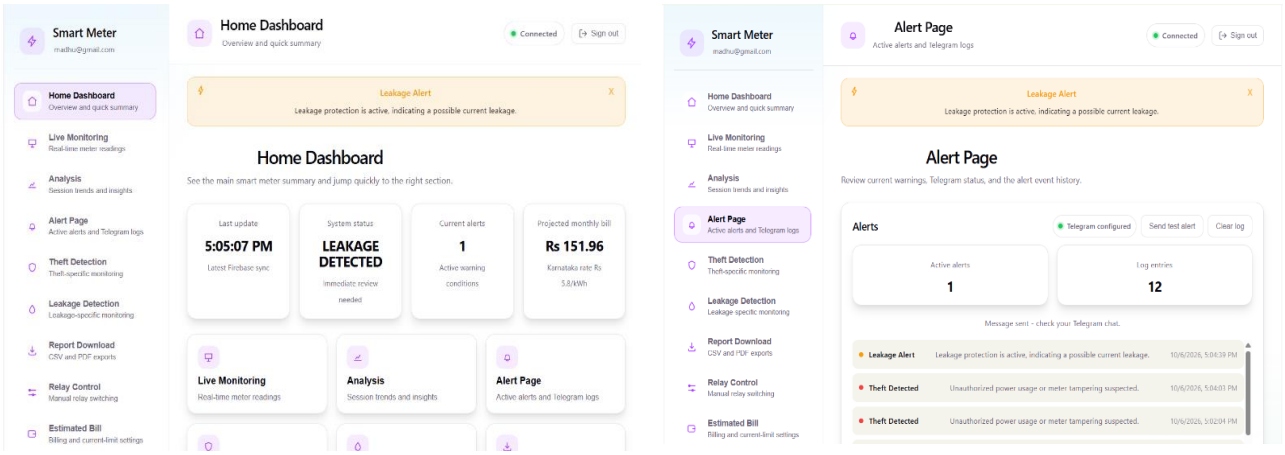


Fig. 5.3.4 Web dashboard displaying the detected Leakage condition.

5.4 AI-Based Prediction and Bill Estimation

The system uses Linear Regression in Python to predict future usage of electricity by analysing past electricity usage data. The predicted values are shown in the web dashboard. This includes predictions for the daily usage, monthly usage, future trends and whether there has been abnormal usage. During tests, the web dashboard showed that the predicted electricity usage was 0.0100 kWh per day and 0.3100 kWh per month. The Estimated Bill page takes the predicted value and multiplies it by the tariffs given. The tariffs can be changed by the user. Here we have an energy cost of ₹5.80 per kWh, a sanctioned load of 1kw, a monthly fee of ₹150 and a electricity duty of 9%. With the Gruha Jyothi option turned off, we get a total estimated bill of ₹151.96. We have an Energy Charge of ₹1.80, Fixed Charges of ₹150 and Duty Charges of ₹0.16. There is also an option to turn on the Gruha Jyothi scheme and change the amount of free units allowed. In the example here we have turned the scheme on and allowed 1 free unit. As the predicted usage is within the allowed free amount, we get a predicted bill of ₹0.00. If the scheme is turned off then the normal tariff rates will be applied. This allows the user to know what their future usage will be and how much they will be charged for electricity. The values obtained here are just results from our prototype estimates based on the set tariffs. The actual bill will depend on the Karnataka tariff being applied, consumer type, if they qualify for any schemes and current billing rules.

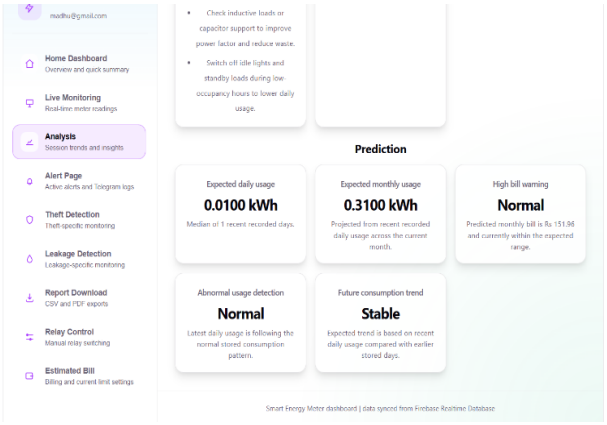


Fig. 5.4.1 AI-Based Energy Consumption Prediction

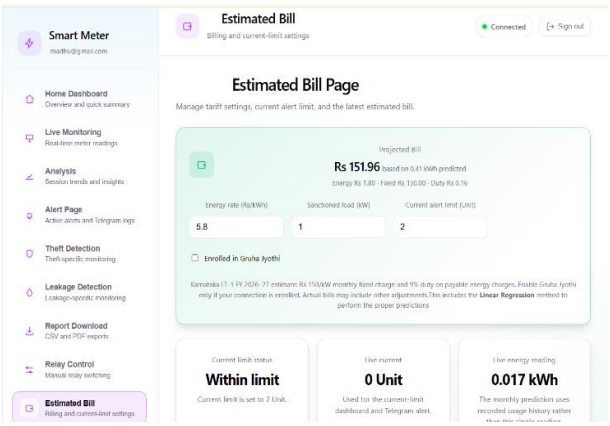


Fig. 5.4.2 Estimated Bill Without Gruha Jyothi

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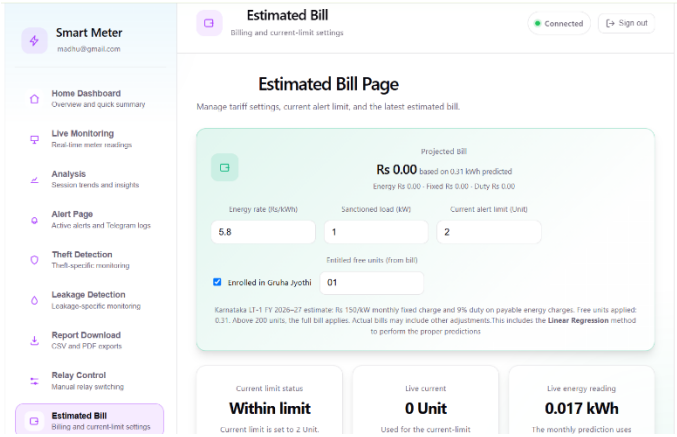


Fig. 5.4.3 Estimated Bill With Gruha Jyothi Scheme.

5.5 Remote Relay Control

The relay can be controlled remotely using the real time responsive web interface. It contains two relays, Home Bulb and Main Switch. The Home Bulb relay can be switched ON/OFF to control the home bulb remotely. The Main Switch is the master cut OFF switch which controls the main power supply to the prototype. Before turning ON the connected loads, the Main Switch needs to be ON. If theft or any leak test or abnormal situations are detected, the system will send out a warning via the web interface and Telegram Bot. The user can then turn OFF the Main Switch to cut the power to the prototype and its connected loads. This makes the response to any abnormal situations very fast. All relay commands and statuses are linked to Firebase Realtime Database so that they can be controlled remotely using the connected web interface. This is one of the most advanced features in this system.

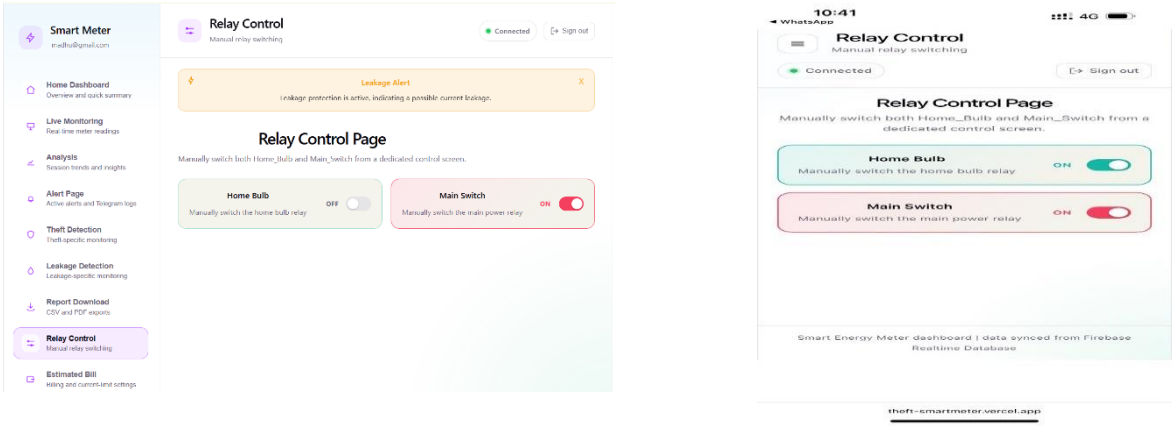


Fig. 5.5.1 Remote Relay Control on the Web Dashboard and Mobile Dashboard

5.6 Downloadable Report Generation

The system will provide the functionality for generating reports. The user can download the data collected during monitoring of the energy usage in the form of .PDF and .CSV. The reports will have time, voltage, current, power, energy consumed, frequency, power factor, system status and estimated monthly electricity bill. The system also provides an option to estimate the bill. If the Gruha Jyothi scheme is applied by the user then based on the configured free unit allowance the bill will be calculated. But if it is disabled then the bill will be calculated normally. The dashboard has been configured with an energy cost of ₹5.80/kWh, and ₹150 monthly flat charge, plus duty.

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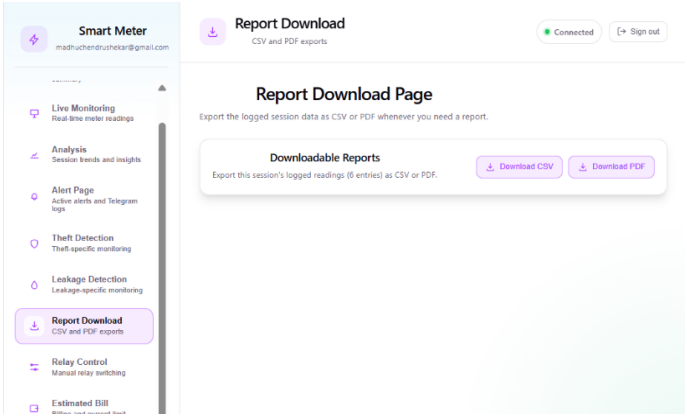


Fig. 5.6.1 Report Download Interface

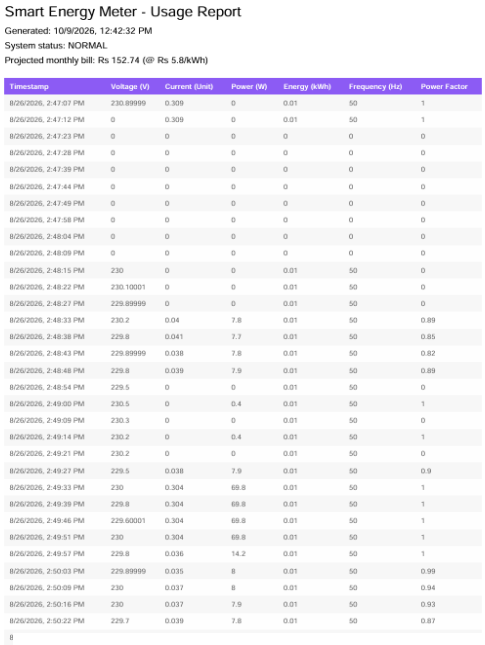


Fig. 5.6.2 Generated Report without Gruha Jyothi Enrollment

VI. CONCLUSION AND FUTURE WORK

This IoT-based smart energy meter allows for real-time energy monitoring, theft detection, leakage notifications, remote relay control and AI-based energy forecasting. With the implementation of ESP32, PZEM-004T, Firebase Realtime Database and an interactive web dashboard, this project displays electrical parameters, maintains historical data and produces notifications via the web dashboard and Telegram Bot. An estimated forecast for energy usage is produced using the Linear Regression algorithm. The dashboard will calculate estimated electricity costs based on tariff settings and whether the user is eligible for the Gruha Jyothi scheme. Reports can be downloaded as a PDF and CSV file. This prototype shows the possibility of using IoT and AI technology to enhance monitoring and control of a household's energy. Future improvements could include adding an emergency safety system to detect electrical issues, automatically notify the relevant emergency contact/service and share the users location if possible. This system can also be adapted to industrial applications by adding 3 phase monitoring, increased load handling and industrial protection. Improvements could include using specialist residual current sensors to detect any leakage, using more data to increase accuracy of the predictions, improving security and enabling automatic load management. This could help to make the system safer, more reliable, scalable and applicable to a wider range of residential and industrial situations.

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