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Smart Energy Monitoring and Power Theft Detection

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Abstract: *This paper presents a privacy-preserving system for detecting power theft in smart grid environments using Advanced Metering Infrastructure (AMI) and Internet of Things (IoT) technology. The primary objective of the system is to reduce power losses and improve energy management in residential, industrial, and smart grid applications. A PZEM-022 AC digital power meter, combined with a current transformer (CT) clamp, continuously monitors electrical parameters such as voltage, current, power, and energy consumption in real-time.*

An ESP32 microcontroller collects the measured data through serial communication and processes it for analysis. The system analyzes energy usage patterns and compares them with predefined threshold values to identify abnormal behavior that may indicate power theft, unauthorized usage, or meter theft. A 16×2 LCD, connected via an I2C interface, displays real-time readings at the installation site for easy monitoring.

To ensure safety and control, a two-channel relay module is used to manage connected electrical loads and automatically disconnect them when unusual activity is detected. At the same time, a buzzer provides an immediate local alert. The system also transmits real-time data and notifications to the Blynk IoT cloud platform via the ESP32's built-in WiFi, enabling users to monitor the system remotely through a mobile application or web interface.

Overall, the proposed system provides a simple, reliable, and cost-effective solution for detecting power theft while maintaining data privacy. It helps reduce financial losses and supports improved energy management in smart grid systems

Keywords: Power theft detection, Smart Grid, IoT, ESP32, Advanced Metering Infrastructure, Energy Monitoring, Blynk Cloud, Anomaly Detection

I. INTRODUCTION

Power theft and energy losses are major financial and operational challenges faced by electricity distribution companies and utility providers worldwide. Unauthorized activities such as illegal tapping of electrical lines, meter tampering, bypassing metering circuits, and unregistered connections allow consumers to use electricity without accurate measurement. This results in significant revenue losses for utility providers and creates serious safety risks within the power distribution network. According to global energy reports, both technical and non-technical losses, including power theft, contribute to billions of dollars in annual losses across developed and developing countries.

Traditional energy meters used in residential and commercial sectors are mostly mechanical or basic electronic devices that record only cumulative energy consumption. These meters lack real-time monitoring, remote communication, and automatic anomaly detection capabilities. As a result, they can be easily tampered with or bypassed without immediate detection, allowing power theft to continue for long periods until manual inspection is carried out.

With the advancement of technology, the Internet of Things (IoT) provides an effective and economical solution to this issue. The PZEM-022 AC digital power meter module is capable of accurately measuring electrical parameters such as voltage, current, active power, and energy consumption. When integrated with an ESP32 microcontroller and connected to an IoT cloud platform, it enables real-time monitoring, automated theft detection, and instantaneous alert generation. This integration transforms a conventional energy meter into an intelligent and connected smart metering system.

This project presents the design and implementation of a privacy-preserving smart energy monitoring and power theft detection system using an ESP32 microcontroller. The system incorporates a PZEM-022 AC digital power meter module with a current transformer (CT) clamp, a two-channel relay module, a 16×2 LCD display, a buzzer, and Blynk IoT cloud connectivity. It provides continuous real-time monitoring of multiple electrical parameters, detects power theft through threshold-based analysis, and generates both local and remote alerts. Additionally, the system enables automatic load control using relay switching, making it a practical and efficient solution for residential, industrial, and smart grid applications.

II. LITERATURE REVIEW

Recent advancements in smart energy monitoring systems have focused on improving energy efficiency and reducing power theft in electrical distribution networks. Several studies have proposed IoT-based energy monitoring systems using microcontrollers and cloud platforms for real-time data acquisition and alert generation (Kumar & Patel, 2022; Sharma & Raj, 2023; Blynk Inc., 2024). These systems enable continuous monitoring of electrical parameters and remote access; however, they often rely on basic detection methods and lack highly accurate theft identification mechanisms.

Researchers (Singh & Verma, 2022; Patel & Mehta, 2023) have explored power theft detection techniques using current transformers and threshold-based analysis. These systems improve detection capability by identifying abnormal variations in current and energy consumption. Despite these improvements, such approaches may not provide sufficient accuracy under varying load conditions and often lack integrated real-time alert and control mechanisms.

Various studies by Ramesh and Krishnan (2022) and Johnson and Lee (2022) highlight the role of Advanced Metering Infrastructure (AMI) in enabling secure and privacy-preserving communication in smart grid systems. These systems support real-time monitoring, data analysis, and remote management. However, they require complex infrastructure and high deployment costs, making them less suitable for low-cost and small-scale applications.

Researchers have also investigated hardware-based energy monitoring systems using dedicated modules such as PZEM-004T for accurate measurement of voltage, current, and power parameters. Espressif Systems (2024) and Peacefair (2023) demonstrated the integration of ESP32 and energy metering modules for efficient real-time monitoring. Although these systems provide improved accuracy, they often lack complete integration of detection, alerting, and control features.

Recent developments using IoT platforms and embedded systems have improved real-time monitoring and remote access capabilities. The integration of ESP32 with cloud platforms enables efficient data transmission and user interaction (olehs, 2023; Blynk Inc., 2024). However, many of these systems still face challenges such as limited automation, delayed response to theft detection, and lack of immediate local alert mechanisms.

Overall, the reviewed studies indicate that while existing systems improve monitoring and detection capabilities, they still suffer from limitations such as high cost, complex infrastructure, and lack of integrated real-time control and alert systems. Therefore, there is a need for a cost-effective and efficient solution that provides accurate real-time monitoring, reliable power theft detection, immediate alerts, and automated load control for improved energy management.

III. METHODOLOGY

The proposed system is designed to provide real-time energy monitoring and automatic power theft detection using IoT technology. The methodology is divided into several functional modules that work together to achieve accurate measurement, analysis, alert generation, and remote monitoring.

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Module 1: Data Acquisition and Measurement

The system uses a PZEM-022 AC digital power meter module along with a current transformer (CT) clamp to measure electrical parameters such as voltage, current, active power, and energy consumption. The CT clamp is installed around the live wire without disturbing the circuit, ensuring safe and non-invasive measurements. The PZEM-022 continuously captures real-time data and sends it to the ESP32 microcontroller through serial communication.

Module 2: Data Processing and Analysis

The ESP32 microcontroller acts as the central processing unit of the system. It receives real-time data from the PZEM-022 module and processes it for analysis. The system compares the measured values with predefined threshold limits to identify abnormal variations in energy consumption. Any deviation beyond the threshold is considered a potential indication of power theft, unauthorized usage, or meter tampering.

Module 3: Local Monitoring and Display

A 16×2 LCD connected via an I2C interface is used to show real-time electrical parameters such as voltage, current, power, and energy consumption. This enables users and operators to monitor system performance directly at the installation site without requiring external devices or internet connectivity.

Module 4: Theft Detection and Alert System

When abnormal energy consumption is detected, the system triggers an alert mechanism. A buzzer is activated immediately to provide a local audio alert indicating possible power theft. This helps in quick identification and response at the site level.

Module 5: Load Control Mechanism

A two-channel relay module is integrated into the system to control the connected electrical loads. When theft or abnormal usage is detected, the ESP32 automatically disconnects the power supply to the loads. This prevents further energy loss and enhances system safety. The relay can also be controlled manually, if required.

Module 6: IoT Cloud Integration and Remote Monitoring

The ESP32 uses its built-in Wi-Fi to connect to the Blynk IoT cloud platform. All real-time data and alert notifications are transmitted to the cloud, allowing users to monitor the system remotely through a mobile application or web dashboard. This feature enables continuous monitoring from any location and ensures timely response to abnormal conditions.

Module 7: System Operation Flow

The overall system operates in a continuous loop where data are collected, processed, analyzed, and transmitted. The process includes real-time measurement, threshold comparison, alert generation, load control, and cloud communication. This ensures efficient and uninterrupted monitoring of energy usage and quick detection of power theft.

IV. EXISTING SYSTEM

The existing energy monitoring systems mainly depend on traditional meters and manual processes. Conventional electromechanical meters measure only cumulative energy consumption and are prone to tampering, such as bypassing and external interference. Basic electronic meters provide better accuracy but still lack real-time monitoring and automatic theft detection.

In most cases, meter readings are collected manually at regular intervals, which is time-consuming and unable to detect theft immediately. Automated Meter Reading (AMR) systems allow remote data collection but do not support real-time analysis or anomaly detection.

Some IoT-based systems are available, but they often use low-accuracy sensors and lack proper alert and control mechanisms. Although Advanced Metering Infrastructure (AMI) systems provide advanced features such as real-time monitoring and remote control, they are expensive and not suitable for small-scale applications.

Overall, existing systems are limited by the lack of real-time monitoring, automatic theft detection, and remote control capabilities.

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V. PROPOSED SYSTEM

The proposed system is a privacy-preserving smart energy monitoring and power theft detection system based on IoT technology. It is designed to provide real-time monitoring, automatic theft
detection, and remote control of electrical loads in an efficient and cost-effective manner.

The system uses a PZEM-022 AC digital power meter along with a current transformer (CT) clamp to measure electrical parameters such as voltage, current, power, and energy consumption. These values are continuously sent to the ESP32 microcontroller, which acts as the central processing unit.

The ESP32 analyzes the received data and compares it with predefined threshold values to detect abnormal energy usage. If any unusual variation is detected, it is considered as a possible power theft or unauthorized usage. The system immediately activates a buzzer to provide a local alert and also disconnects the load using a relay module to prevent further energy loss.

A 16×2 LCD display is used to show real-time electrical parameters at the installation site, enabling easy monitoring. Additionally, the ESP32 connects to the Blynk IoT cloud platform through its built-in Wi- Fi and transmits real-time data and alert notifications. This allows users to monitor the system remotely through a mobile application or web dashboard.

The proposed system offers advantages such as real-time multi-parameter monitoring, automatic theft detection, instant alert generation, remote monitoring, and load control. It provides a reliable, scalable, and cost effective solution for reducing power theft and improving energy management in residential, industrial, and smart grid applications.

VI. SYSTEM DESIGN

The system design of the Smart Energy Monitoring and Power Theft Detection System focuses on a simple, efficient, and IoT-based architecture to ensure real-time monitoring and effective control of electrical energy usage. The design integrates energy measurement modules, processing units, display components, alert systems, and cloud connectivity into a compact and reliable structure.

The core components of the system include a PZEM-022 AC digital power meter, current transformer (CT) clamp, ESP32 microcontroller, 16×2 LCD display, relay module, buzzer, and IoT cloud platform. The PZEM-022 module, along with the CT clamp, is used to measure electrical parameters such as voltage, current, power, and energy consumption in real time. The CT clamp is placed around the live wire to ensure safe and non-invasive measurement of current.

The sensor outputs are transmitted to the ESP32 microcontroller through serial communication. The ESP32 processes the received data and performs real-time analysis by comparing the measured values with predefined threshold limits. Based on this comparison, the system identifies abnormal energy consumption patterns that may indicate power theft, unauthorized usage, or meter tampering.

A 16×2 LCD display is used to present real-time electrical parameters at the installation site. This allows users to easily monitor system performance without the need for external devices. The processed data is also used to trigger alert and control mechanisms.

The system incorporates an alert and control mechanism to enhance safety and response. A buzzer is activated when abnormal energy usage is detected, providing an immediate local alert. At the same time, a relay module is used to automatically disconnect the electrical load to prevent further energy loss and ensure system protection.

The system also integrates IoT functionality for remote monitoring and control. The ESP32 connects to the Blynk IoT cloud platform using built-in Wi-Fi. Real-time data and alert notifications are transmitted to the cloud, enabling users to monitor the system through a mobile application or web interface from any location.

The system is powered using a regulated power supply unit that ensures stable voltage for all components. All hardware components are integrated into a compact and secure setup, ensuring proper connectivity, durability, and ease of installation.

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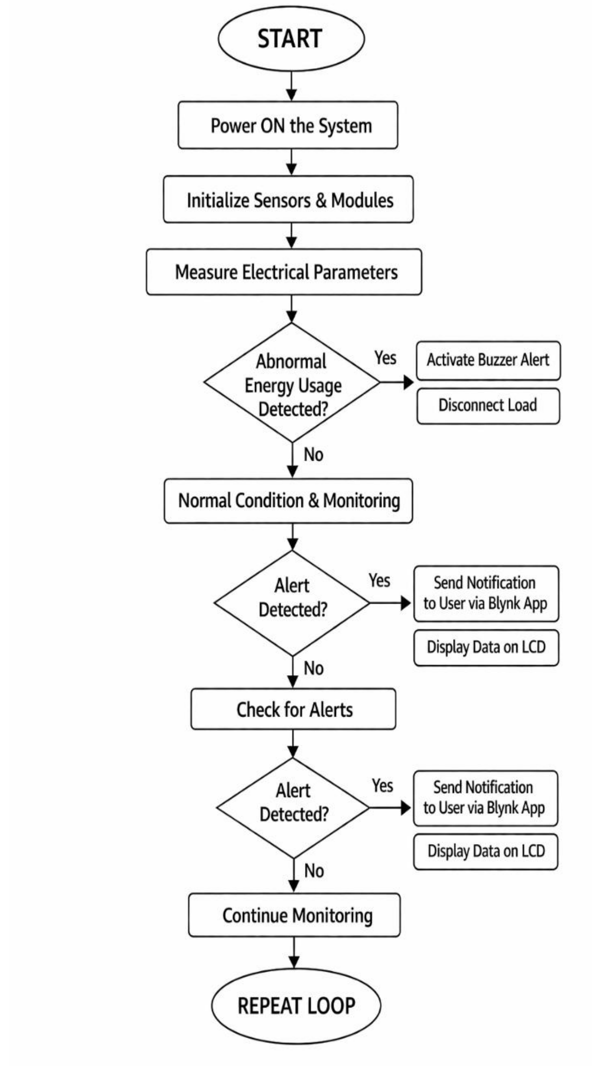

Fig 1 – Flow chart

Overall, the system design emphasizes simplicity, accuracy, reliability, and cost-effectiveness. By combining real-time monitoring, automatic theft detection, alert generation, remote access, and load control, the system provides an efficient and practical solution for smart energy management.

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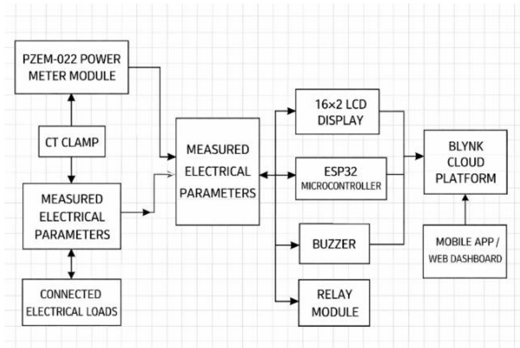

Fig2-Block Diagram

VII. COMPONENTS

1. PZEM-022 AC Power Meter: The PZEM-022 module is used to measure electrical parameters such as voltage, current, power, and energy consumption. It provides accurate real-time data and communicates with the microcontroller through serial communication.
2. Current Transformer (CT) Clamp: The CT clamp is used to measure the current flowing through the electrical line. It is placed around the live wire without direct electrical contact, ensuring safe and non-invasive current measurement.
3. ESP32 Microcontroller: The ESP32 acts as the main processing unit of the system. It receives data from the PZEM-022 module, processes it, and performs analysis to detect abnormal energy usage. It also handles communication with the IoT platform.
4. 16×2 LCD Display: The LCD display is used to show real-time electrical parameters such as voltage, current, power, and energy consumption. It helps users monitor system performance directly at the installation site.
5. Relay Module: The relay module is used to control electrical loads. When abnormal energy usage or power theft is detected, the relay automatically disconnects the load to prevent further energy loss.
6. Buzzer: The buzzer is used to provide an immediate local alert when power theft or abnormal conditions are detected. It helps in quick identification of issues at the site.
7. IoT Cloud Platform (Blynk): The Blynk platform is used for remote monitoring and control. The ESP32 sends real-time data and alert notifications to the cloud, allowing users to monitor the system through a mobile application or web dashboard.
8. Wi-Fi Communication (Built-in ESP32): The ESP32 has an inbuilt Wi-Fi module that enables wireless communication with the cloud platform. It ensures real-time data transmission and remote accessibility.
9. Power Supply Unit: The system is powered using a regulated power supply that provides stable voltage to all components. It ensures proper functioning and protects the system from voltage fluctuations.
10. Electrical Load (Bulbs/Appliances): The connected electrical loads represent the devices being monitored. These loads are controlled by the relay module and are automatically disconnected during power theft detection.

VII. OUTPUT AND RESULT

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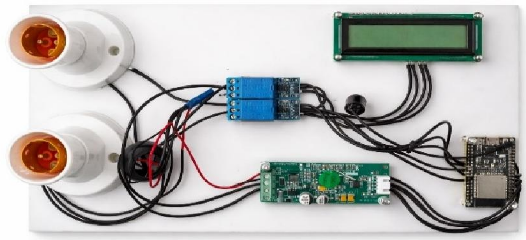

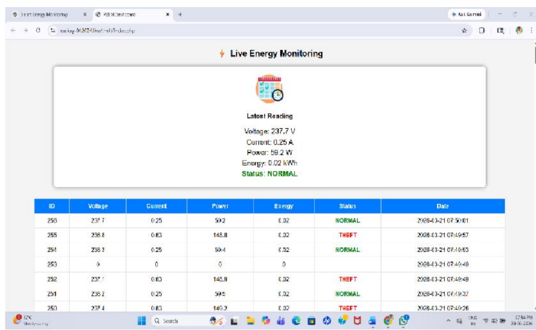

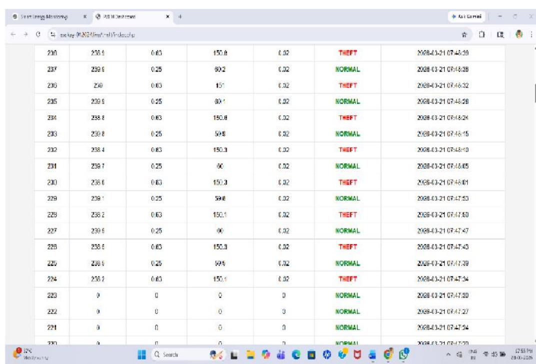

IX. CONCLUSIONS

The Smart Energy Monitoring and Power Theft Detection System provides an efficient and reliable solution for reducing power losses and improving energy management using IoT technology. The system successfully measures real-time electrical parameters such as voltage, current, power, and energy consumption using the PZEM-022 module and processes the data using the ESP32 microcontroller.

By analyzing energy consumption patterns and comparing them with predefined threshold values, the system is able to detect abnormal usage that may indicate power theft or unauthorized access. The integration of a buzzer and relay module ensures immediate local alert and automatic load disconnection, which helps prevent further energy loss and enhances system safety.

The use of the Blynk IoT cloud platform enables real-time remote monitoring and alert notifications, allowing users to access system data from anywhere. The inclusion of a 16×2 LCD display also provides easy on-site monitoring of electrical parameters.

Overall, the proposed system is simple, cost-effective, and practical for real-world applications. It improves transparency, reduces financial losses due to power theft, and supports efficient energy utilization. This system can be

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effectively implemented in residential, industrial, and smart grid environments for better energy management and control.

X. FUTURE SCOPE

1.Three-Phase Monitoring : Add three PZEM-004T modules to support three-phase industrial power monitoring with independent theft detection for each phase.

2.AES Encrypted Data Transmission: Implement AES-128 or AES-256 encryption of energy data payloads before cloud transmission to provide a true privacy-preserving secure communication layer.

3. GSM Backup Communication: Add a SIM800L or SIM7600 GSM module to enable SMS alerts and data transmission when Wi-Fi internet connectivity is unavailable.

4. OLED or TFT Display Upgrade: Replace the 16x2 LCD with a graphical OLED or TFT display to show real-time energy consumption bar graphs and trend charts at the installation site.

5. Blockchain-Based Tamper-Proof Logging: Store energy meter readings on a blockchain network to create an immutable and tamper-proof consumption record that cannot be altered even if the cloud database is compromised.

6. Machine Learning Anomaly Detection: Implement an ML-based consumption pattern analysis model trained on historical PZEM data that can detect subtle theft patterns that simple threshold comparison misses.

7. PZEM Energy Reset Prevention: Add cryptographic locking of the PZEM-004T energy reset command so that the energy counter can only be reset by authenticated utility personnel preventing concealment of theft.

8. Battery Backup Power: Add a UPS or battery backup circuit to maintain system operation during mains power failures ensuring continuous monitoring when power is most likely to be manipulated.

9. Multi-Meter Network Dashboard: Deploy multiple units across a distribution network all reporting to a centralized web dashboard giving utility operators a complete network-wide theft monitoring view.

10. Automated Billing Integration: Connect the energy accumulation data from the PZEM-004T to an automated billing system that generates consumption-based invoices directly from measured energy data.

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