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IOT-BASED LOW-COST SMART ENERGY METER USING ESP32 FOR REAL-TIME MONITORING AND LOAD MANAGEMENT

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ABSTRACT

The increasing demand for electricity and the limitations of traditional metering systems require smarter monitoring solutions. This work presents a low-cost IoT-based smart energy meter using the ESP32 microcontroller. The system measures real-time voltage, current, power factor, and energy consumption, and sends the data wirelessly to a cloud platform. Users can monitor energy usage remotely and receive alerts for abnormal consumption. The system improves transparency, reduces manual effort, and supports remote load control, making it suitable for residential and small-scale industrial applications.

Keywords: IoT, Smart Energy Meter, ESP32, Voltage Sensor, Current Sensor, Real-Time Monitoring, Load Management

I. INTRODUCTION

Electricity consumption has increased significantly due to urbanization, industrial expansion, and the widespread use of electrical appliances. Conventional electromechanical and digital meters primarily provide cumulative readings and require manual intervention for data collection. This approach is labor-intensive, prone to human error, and incapable of offering real-time monitoring.Smart metering systems based on IoT technology enable automated data acquisition, remote access, and advanced analytics. By integrating sensing devices with wireless communication modules, real-time monitoring of electrical parameters becomes possible. This paper proposes an IoT-enabled smart energy meter using the ESP32 microcontroller to provide accurate measurement and remote accessibility at a low implementation cost.

II. LITERATURE REVIEW

Recent research in IoT-based energy monitoring highlights the shift from manual metering toward intelligent, network-connected systems. Various studies have implemented microcontroller-based smart meters using GSM, Wi-Fi, and cloud platforms. However, many existing systems suffer from high deployment costs, limited scalability, or complex architecture.Microcontroller platforms such as Arduino and ARM-based systems have been widely used. The ESP32 offers significant advantages, including built-in Wi-Fi, Bluetooth connectivity, dual-core processing capability, low power consumption, and high-speed data handling. These features make it an ideal candidate for smart energy metering applications.Despite technological advancements, challenges remain in ensuring data security, measurement accuracy, and affordability. The proposed system addresses these issues by combining efficient hardware design with optimized software architecture.

III. PROBLEM STATEMENT

Traditional energy metering systems have several limitations. Manual meter reading leads to operational inefficiency, while delayed billing cycles prevent real-time energy management. The lack of remote monitoring reduces user awareness of energy usage, and the absence of tamper detection mechanisms can affect system reliability. Additionally, these systems have limited capability for load control and automation. Therefore, there is a need for a cost-effective, accurate, and remotely accessible energy monitoring solution that minimizes human involvement and improves overall operational efficiency.

IV. PROPOSED SYSTEM ARCHITECTURE

A.System Overview

The proposed system consists of an ESP32 microcontroller, a voltage sensor module (ZMPT101B), a current sensor (SCT-013), a power supply unit, a Wi-Fi communication interface, and a cloud platform or mobile application. The system measures voltage and current signals, calculates power parameters, and transmits the collected data to a remote server through Wi-Fi for monitoring and analysis.

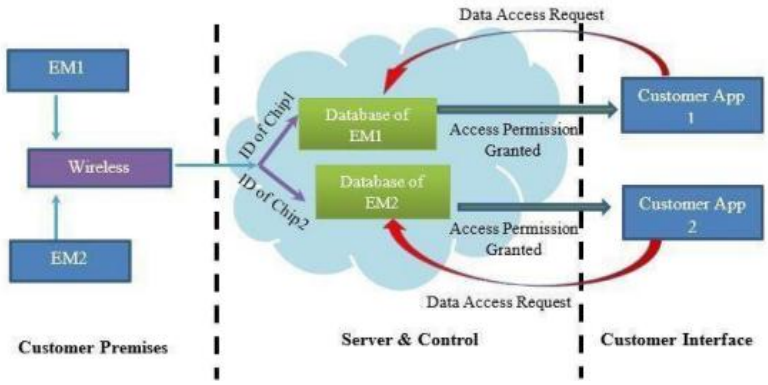


Fig: 4.1.1 Model Diagram of Proposed System

B. Hardware Components

i.ESP32 Microcontroller

The ESP32 is a 32-bit dual-core microcontroller with integrated Wi-Fi and Bluetooth capabilities. Its high processing speed and multiple GPIO pins allow it to handle both data acquisition and communication tasks simultaneously. It operates at a clock speed of up to 240 MHz and includes 12-bit ADC channels for accurate analog signal reading. The microcontroller also supports integrated Wi-Fi (802.11 b/g/n), low power operation, and advanced security features such as secure boot and encryption support.

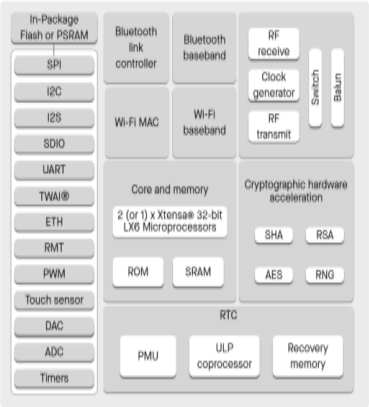


Fig:4.2.1.1 ESP32 Functional Block Diagram

ii.Current Measurement

The SCT-013 non-invasive current sensor measures AC current using electromagnetic induction. It provides isolation and ensures user safety while monitoring current flow. The output signal is conditioned and fed into the ESP32 ADC for processing.

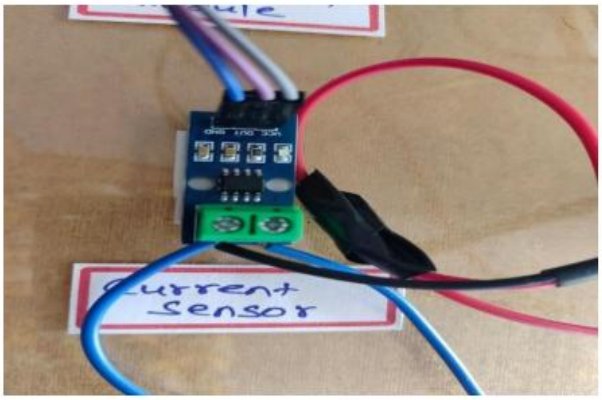


Fig:4.2.2.1 Current Sensor

iv. Voltage Measurement

The ZMPT101B voltage sensor module is used to measure AC voltage. It provides galvanic isolation and converts high AC voltage into a measurable low-voltage signal suitable for microcontroller input.



Fig: 4.2.3.1 Voltage Sensor

C. Working Principle

The voltage and current sensors continuously measure electrical parameters. The ESP32 reads the analog signals and calculates RMS voltage, RMS current, real power, apparent power, power factor, and energy consumption (kWh). The processed data is then transmitted to a cloud server through Wi-Fi. Users can monitor their energy usage using a web or mobile application. Additionally, an optional relay control feature allows remote switching of electrical loads

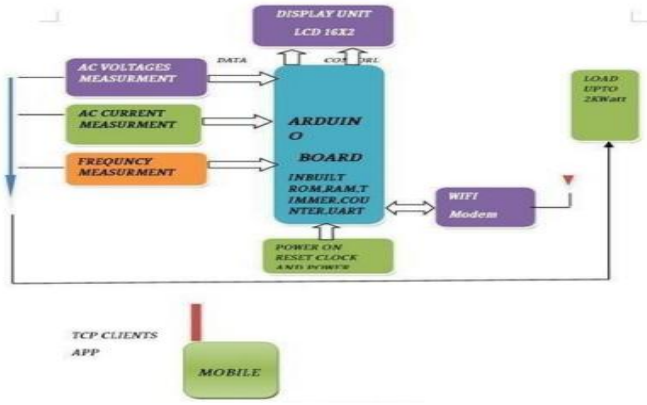


Fig : 4.3.1 Block Diagram of IoT Meter

V. SOFTWARE DESIGN

The system software includes embedded firmware for the ESP32, data acquisition algorithms, a Wi-Fi communication protocol, a cloud integration platform, and a user interface dashboard. The firmware is developed using the Arduino IDE. Sensor calibration routines are implemented to ensure accurate measurements, and the collected data is transmitted to the cloud using HTTP or MQTT protocols for reliable communication.

VI. EXPERIMENTAL RESULTS

The prototype was tested under various load conditions. The results showed accurate voltage measurement with an error margin of ±1% and current measurement accuracy within ±3%. The system maintained stable Wi-Fi connectivity for continuous data transmission, and the dashboard displayed real-time updates without noticeable delay. Remote switching of the connected load was also successfully performed. Overall, the system demonstrated consistent performance under residential load conditions up to 20A.

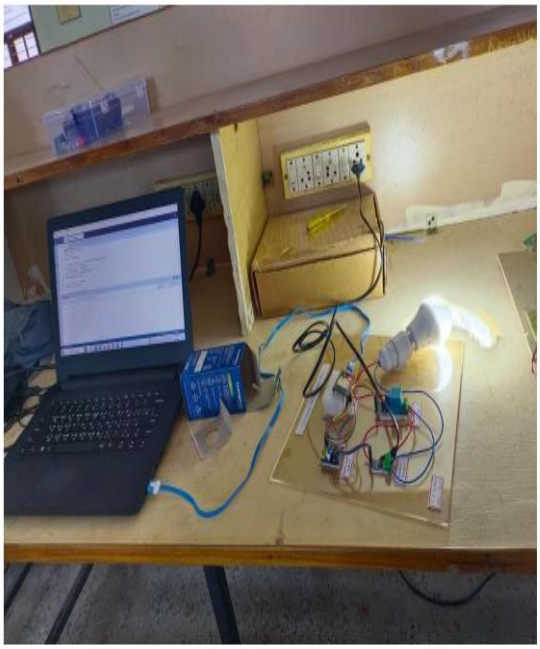


Fig:6.1 Overall IoT Meter Kit

Display results

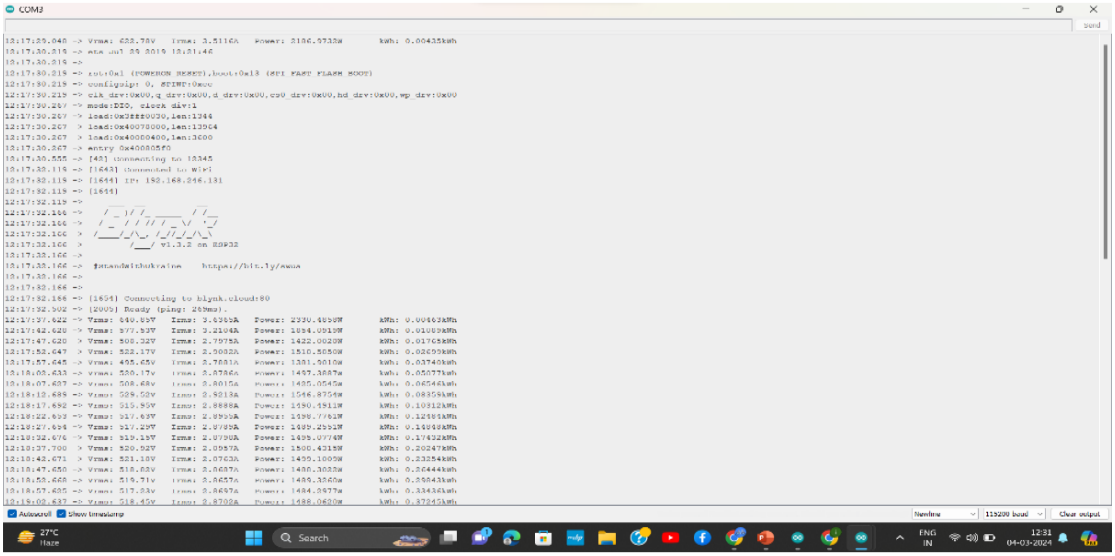


Fig: 6.2 The above Figure displays the results in Laptop

VI. BENEFITS

The system eliminates the need for manual meter reading and enables real-time energy monitoring. It helps reduce operational costs and supports remote load control for better energy management. Additionally, it can detect abnormal power consumption and is scalable for smart grid applications. The system is also cost-effective due to its low implementation cost.

VIII. CONCLUSION& FUTURE SCOPE

This paper presents a low-cost IoT-based smart energy meter using the ESP32 microcontroller. The system effectively measures electrical parameters and provides real-time remote monitoring capabilities. Compared to traditional metering systems, the proposed solution enhances efficiency, transparency, and energy management. The experimental results confirm accurate measurement and reliable communication performance.The architecture is scalable and suitable for integration into future smart grid networks.The future of IoT-based low-cost energy meters lies in better data analytics and AI integration. These technologies enable predictive maintenance, anomaly detection, and energy forecasting. By analyzing usage data, the system can optimize energy consumption and provide personalized energy management, improving efficiency and reducing energy waste.

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