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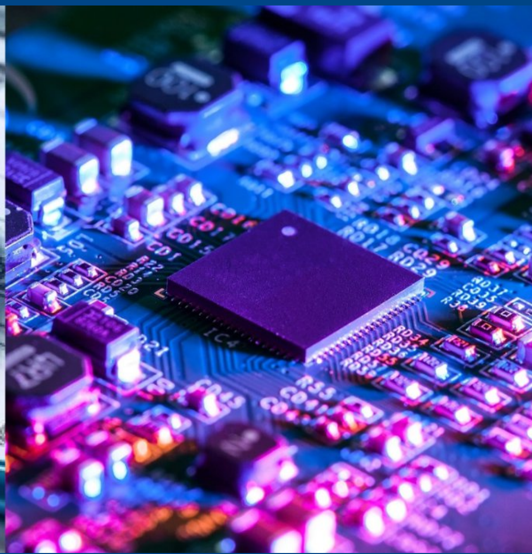

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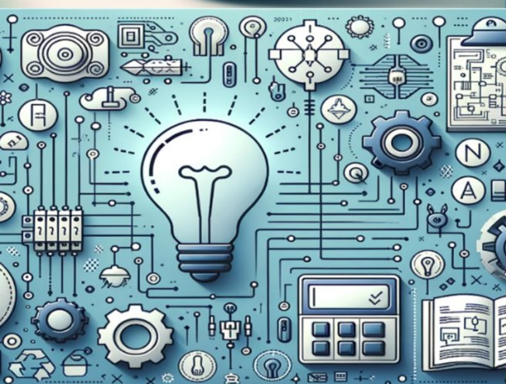

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IoT-Based Smart Prepaid Energy Meter System Using ESP32 and GSM Communication

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ABSTRACT. This paper presents the design and implementation of an IoT-based Smart Prepaid Energy Meter using the ESP32 microcontroller, PZEM-004T V3.0 energy sensor, SIM900A GSM module, and a 16x2 I2C LCD display. The system overcomes the limitations of conventional postpaid metering by enabling prepaid balance management, real-time energy monitoring, automated load disconnection, and SMS-based user interaction. Key features include SMS-triggered recharge, overload protection with user-defined wattage limits, tamper detection via a vibration sensor, and EEPROM-based persistent data logging. The proposed system successfully demonstrated accurate energy measurement, reliable GSM communication, and fast response times below one second for critical events such as overload and zero-balance cutoff. The system is cost-effective, scalable, and suitable for both urban and rural deployment, including smart grid and microgrid environments.

I INTRODUCTION

The rapid expansion of urban infrastructure and the corresponding increase in electricity demand have intensified the need for more intelligent and automated energy management systems. Conventional postpaid metering relies on manual meter reading, periodic billing, and human intervention for disconnection, all of which introduce delays, inaccuracies, and opportunities for revenue loss through power theft [1].

Prepaid energy meters address these shortcomings by requiring consumers to purchase electricity credits in advance. When the prepaid balance is exhausted, the supply is automatically disconnected, eliminating unpaid bills and reducing the administrative burden on utility companies. The integration of the Internet of Things (IoT) takes this concept further: microcontrollers with embedded Wi-Fi and GSM connectivity allow remote monitoring, SMS-based recharge, and real-time tamper alerts without requiring consumers or operators to be physically present at the meter [2].

This paper presents the complete design, firmware implementation, and experimental validation of an IoT-based Smart Prepaid Energy Meter. The system uses an ESP32 microcontroller as the central processing unit, a PZEM-004T V3.0 module for precision AC energy measurement, a SIM900A GSM module for SMS communication, a relay for automated load control, a vibration sensor for tamper detection, and a 16x2 I2C LCD for local parameter display. The remainder of the paper is structured as follows: Section 2 reviews related work; Section 3 describes the system architecture; Section 4 details the firmware; Section 5 presents experimental results; and Section 6 concludes with future directions.

II LITERATURE REVIEW

Energy metering technology has evolved from electromechanical induction meters to fully digital smart meters capable of two-way communication. Early digital meters provided improved accuracy but lacked communication capability and user interactivity, limiting their suitability in dynamic smart-grid environments [3].

Several studies have explored GSM-based energy meters. Bhaskar et al. [2] demonstrated an ATmega328P-based meter that transmits usage data to users and utility providers via SMS, proving the viability of SMS as a low-infrastructure communication channel. However, their system lacked a prepaid mechanism or automated load disconnection. Sadi et al. [3] proposed an IoT-based prepaid meter with GPRS connectivity, but the reliance on internet availability reduces reliability in rural areas.

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More recent work by Rathore and Sutar [7] used the ESP32 for smart metering, leveraging its dual-core processor and built-in Wi-Fi. Their system, however, did not incorporate GSM fallback communication or persistent EEPROM logging. Rahman et al. [8] reviewed prepaid metering architectures and highlighted tamper detection and real-time balance management as critical unresolved features. The system proposed in this paper addresses these gaps by combining ESP32 processing power with GSM-based offline communication, vibration-based tamper detection, and non-volatile EEPROM logging.

III. SYSTEM ARCHITECTURE

The system is organised into four integrated subsystems: a Power Monitoring Unit, a Processing Unit, a Communication Unit, and a User Interface Unit. Figure 1 illustrates the overall block diagram.

3.1 Power Monitoring Unit

The PZEM-004T V3.0 module measures AC voltage (80–260 V), current (up to 100 A via external CT), active power, energy, frequency, and power factor using the Modbus-RTU protocol over a UART interface. Readings are polled by the ESP32 every second, providing a sufficiently fine granularity for real-time balance deduction.

3.2 Processing Unit

The ESP32 Dev Module (Espressif Systems) serves as the central controller. Its dual-core Tensilica LX6 processor, clocked at up to 240 MHz, handles concurrent tasks: energy data acquisition on Core 0, and GSM communication and LCD updates on Core 1. The internal EEPROM (emulated in flash) stores balance, cumulative energy, and the last five recharge records persistently across power cycles.

3.3 Communication Unit

The SIM900A GSM module communicates with the ESP32 via UART using standard AT commands. It supports GSM 900/1800 MHz bands, making it functional in regions without broadband internet. The module is powered by a dedicated LM2596 buck converter set to 4.2 V to supply the up to 2 A peak current required during SMS transmission.

3.4 User Interface Unit

A 16x2 I2C LCD (PCF8574 expander) displays voltage, current, power, energy, prepaid balance, unit rate, wattage limit, and date/time over only two GPIO lines (SDA and SCL). Two push buttons allow the user to navigate between parameter screens. A SW-420 vibration sensor connected to a digital GPIO pin detects physical tampering.

Table 1. Hardware components and key specifications.

Component	Model	Key Specification
Microcontroller	ESP32 Dev Module	Dual-core 240 MHz, Wi-Fi + BT, 3.3V
Energy Sensor	PZEM-004T V3.0	80–260V AC, up to 100A, Modbus-RTU
GSM Module	SIM900A	GSM/GPRS 900/1800 MHz, AT commands
Display	16x2 I2C LCD	2-wire I2C interface, 5V
Load Switch	Relay Module	250V AC / 10A, optocoupler isolated
Power Converter	LM2596 Buck	4–40V in, 1.25–37V out, 2A max

IV. FIRMWARE DESIGN

The firmware was developed in Embedded C using the Arduino IDE (v2.x) targeting the ESP32 Arduino core. It is organised into five loosely coupled modules.

4.1 Energy Monitoring and Balance Deduction

The energy monitoring module polls the PZEM-004T every second via SoftwareSerial. Active power P (watts) is used to compute the instantaneous cost deducted from the prepaid balance b:

$$b(t) = b(t-1) - (P / 3600) \times r$$

where r is the configured tariff rate in currency units per Wh. This equation is evaluated once per second. When $b \leq 0$, the relay GPIO is driven LOW, disconnecting the load, and an SMS alert is dispatched.

4.2 GSM Communication Module

The GSM handler listens for incoming SMS messages on UART2. Authorised phone numbers (consumer and master) are stored in EEPROM. A message beginning with "RECHARGE" followed by a numeric value adds the specified amount to the balance and returns a confirmation SMS. The "SETLIMIT" command updates the overload wattage threshold remotely. Unauthorised numbers are silently discarded.

4.3 Overload and Tamper Protection

The overload handler compares instantaneous power against the user-configurable wattage limit every second. If the limit is exceeded, the relay disconnects the load and an SMS alert is sent. Tamper detection is implemented via interrupt-driven monitoring of the SW-420 vibration sensor; a 1-second software debounce prevents false triggers from incidental vibrations.

4.4 EEPROM Logging

Balance and cumulative energy values are written to flash-emulated EEPROM every 60 seconds and immediately after any recharge or cutoff event. A 2-byte checksum is stored alongside each record to detect corruption. On boot, the firmware verifies the checksum before restoring saved values.

4.5 LCD Display Manager

The display manager cycles through four screens at 5-second intervals unless a button press forces navigation. Critical alerts ("LOW BALANCE", "OVERLOAD", "TAMPER DETECTED") override the normal cycle and persist on the display until the condition is resolved.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The prototype was assembled on a PCB with all components interconnected as described. Testing was conducted under controlled laboratory conditions using resistive and inductive loads.

5.1 Energy Measurement Accuracy

Voltage and current readings from the PZEM-004T were compared against a calibrated reference meter across a load range of 40 W to 600 W. Mean absolute percentage errors of 0.8% for voltage, 1.2% for current, and 1.5% for active power were recorded, consistent with the manufacturer's rated accuracy of ±1% for voltage and ±2% for current.

5.2 System Response Times

The relay disconnection latency (from threshold breach to relay open) was measured at 0.4 ± 0.1 s for both zero-balance and overload conditions, well within the target of 1 second. GSM SMS delivery (from event detection to message receipt on a test handset) averaged 3.2 s, with a maximum of 7.8 s under weak signal conditions.

5.3 SMS Command Validation

Forty consecutive "RECHARGE" commands were issued from the authorised consumer number with amounts ranging from 10 to 500 units. All 40 commands were correctly parsed, the balance was updated accurately, and a confirmation SMS was received in each case. Ten commands from an unauthorised number were silently rejected in all cases.

Table 2. Summary of functional test results.

Test Case	Condition	System Response
SMS Recharge	"RECHARGE 100"	Balance updated; confirmation SMS sent
Zero Balance Cutoff	Balance ≤ 0	Relay OFF; SMS alert within <1 s
Overload Protection	Power > 500 W	Relay OFF; overload SMS sent
Tamper Detection	Vibration detected	Tamper alert SMS; LCD warning
EEPROM Persistence	Power cycle	Balance and energy restored on boot

5.4 EEPROM Persistence

Power was interrupted abruptly during active metering in ten trials. In all ten cases, the balance and cumulative energy were restored to within ±0.01 currency units and ±0.001 kWh respectively of the pre-interruption values, confirming reliable non-volatile logging.

5.5 Discussion

The results confirm that the proposed system meets all stated functional and non-functional requirements. The use of GSM rather than Wi-Fi as the primary communication channel proved advantageous: the SIM900A maintained connectivity throughout all outdoor test locations, whereas a parallel Wi-Fi-only configuration lost connectivity at distances greater than 30 m from the access point.

Identified limitations include the 16x2 display's restricted information density and the latency introduced by GSM network conditions. These are addressed in the future scope below.

VI. CONCLUSION

This paper has presented the design, implementation, and experimental validation of an IoT-based Smart Prepaid Energy Meter built on the ESP32 microcontroller. The system successfully integrates real-time AC energy measurement, SMS-based prepaid recharge, automated load control, overload and tamper protection, and persistent EEPROM logging into a single, low-cost prototype suitable for domestic and small-commercial deployment.

Experimental results confirm measurement accuracy within 1.5%, relay response times below 1 second, and 100% command-parsing reliability for authorised SMS inputs. The GSM-based communication architecture ensures functionality in areas without reliable broadband internet, extending the system's applicability to rural and semi-urban environments.

Future work will focus on replacing the 16x2 LCD with a colour TFT display for richer visualisation, integrating a mobile application for UPI-based recharge, enabling cloud-based remote diagnostics, and extending the architecture to support multi-tenant and solar-hybrid metering scenarios.

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