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IoT-Based Smart Energy Meter with Real-Time Monitoring, Prepaid Billing and Tamper Detection

Mali Prashant Mohan[1],Shruti Sunil Bunge[2]and Dhanshri Shantaram Dhanwate[3]

Department of Electrical Engineering, NIT's Late Annasaheb Patil Polytechnic,Nashik,Maharashtra,India
pm9583428@gmail.com, shrutibunge30@gmail.com, dhanshridhanwate96@gmail.com

ABSTRACT—

Conventional electromechanical energy meters need manual reading, give the consumer no visibility of usage and are easy to tamper with. This paper presents the design and simulation of a low-cost smart energy meter based on the ESP32 microcontroller and the PZEM-004T energy-monitoring module. The meter measures voltage, current, active power, power factor and energy in real time, calculates the bill with a slab tariff, supports prepaid operation with a remote-disconnect relay, and publishes data to a cloud dashboard over Wi-Fi using the MQTT protocol. A second current transformer on the neutral conductor allows bypass-type energy theft to be detected within 10 s. The measurement chain, a household load model and the billing logic are evaluated by simulation. The modelled power error stays within ±0.4% (1σ) for loads above 250 W, the daily energy error is 0.31% on average, and a 3.6 MWh/yr household is billed correctly under a four-slab tariff. The components cost about ₹2,550, which makes the design attractive for large-scale metering in developing regions.

Index Terms—Smart energy meter, Internet of Things, ESP32, MQTT, prepaid metering, energy theft detection, PZEM-004T.

I. INTRODUCTION

Electricity distribution utilities lose a large part of the energy they purchase through technical losses, billing errors and theft. Manual meter reading is slow and expensive, bills are often estimated, and consumers see their consumption only once a month, too late to change their behaviour. Smart metering addresses these problems by measuring energy digitally, recording it frequently and communicating it automatically. In India, prepaid smart metering is a central part of the Revamped Distribution Sector Scheme (RDSS) of the Government of India [1].

A smart meter is more than a digital watt-hour meter. It adds two-way communication, remote connection and disconnection, tariff handling and tamper alarms, and it gives data for load forecasting and demand response [2], [3]. Commercial smart meters meet these requirements but are costly for small utilities, educational projects and retrofit applications. Open hardware such as the ESP32, which has built-in Wi-Fi, together with a factory-calibrated metering module, can provide most of these functions at a fraction of the cost.

This paper presents an IoT-based smart energy meter with the following contributions: (i) a hardware architecture based on ESP32 and PZEM-004T with a second neutral current sensor; (ii) firmware that provides real-time measurement, slab-tariff billing, prepaid control, overload protection and MQTT telemetry; (iii) a tamper-detection index computed from phase and neutral currents; and (iv) a simulation-based evaluation of measurement accuracy, billing and theft detection using a realistic household load model.

Section II reviews related work, Section III describes the architecture, Section IV gives the measurement and billing equations, Section V explains the firmware, Section VI discusses the results and Section VII concludes the paper.

II. RELATED WORK

Surveys of smart metering cover the measurement units, the communication technologies (power-line carrier, ZigBee, GSM and Wi-Fi) and the data-management layers of the advanced metering infrastructure (AMI) [4]. Wi-Fi is attractive for indoor meters because the infrastructure already exists and no recurring cellular charges are required. Fine-grained metering data also makes non-intrusive appliance load monitoring possible, in which the on/off events of individual appliances are identified from the aggregate power signal [5]. At the same time, the load of a household is a valuable record that raises privacy concerns, so secure communication is necessary. Energy theft, mostly by bypassing the meter or reversing connections, remains the main source of non-technical loss; the AMI can detect it by comparing independent measurements of the same quantity [6]. The present design follows this idea at the meter level by comparing the phase and neutral currents.

III. SYSTEM ARCHITECTURE

A. Overall Architecture

The meter, shown in Fig. 1, has three layers. The power path carries the mains supply through a miniature circuit breaker (MCB) with a surge protector and a 30 A disconnect relay to the consumer. The sensing and control layer measures the line quantities and decides on protection and billing. The communication layer sends the data to a cloud broker, from which a web or mobile application displays it and sends alerts. A flash memory stores the accumulated energy so that no reading is lost during a power failure.

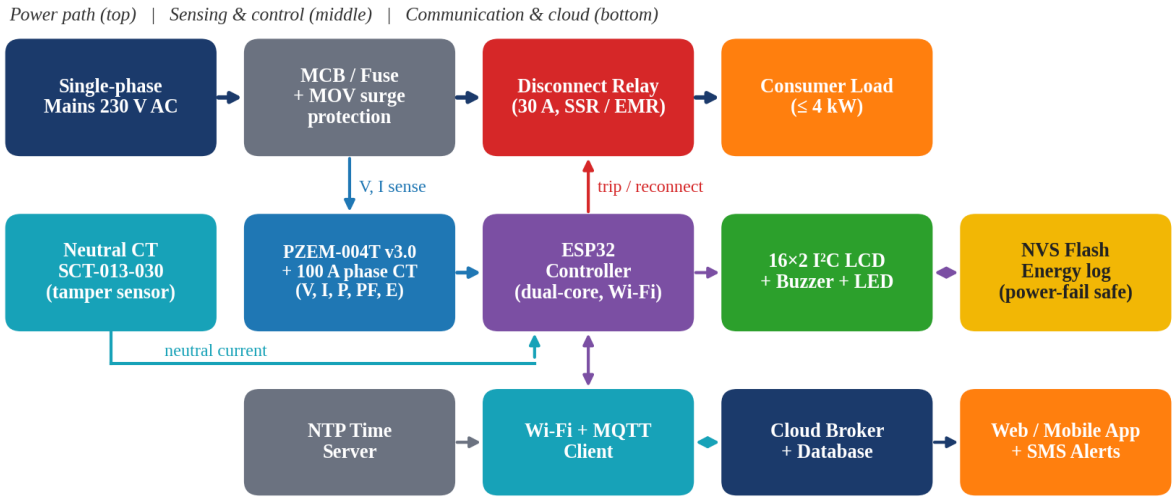


Fig. 1. Block diagram of the proposed IoT-based smart energy meter.

B. Sensing Unit

The PZEM-004T v3.0 module measures voltage, current, active power, frequency, power factor and energy using a dedicated metering chip and a 100 A split-core current transformer (CT), and reports them to the ESP32 over a UART (Modbus-RTU) link [8]. The module has a rated measurement accuracy of 1.0%, which corresponds to the class-1 requirement for static meters [9], [10]. A second non-invasive SCT-013-030 CT is clamped on the neutral conductor. Its output is biased to mid-supply with two 10 kΩ resistors and a 10 µF capacitor and is read by the 12-bit ADC of the ESP32, as shown in Fig. 2. Comparing the phase current I_p from the PZEM with the neutral current I_n reveals a bypass or earth leakage.

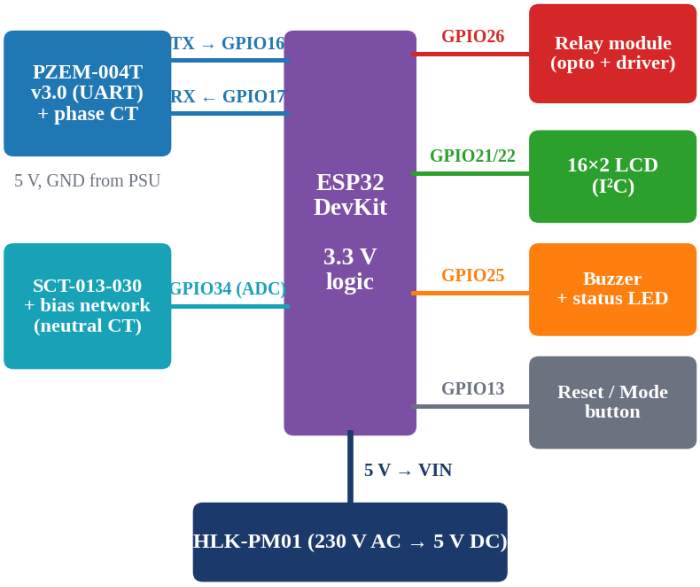


Fig. 2. Hardware connections between the ESP32, sensing modules and peripherals.

C. Controller, Display and Disconnect Relay

An ESP32 DevKit (dual-core 240 MHz, Wi-Fi and Bluetooth) [7] is the central controller. A 16 × 2 I²C LCD shows the instantaneous power, accumulated energy, present bill and prepaid balance. A 30 A relay module with an optocoupler driver opens the supply to the consumer when a fault, overload or zero balance occurs. A buzzer and status LED signal alarms. The 230 V supply is converted to 5 V by an isolated HLK-PM01 power module. Table I lists the specifications and Table II the pin connections.

TABLE I

Specifications of the Smart Meter

Parameter	Specification
Supply / frequency	230 V ±20%, 50 Hz, single phase
Metering module	PZEM-004T v3.0, 100 A CT
Measured quantities	V, I, P, PF, f, E (kWh)
Rated accuracy	1.0% (class 1 target)
Sanctioned load	4 kW; relay trip at 10 s overload
Controller	ESP32 DevKit (Wi-Fi, 12-bit ADC)
Communication	Wi-Fi, MQTT 3.1.1, 5 s interval
Storage	ESP32 NVS flash, saved every 15 min
Display / alarm	16×2 I²C LCD, buzzer, LED

TABLE II

ESP32 Pin Connections

Module	Signal	ESP32 pin
PZEM-004T	TX / RX	GPIO16 / GPIO17
SCT-013 (neutral)	Analog out	GPIO34 (ADC1)
Relay module	IN	GPIO26
16×2 LCD (I²C)	SDA / SCL	GPIO21 / GPIO22
Buzzer	OUT	GPIO25
Status LED	OUT	GPIO2
Mode button	IN	GPIO13

D. Communication and Cloud

The ESP32 connects to the local Wi-Fi network and publishes a JSON message containing the meter ID, time stamp, V, I, P, PF, E and bill every 5 s to an MQTT broker. MQTT is a light publish/subscribe protocol designed for constrained devices and unreliable networks [11], so it suits a meter that sends small periodic messages. The same broker delivers commands back to the meter, such as remote disconnect, reconnect, tariff update and balance top-up. The time stamp is obtained from an NTP server. Messages are sent over TLS with a per-meter username and password, because load data can reveal the habits of the occupants [12].

IV. DESIGN METHODOLOGY

A. Electrical Measurement

The metering module samples the voltage v_k and current i_k at a high rate and computes the root-mean-square values, active power and power factor over N samples:

$$V_{rms} = \sqrt{((1/N)\,\Sigma\, v_k^2)}, \quad I_{rms} = \sqrt{((1/N)\,\Sigma\, i_k^2)} \quad (1)$$

$$P = (1/N)\,\Sigma\, v_k \cdot i_k, \quad PF = P / (V_{rms} \cdot I_{rms}) \quad (2)$$

The controller reads these values every second ($\Delta t = 1$ s) and accumulates the energy in kilowatt-hours:

$$E_n = E_{n-1} + P_n \cdot \Delta t / 3.6 \times 10^6 \quad (3)$$

B. Slab-Tariff Billing

Indian distribution utilities commonly use an increasing-block (slab) tariff. For a monthly consumption E, a fixed charge F and slab limits U_j with rates r_j, the bill is

$$\text{Bill} = F + \Sigma_j\, r_j \cdot \max(0, \min(E, U_j) - U_{j-1}) \quad (4)$$

An illustrative tariff is used here: F = ₹100, and rates of ₹5.0, ₹8.5, ₹12 and ₹14 per kWh for 0–100, 101–300, 301–500 and above 500 kWh. It is not the tariff of any particular utility and can be changed over MQTT. In prepaid mode the balance is reduced by the cost of the incremental energy and the relay opens when the balance is zero.

C. Tamper Detection

In a healthy single-phase installation the phase and neutral currents are equal. If a part of the load is connected directly to the supply, bypassing the meter, the current seen by the meter in one conductor is lower than that of the other. The tamper index is defined as

$$\delta = |I_p - I_n| / I_p \quad (5)$$

An alarm is raised when δ exceeds 10% in three consecutive samples and the phase current is above 0.5 A, which avoids false alarms from sensor offset at very low loads. The same index also flags earth leakage.

D. Accuracy Model

The measured power is modelled as $P_m = P(1 + g) + o$, where g is a gain error with standard deviation 0.4% and o is an offset error with standard deviation 0.5 W. The percentage error is

$$\varepsilon = 100\,(P_m - P) / P \quad (6)$$

and is compared with the class-1 limits of IEC 62053-21 [9]: ±1.5% for $0.05I_b \le I < 0.1I_b$ and ±1.0% above $0.1I_b$, with I_b = 10 A (about 2.3 kW at 230 V).

V. FIRMWARE AND WORKING

The firmware, written in the Arduino framework, follows the flowchart of Fig. 3. At start-up the meter connects to Wi-Fi and NTP, initializes the PZEM module and restores the stored energy from flash. In every cycle it reads the line quantities and the neutral current, updates the energy and the bill, and then runs three protection checks: overload (power above the sanctioned limit for 10 s), tamper (δ > 10%) and prepaid balance. An overload or empty balance opens the relay, sounds the buzzer and sends a message; a tamper event sends an alert without disconnecting the consumer. The LCD is refreshed every second, telemetry is published every 5 s and the energy is saved to flash every 15 min, which limits flash wear while keeping the possible loss after a power failure below 15 min of consumption.

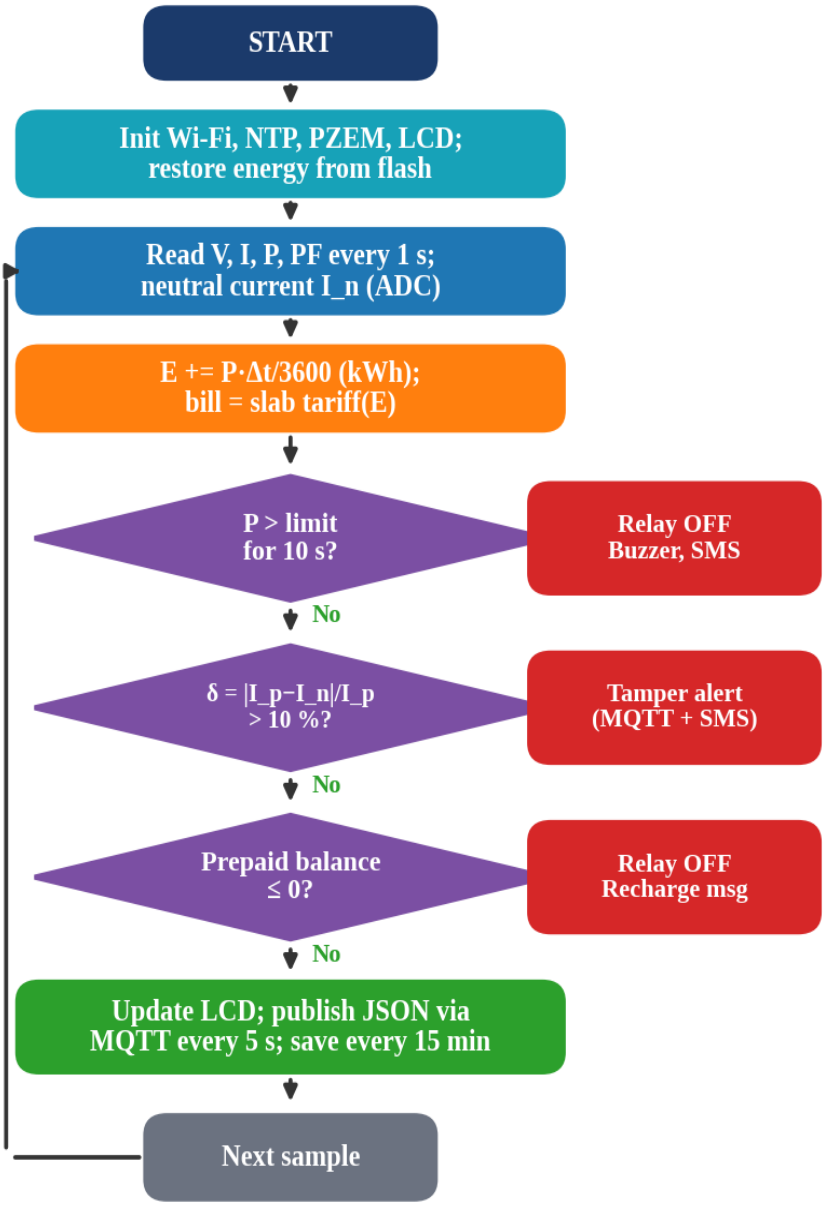


Fig. 3. Flowchart of the smart meter firmware.

VI. RESULTS AND DISCUSSION

A. Simulation Setup

The meter was evaluated with a Python model. A typical 2-BHK household was represented by eight appliance groups (air conditioner, fans, refrigerator, LED lighting, TV, water pump, washing machine and kitchen/miscellaneous loads) with hourly schedules. The cooling load was scaled month by month to follow the Indian climate. The measurement errors follow Section IV-D, and the tariff of Section IV-B is used. All values are model results, not field measurements.

B. Daily Load Profile

Fig. 4 shows the metered power and the cumulative energy of a typical April day. The base load comes from the refrigerator and standby devices, the night-time level from the air conditioner and fans, and the peak of 1.08 kW occurs near 22:40. The household uses 13.8 kWh per day, and the peak is well below the 4 kW sanctioned limit, so no overload trip occurs.

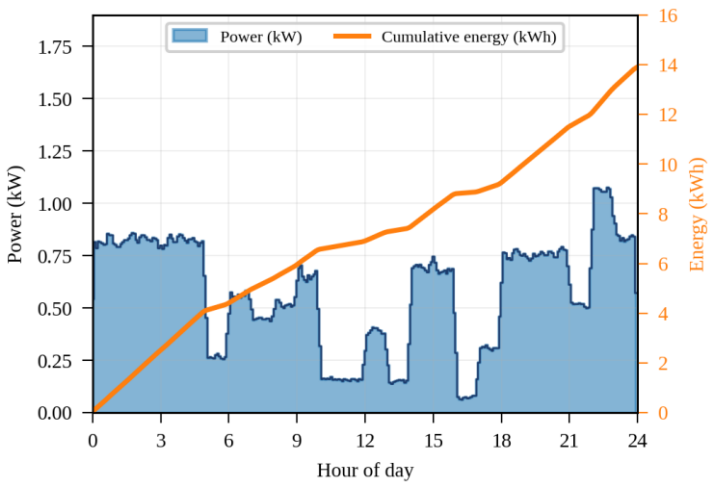


Fig. 4. Metered power and cumulative energy of a typical day.

C. Measurement Accuracy

Fig. 5 and Table III show the power error of the modelled measurement chain. For loads of 250 W and above, the 1σ error is about 0.40–0.45% and the ±2σ band lies within the ±1.0% class-1 limit. At 100–150 W the ±2σ band is slightly larger because the fixed offset becomes relevant, and at 50 W it reaches ±2.2%. Over a complete day the energy error is small, because the positive and negative errors of the individual samples average out: the mean absolute error of the daily energy is 0.31% and the worst case in 2000 trials is 1.37%.

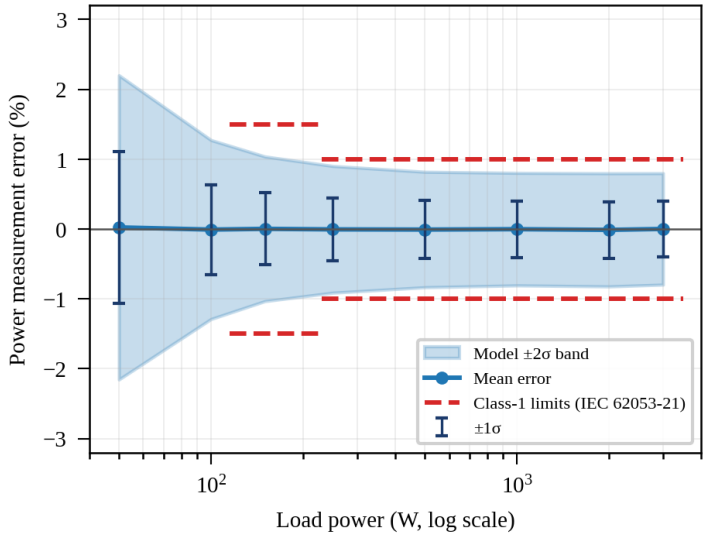


Fig. 5. Modelled power measurement error versus load with the IEC 62053-21 class-1 limits.

TABLE III

Modelled Measurement Error

Load (W)	Mean error (%)	Std. dev. (%)
50	+0.02	1.09
100	−0.01	0.64
250	−0.01	0.45
500	−0.01	0.41
1000	0.00	0.40
3000	0.00	0.40

D. Monthly Consumption and Billing

Fig. 6 shows the monthly energy of the household split by tariff slab, together with the resulting bill. The consumption varies from 197 kWh in December to 481 kWh in May, giving 3613 kWh per year. Because of the increasing-block tariff, the bill rises faster than the energy: May uses 2.4 times the energy of December but costs 3.1 times as much (₹4,469 against ₹1,423). The annual bill is ₹29,123. The real-time display of the present slab and bill lets the consumer see the effect of switching off the air conditioner, which is the main cause of the high-slab consumption.

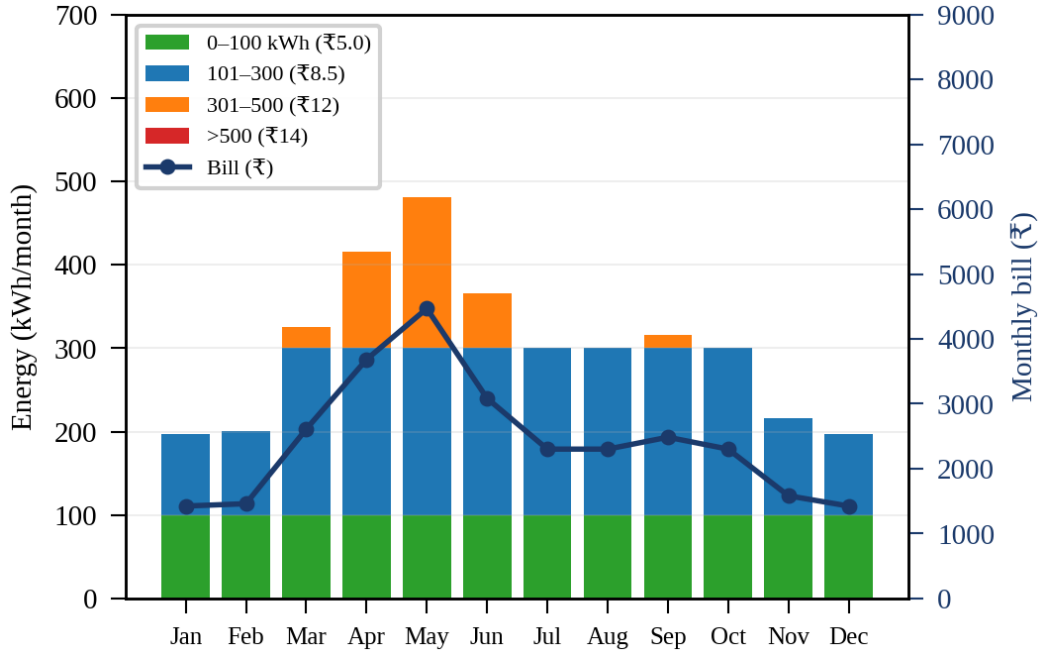


Fig. 6. Monthly energy by tariff slab and the monthly bill.

E. Appliance Share and Tamper Detection

Fig. 7(a) shows the annual share of each appliance group, which would be available to the user from the metering data. The air conditioner accounts for 29% of the energy, the kitchen and miscellaneous loads for 17%, the fans for 16% and the refrigerator for 15%. Fig. 7(b) shows a simulated meter bypass starting at minute 60. Before the event, δ stays at about 1–2%. After the bypass, δ rises to about 30%, and the alarm is raised 10 s later, after three consecutive samples above the 10% threshold. No false alarm occurred in the 60 min before the event.

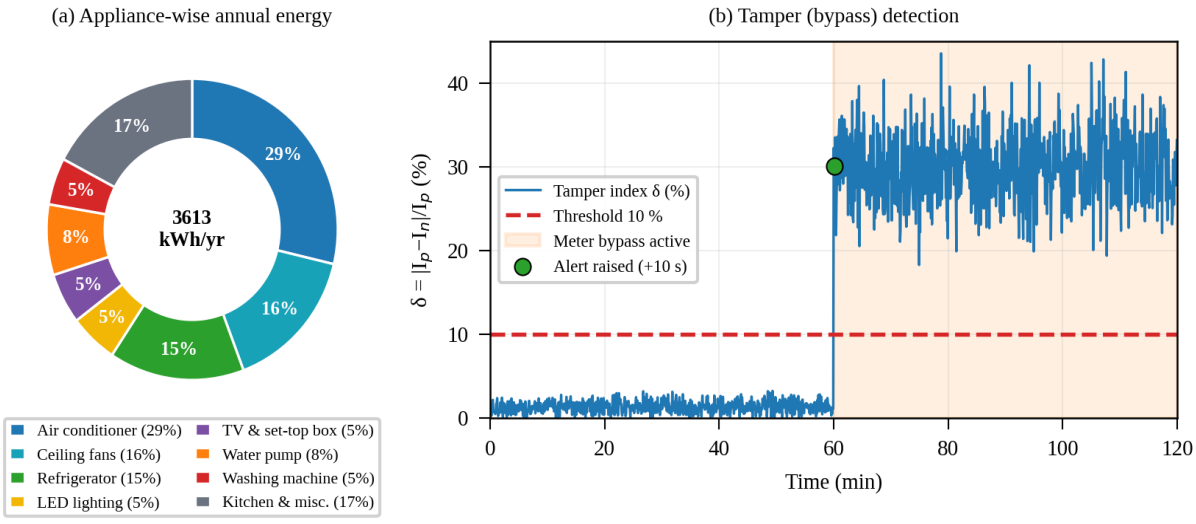


Fig. 7. (a) Appliance-wise annual energy of the simulated household and (b) detection of a meter-bypass event using the tamper index δ.

F. Comparison and Cost

Table IV compares the proposed meter with an electromechanical meter and a conventional digital meter. The proposed meter adds remote reading, prepaid operation, tamper detection and a cloud log. Table V lists the approximate cost of the prototype, which is about ₹2,550 and is dominated by the metering module and the ESP32. The values are approximate retail prices and exclude the enclosure certification and installation.

TABLE IV

Comparison of Meter Types

Feature	Electro-mechanical	Digital (static)	Proposed
Reading	Manual	Manual / LCD	Remote, cloud
Data interval	Monthly	Monthly	5 s
Prepaid / remote cut-off	No	No	Yes
Tamper alert	No	Limited	Phase–neutral
Live bill display	No	No	Yes, slab-based
Power-fail data	Mechanical	Memory	Flash log

TABLE V

Approximate Prototype Cost (INR)

Item	Cost (₹)
ESP32 DevKit	450
PZEM-004T v3.0 with 100 A CT	650
SCT-013-030 CT and bias network	400
30 A relay module	150
16×2 I²C LCD	200
Buzzer, LED, push-button	50
HLK-PM01 power supply	250
Enclosure, wiring, MCB	400
Total	**2,550**

G. Discussion

The results show that a metering module with a rated accuracy of 1.0% and a low-cost microcontroller can provide the main smart-meter functions. The slab-tariff display and the appliance breakdown give the consumer information that a conventional meter cannot supply, and the neutral-current comparison gives a very low-cost first line of defence against bypass theft. The limitations are as follows. The measurement chain is not certified as a revenue meter, and a revenue-grade product must be tested against the Indian standard for smart meters [10]. The tamper index cannot detect theft that affects both conductors equally, such as a tap before the meter on a different phase, and Wi-Fi depends on local coverage. The values in Section VI are from a simulation and need to be confirmed with a calibrated reference meter on the prototype.

VII. CONCLUSION AND FUTURE SCOPE

This paper presented the design and simulation of an IoT-based smart energy meter using the ESP32 and the PZEM-004T module. The meter measures V, I, P, PF and energy, computes the slab-tariff bill, supports prepaid operation with a remote-disconnect relay, reports to the cloud through MQTT and detects bypass theft with a phase–neutral current index. The simulation indicates a power error below ±0.45% (1σ) above 250 W, a mean daily energy error of 0.31%, correct billing of a 3.6 MWh household and tamper detection within 10 s, at a prototype cost of about ₹2,550. Future work includes calibration against a reference meter, extension to three-phase metering, non-intrusive appliance disaggregation, over-the-air firmware updates with secure boot, and integration with UPI-based balance top-up.

ACKNOWLEDGMENT

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