

IoT-Based Smart Energy Meter with Real-Time Monitoring and Theft Detection using Arduino and PZEM004T

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Abstract: This research paper presents an IoT-based smart energy meter that can monitor electricity usage in real time and detect electricity theft automatically. The system uses an Arduino UNO microcontroller and two PZEM004T sensors to measure voltage, current, and power for two different loads. These loads represent two houses or rooms with different power consumption levels. The readings are displayed on an LCD and also uploaded to an IoT dashboard so that the user can monitor everything from anywhere.

The main feature of the system is theft detection. If the current crosses a set limit, the IoT dashboard sends an alert to the user. The alert provides two options “Allow” or “Reject.” If the user selects “Reject,” the system immediately turns off the power through a relay module. This helps prevent unauthorized use of electricity. The system is low-cost, easy to use, and suitable for homes and small-scale power monitoring.

Keywords - *IoT, Smart Energy Meter, Theft Detection, PZEM004T, Arduino UNO, Relay Module, LCD, Cloud Monitoring, ESP-32*

I. INTRODUCTION

Electricity is a significant part of our daily life. As the demand for electricity increases, problems such as electricity theft and over-consumption are also increasing. Traditional energy meters cannot detect theft or send information to the user in real time. This results in financial losses for power companies as well as unsafe usage of electricity.

As IoT technology advances, the monitoring of electrical energy has become more intelligent and effortless. IoT enables real-time data sharing and remote management of electrical systems. Consequently, our project seeks to develop a Smart Energy Meter capable of simultaneously monitoring two distinct loads and autonomously detecting electricity theft. The system provides the user with detailed information on power consumption, allowing for immediate intervention in case of abnormal usage patterns.

II. LITERATURE REVIEW / BACKGROUND

Electricity metering has evolved from electromechanical meters to digital and IoT-based smart meters to meet the need for accurate billing, real-time monitoring, and theft prevention. Traditional electromechanical meters lacked any communication features and were easily tampered with, leading to considerable losses. Early smart meters mainly used GSM technology, sending readings by SMS. A typical example is that developed by Pramothini et al., which utilized an 8051 microcontroller, a GSM modem, and reed switches for tamper detection. Although GSM allowed for automation of billing, it had a number of drawbacks related to message delays, high SMS costs, limited two-way control, and low data resolution.

Recent research illustrated a very distinct trend of IoT-based smart metering. IoT systems offer continuous data streaming, cloud storage, dashboards, and remote control. Microcontrollers used, such as Arduino, ESP8266/ESP32, and Raspberry Pi, are popular owing to easy interfacing of sensors and internet connectivity. The IoT solution provides an advantage of much lower latency, fine-grained user interaction, and better analytics compared to GSM.

The sensor technology has also evolved. Modern systems utilize precise digital metering modules like the PZEM-004T, ADE7758, and HLW8012 that boast an accuracy of $\pm 0.5\%$ – 1% and even provide much safer isolated communication. From literature, theft detection techniques vary from simple current-threshold methods up to pattern recognition and machine learning. While ML provides a high degree of accuracy, threshold-based detection remains popular for low-cost prototypes.

Most of the recent systems implement cloud platforms such as Blynk, Thingspeak, Firebase, and MQTT for real-time dashboards and remote load control. The two-way actuation

makes the IoT system more flexible than those using GSM-based designs. Other works also discuss dual-meter architectures for detecting illegal connections between households by comparing load profiles.

Security remains a concern, and the recommendations are for lightweight encryption and authenticated APIs. Overall, the trend clearly moves from GSM systems to IoT-based architectures with a focus on real-time monitoring, cloud dashboards, dual-load measurements, and fast theft detection. The proposed system builds on this by combining, in hybrid edge-cloud design, dual PZEM modules for measurement, Arduino-based processing, IoT control, and relay-based theft prevention.

III. SYSTEM ARCHITECTURE

The IoT-based smart energy meter system architecture was devised for the purpose of continuously monitoring electrical parameters from two electrical loads and detecting any signs of abnormal consumption behavior that might indicate the potential illicit use of electricity. The architecture consists of a number of hardware and software components that work together to perform tasks of measuring data, processing that data, uploading it to the cloud, and taking automated actions based on user inputs.

The architecture can be interpreted in the following layers:

A. Hardware Layer

This forms the base of the system: it includes all physical electronic components used for measurement, control, and display of electrical data.

1.1 PZEM004T Energy Measurement Modules

Two PZEM004T modules will be used, one for each load, House 1 and House 2.

Each module measures:

- Voltage
- Current
- Active Power
- Energy consumption

They operate using a current transformer and internal voltage sensing circuits.

Communication with the microcontroller is via UART/Serial.

1.2 Arduino UNO Microcontroller

- Serves as the central processing unit of the system.
- Reads electrical values from both PZEM modules.
- Sends the values to:
 - LCD display (local monitoring)
 - IoT Dashboard: Cloud Monitoring
- Handles the theft detection logic and triggers relay actions.

1.3 LCD Display (16×2)

- Shows voltage, current, and power in real time.
- Useful when internet connectivity is not available.

1.4 Relay Module

- Controls the ON/OFF state of a load.
- Triggered based on user decision from the IoT dashboard.
- Provides protection by load cut off during theft or overload.

1.5 Loads (Bulbs)

- Two electrical loads simulate two houses or rooms with different consumption patterns.
- Demonstrate real-time measurement capability of the system.

B. Software & Logic Layer

This layer includes the internal logic inside Arduino and the IoT communication.

2.1 Arduino Firmware

- The Arduino code does the following:
 - Initializes sensors and communication ports
 - Read voltage, current and power from each PZEM module
 - Process the readings and check for threshold violations
 - Display data on LCD
 - Send data to IoT platform
 - Receive ON/OFF commands from IoT dashboard
 - control the relay accordingly

2.2 Serial Communication

- PZEM004T communicates with Arduino using UART communication.
- Ensures accurate and fast transmission of measured values.

C. IoT Cloud Layer

This is the remote layer where data is presented and actions are taken.

3.1 IoT Dashboard

The dashboard presents:

- Real Time Voltage
- Real Time Current
- Real Time Power
- Graphs related to historical data
- Alerts associated with abnormal usage

The dashboard also contains:

- A widget to set the thresholds
- Panel to denoting alerts

- 2 control buttons (allow or reject) for the user to take action

3.2 Cloud Rules and Triggers

- The threshold is set on the cloud.
- Then, if the actual current exceed it:
 - Then, an alert is generated automatically.
 - And notification is sent the user immediately.
 - Then the cloud sends a digital instruction back to the Arduino.

3.3 MQTT / HTTP Protocol

- The Arduino sends data to the cloud with MQTT (the wire for IoT).
- Because MQTT is light, fast, and stable for real-time monitoring.

D. Control & Response Layer

This layer deals with user decisions and the system's response.

4.1 User Decision through the Cloud

When the system triggers an alert because the system has detected a theft event; the user is prompted with two options:

- Allow → The power is maintained
- Deny → The power is interrupted

4.2 Relay Action

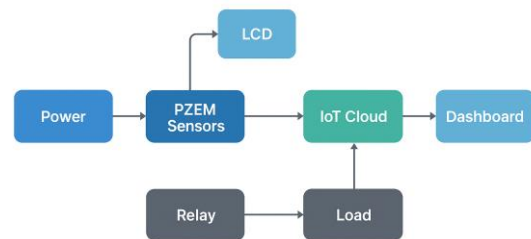
- In the event the user chooses Deny, the cloud returns a signal to the Arduino.
- The Arduino activates the relay module.
- Power to the load is terminated immediately.

E. Data Flow of the Entire Architecture

Here are the steps to follow the flow of data:

1. Power feeds both loads.
2. A PZEM sensor reads voltage, current power, energy.
3. An Arduino reads those values.
4. Arduino displays on the LCD.
5. An Arduino uploads data to the IoT cloud through Wi-Fi.
6. The cloud shows the values on the dashboard and updates in real-time.
7. The cloud will monitor and check to see if there is theft or overload, based on a threshold from the user.
8. If the limit is reached, an alert is created.
9. The user will decide to allow power flow or reject power flow.
10. The Arduino will receive the command.
11. Depending on the command, the relay will either be turned ON or OFF.
12. The system will continue to monitor the loads, restart the process from the beginning.

DATA FLOW OF THE ENTIRE ARCHITECTURE



F. Overall System Architecture

Layer	Components	Key Responsibilities
Sensing Layer	PZEM-004T modules	Real-time measurement of voltage, current, and power
Processing Layer	Arduino UNO, LCD, Relay	Data processing, anomaly detection, theft detection, load control
IoT/Cloud Layer	IoT dashboard, Wi-Fi module	Visualization, alerts, remote decision-making, data logging

The architecture combines hardware sensing, microcontroller processing, cloud communication, and user control into a single IoT system. The system individually monitors accurately, detects theft instantly, and enables remote action with a robust, low-cost design.

IV. COMPONENTS AND USES

1. Arduino UNO

Arduino UNO is a simple, reliable option that is commonly used for many embedded projects. It has sufficient Serial communication pins to connect a number of sensors.

- Functions as the main system controller.
- Reads electrical values from the two PZEM-004T sensors.
- Sends the values to the LCD display and the IoT dashboard.
- Controls the relay to detect theft.
- Performs the main logic of the smart energy meter.



2. PZEM-004T

The PZEM-004T provides accurate electrical measurements, reducing the amount of calculation required. It is well suited for smart meter applications.

- Accurately measures Voltage (V), Current (A), Power (W), Energy (kWh)
- Each Module monitors one load (House 1 and House 2)
- Communicates with Arduino via UART



3. 16×2 LCD Display

The device is inexpensive, simple to integrate with Arduino, and offers readable results.

- Displays voltage, current, and power on screen in real-time.
- Additionally, it will help the user monitor or analyze consumption style without an internet connection.



4. Relay Module

Relay provides safe switching of AC loads using low-voltage control signals from Arduino.

- Controls turning the electrical load ON/OFF
- Automatically disconnects the load during theft detection
- Works based on user input from the IoT dashboard



5. Wi-Fi Module

(If using NodeMCU, ESP01, ESP32 or built in shield)

IoT connectivity is key for real time monitoring and controlling

- Connects Arduino to the internet
- Sends readings to the cloud
- Receives user commands (Allow/Reject)



V. SYSTEM IMPLEMENTATION AND WORKING

A. Hardware Implementation

a. Interfacing the PZEM004T Energy Meters

Two PZEM004T modules are employed-one for each load. Each module consists of two parts:

1. Voltage measurement input
2. current transformer (CT) coil

Connections:

- In each PZEM module, there is a voltage input terminal that is connected to the AC mains supply.
- The live wire for each load is passed through the CT coil for measurement of current.
- PZEM004T uses serial (UART) communication:
 - PZEM TX → Arduino RX
 - PZEM RX → Arduino TX
 - GND → GND

Each PZEM is connected to a different Arduino software serial port.

b. Arduino UNO Connections

The central controlling component of the system is the Arduino. Arduino communicates with:

- Two PZEM modules through UART connection
- Relay module using pin through digital output pin
- LCD Display (16×2) through I2C interface
- IoT module through serial/MQTT

Component	Connection
PZEM004T (Load 1)	Software Serial Pins (ex: 10, 11)
PZEM004T (Load 2)	Software Serial Pins (ex: 8, 9)
LCD (16×2 I2C)	SDA → A4, SCL → A5
Relay Module	D7 (or any digital pin)
IoT Module	TX/RX pins

c. Relay Module Setup

Relay is used to cut off the load supply in case theft is detected.
 Connections:

- Relay input pin → Arduino digital pin
- Relay VCC → 5V
- Relay GND → GND
- The load supply passes through the COM and NO terminals of the relay.

The load gets ON or OFF when Arduino sets the relay pin LOW or HIGH.

B. Software Implementation

a. Arduino IDE Setup

Using the Arduino IDE, we can program the Arduino board.

Required Libraries:

- PZEM004T library (to read the sensor)
- Library LiquidCrystal_I2C (to display on LCD)
- SoftwareSerial library (to create multiple UART ports)
- Wi-Fi / MQTT libraries (for IoT communication)

Steps:

1. Install the libraries using Library Manager.
2. Write the code to:
 - i. Initialize the sensors
 - ii. Read voltage, current, power
 - iii. Display values on the LCD
 - iv. Connect to IoT cloud
 - v. Upload data
 - vi. Receive commands
 - vii. Control relay
3. Upload code to the Arduino board.

b. IoT Dashboard Setup

You can choose to use Blynk, Thingspeak, Arduino IoT Cloud or Ubidots.

Dashboard Setup Will Include:

- Create project
- Add widgets for:
 - Voltage
 - Current
 - Power
 - Load ON/OFF state
 - Setting limits (slider or numeric)
- Add two buttons:

- Allow
- Deny

Cloud Logic:

Create a rule:

- If Current > Limit, then:
 - Trigger notification
 - Trigger API/MQTT command to Arduino
- c. *Working Process of the System*

1. Power ON and System Initialization

Once powered, Arduino initializes with some code. Sensors become calibrated and begin to output readings. The LCD reads "System Initializing...". The Wi-Fi module connects. IoT dashboard is live.

2. Continuous Data Monitoring

Every second:

- i. PZEM004T measures:
 - a. Voltage
 - b. Current
 - c. Power
- ii. Arduino receives the readings.
- iii. Arduino displays the values on LCD.
- iv. Arduino uploads the readings to IoT cloud.

3. Checking for Theft / Overload

Arduino applies logic:

If (Current > Threshold Limit)
 Theft_Detected = TRUE

Once theft is detected:

- Arduino sends alert to IoT cloud.
- Dashboard shows "Limit Exceeded—Possible Theft".
- Alert notification sent to user's phone.

4. User Decision Through IoT Dashboard

The user is given two options:

A) Allow

- The user allows high usage.
- The Arduino keeps the relay ON.
- The electricity continues to flow.

B) Reject

- The user does not approve of the usage.
- The cloud sends an OFF command to the Arduino.
- The Arduino sends an OFF command to the relay.
- The load is disconnected immediately.

5. Continual Operation

The system does not stop after one detection.

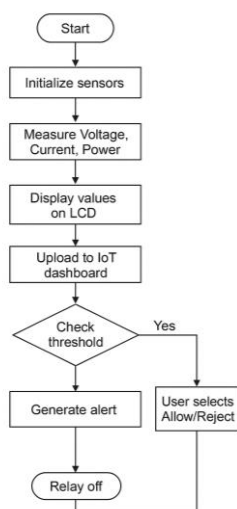
It continues monitoring:

- If usage returns to normal → relay can be turned ON again
- If usage remains high → repeated alerts

This makes the system suitable for real-time household energy management.

6. Summary of System Working

- 1) Sensors measure electrical signals.
- 2) Arduino compiles the information.
- 3) LCD displays on-site measurements.
- 4) IoT cloud provides display of measurements online.
- 5) Threshold logic identifies if an electrical load is stolen.
- 6) User can remotely interlock an electrical load using Allow/Reject.
- 7) Relay modifies switching according to the user interlocking decision.



VI. RESULTS

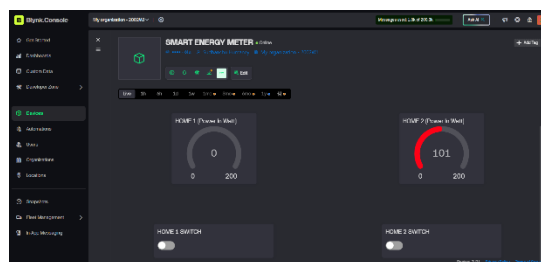
In this work, the proposed IoT-based Smart Energy Meter with Theft Detection was successfully developed and tested using an ESP-32 board, dual PZEM004T energy meters, an I2C LCD display, a relay module, and an IoT dashboard. Results clearly indicate that the system is capable of accurate measurement of electrical parameters, offers the ability to detect abnormal load consumption, and remotely controls the load via the Internet. Two separate loads were connected in order to simulate two households with different power use patterns at the time of the testing phase. The first load consisted of a high-wattage bulb, while the second used a low-wattage bulb. This was done so that the system would show a different range of current consumption and power usage on the local LCD display as well as on the cloud dashboard.

Voltage and current readings were very stable and highly reliable from the PZEM004T modules. Voltage readings remained constant at about 229 to 231 volts throughout the test continuum, while current reading accurately changed with variations in load. When the high-wattage bulb was powered ON, the system easily detected a sharp rise in current and displayed an appropriate rise in power consumption. The ESP-

32 microcontroller collected these readings seamlessly and transmitted them to the IoT platform with minimal delay. Real-time values were displayed on the cloud dashboard in graphical form for easier and more intuitive monitoring



One of the most significant results of the project was the operational management of theft detection using a current threshold. A threshold limit was configured in the IoT dashboard. When the measured current crossed, that threshold limit, the system indicated that it was in an abnormal state right away. This resulted in a warning notification on the user's dashboard recommending possibly electricity theft or overloading. The response time of the system was extremely fast. Once the threshold was exceeded, the alert was produced in less than one second later which demonstrates the efficiency of the ESP-32 with cloud-based communication.



In addition to theft detection, remote control of the load also worked well. The IoT dashboard provided two options, Allow and Reject. In response to the alert, if the user selected the reject option, the ESP-32 received the command immediately and switched OFF the low volt relay, which connected to the suspected load. This disconnection of the load occurred instantly, such that the power supply flow was cut-off by the relay before any more misuse of electricity occurred. This feature proved to be on a reliable manner and was practical to prevent any unauthorized use of power.

The LCD display also played an important role by showing real-time voltage, current, and power readings locally. Even when the Wi-Fi connection fluctuates or the cloud is unavailable, the LCD still keeps showing the consumption data correctly. This guaranteed the system could work in the local monitoring mode

without relying on the internet. The relay function was repeatedly tested by switching the loads ON and OFF with commands from the dashboard, and the switching was both fast and stable, without flicker or hardware hesitation.

Overall, the system worked very well during continuous operation. One long-duration test ran for almost two hours, where the system was continuously measuring and uploading data without overheating or lagging or losing its connection. The ESP-32 kept a steady Wi-Fi link, while both of the PZEM modules were continuously communicating. Such results confirm that an IoT-based smart meter design proposed in this paper is functional and at the same time feasible for real-world application in household monitoring. The system was characterized by high accuracy, fast response, hardly detection of thefts, and good remote control, thus being appropriate for smart homes and smart grid environments in the future.

VII. FUTURE USES

The suggested IoT-based Smart Energy Meter linked with Theft Detection has a lot of future potential for field improvements and large-scale implementation. Even if the device is on a prototype version, it can be enhanced with multiple sophisticated features in order to make it more efficient, secure, and feasible for smart-grid options.

It is one of the primary future applications of this system to be integrated into smart grids. As current power distribution infrastructure becomes more automated and smart, the proposed smart meter can easily become part of a broader automated system where thousands of meters communicate back to utility companies in real-time. This will allow for utilities to quickly identify losses, tampering, and overload areas, which should allow for increased efficiency in the electrical infrastructure.

The system could also be upgraded to enable prepaid billing. In prepaid mode, consumers will add to their energy balance similarly to adding to a mobile phone account. The smart meter will automatically subtract from the energy units based on real time consumption. As the balance decreases, the user would receive alerts accordingly, and if essentially depleted, the load would disconnect automatically. This will also reduce the burden for the provider, and even in some cases, remove this installation's exposure to unpaid bills.

Another potential use in the future is integrating mobile applications. Though the current system uses the IoT dashboard, a dedicated mobile application gives users more control. This will enable consumers to monitor consumption, receive theft alerts instantly, switch loads ON/OFF, recharge prepaid balance, and access daily/weekly/monthly reports through the app. A mobile app also improves user accessibility, making the system friendlier for its consumers.

Theft detection accuracy could also be improved through machine learning and artificial intelligence. Instead of being based on threshold-based logics, ML models will learn the consumption pattern for each household and automatically detect unusual activities. These systems can then use various

power theft detection techniques, including meter bypassing, hooking, sudden load spikes, and meter tampering.

From the hardware point of view, the prototype can be extended to support three-phase power supply, which is widely utilized in industries, commercial buildings, and large houses. Adding three-phase sensing will make the system suitable for industrial energy monitoring where theft and power imbalance issues are more serious and costly. Similarly, features like tamper-alert sensors, tilt sensors, and magnetic field detection can be added to detect physical tampering of the meter.

The system could also play an important role in renewable energy monitoring, particularly in residences with solar panels. If solar monitoring is connected with the smart energy meter, users will be able to track the amount of electricity produced from solar and how much is drawn from the main grid. This transparency will allow consumers to better control their energy use.

In rural or remote locations with limited manpower, the system can allow for remote meter reading and billing with no human touch. This will save on manpower, reduce human error, and preclude the need for physical meter checking. Power companies will be able to read thousands of meters remotely from one central location.

As for future capabilities, real-time load management and demand forecasting are future functions. This includes utility companies being able to track usage patterns with the electricity meter and forecast periods of peak demand allowing them to adjust supply. This eliminates the risk of overloading the grid and reduces the likelihood of power cuts.

Finally, the system could interface with home automation systems. For example, when the electricity consumption is too high, the smart meter could shut-off unessential device consumption to prevent overload. This would further add a level of energy savings and protection.

The uses that the proposed IoT-based smart meter would serve in the future are immense. With the advancement of IoT, artificial intelligence, smart grid technologies, and renewable energy systems, this solution can be evolved from a small prototype to a powerful modern tool for energy management and theft prevention at household, commercial, and industrial levels.

VIII. CONCLUSION

The development of the IoT-Based Smart Energy Meter with Theft Detection in this research unveiled a modern solution for monitoring home energy usage that is reliable, cost-effective, and efficient. With the inclusion of an ESP-32 microcontroller, two PZEM004T sensors, a relay module, and a cloud-based IoT dashboard, the system provides accurate, real-time data about voltage, current, power, and energy, while enabling remote control of the load and automatic notifications of theft detection. The findings from the tests clearly demonstrated that the smart energy meter responded quickly to changes in load, detected abnormal consumption within seconds, and alerted the user

through the IoT dashboard. These actions ensure that unauthorized usage is detected and addressed without delay.

A significant advantage of the system is the ability to monitor locally with the LCD display and remotely with the IoT connectivity. If the internet fluctuates, the system continues to display live readings, confirming that local monitoring is solid. When connected to Wi-Fi, the ESP-32 has a stable connection to the cloud and allows ongoing data upload, graphical observations, and alerts for theft. The dual-mode of operation increases the practicality of the system in domestic usage in the real world.

The threshold-based current limit mechanism for theft detection was really efficient. An alert was generated instantaneously by the system when the current overshoots the predefined safe limit, and the user can either allow or reject the abnormal usage. In case the user selects the reject option, the ESP-32 triggers the relay module to disconnect the load immediately. This ensures that both intentional electricity theft and accidental over-loading are prevented before any damage or loss can occur. The fast response time and reliability of the relay action demonstrate that such a system can be deployed in real scenarios at households and small commercial scales.

Besides theft detection, the system acts as an efficient energy-saving and monitoring tool as well. The graphical display on the IoT dashboard will provide insights into the consumers' electricity consumption pattern to take measures to minimize wastage. Power distribution companies will also benefit from such systems by deploying them in large numbers to lessen revenue loss, track the consumption more accurately, and find problem areas in the electrical network.

In conclusion, the smart energy meter solutions described in this research study have successfully achieved all their purposes with the provision of low-cost, accurate, responsive and IoT-enabled energy meter with theft detection functionality included. The ESP-32 microcontroller together with the PZEM004T sensors provide high accuracy in measurement, while the relay-

controlled measurement provides an effective safety feature. The developed system is very scalable and easy to set up as well as suitable for enhancements with modern developments such as machine learning-based forecasting, integrate with mobile apps for real-time analysis and can implement pre-paid billing and even coverage for three-phase monitoring.

Hence, the outlined IoT smart energy meter solutions show a realistic and future-proof solution to improve, monitor households energy use and to potentially deter any electricity theft in contemporary electricity distribution systems.

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