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Intelli Plug: Smart Energy Budgeting and Adaptive Phantom Load Killer

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ABSTRACT :

The Intelli Plug system is a smart plug designed for real-time energy monitoring and automatic phantom load elimination. It uses the PZEM-004T V4 energy meter to measure voltage, current, power, and energy consumption accurately. An ESP32 microcontroller processes this data and controls a relay to cut off appliances when phantom power is detected or when the user's energy budget is exceeded.The system displays real-time data on an LCD and sends notifications through IoT platforms. By automating power monitoring and controlling wastage, Intelli Plug helps reduce electricity bills, improves awareness, and promotes sustainable energy usage in homes, hostels, and PGs.

Keywords: Smart Plug, Phantom Load Detection, Energy Monitoring System,IoT-Based Power Management, PZEM-004T V4 Sensor, ESP32 Microcontroller, Real-Time Energy Measurement, Automatic Load Control, Energy Budgeting, Smart Home Automation,Power Consumption Analysis, Standby Power Elimination, Relay Switching System, Sustainable Energy Usage, Smart Energy Management

INTRODUCTION

The increasing dependence on electrical and electronic appliances in homes, hostels, and commercial buildings has led to a steady rise in energy consumption. A significant portion of this consumption occurs through *phantom loads*, where devices continue to draw power even when they appear to be switched off. These unnoticed standby losses contribute to higher electricity bills and reduce overall energy efficiency. Traditional energy meters offer only aggregated monthly readings, providing no insight into appliance-level consumption or real-time usage patterns. As a result, users lack the means to identify energy-wasting devices or take timely corrective actions.

Advancements in embedded systems and IoT technologies have enabled the development of smart plugs capable of monitoring and controlling individual loads. By integrating sensors, microcontrollers, and communication technologies, these systems provide granular visibility of voltage, current, power, and energy usage at the socket level. The **Intelli Plug** proposes a reliable, low-cost solution that combines real-time energy monitoring with automatic phantom load elimination. Utilizing the PZEM-004T V4 energy meter and ESP32 controller, the system analyzes consumption patterns, detects abnormal standby loads, and disconnects appliances through relay control when necessary. Additionally, IoT connectivity allows users to track consumption, receive alerts, and manage energy budgets remotely.

This intelligent approach not only enhances energy awareness but also promotes sustainable power usage by reducing avoidable wastage. The Intelli Plug system therefore addresses a practical and growing need for efficient household energy management, aligning with modern smart home technologies and conservation practices

PROBLEM STATEMENT

In many residential and shared living environments, a substantial amount of electricity is unknowingly wasted due to phantom loads—appliances that continue to consume power even when they appear to be switched off. Users often lack real-time visibility into plug-level energy consumption, making it difficult to identify where and how electricity is being wasted. Conventional energy meters provide only aggregate readings and do not offer detailed information about individual appliances, resulting in inefficient usage patterns and increased monthly electricity bills. Furthermore, there is no automated system in place that can intelligently monitor electrical parameters, detect standby power usage, or enforce user-defined energy limits. This creates a pressing need for a smart, autonomous, and affordable energy-management solution capable of measuring real-time voltage, current, power, and energy, while eliminating phantom loads through automated cutoff. The problem, therefore, is to design and implement a reliable IoT-based smart plug system that enhances user awareness, optimizes energy usage, and supports sustainable power management without requiring modifications to existing household wiring

LITERATURE SURVEY

Recent advancements in smart home technologies have led to the development of intelligent energy monitoring systems aimed at improving household energy efficiency. Early research focused on conventional smart meters that recorded aggregate consumption data but lacked appliance-level visibility. These systems helped users track total usage but offered limited capability in identifying standby losses or managing individual loads.

Several studies introduced IoT-enabled energy monitoring platforms that provide real-time measurement of voltage, current, and power. Sensors such as ACS712 and ZMPT101B were commonly used, but their accuracy was affected by drift and calibration issues. To overcome these limitations, researchers began adopting integrated modules like the PZEM-004T series, which offered improved precision and simplified communication with microcontrollers.

Multiple works have explored the use of Wi-Fi-enabled microcontrollers such as ESP8266 and ESP32 to process sensor data and transmit it to cloud platforms. These systems demonstrated the ability to remotely observe consumption trends and generate alerts. However, many of these solutions remained passive and lacked autonomous decision-making capabilities, resulting in ineffective control over phantom loads.

Recent studies shifted toward smart plug architectures capable of appliance-level detection and relay-based control. These designs introduced automated load disconnection when abnormal or excessive consumption patterns were detected. Some researchers also proposed adaptive cutoff mechanisms based on threshold power levels, though most did not integrate user-defined energy budgeting or multi-parameter monitoring in a single system.

The emerging need for low-cost, plug-and-play solutions has influenced the design of next-generation energy management devices. Literature highlights the importance of integrating accurate sensing, real-time analytics, IoT connectivity, and automated control to minimize energy wastage effectively. Building on these findings, the Intelli Plug system advances smart plug technology by combining high-accuracy energy measurement, phantom load elimination, and budget-based automation within a unified, user-friendly platform. This makes it suitable for practical deployment in homes, hostels, and PG environments where energy wastage remains a persistent challenge.

1. HARDWARE AND SOFTWARE IMPLEMENTATION

The Intelli Plug system is developed using an integrated combination of hardware components and software tools that work together to measure energy parameters, analyze consumption patterns, and automate load control. The implementation focuses on achieving high accuracy, real-time monitoring, and reliable switching while maintaining a compact and user-friendly design.

2. CIRCUIT DIAGRAM

The circuit diagram of the Intelli Plug system shows how each hardware module is interconnected to achieve real-time energy monitoring and automated load control. The ESP32 microcontroller serves as the central unit, communicating with the PZEM-004T V4 energy meter through UART pins to measure voltage, current, power, and energy consumption. A 16×2 I2C LCD display is connected to the ESP32 using the SDA and SCL lines to present live electrical readings to the user. The relay module is interfaced with a digital output pin of the ESP32, enabling it to switch the 230V appliance ON or OFF based on phantom load detection or energy-budget conditions.

A buzzer and status LEDs are integrated to provide audible and visual indications of system events such as warnings, overload conditions, and cutoff status. The entire setup is powered through a regulated 5V DC supply derived from the mains input. The AC plug and socket assembly connects the appliance through the relay and PZEM module, allowing both measurement and controlled switching. All components are mounted securely and interconnected on a PCB or prototyping board to ensure safe, reliable operation in real-time environments.

Component Roles:

1. ESP32 Microcontroller (System Controller)

Acts as the core processing unit of the design.

It reads data from the PZEM energy meter, analyzes the values to detect phantom loads or budget violations, drives the relay for load switching, and sends status updates to the IoT dashboard.

2. PZEM-004T V4 Energy Meter (Measurement Unit)

Accurately measures voltage, current, power, and energy consumed by the connected appliance.

Provides the ESP32 with continuous electrical parameter data for monitoring and automated control.

3. Relay Module (Load Switching Device)

Functions as an electrical switch to turn the appliance ON or OFF.

It disconnects the load during phantom load conditions, overload situations, or when the user-defined energy budget is exceeded.

4. I2C LCD Display (User Interface)

Shows real-time readings such as voltage, current, power, and kWh consumption.

Allows the user to view system status instantly without needing a mobile device.

5. Buzzer and LED Indicators (Alert System)

The buzzer provides warning tones during high usage or cutoff events.

LEDs indicate operating modes such as normal operation, warning level, or relay shutdown.

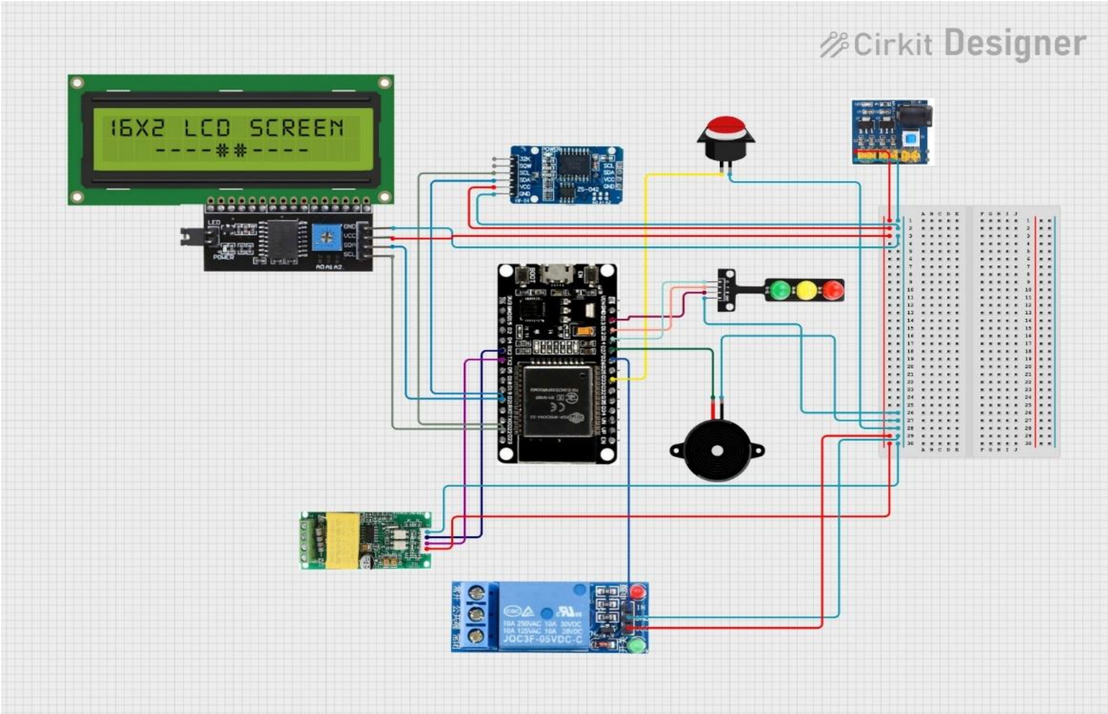
6. Plug and Socket Assembly (Load Connection Point)

Serves as the interface between the Intelli Plug and the household appliance.

AC mains pass through the PZEM meter and relay before reaching the load, enabling both monitoring and controlled switching.

7. Regulated Power Supply (5V DC Source)

Supplies stable 5V power to the ESP32, LCD, relay, and other low-voltage components.
Ensures safe isolation between high-voltage AC lines and the low-voltage control circuitry.



Circuit diagram

Operational Scenarios

➤ Real-Time Energy Monitoring

When the Intelli Plug is powered and an appliance is connected, the PZEM-004T V4 energy meter continuously measures voltage, current, power, and energy consumption. These readings are processed by the ESP32 microcontroller and displayed on the LCD in real time. Users can instantly observe how much electricity each device consumes during operation.

➤ Automatic Phantom Load Detection

If the connected appliance enters standby mode and its power consumption falls below a predefined threshold, the system identifies it as a phantom load. After confirming the condition for a fixed duration, the ESP32 automatically switches OFF the relay to prevent wastage. This scenario helps eliminate unnecessary energy usage from devices left plugged in but not actively operating.

➤ IoT-Based Wireless Monitoring

Through Wi-Fi connectivity, the ESP32 transmits live energy readings to an IoT platform such as Blynk. Users can view voltage, current, power, and cumulative energy on their smartphone from anywhere within network range. This wireless monitoring capability provides convenience and ensures continuous visibility of energy usage without physical access to the device.

➤ Energy Budget Tracking and Automatic Cutoff

The Intelli Plug allows the user to set a daily or monthly energy budget. As the system records accumulated energy consumption, it compares the value with the user-set limit. If the consumption approaches the threshold, a warning is issued through the display and IoT app. Once the limit is exceeded, the relay disconnects the appliance automatically to prevent further usage. This scenario supports controlled electricity usage and helps avoid high energy bills.

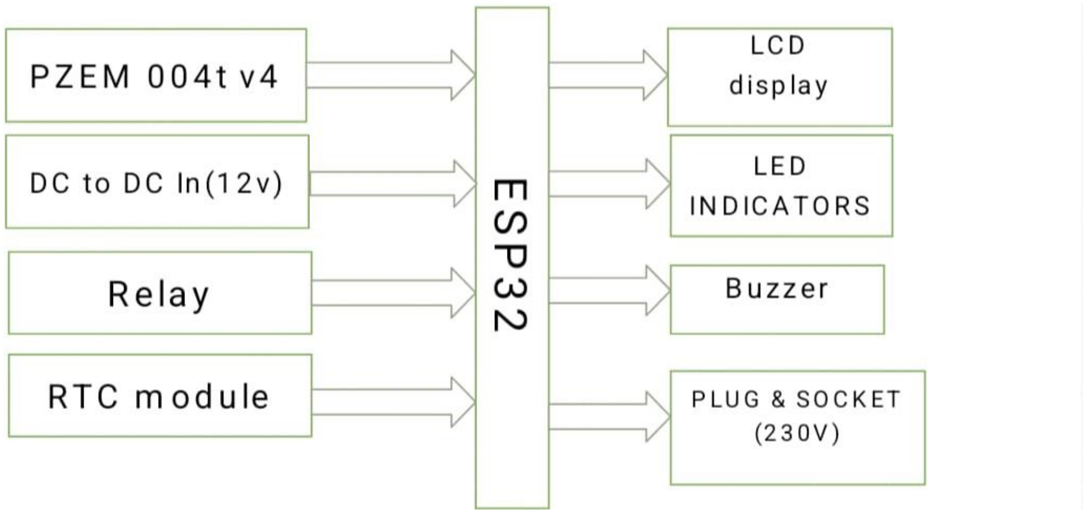
➤ ***Logging of Electrical Parameters for Analysis***

Throughout operation, the system gathers a continuous stream of electrical measurements. These data points can be viewed in the IoT dashboard or logged for later analysis. Such records help study load behavior, identify inefficient appliances, understand consumption patterns over time, and generate insights for improving energy management.

➤ ***Autonomous Operation with Safe Power Management***

The entire Intelli Plug system functions independently once powered by a regulated 5V supply. Built-in safety features monitor overloads, abnormal voltage variations, and unexpected current spikes. When unsafe conditions are detected, the system isolates the appliance by turning OFF the relay. This ensures safe and reliable functionality without requiring manual intervention.

BLOCK DAIGRAM



Block Diagram

The block diagram illustrates the overall functioning of the Intelli Plug system, showing how each hardware module interacts with the ESP32 microcontroller. The PZEM-004T V4 energy meter is connected to the ESP32 and provides continuous measurements of voltage, current, power, and energy consumed by the connected appliance. A DC-to-DC converter supplies regulated low-voltage power to the ESP32, relay, indicators, buzzer, and display, ensuring stable and safe operation. The relay module receives control signals from the ESP32 and switches the 230V appliance ON or OFF based on conditions such as phantom load detection, overload, or energy budget limits.

An RTC module is included to provide accurate time information, which is essential for daily energy budgeting and time-based monitoring. The ESP32 also communicates with an LCD display to present real-time electrical parameters and system status to the user. LED indicators connected to the controller provide visual feedback for normal operation, warning states, and cutoff conditions, while a buzzer generates audible alerts when abnormal or high-usage situations occur.

Finally, the plug and socket section represents the AC interface through which the appliance receives power. The supply passes through both the PZEM sensor and the relay, allowing the system to measure electrical parameters and control the load simultaneously. Together, these interconnected blocks enable the Intelli Plug to function as an intelligent, automated, and user-friendly energy management device.

RESULTS

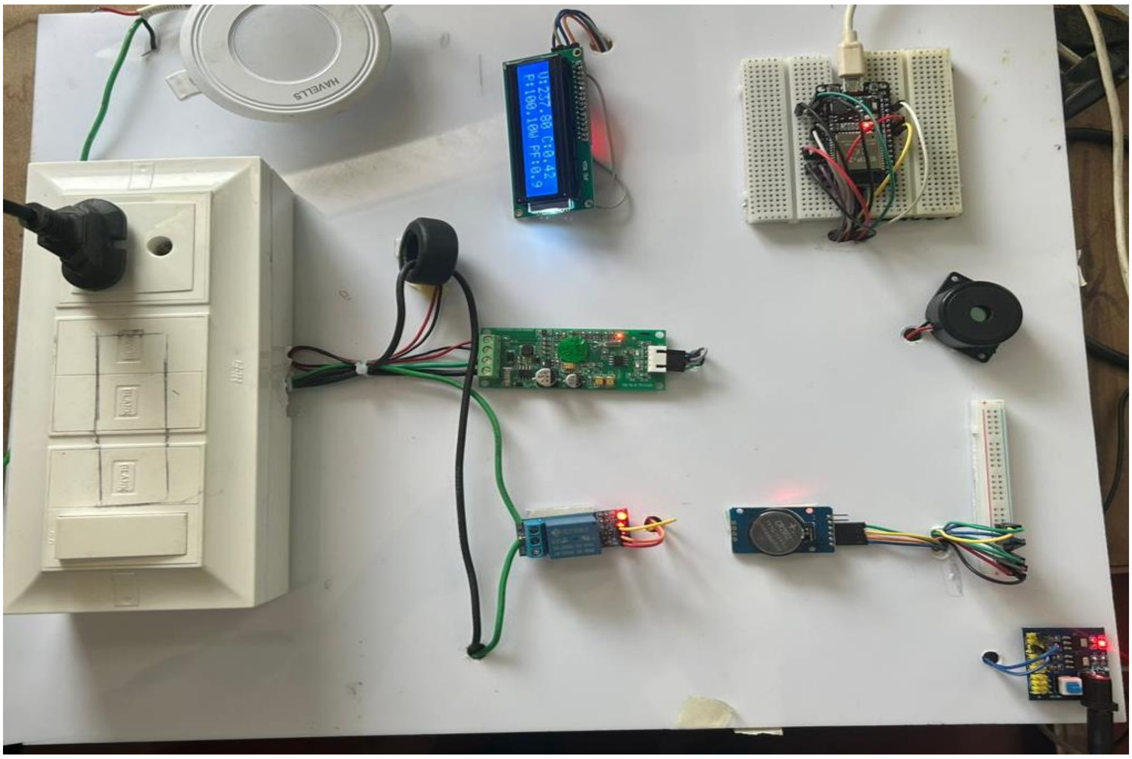


Fig 1:view of project

Fig 2:Led reading in LCD display

The Intelli Plug prototype was successfully developed and tested under different electrical load conditions to evaluate its accuracy, response time, and ability to control energy usage. The system consistently measured voltage, current, power, and energy with the PZEM-004T V4 module, and the readings displayed on the LCD closely matched the values shown on the IoT dashboard, confirming reliable sensor-to-cloud communication. During testing with small loads such as a 3W LED lamp, the device accurately detected low-power consumption and updated the real-time values without noticeable delay.

One of the key outcomes was the successful detection of phantom loads. When the connected appliance consumed power below the predefined threshold, the ESP32 correctly identified the condition and switched OFF the relay after the fixed time window. This demonstrated the system's ability to reduce unnecessary standby power usage. The LCD and IoT app both displayed "Phantom Load Detected," validating that the alert and cutoff mechanisms functioned as intended.

The energy budgeting feature was also evaluated by setting a low kWh limit for testing purposes. As soon as the cumulative energy consumption reached the set value, the system issued an 80% usage warning, followed by an automatic relay cutoff once the full limit was exceeded. These results confirmed that the Intelli Plug can effectively prevent overconsumption and help users manage their electricity usage more efficiently.

In addition, overload protection was tested by temporarily connecting a higher-power appliance. The system immediately identified abnormal current values and disconnected the load to ensure safety. The buzzer and LED indicators provided clear alerts, demonstrating dependable fault-handling capability.

Overall, the experimental results show that the Intelli Plug operates reliably across multiple scenarios—normal operation, phantom load detection, energy budgeting, overload protection, and IoT monitoring. The system performed as expected and successfully achieved its objective of enabling intelligent, automated, and user-friendly energy management.

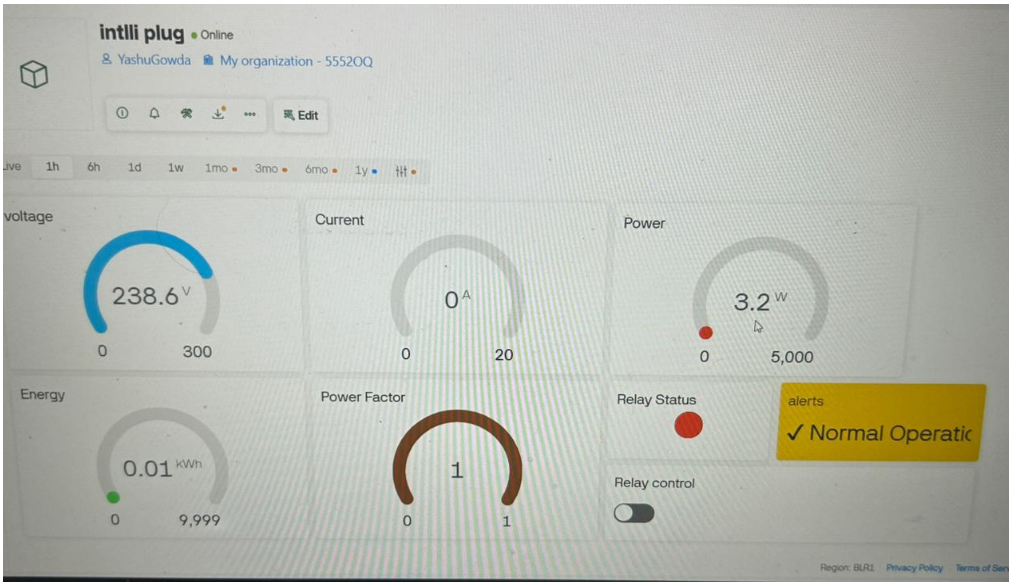


Fig 3:Results Shown in Blynk

CONCLUSION

The Intelli Plug system was successfully designed and implemented as an intelligent solution for real-time energy monitoring and automated power management. By integrating the PZEM-004T V4 energy meter with the ESP32 microcontroller, the system accurately measured voltage, current, power, and energy consumption at the appliance level. The incorporation of phantom load detection, energy budgeting, and overload protection enabled the device to reduce unnecessary electricity usage and enhance overall safety. Real-time communication through the LCD display and IoT dashboard ensured that users could conveniently monitor their consumption and receive timely alerts regarding abnormal or excessive usage.

The results of the prototype testing confirm that the Intelli Plug operates reliably across various scenarios, including standby load conditions, user-defined energy limit enforcement, and fault conditions. Its automated relay control demonstrated the potential to significantly minimize wastage and support smarter energy consumption habits in homes, hostels, and PG environments. Overall, the Intelli Plug provides a low-cost, practical, and user-friendly approach to sustainable energy management, making it a promising tool for future smart home applications.

FUTURE SCOPE

- Add more sensors to monitor appliances and power quality.
- Use AI to make smarter decisions and detect appliance behavior automatically.
- Provide cloud alerts for overloads, high usage, or unusual power spikes.

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