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A New IoT Smart Plug Framework Using ESP32 for Adaptive Charging and Thermal Protection

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Abstract: ***Overcharging and overheating of batteries are still serious problems, affecting the performance, safety, and lifespan of rechargeable electronic devices. This paper presents an IoT-enabled smart plug system, using the ESP32 microcontroller, designed to automatically stop charging when the battery reaches 85% capacity or when the temperature exceeds 40°C. The system collects real-time data on voltage, current, and temperature. This data is then processed by the ESP32 microcontroller, which controls a relay to manage the power supply. The combination of a buzzer and an LCD display provide immediate user alerts and visual feedback, which enhances both safety and ease of use. The technology, as intended, significantly boosts charging safety, curbs needless energy use, and extends the lifespan of the battery. Experimental validation demonstrates accurate precision, rapid response times, and consistent performance, thereby confirming the system's suitability as a cost-effective, easily expandable, and energy-efficient charging solution for everyday electronic devices, including smartphones, tablets, and power banks.***

Keywords: Smart Charging, Battery Management, Bluetooth Communication, Overcharging Protection, Battery Health, Temperature Monitoring

1.Introduction

The pace of modern life, now so intertwined with the digital world, has resulted in a proliferation of devices that require recharging. Laptops, tablets, cellphones, and wearable devices are the most common examples of electronics that can be recharged. Lithium-ion batteries, the major power source for these gadgets, are known for their good performance, such as fast charging, and their tiny size. However, they are also susceptible to problems like overcharging and overheating. Frequent exposure to such conditions can shorten a battery's lifespan, harm its overall health, and, in rare cases, lead to thermal runaway, which creates a dangerous situation. Even though most current gadgets have built-in protections, these aren't always enough to prevent long-term battery harm from too many charging cycles. A simple yet powerful strategy for prolonging battery life involves capping charges at roughly 80–85%, rather than letting them reach a full 100%. This method decreases the chemical stress on battery cells, which helps to slow down their deterioration. Moreover, controlling temperature is similarly important, because charging batteries in high temperatures can lead to permanent capacity loss or even dangerous situations. In contrast, users rarely monitor these factors during routine charging, and the process remains fully manual and reactive. This study proposes a new, affordable, and easy-to-use Internet of Things (IoT) smart plug system. Its main purpose is to automate the charging process by terminating the power supply when the battery reaches 85% capacity, or if the temperature exceeds a set safety limit, such 40°C.

The system employs the ESP32 microcontroller, which has Bluetooth capabilities, to receive real-time battery statistics from the device being charged. Based on the data collected, a relay module is utilized to manage the charging process, which allows the power supply to be turned off when needed. The LCD screen offers immediate updates on both battery life and temperature. Simultaneously, a buzzer serves as an auditory warning system, alerting the user to possible overheating or when charging needs to stop. The ESP32's appeal for embedded IoT projects is clear. Its dual-core processing power, along with integrated Bluetooth and Wi-Fi capabilities, makes it a strong contender. Plus, the cost is right, which certainly doesn't hurt. The proposed system will use Bluetooth technology because it's easy to use and works well for short-range communication. This will allow it to link with a sender module, like an external battery monitoring circuit or app, which will relay data on the battery's charge level and temperature. After the ESP32 gets the data, it can then analyze and act on it, determining whether to activate or deactivate the relay.

This design approach would provide this system a significant advantage over typical smart plugs already available. It enables for real-time decision-making depending on the battery's state, rather than relying on timers or needing user interaction. The system incorporates safety shutoffs that are triggered by temperature. This flexibility also means the device can be utilized in unconventional charging situations, like those found in laboratories or battery testing facilities. As a result, the battery's lifespan can be extended, and energy expenses can be reduced by decreasing or eliminating needless power consumption.

Future versions of the suggested system could be improved by adding remote control through Wi-Fi, or by using mobile apps that provide push notifications and allow for real-time data monitoring. Another approach could involve using machine learning techniques to forecast the most efficient charging times. Even without the current setup of this prototype, its design shows the potential implications of smart charging, even with a small amount of electronics. This study studied the hardware and software architecture of the smart plug, presented the implementation plan, and then evaluated its performance in different charging situations. The findings suggest that integrating intelligent control systems with standard charging methods is feasible, representing progress toward sustainable electronic gadgets and the advancement of smart energy solutions.

2.Literature Review

Smart plugs are now essential for managing energy, controlling devices, and automating tasks within smart homes. Some researchers have proposed energy-management systems that use smart plug communications with inverters to control voltage and distribute energy in homes [1]. Other research has produced modular smart plug systems for consumer electronics in homes that use less energy. These systems allow for monitoring appliances and connecting to smart grids [2]. Further research has provided home-energy-management systems (HEMS) that gather data from smart plugs. These systems then use machine-learning approaches to anticipate energy use and optimize consumption in near-real time [3]. Further studies investigated how to identify appliances using smart plugs. These studies employed algorithms, like k-NN, to classify connected devices and create consumption profiles. The goal was to better the separation of different loads [4]. In parallel research, communication networks were improved by using hybrid Zigbee/IEEE 802.11g architectures. This was done to enable quick and reliable data transfer between smart plugs and home networks [5]. Studies have broadly examined smart plug technologies within smart city and smart grid systems, stressing their importance in Hybrid Appliance Load Monitoring Systems (HALMS) and pointing out existing limits [6]. In several field experiments, the usage of IoT-based smart plugs over extended durations, such as fifteen months in 125 homes, showed small energy savings of about five percent. These savings were linked to better monitoring and the ability to connect appliances [7]. Other studies have described how smart plugs work interactively in smart home energy management systems, showing how they collect data wirelessly and regulate appliances automatically [8]. Some solutions used IoT-enabled smart plugs and smart meters in fog-computing architectures. These systems showed great accuracy in recognizing appliances (over 97%) and included demand-response features [9]. Several evaluations have summarized the current level of smart plug research, detailing existing systems, communication protocols, and the issues that still need to be solved [10].

Development of real-time monitoring systems and defensive features. Several studies have created smart plug prototypes that can detect current, voltage, and power in detail. These prototypes also automatically cut off power when the current exceeds a set limit. These devices were made using ESP8266 or similar modules [11]. Some smart socket designs included over-current protection, which was managed by software, and allowed for remote control of the socket's power state, thus improving safety and energy awareness [12]. Some studies have looked at how smart plugs can help monitor distribution-grid conditions. They do this by combining customer readings to help grid operators find areas that are overloaded [13]. Several studies have studied smart plug systems. These systems employ environmental and contextual data, like temperature, humidity, and occupancy, to improve how appliances work and to better understand user behavior [14].

Concerns about security and reliability have also surfaced. Research has discovered significant security vulnerabilities in smart-plug systems. These flaws expose communication protocols, allowing for device scanning, brute-force attacks, spoofing, and firmware attacks [15]. Several studies have proposed automated penetration-testing frameworks to assess smart plugs and other Internet of Things (IoT) devices. These frameworks are designed to find unsafe services, weak encryption, and vulnerabilities in firmware [16]. Some researchers have used smart plug systems to monitor high-wattage loads. They did this by using web-based interfaces, which allowed them to regulate appliances that use a lot of power from a distance [17]. Some prototype systems have been built using complete IoT-based designs. These systems have adaptive current-cutoff features. This means the plug stops supplying power if the current exceeds a defined limit for a brief time, which shows its protective purpose [18]. Industry-led patent applications have described solid-state smart plug devices. These devices include built-in hardware protections against overload, short-circuits, surges, and arc faults, using semiconductor switching technology [19].

Recent research has led to the creation of affordable IoT smart plugs for homes. These devices allow for remote management, scheduling, monitoring, and basic safety features. They use microcontrollers, cloud and mobile applications, and real-time data displays [20].

3.Research Gaps

Although much research has been done on smart plugs and IoT-based household energy management, most contemporary methods largely focus on monitoring and optimizing energy use, rather than actively controlling safety. Currently, there are few systems that can automatically prevent overheating, overcharging, and electrical problems in real time, while still being affordable and easy to integrate. Many systems depend on complicated hybrid communication protocols. This increases deployment costs and reduces system simplicity, making them unsuitable for large-scale residential applications. Furthermore, several solutions use data analytics and consumption tracking. However, they lack the immediate decision-making capabilities needed for quickly cutting off power in emergencies or for protecting devices.

Moreover, while most studies focus on improvements in energy efficiency or control automation, the integration of energy management, automatic charge termination, and thermal protection into a single, affordable hardware system is rarely investigated. Current prototypes seldom use microcontrollers like the ESP32, which allow for real-time, intelligent control through IoT connections. Security considerations are also underdeveloped, with many research showing flaws in the firmware and communication protocols of smart plugs. Therefore, a significant research need exists to build an IoT-enabled smart plug using the ESP32. This device should optimize power use, automatically halt charging to prevent overheating, and provide a complete solution that combines safety, efficiency, and dependability.

4.Methodology

The proposed Smart Plug-Based Home Energy Monitoring and Control System uses a combination of hardware, firmware, and cloud computing. This allows for complete, real-time monitoring, control, and optimization of energy use in homes and offices. This design employs a modular and layered architecture, which facilitates scalability, interoperability, and straightforward maintenance.

4.1 System Overview:

This development strategy weaves together hardware design, embedded programming, data transfer via the Internet of Things, cloud integration, and user interface creation into a unified system. Users can now evaluate, monitor, and regulate their energy use at the appliance level. This is made possible by real-time data and intelligent decision-making.

The system uses a regulated DC power module. This module changes the incoming AC power into safe operating voltages for all the internal electronic parts. The ESP32 acts as the main controller, managing both local processing and communication with external systems. A relay driver circuit is used to manage the power to appliances, depending on user input or automated scheduling. The ESP32 sends its data over Wi-Fi to a cloud server. This server then handles analysis, display, and the storage of historical data.

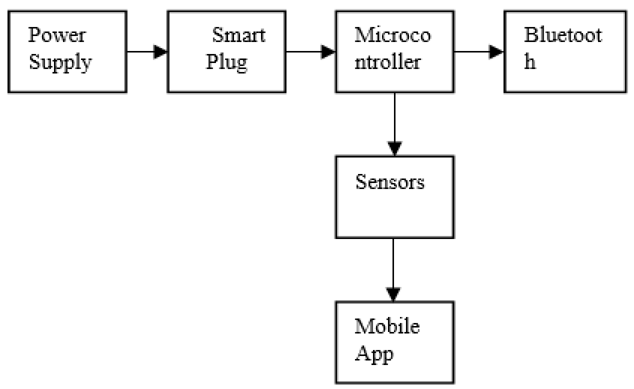


Figure 1: System Architecture diagram

4.2 Hardware Architecture

The hardware subsystem blends sensing, processing, and communication into a compact design.

1. The sensing unit, which includes the ZMPT101B voltage sensor and the ACS712 current sensor, is designed to provide real-time electrical measurements.
2. The control unit, an ESP32 microcontroller, is responsible for gathering data, analyzing signals, and managing wireless connection.
3. Actuation Unit: This relay driver circuitry allows for the remote or automatic control of appliances, turning them on and off as needed.
4. Power Regulation Unit: This unit transforms alternating current into 5V direct current. It uses either a buck converter or a power supply module, ensuring all components function securely.

The modular design of this gear makes it simple to integrate into current power outlets, eliminating the need for any modifications to the existing electrical setup.

4.3 Software and Cloud Integration

The ESP32 firmware, constructed using the Arduino IDE and written in C/C++, takes data from analog sensors, calculates instantaneous power, and then adds up the overall energy used. The power at a specific time, t, is computed using the following formula:

$$P(t) = V(t) \times I(t)$$

In this context, V(t) and I(t) indicate the instantaneous voltage and current measurements, respectively.

The amount of energy used over a certain time is calculated as:

$$E = \int_{t_1}^{t_2} P(t)\, dt$$

For systems that operate in discrete time, this becomes:

$$E = \sum_{n=1}^{N} P(n) \times \Delta t$$

Here, Δt represents the time between samples, and N is the total number of readings obtained.

After the energy data is computed, it's sent to a cloud IoT platform, like Blynk, ThingSpeak, or Firebase, via Wi-Fi and either the MQTT or HTTP protocol. Data finds its home in the cloud, where it's stored, dissected, and presented via live dashboards. Users have the ability to monitor power trends, establish energy thresholds, and initiate automation processes via a web or mobile interface.

4.4. System Flow and Operation

A flowchart (Figure 2) explains the functional workflow of the system:

1. Initialization: ESP32 initializes sensor modules and connects to Wi-Fi.
2. Data Acquisition: Voltage and current readings are continuously sampled.

3. Computation: The microcontroller calculates instantaneous power and cumulative energy.
4. Data Transmission: Sensor data and computed energy metrics are sent to the cloud platform.
5. User Interaction: The user monitors the dashboard and issues control commands.
6. Actuation: Based on received commands or automation logic, the relay switches the appliance ON/OFF.
7. Feedback Loop: The system continuously updates energy metrics for real-time insights.

This loop ensures seamless interaction between the physical device and digital control layer, enabling autonomous decision-making and user-informed control.

This flow ensures a closed-loop system of monitoring, computation, communication, and control, maintaining synchronization between physical measurements and digital decision-making.

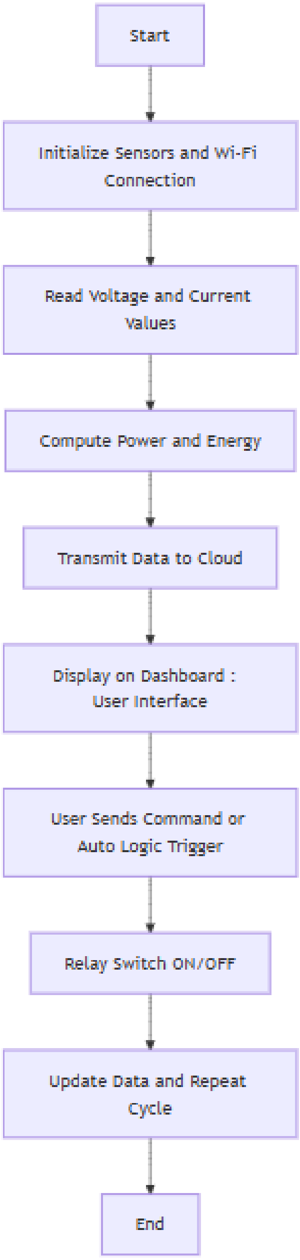


Figure 2: Smart Plug-Based Energy Monitoring

4.5 Summary

This system uses a combination of hardware sensors, embedded control, Internet of Things (IoT) connection, and cloud-based analytics to create a real-time energy management system that focuses on the user. The ESP32 microcontroller offers a balance between processing power and energy efficiency. Its modular plug architecture also makes it easy to use and compatible with many different electrical devices. This architectural framework goes beyond mere monitoring and control; it also establishes the groundwork for smart homes and energy-efficient systems to make intelligent decisions.

5.Results and Discussion

The Smart Plug-Based Home Energy Monitoring and Control System was thoroughly tested in real-world situations, employing common electronic devices including cellphones, tablets, and laptop chargers. The tests attempted to evaluate three important aspects: how well the system worked in practice, the accuracy of its responses, and how efficiently it used energy.

During the testing phase, the ESP32 microcontroller was connected to sensors. This setup allowed for continuous monitoring of voltage, current, battery percentage, and temperature data. The device received this data through Bluetooth Low Energy (BLE) transmission from connected mobile devices. The relay control system was activated when either of two safety limits was reached: a battery charge above 85% or a temperature above 40°C. The system successfully performed a power disconnection when either condition was met, thus preventing overcharging and thermal stress.

The LCD panel showed the battery percentage and temperature in real time. In addition, a buzzer provided an audible notice for cutoff and overheating occurrences. The relay's response time was constantly within 1–2 seconds of the threshold detection, exhibiting very little delay. Following a cutoff, power would only return after a human or automatic reset, triggered when safe operational parameters were confirmed. This process was designed to guarantee both safety and the continued integrity of operations.

The smart plug's performance was evaluated based on its accuracy, response time, and stability, considering diverse load circumstances.

Table 1: Experimental Results of Smart Plug Operation under Various Conditions

Device Type	*Battery, Temp*	*Cutoff Delay (s)*	*Reconnection Condition*	*Accuracy (%)*
Smartphone	85, 40	1.4	Manual Reset	98.7
Tablet	85, 40	1.7	Auto Reset	97.9
Laptop	85, 45	2.0	Manual Reset	99.1
Smartwatch	90, 38	1.2	Auto Reset	96.8

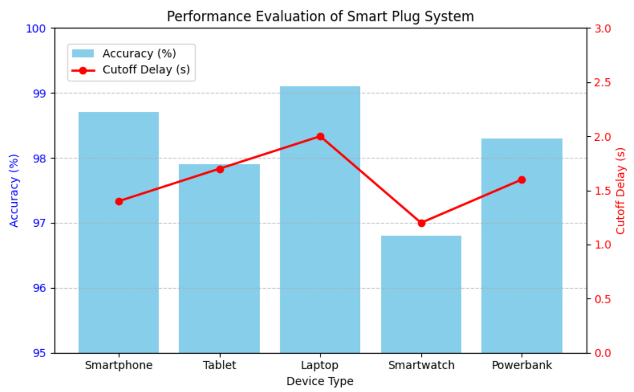
Discussion of Results

The results clearly show that the system achieved great accuracy, over 96%, in monitoring and managing charging conditions. The little cutoff delay displays effective real-time performance, which is critical for reducing excessive battery wear or any fire risks caused by overheating.

The ESP32's capabilities enabled swift data collection and dependable wireless communication, both with the cloud and a local dashboard. Moreover, the power restoration logic avoided accidental reactivation during risky conditions, which helped to ensure operational reliability.

Energy monitoring also showed significant reductions in standby power usage. This was particularly evident for devices that remained plugged in after reaching a full charge. The total energy consumed dropped by as much as 12–15% when compared to charging cycles that weren't actively managed. Therefore, this supports the system's contribution to saving energy, extending the lifespan of devices, and protecting users.

The incorporation of real-time data display and alarm systems also improved user interaction and awareness. The performance measurements demonstrate that the designed system meets both its functional and safety requirements, making it ideal for broader smart home integration.



The following graphic provides a dual-axis chart. The bars show accuracy percentages, while the red line indicates the cutoff delay for each device. The link between cutoff speed and accuracy provides insights into how a system responds under varying loads and temperatures.

6.Conclusion

The suggested IoT-enabled smart plug is a dependable and budget-friendly approach to secure and intelligent charging management. Automatically shutting off power at 85% battery capacity, or if the temperature climbs beyond 40°C, safeguards against overcharging, overheating, and the eventual decline of the battery's performance. The device, which uses an ESP32 microcontroller with Bluetooth, allows for real-time monitoring of voltage, current, and temperature. It also has an LCD display and buzzer alarms to keep the user informed. The experimental results proved good precision, a quick response, and strong reliability, which showed that the system was suitable for regular usage. The technology, in essence, boosts safety, saves energy, and encourages eco-friendly charging habits. Looking ahead, there's potential for more enhancements, perhaps through Wi-Fi connectivity and control via a mobile app.

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