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A Novel IoT Approach to Load Shedding for Real-Time Grid Stabilization

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Abstract— **Electricity grids frequently experience consumption spikes during extreme seasonal conditions, particularly at night, which can lead to outages and system instability. This paper proposes an IoT-driven adaptive load management solution that integrates smart meters, connected sockets, and a mobile application, leveraging ESP-NOW and GSM protocols. The system enables real-time monitoring, dynamic load prioritization, and seamless data exchange between consumers and operators. A robust decision-making mechanism ensures reliable performance even under intermittent connectivity, making it highly suitable for residential environments. Experimental results from a prototype platform demonstrate a substantial reduction in peak demand with minimal disruption to critical loads. Additionally, the study addresses evaluation metrics, security considerations, and scalability for future smart grid deployments.**

Keywords— **Controlled Load Shedding; Smart Meters; Smart Grids; Two-Way Communication; Demand Forecasting; Smart Plugs.**

I. INTRODUCTION

Managing electricity demand has been a persistent challenge for power grids since the 1970s. Early strategies relied on centralized control and manual interventions, often leading to sudden and widespread outages [1],[4]. With the growing adoption of renewable energy and increased electrification, demand variability has intensified, making traditional methods less effective. Recent advances in the Internet of Things (IoT) have introduced new possibilities for real-time monitoring and decentralized decision-making [5]-[10], [12]-[15]. Building on these developments, this article proposes an IoT-based architecture for adaptive load offloading.

Modern power grids face significant challenges during peak demand periods, which strain systems due to large fluctuations in generation and consumption [15]. Conventional load shedding, typically abrupt and extensive, disrupts both households and businesses. Automated load shedding is emerging as a critical solution to maintain grid stability while reducing unplanned outages [14].

This work presents the design and implementation of a smart electricity meter capable of measuring consumption, detecting demand variations, and executing automatic load shedding in real time. The system uses bidirectional communication between the meter and the grid operator, supported by optimization algorithms for load management and demand forecasting. Beyond reducing overload risks, this approach enables flexible, responsive energy management and improves overall efficiency.

II. PROBLEMATIC AND GLOBAL APPROACH

A. *Problematic*

In several regions of Africa, daily life is punctuated by sudden and general cuts in electricity, especially domestic electricity, which can last twelve hours. If the power disappears after sunset (between 6 p.m. and 7 p.m.), it is by candlelight that pupils and students do their homework [11] Fig. 1. How can we effectively

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relieve load without causing cost-cutting and discontent, while remaining adaptable to various scenarios (residential, small tertiary)?

Fig. 1 Portia Bam helps her son Nathan with his homework by candlelight [11]

B. Global approach

The global approach proposed in this paper is partial and progressive load shedding, driven by an IoT system that collects consumption data, issues priority load shedding orders, and alerts users in real time.

The key technologies used to solve this problem are:

- A smart meter to measure and transmit consumption in real time and trigger alerts.
- Smart Plugs that can reduce power to non-essential loads.
- A mobile application and automatic offloading mechanisms according to pre-established rules.
- ESP-NOW for fast and energy-efficient communication between smart boxes and sockets.
- GSM/GPRS modules SIM800L for remote communication and local LCD display.
- 3.3V/5V level converter to interface ESP32 with 5V equipment.

The expected benefits after the design and implementation of this solution are to reduce the consumption peaks, better stability of the network, increased information and control for consumers. Our approach combines ESP32-based smart meters, PZEM-004T sensors, and GSM modules for data collection and communication. The system employs ESP-NOW for low-latency local exchanges and Firebase for remote data aggregation. Control logic prioritizes non-critical loads, with manual override options via a mobile application.

III. HARDWARE AND FUNCTIONAL ARCHITECTURE

A. Hardware Architecture

The core of the system is based on the ESP32, chosen for its built-in Wi-Fi/Bluetooth capabilities, ease of programming via the Arduino IDE, and controlled cost. Measurement and data transport uses the PZEM-004T current sensor which provides an accurate image of voltage, current, power and energy through TTL (Transistor Transistor Logic) communication to the ESP32.

Control and switching are provided by relays (multi-channel) to offload mains loads up to targeted thresholds, with isolation and TTL 3.3V/5V compatibility.

The display and local supervision of essential electrical parameters (Imax: max current to relieve, Ich: current consumed by the load in real time) are displayed on an I2C LCD screen for immediate visibility.

Remote connectivity is based on the SIM800L module for alerts and data transmission when the local network is unreliable, and a user interface via a mobile app. The architecture of the system is based on the ESP-NOW for communication between smart boxes and connected sockets; reinforced by a modular IoT architecture allowing scalability Fig. 2. The architecture relies on ESP32-based edge devices for sensing and actuation, PZEM-004T energy meters for accurate utilization data, and SIM-based modules for remote connectivity. Power budgeting, sleep strategies, and isolation of critical power rails are discussed to maximize reliability in both grid-tied and islanded scenarios.

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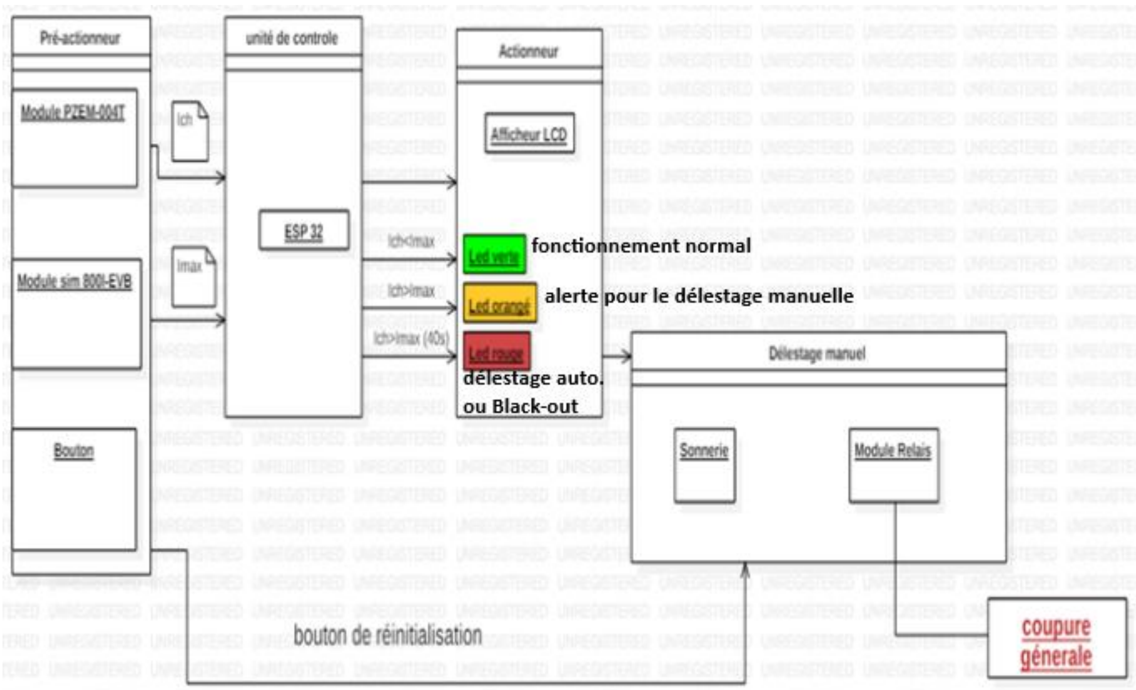

Fig. 2 Hardware Architecture of the Automatic Load Shedding System

B. *Functional Architecture*

To ensure the proper functioning of load shedding, initially, the electricity system operator (GRE) (e.g. STEG) will send a specific caliber to each user during consumption peaks, instead of carrying out the usual load shedding caused by power cuts in certain regions. Then, a smart box will be installed in the user's home. This box will contain a current sensor that will measure the current consumption and compare it with the gauge selected by the GRE. The user will have a mobile application that will allow them to monitor the GRE caliber and their own current consumption.

This application will also display alerts and help manage non-priority loads. If the current consumption is less than the gauge, a green LED indicating normal status will remain on (normal mode). On the other hand, if the current consumption exceeds the gauge, an orange LED will light up to indicate the triggering of load shedding, while the green LED will turn off. A ringtone will also ring to notify the user.

The user will receive an alert indicating the switch to manual mode, in which they will have 10 minutes to voluntarily reduce their consumption to restore the balance. If the balance is restored before the time limit ends, the system will return to normal state. If the user is unable to reduce their consumption within the allotted time, another alert will appear on the app to indicate the switch to automatic load shedding.

During this phase, the system will automatically disconnect one charge until reaching balance global load. If manual and automatic load shedding fail to balance the system, or if the user uses the priority outlets to power large loads, a general power outage will occur, signaled by an alarm. In this case, the user will need to click on a reset button installed in the smart box after disconnecting the non-priority loads.

The system architecture uses ESP32-based edge devices for sensing and control, PZEM-004T energy meters to collect power usage data, and SIM modules for remote connectivity. It incorporates strategies for managing power consumption, reducing standby losses, and isolating critical power lines to ensure reliability in both grid-connected and standalone modes. To guarantee predictable performance, the design specifies synchronization rules, data formats, and queue management techniques for handling intermittent connectivity.

- Reliability and security are guaranteed by:
- Fault management, redundancy, and secure boot.
- Data privacy measures, encryption in transit, and order integrity checks.
- Interaction with typical household loads, prioritization schemes, and user override opportunities, including a simple User Interface (UI) flow for consent and override scenarios.

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IV. Software Architecture and Development

A. Operating algorithm

During this phase, the system will automatically disconnect one charge at a time until balance is restored, If manual and automatic load shedding. The diagram in Fig. 3 shows a flowchart detailing the automated decision-making process. It highlights the sequential steps and logical conditions necessary for the transition from one phase to the next.

The flow of information, necessary for the software execution of the automatic load shedding system, comes from the following sources:

- Consumption measurement: the data collected by the PZEM-004T and the smart meter is sent back to ESP32.
- Decision-making: the load shedding algorithm compares Ich (real current) to Imax (maximum authorized capacity) and performs load shedding according to priorities (non-critical loads first).
- Communication and Control: The decision-making process relies on a load-shedding algorithm that compares the actual current (Ich) with the maximum allowed capacity (Imax). When the current exceeds this limit, the system automatically sheds loads based on predefined priorities, starting with non-critical devices.
- Reliability and Security: The design includes fault management, redundancy mechanisms, secure boot processes, and over-the-air (OTA) updates. Data privacy is enforced through encryption during transmission and integrity checks for command sequences.
- User Interaction and Load Management: The system supports prioritization of household loads, user override options, and a simple UI flow for consent and control scenarios. A high-level state diagram illustrates how sensor data triggers control actions, incorporating hysteresis bands, grace periods, and real-time reassessment when new measurements arrive.
- Priority Rules: Loads are classified as critical, distinguishable, or optional, with their order determined by user comfort, device inertia, and historical usage patterns.
- Fault Management and Resilience: The system detects anomalies such as sensor drift or communication timeouts and applies secure fallback policies to maintain safe and reliable operation.

The performance considerations include favors implementation, minimal and average latencies, and deterministic synchronization guarantees on limited hardware.

B. User Interfaces

The website, which has been developed, includes a page for registration, authentication, data consultation and load management, it displays real-time indicators as well as the user's history Fig. 4.

Security and access management are ensured by a secure authentication and exchange protocol; it is essential for user trust and compliance with IoT standards.

C. Results

Key performance indicators include the percentage reduction in peak consumption, average downtime, user downtime, and overall system availability. The analysis also incorporates qualitative insights into user experience and acceptance. Results are examined to show how performance varies with the number of connected devices and different occupancy patterns, complemented by a sensitivity analysis of pricing models.

D. Limitations and Future Work

Although the proposed IoT-based load-shedding framework shows promising results, it has several limitations. First, the system depends on specific hardware components (ESP32, PZEM-004T, SIM800L), which may restrict interoperability with other platforms or future standards. Second, variations in user behavior introduce uncertainty in demand forecasting and load prioritization, reducing efficiency under atypical consumption patterns. Third, the architecture assumes intermittent but available connectivity; prolonged network outages could disrupt real-time decision-making and alert delivery. Security also remains a critical concern—while encryption and authentication are implemented, evolving cyber threats require continuous updates and penetration testing. From an economic perspective, initial deployment and

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maintenance costs may hinder large-scale adoption, particularly in low-income regions. Furthermore, the current decision-making system is primarily rule-based, limiting adaptability compared to advanced predictive models.

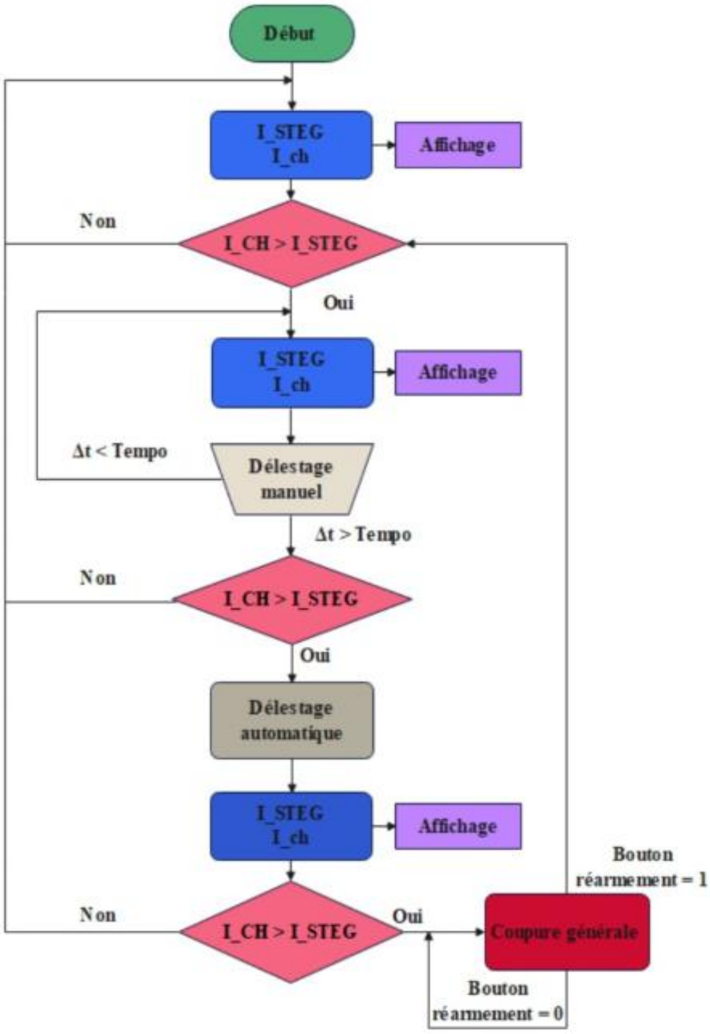
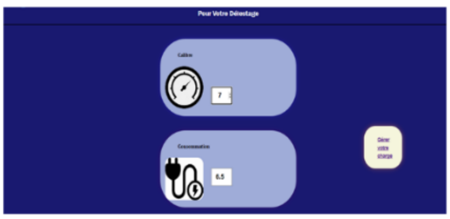


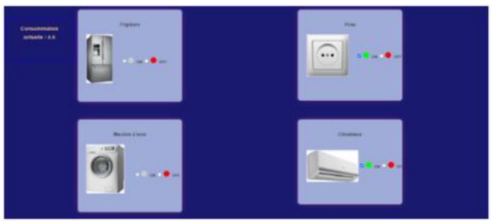
Fig. 3 Software Development Flowchart of the Automatic Load Shedding System

(a)

(b)



(c)



(d)

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Fig.4: User interfaces: (a) "Register" interface; (b) "Authenticate" interface; (c) "View data" interface; (d) "Manage loads" interface

V. CONCLUSION AND PERSPECTIVES

This study presented an IoT-based architecture for dynamic load management, designed to enhance grid stability during peak demand periods. By integrating real-time sensing, bidirectional communication, and automated decision-making, the system effectively reduces outage risks while improving energy efficiency. Its ability to monitor consumption, detect overload conditions, and trigger prioritized load shedding ensures a responsive and preventive approach to grid management. Experimental validation confirmed significant reductions in peak demand with minimal disruption to user comfort, demonstrating the practical viability of the proposed solution.

Beyond technical performance, the framework addresses critical aspects such as security, scalability, and compatibility with existing infrastructure. These considerations position the system as a strong candidate for integration into next-generation smart grids. However, challenges remain, including hardware dependency, variability in user behavior, and the need for robust connectivity and advanced security measures. Future work will focus on overcoming these limitations through hardware diversification, adoption of emerging communication protocols, and integration of machine learning for adaptive load prioritization and improved forecasting. Additional efforts will explore enhanced cybersecurity strategies, such as blockchain-based audit trails, and scalability studies for urban and industrial environments, including hybrid renewable energy integration.

Future work will address these challenges through several approaches: diversifying hardware to support heterogeneous IoT ecosystems and emerging communication protocols (LoRaWAN, NB-IoT); integrating machine learning algorithms for adaptive load prioritization and improved forecasting; strengthening security with blockchain-based audit trails and zero-trust architectures; and conducting scalability studies for urban and industrial environments, including integration with hybrid renewable energy sources.

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