

Development of Smart Energy Management Socket Using Real-Time Metering and Demand Response Control

JOHNSON GBADEBO ADENLE¹, OPAKUNLE JAMES AKINPELU², AYODELE ELIJAH BLESSING³

^{1,2,3} *Department of Electrical and Electronic Engineering, Ajayi Crowther University, Oyo, Nigeria.*

Abstract- *The need for energy conservation, management, control, and overload protection for optimal energy deployment and consumption in domestic, commercial, and industrial applications has necessitated the design of an energy supply system that can be controlled and monitored in real time from any location worldwide. The proposed system leverages an ESP32 Wi-Fi-enabled micro-controller integrated with the PZEM-004T sensor module to measure current, voltage, energy, power, frequency, and power factor. Each outlet is switched via a 2N2222A bipolar junction transistor driving individual relay channels that control AC supply to the connected loads. Parameters are monitored, controlled, and driven online through a Firebase Real-time Database web interface. Functional testing showed an average voltage measurement error of 0.14% over a 227 V-230 V range, an average current error of 1.18%, and a power measurement error of 2.11%. These negligible deviations confirm the accuracy, reliability, and suitability of the system for smart-home and industrial energy management applications.*

Keywords: *Internet of Things (IoT), ESP32, Smart Socket, Energy Monitoring, PZEM-004T, Firebase, Relay Control, Wi-Fi, Automation, Energy Management*

I. INTRODUCTION

The increasing demand for efficient energy management in domestic and industrial settings has driven significant advances in automated control systems. Automation defined as the use of technology to perform tasks with minimal human supervision through programmed instructions is achieved through mechanical, electrical, electronic, or networked means. The convergence of the Internet of Things (IoT) with power systems has opened new pathways for real-time monitoring, remote control, and intelligent decision-making in energy distribution.

In Nigeria, the electric power sector faces critical challenges: energy generation meets less than 30% of national demand, and over 50% of generated power is lost through distribution inefficiencies. These losses impose significant economic burdens on households and industries. The proliferation of uncontrolled electrical loads further exacerbates safety risks, including electrical fires and equipment damage due to overloads.

Existing solutions such as manual circuit breakers and conventional timer switches lack the flexibility for real-time remote monitoring and dynamic set-point adjustment. Recent advances in low-cost Wi-Fi micro-controllers (e.g., ESP32) and cloud platforms (e.g., Firebase) have made it feasible to deploy intelligent socket systems at consumer scale.

This paper presents the design, implementation, and evaluation of an IoT-based automated socket system featuring:

- i. Eight independently controllable 13 A AC socket channels;
- ii. Real-time measurement of voltage, current, active power, power factor, frequency, and cumulative energy;
- iii. Onsite PIR-based motion-triggered automation;
- iv. Remote monitoring and control via a Firebase web interface accessible from any internet-enabled device;
- v. Configurable set point protection for overcurrent, overvoltage, and overpower conditions.

1.1 Problem Statement

The rapid increase in residential, commercial, and institutional electricity consumption has intensified the need for intelligent energy management systems

capable of reducing energy wastage and improving operational efficiency. Conventional electrical sockets provide power delivery without any capability for real-time monitoring, remote control, or intelligent decision-making regarding connected loads. Consequently, many electrical appliances continue to consume power unnecessarily due to user negligence, standby power losses, and the absence of continuous energy usage feedback. Although smart plugs and energy monitoring devices exist, many available solutions focus either on remote switching or energy measurement alone, with limited integration of real-time Internet of Things (IoT) connectivity, automated load control, and detailed energy consumption analytics. Furthermore, existing systems often lack adaptive control mechanisms that can automatically disconnect appliances based on predefined energy thresholds, excessive power consumption, abnormal operating conditions, or user-defined schedules. This limitation reduces their effectiveness in minimizing energy waste and preventing excessive electricity bills.

In developing regions such as Nigeria, where electricity supply is often unstable and energy costs continue to rise, consumers require affordable and intelligent solutions that enable effective monitoring and management of electrical loads. The absence of low-cost, Wi-Fi-enabled smart socket systems with integrated energy metering prevents users from obtaining accurate information about appliance energy usage and making informed decisions regarding energy conservation. Therefore, there is a need to develop an IoT-based automated socket integrated with a Wi-Fi communication module and electrical energy consumption meter sensor capable of real-time monitoring, remote control, automated load management, and cloud-based data reporting. Such a system would provide users with detailed energy consumption information, enhance energy efficiency, reduce unnecessary power usage, improve electrical safety, and support the advancement of smart home and smart energy management technologies.

The remainder of this paper is organized as follows: Section 2 reviews related work. Section 3 describes the system architecture and hardware/software

design. Section 4 presents prototype implementation and test results. Section 5 discusses findings and limitations. Section 6 concludes with recommendations for future work.

II. LITERATURE REVIEW

2.1 History and Evolution of Automation

Automation traces its origins to mechanical tools of the pre-industrial era and accelerated through the Industrial Revolution with the adoption of electromechanical relay logic in the 1920s-1950s. Relay logic systems enabled complex switching operations in telephone exchanges and factory floors. The introduction of programmable logic controllers (PLCs) and distributed control systems (DCS) in the 1970s further displaced relay-based designs, enabling flexible reprogramming without hardware changes. The evolution continued into the digital era with embedded micro-controllers and single-board computers, culminating in the current IoT paradigm where physical devices communicate autonomously over the internet.

2.2 Internet of Things

The Internet of Things (IoT) is a network of interrelated physical devices that connect and exchange data with other IoT devices and cloud platforms (Alexanda & Kinsar, 2025). The operational pipeline of an IoT system follows four stages: (1) Devices/sensors collect data; (2) data traverses the Internet/network; (3) data is stored and analyzed in a cloud/data center; (4) the user monitors or controls devices via a smartphone or computer. This cyclical data flow is illustrated in Figure 1.

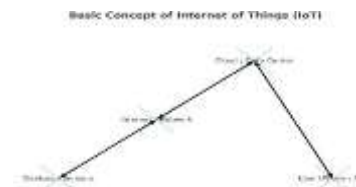


Fig 1: Basic concept of Internet of Things (IoT): relationship between components in an IoT system (Chat GPT, 2025)

A key advantage of IoT networks is their ability to transfer data across the internet without requiring

direct human-to-human or human-to-computer interaction, enabling autonomous and intelligent control.

2.3 Smart Socket Technologies

Smart sockets integrate micro-controllers, relay modules, and communication interfaces to provide automated and remote control of electrical loads. Key enabling components include:

2.3.1 Switches

A Double Pole Double Throw (DPDT) switch provides two separate switching paths from a single actuator, enabling both phase and neutral interruption for improved safety (Figure 2).



Fig 2: Double Pole Double Throw (DPDT) rocker switch used for mains isolation (Amazon, 2025).

2.3.2 Capacitors

Capacitors store and release electrical energy, filter power supply noise, and decouple supply rails (Samuel et al, 2016). Two configurations parallel plate and rolled film are commonly employed in power supply filtering stages (Figure 3).

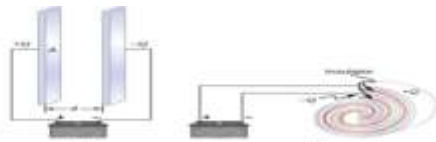


Fig 3: Parallel plate capacitor (a) and rolled film capacitor (b) configurations.

2.3.3 Resistors

Resistors limit current flow and set biasing conditions. Color-coded bands indicate resistance value and tolerance (Figure 4). In this design, $1\text{ k}\Omega$ resistors provide base current limiting for the 2N2222A switching transistors.

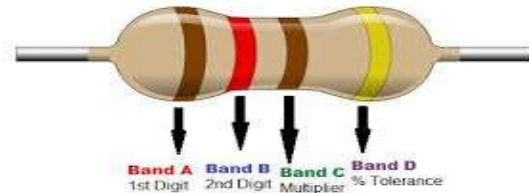


Fig 4: Resistor color code bands indicating value and tolerance (Mehta, 2008).

2.3.4 Diodes

Diodes are semiconductor devices that permit unidirectional current flow. Three types are employed in this design:

- i. Crystal (PN junction) diode: used in rectification within the power supply.
- ii. Light Emitting Diode (LED): provides visual status indication.
- iii. Freewheeling (fly back) diode: connected in reverse bias across each relay coil to suppress inductive voltage spikes during relay de-energization, protecting the switching transistor.

2.3.5 Bipolar Junction Transistors (BJT)

The 2N2222A NPN BJT operates as a digital switch in each relay driver circuit. A small base current from the micro-controller GPIO pin controls a larger collector current through the relay coil (Maftunzada, 2022).. The internal construct of a BJT is shown in Figure 5 .

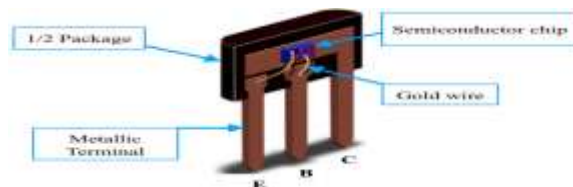


Fig 5: Internal construct of a BJT transistor showing emitter (E), base (B), and collector (C) terminals (Luis, et al, 2022)

2.3.6 Relays

A relay is an electromechanical switch that allows a small control current to switch a large load current. The SRA-05VDC-CL relay module (Figure 6) operates on a 5 V DC coil and can switch up to 10 A at 250 V AC, providing electrical isolation between the low-voltage control circuitry and the mains

supply (Asadi, 2024). Ozuno (2025) provide comprehensive treatments of relay ratings and selection criteria.



Fig 6: Double Pole contact electromechanical relay module (SMI-S-212L) rated 5 A at 250 V AC .

2.3.7 Micro-controllers

A micro-controller integrates a CPU, memory (RAM/ROM), and I/O interfaces on a single chip (Figure 7). The ESP32 DEVKIT V1 (Figure 8) was selected as the controller due to its integrated dual-core processor, 520 KB SRAM, built-in Wi-Fi (802.11 b/g/n) and Bluetooth 4.2, 34 programmable GPIO pins, and support for multiple communication protocols (UART, SPI, I2C) .

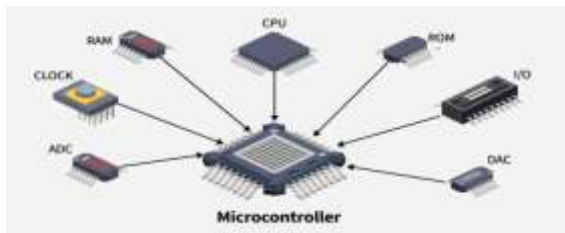


Fig 7: micro-controller peripheral architecture showing integration of CPU, RAM, ROM, ADC, DAC, clock, and I/O.

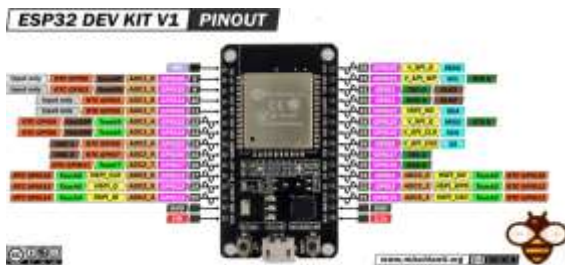


Fig 8: ESP32 DEVKIT V1 pin-out diagram showing GPIO, ADC, DAC, SPI, I2C, and UART assignments.

2.4 Energy Monitoring Techniques

Energy monitoring in IoT systems typically employs dedicated metering ICs or modules. The PZEM-004T is a single-phase AC energy meter module capable of measuring voltage (80-260 V), current (0-100 A), active power (0-23 kW), power factor (0-1.0), frequency (45-65 Hz), and cumulative energy (0-9999 kWh) with communication via (Universal Asynchronous Receiver/Transmitter) UART at 9600 baud.

2.5 Related Work

Several prior studies have addressed IoT-based smart socket and energy monitoring systems. Adyanth et al. developed intelligent sockets for home automation using IoT, demonstrating remote appliance control. Lamya et al. implemented an IoT-based smart socket plug energy monitoring system with real-time data visualization. Hamosi et al. developed an IoT-based system for monitoring electrical energy consumption in smart houses in Tanzania. Omar et al. designed a smart meter with load control for home energy management. Yugerita et al. designed a monitoring and controlling system on IoT-based sockets using Firebase. Vikas et al. proposed smart electricity meter monitoring using I-Socket with prediction capabilities. Ravindra & Smita investigated IoT-based relay operations for automated control.

2.6 Research Gap

While existing systems address remote monitoring or basic switching, few integrate all of the following in a single compact device: (1) multi-channel independent relay control, (2) comprehensive real-time parameter measurement (voltage, current, power, frequency, power factor, energy), (3) configurable set-point-based overload protection, and (4) onsite PIR-based motion automation alongside remote Firebase control. This work addresses these gaps by providing a complete, tested prototype.

III. SYSTEM DESIGN AND METHODOLOGY

3.1 System Overview

The IoT-based automated socket system comprises five functional units: (1) Power Supply Unit, (2) Electrical Meter Sensor Unit, (3) Display Unit, (4) Motion Sensor Unit, and (5) Controller and Actuator

Units. The block diagram of the complete system is shown in Figure 9.

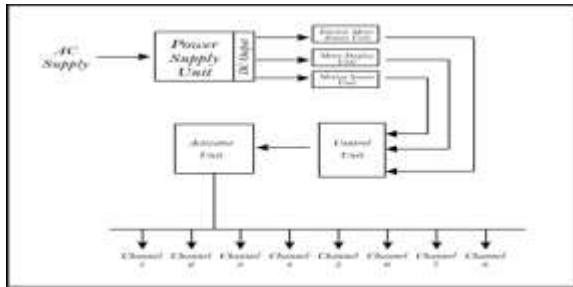


Fig 9: Block diagram of the IoT-based smart socket system with energy meter sensor, showing eight independent load channels.

3.2 Power Supply Unit

The HLK-PM01 AC-to-DC switching converter steps down the 110-240 V AC mains supply to a regulated 5 V DC output at up to 600 mA. This powers the ESP32 micro-controller, relay modules, PZEM-004T sensor, LCD display, and PIR sensor. A 1000 μ F bulk capacitor and a 100 nF bypass capacitor filter the DC output to suppress ripple and high-frequency noise.

3.3 Electrical Meter Sensor Unit

The PZEM-004T module (Figure 10) measures all relevant AC electrical parameters. The module's built-in current transformer (CT) is clamped around the live load conductor. Data is transmitted to the ESP32 via UART serial communication at 9600 baud.



Fig 10: PZEM-004T single-phase AC energy meter sensor module with integrated current transformer and UART interface.

3.4 Display Unit

A 20" \times 4 character I2C LCD module (Figure 11) provides onsite display of measured electrical parameters. The I2C interface reduces GPIO pin usage to only two pins (SDA, SCL) on the ESP32.



Fig 11: 20" \times 4 character I2C LCD module used for onsite display of electrical parameters.

3.5 AC Socket Outlets

Eight 13 A BS1363-type socket outlets (Figure 12) serve as the load connection points. Each socket is connected to an independent relay channel for individual switching control.



Fig 12: 13 A BS1363 socket outlet with switched connection for individual load control.

3.6 Controller Unit

The ESP32 DEVKIT V1 serves as the central controller. It receives sensor data via UART from the PZEM-004T, reads the PIR motion sensor via a digital GPIO pin, communicates with the LCD via I2C, drives eight relay channels via GPIO-controlled transistor switches, and maintains bidirectional communication with the Firebase Real-time Database over Wi-Fi.

3.7 Actuator Unit

Each of the eight actuator channels consists of a 1 k Ω base resistor, a 2N2222A NPN transistor, a 1N4007 freewheeling diode, and an SRA-05VDC-CL relay. The relay contacts switch the 13 A AC load socket. This design provides galvanic isolation between the 5 V control domain and the 230 V AC load domain.

3.8 Load Design

The socket outlet ratings were determined based on common domestic and commercial load profiles. Table 1 presents the load design specifications.

Load Design for Socket Outlet Ratings

S/N	Heavy Household Load	Wattage (W)
1	Refrigerator	100-800
2	Electric Kettle	2200-2400
3	Electric Iron	100-1800
4	Borehole Pump (1 Hp)	1400-2331
5	Microwave Oven	600-1200
6	Air Conditioner	782-1865

The relay and socket ratings (10 A/250 V AC) are sufficient for all listed loads within the per-channel capacity. Set-point protection limits are configured in the Firebase database to prevent overloading.

3.9 Circuit Design

The complete circuit schematic (Figure 13) integrates all five functional units. The power supply unit (top-left) feeds the 5 V DC bus. The eight actuator channels (left and bottom) each contain the BJT-relay driver circuit. The control unit (center-right) shows the ESP32 with its UART connection to the PZEM-004T energy meter sensor, I2C connection to the LCD, and digital input from the PIR motion sensor.

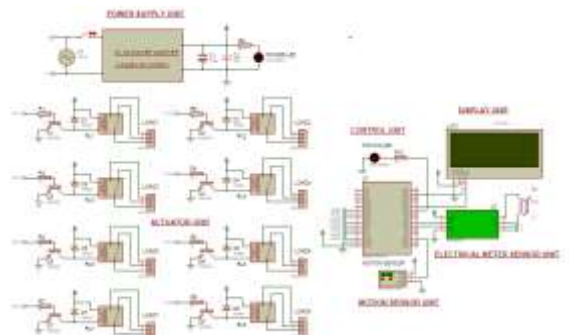


Fig 13: Complete circuit diagram of the IoT-based automated socket system showing power supply, actuator channels, control unit, display unit, electrical meter sensor unit, and motion sensor unit.

3.9.1 Electric Meter Sensor Design

The PZEM-004T module is connected in series with the load supply line for voltage sensing (via internal voltage divider) and current sensing (via the external CT clamped on the live wire). The UART TX/RX lines are connected to the ESP32 GPIO pins for serial data transfer.

3.9.2 Control Design

The ESP32 GPIO output pins (configured as digital outputs) drive the base of each 2N2222A transistor

through a 1 k Ω current-limiting resistor. When a GPIO pin is driven HIGH (3.3 V), the transistor saturates, energizing the relay coil and closing the relay contacts to power the load.

3.9.3 Actuator Design

The freewheeling diode (1N4007) is connected in antiparallel across each relay coil. When the transistor switches off, the collapsing magnetic field in the relay coil generates a back-EMF. The freewheeling diode provides a low-impedance path for this current, clamping the voltage spike and protecting the transistor from breakdown.

3.10 Software Tools

Arduino IDE

The Arduino Integrated Development Environment (IDE) was used to program the ESP32 micro-controller in C/C++. Required libraries include:

- i. WiFi: Wi-Fi connectivity management;
- ii. FirebaseESP32.h: Firebase Real-time Database integration;
- iii. PZEM004Tv30.h: PZEM-004T sensor communication;
- iv. LiquidCrystal_I2C.h: I2C LCD display driver.

3.11 Firebase Real-time Database

Google Firebase Real-time Database serves as the cloud backend. The database structure organizes data into three nodes:

- i. SBOT-READINGS: stores real-time sensor values (voltage, current, power, frequency, power factor, energy);
- ii. SBOT-SETTINGS: stores user-configurable set-points (V_{max} , V_{min} , current limit, power limit, energy limit);
- iii. SBOT-SWITCH: stores the ON/OFF state (0 or 1) for each of the eight load channels (L1-L8).

3.12 System Operation

The operational sequence of the system is as follows:

1. The user sends an ON/OFF command via the Firebase mobile web interface.
2. The ESP32 micro-controller receives the command over the internet through Wi-Fi and

processes the received signal according to the uploaded firmware.

3. The ESP32 outputs a control signal to the appropriate actuator channel, switching the relay ON or OFF.
4. The PZEM-004T energy meter sensor continuously measures electrical parameters and sends data to the ESP32.
5. The ESP32 updates the Firebase SBOT-READINGS node with the measured values.
6. Data is simultaneously displayed on the onsite 20"×" 4 LCD and on the Firebase online portal.
7. If measured values exceed the set points stored in SBOT-SETTINGS, the firmware automatically switches off the affected channel(s) for overload protection.
8. The onsite PIR motion sensor provides autonomous switching: detecting human presence activates the loads; absence after a configurable timeout switches them off.

IV. PROTOTYPE IMPLEMENTATION AND RESULTS

4.1 Prototype Development

The working prototype was developed from the block diagram architecture and circuit design, integrating all functional units into a compact packaged system. The key hardware components used in the prototype assembly are summarized in Table 2.

Key Hardware Components for Prototype Assembly

Component	Function	Module/Part
ESP32 micro-controller with Wi-Fi	Central processing unit; controls all subsystems, manages Wi-Fi communication, and executes firmware logic	ESP32 DEVKIT V1
Energy Monitoring Module	Measures AC electrical parameters: voltage, current, active power, power factor, frequency, and energy	PZEM-004T
Relay Module	Electrically controlled switch for each AC load channel; provides isolation between control and power domains	SRA-05VDC-CL (8×)

AC-to-DC Power Supply	Steps down 110-240 V AC mains to regulated 5 V DC for all control electronics	HLK-PM01
Enclosure	Safe, insulated housing for all components	Custom plastic (IPV6)
Socket and Plug	Standard 13 A electrical socket outlets and supply plug	BS1363 (8× sockets)

4.2 Prototype Development Steps

4.2.1 Hardware Assembly

- i. Power Supply: The HLK-PM01 AC-to-DC converter was integrated in the enclosure to supply 5 V DC to all low-voltage components.
- ii. Sensor Integration: The PZEM-004T module was connected to the ESP32 via UART; the CT was clamped around the live AC load conductor.
- iii. Relay Connection: Eight relay modules were interfaced to ESP32 GPIO pins through 2N2222A transistor driver circuits.
- iv. Safety Isolation: All 230 V AC components were physically and electrically isolated from the 5 V DC control circuitry using the relay's galvanic isolation and appropriate cable routing within the enclosure.

4.3 Software and Firmware Development

The Arduino IDE was used to program the ESP32. Firebase libraries were configured with the project credentials. The firmware implements:

- i. Wi-Fi connection management with automatic reconnection;
- ii. Periodic PZEM-004T polling (every 2 s) and Firebase database updates;
- iii. Real-time reading of Firebase SBOT-SWITCH and SBOT-SETTINGS nodes;
- iv. Automatic overload protection by comparing measured values against configured set-points;
- v. PIR sensor interrupt handling for onsite motion-triggered automation;
- vi. I2C LCD refresh with current electrical parameters.

4.4 Testing and Calibration

4.4.1 Sensor Calibration

Voltage and current sensors were calibrated against a Fluke digital multi-meter and a clamp meter, respectively. The PZEM-004T energy readings were validated against an analogue energy meter over a three-hour test period. Measured deviations were within 0.01-0.05 A for current and within 1 V for voltage, confirming adequate calibration accuracy.

4.4.2 Functional Testing

The core functionalities were tested using a mobile Wi-Fi hotspot for ESP32 connectivity and a mobile data network for smartphone access. Results are presented below.

4.4.3 Real-Time Parameter Display

Figure 14 shows the Firebase Real-time Database console displaying live electrical parameters at no load: voltage = 213.50 V, frequency = 50.00 Hz, current = 0.00 A, power = 0.00 W, power factor = 0.00, and energy = 0.01 kWh. The webpage interface updates in real time every 2 s.



Fig 14: Firebase Real-time Database console showing live electrical parameter readings (SBOT-READINGS node) at no-load condition: V = 213.50 V, f = 50.00 Hz.

4.4.4 Set-point Configuration

Figure 15 shows the SBOT-SETTINGS node with configured protection limits: energy limit (EL) = 10, current limit (IL) = 30 A, power limit (PL) = 40 W, Vmax = 250 V, and Vmin = 100 V. The system successfully enforced these limits during testing, automatically de-energizing channels when thresholds were exceeded.



Figure 15 shows the SBOT-SETTINGS node with user-configurable protection set-points and SBOT-SWITCH node showing channel states (L1=1, L2=1, L8=1 indicating ON; others OFF).

4.4.5 Remote Channel Switching

Figure 16 shows the SBOT-SWITCH node with individual channel states. Channels L1, L2, and L8 are set to 1 (ON) while L3-L7 are set to 0 (OFF). The loads connected to active channels responded within 2-3 s of the command being issued, confirming reliable remote switching.



Fig 16: Firebase Real-time Database console showing SBOT-SWITCH node with individual channel control states: L1=1, L2=1, L8=1 (ON); L3-L7=0 (OFF).

4.4.6 Packaged Prototype

The fully assembled prototype (Figure 17) shows the three enclosure units: the actuator/socket unit (8"×13 A socket outlets), the micro-controller/relay unit, and the meter display unit (20"×4 LCD showing live parameters). The system demonstrated stable operation across all tested appliances including fans, lamps, televisions, and mobile phone chargers.



Fig 17: Packaged prototype of the IoT-based automated socket system showing eight 13 A socket outlet (actuator unit), control enclosure, and 20"×4 LCD meter display unit.

4.5 Performance Analysis

The following performance outcomes were verified during testing:

1. The system successfully controlled up to 8 independent electrical devices within the designed channel capacity.
2. Voltage, current, active power, frequency, power factor, and cumulative energy were accurately measured and displayed simultaneously on both the onsite LCD and the online Firebase portal.
3. Automation features (PIR motion-triggered switching) and remote control (Firebase web interface) operated reliably.
4. The switching response delay was within 2-3 s, providing near-real-time control suitable for domestic and light-industrial applications.
5. Measurement accuracy: average voltage error = 0.14% (range: 227-230 V), average current error = 1.18%, average power error = 2.11%.

4.6 Discussion

4.6.1 Advantages of the Proposed System

The proposed IoT-based automated socket system offers several significant advantages over conventional power distribution systems:

- i. Remote Monitoring and Control: Users can monitor and control all eight load channels from any location with internet connectivity, eliminating the need for physical presence.
- ii. Dual-Mode Automation: The combination of PIR-based onsite automation and Firebase-based remote control provides operational flexibility for both attended and unattended scenarios.
- iii. Comprehensive Energy Metering: The PZEM-004T provides six electrical parameters simultaneously, enabling detailed load analysis and energy auditing.
- iv. Configurable Overload Protection: User-defined set-points for voltage, current, power, and energy provide adaptive protection without hardware modifications.
- v. Safety: Galvanic isolation through relay contacts and freewheeling diodes ensures safe operation with high-voltage AC loads.
- vi. Energy Conservation: Real-time monitoring and automated load shedding at set-point

limits promote efficient energy use, directly addressing Nigeria's energy loss challenges.

4.6.2 Limitations

- i. Network Dependency: Full remote functionality requires both Wi-Fi and internet connectivity. Loss of network connectivity disables remote monitoring and control, though onsite PIR automation and local LCD display continue to function.
- ii. Per-Channel Load Rating: Each relay channel is rated at 10 A/250 V AC (2.5 kW), which limits connection of high-power appliances such as electric kettles or air conditioners as single loads per channel.
- iii. Single-Phase Measurement: The PZEM-004T measures a single-phase supply. Three-phase industrial applications would require additional sensor modules.

4.7 Comparison with Related Work

Compared to Lamya et al., who implemented a single-channel smart socket plug, the proposed system provides eight independently controllable channels with comprehensive set-point protection. Unlike Hamosi et al., who focused on monitoring without integrated automation, this work combines real-time monitoring, PIR automation, and remote switching in a single device. The measurement accuracy (voltage error: 0.14%, current error: 1.18%) is comparable to or better than values reported in similar PZEM-004T-based systems.

V. CONCLUSION

This paper presented the design, implementation, and evaluation of an IoT-based automated socket system using Wi-Fi with an electrical energy consumption meter sensor. The system was successfully developed using an ESP32 micro-controller integrated with a Wi-Fi module for real-time monitoring and control via the Firebase Real-time Database platform. The PIR sensor enabled onsite motion-triggered automation, while the remote-control features were implemented through the Firebase web interface.

The system demonstrated accurate electrical parameter measurement with average errors of 0.14%

for voltage, 1.18% for current, and 2.11% for power. The switching response time of 2-3 s and the reliable operation across eight independent channels confirm the feasibility and reliability of the proposed design for smart-home and light-industrial energy management applications. The configurable set-point protection contributes to load safety and energy conservation.

5.1 Recommendations for Future Work

Future enhancements to the system may include:

- i. Integration of AI/machine learning algorithms for predictive energy management and anomaly detection;
- ii. Support for renewable energy source monitoring (e.g., solar PV panels, battery storage);
- iii. Enhanced safety features including ground fault circuit interruption (GFCI) detection;
- iv. Expansion to 8-channel or 16-channel configurations for larger domestic and industrial applications;
- v. Voice control compatibility (e.g., Amazon Alexa, Google Home) for hands-free operation;
- vi. Development of a dedicated mobile application with improved user interface and push notification support;
- vii. Three-phase power monitoring capability for industrial deployments.

VI. ACKNOWLEDGEMENTS

The author gratefully acknowledges the support and guidance provided by Mr Opakunle Akinpelu, a technologist in the department of Electrical/Electronic Engineering, Ajayi Crowther University Oyo, throughout the course of this research. Special thanks are extended to the Mr Ayodele Elijah, for his immeasurable support during the design, implementation, and testing phases of this work.

The author also acknowledges the contributions of Departmental Head, Engr Obanisola who provided access to testing equipment and facilities, and fellow students who offered insights and assistance during prototype construction and field testing. Finally, the

author expresses gratitude to family members for their unwavering support, patience, and encouragement throughout the duration of this research project.

REFERENCES

- [1] H. Adyanth, M. B. Ananya, V. N. Bharati, and T. Shreekanth, "Intelligent sockets for automation through IoT," *International Journal of Engineering Research & Technology (IJERT)*, vol. 6, no. 13, pp. 1-5, 2018.
- [2] S. G. Alexander and Y. Kinza, "Ultimate IoT implementation guide for business," *TechAccelerator*, 2006. [Online]. Available: <https://www.techtarget.com/iotagenda/definition/internet-of-Things-IoT>
- [3] Amazon, "Double Pole Double Throw Switch," 2025. [Online]. Available: <https://www.amazon.com>
- [4] C. Argha, M. Monitoring, R. Rohan, and D. Arnot, "IoT-based smart energy meter for efficient energy utilisation in smart grid," *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, vol. 17, no. 5, pp. 32-40, 2022.
- [5] F. Asadi, "Relays," in *ABCs of Electronics, Maker Innovations Series*. Berkeley, CA: Apress, 2024. https://doi.org/10.1007/979-8-8688-0134-1_9
- [6] G. Bayrem, "Internet of Things prototyping with Firebase: How to do more with less," *FreeCodeCamp*, 2019. [Online]. Available: <https://medium.com/free-code-camp/iot-prototyping-with-firebase-doing-more-with-less-2f5c746dac8b>
- [7] ChatGPT, "Basic concept of Internet of Things (IoT) diagram," *OpenAI*, 2025.
- [8] Device Authority, "Understanding IoT networks: A beginner's guide," 2025. [Online]. Available: <https://deviceauthority.com/understanding-iot-networks-a-beginners-guide>
- [9] Elpocus, "Freewheeling or flyback diode working and its function," 2025. [Online]. Available:

- <https://www.elprocus.com/freewheeling-or-flyback-diode-circuit-working-functions/>
- [10] Espressif, “ESP32 series datasheet,” version 5.1, 2025. [Online]. Available: <https://www.espressif.com>
- [11] Eureka, “The evolution of relay logic systems,” 2025. [Online]. Available: <https://www.eureka.com>
- [12] M. Hamosi, W. Daniel, S. Juma, R. Florian, S. Ramadan, and K. Michael, “Development of IoT-based system for monitoring electrical energy consumption of the smart and rental houses in Tanzania,” *International Journal of Advances in Scientific Research and Engineering (IJASRE)*, vol. 8, no. 8, pp. 1-10, 2022.
- [13] International Energy Technik (IET) Africa, “The evolution of electrical automation,” 2025. [Online]. Available: <https://www.ietafrika.com/the-evolution-of-electrical-automation/>
- [14] P. Jignesh, “Energy demand factor, diversity factor, utilisation factor, and load factor,” *Electrical Engineering Portal*, 2024. [Online]. Available: <https://electrical-engineering-portal.com/demand-factor-diversity-factor-utilization-factor-load-factor>
- [15] C. Keller, “Relay and switches,” *IEEE Journals & Magazine*, vol. 50, no. 5, pp. 932-934, 1962. DOI: 10.1109/JRPROC.1962.288375.
- [16] Lamy, A. Haifa, A. Najoud, A. A. Lenah, and B. G. Sarah, “An IoT-based smart socket plug energy monitoring system,” *International Journal of Advanced Computer Science and Applications*, vol. 14, no. 10, pp. 353-362, 2023.
- [17] Liam, “Getting started with Arduino tools,” *ArduinoDocs*, 2024. [Online]. Available: <https://docs.arduino.cc/learn/starting-guide/getting-started-with-arduino-tools>
- [18] Lius, “An overview on bipolar junction transistor as a sensor for X-ray beams used in medical diagnosis,” *Open Access Article*, vol. 22, no. 5, pp. 1-54, 2022.
- [19] S. A. L. Maftunzada, “The structure and working principle of a bipolar junction transistor (BJT),” *Physical Science International Journal*, vol. 26, no. 11-12, pp. 35-39, 2022.
- [20] V. K. Metha and V. Rohit, *Principles of Electronics*, 11th ed. New Delhi: S. Chand & Company, 2008.
- [21] G. Mikell, “Automation,” *Encyclopaedia Britannica*, 2025. [Online]. Available: <https://www.britannica.com/technology/automation>
- [22] Nathan, “The evolution of automation,” *Progressive Automations*, 2022. [Online]. Available: <https://www.progressiveautomations.com/blogs/news/the-evolution-of-automation>
- [23] Nested, “IoT-based extension socket for power outage management,” *Journal Resource*, vol. 10, no. 2, pp. 1-18, 2022.
- [24] M. Omar, R. Adolf, R. Pedro, A. Alexis, S. Alejandro, and L. Fernando, “Design and development of an IoT smart meter with load control for home energy management,” *Energies*, 2022.
- [25] O. Olusegun and O. Kingsley, “Nigeria’s electric power sector: Challenges and prospects,” *Energy Policy*, 2020.
- [26] Ozuno, “Understanding relay ratings,” 2025. [Online]. Available: <https://www.ozuno.com/blog/understanding-relay-ratings/>
- A. Paul, “Making power adapters,” in *Proc. IEEE International Symposium on Sustainable Systems and Technology (ISSST)*, 2009, pp. 10-15. DOI: 10.1109/ISSST.2009.5156696.
- [27] P. Ravindra and P. Smita, “IoT based relay operation,” *International Journal of Engineering and Advanced Technology (IJEAT)*, vol. 9, no. 1, pp. 6515-6520, 2019.
- [28] J. L. Samuel, S. Jeff, and M. William, *University Physics*, vol. 2. Houston, TX: OpenStax, Rice University, 2016.
- [29] G. H. R. Vikas, B. V. Naveen, S. Kilian, G. K. P. Chandran, and S. Shazia, “Smart electricity meter monitoring and prediction using I-socket,” *International Open Access Journal*, 2024.

- [30] G. Vladimir, *Electric Relays: Principles and Applications*. Boca Raton, FL: CRC Press, Taylor and Francis Group, 2006.
- [31] F. Yugerita, A. Siting, and Kartiria, "Designing a monitoring and controlling system on IoT-based sockets," *Jurnal Teknik Elektro*, vol. 15, no. 1, pp. 18-23, 2023.