Development of Iot-Based Smart Circuit Breaker

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Abstract

This research project focuses on the development of an intelligent circuit breaker system designed to measure and monitor electrical current through the use of an ESP8266 microcontroller together with a current transformer. This equipment is to be used to enable the identification of both underload and overload situations in a simplified yet efficient fashion, particularly on alternating current power systems. Whenever current measurements exceed defined safe limits, the system automatically engages the relay to disconnect supply and protect the related devices. At the same time, real-time values such as current values as well as relay working condition are relayed to a web program for monitoring as well as documentation purposes.

The core part of the system is the ESP8266 microcontroller, which receives analog inputs from the current transformer, processes the inputs, and sends the data through Wi-Fi to the web-based application dashboard. It has been kept very simple intentionally to ease the installation and versatility for the domestic or small-scale renewable energy systems. Testing has been carried out through AC power, together with three 10W bulbs representing various load conditions (underload, normal, and overload). It was observed that the system clearly detected and responded to each condition of the load while properly taking data remotely.

Overall, the project provides an economically reasonable, portable, and dependable technique of smart energy monitoring and circuit protection, together with the possibility to be upgraded to include additional parameters as well as predictive features.

Key Words: Smart Circuit Breaker, Internet of Things (IoT), Electrical Safety, Overload Protection, Remote Monitoring, Home Automation, Energy Management

1. Introduction

Electrical power systems are the fundamentals on which modern infrastructure is built(Marston, 2018). Electrical power systems are the foundation of modern infrastructure, enabling the efficient and reliable supply of electricity to households, industries, and public services. They include generation, transmission, and distribution networks, which work in conjunction to ensure that end-users have an efficient supply of energy. These have been quite vital in the process of industrialization, urbanization, and technological progress. It is this dependence on electricity that calls for continuous need and progress in functionality and safety features in electrical power systems(Saifuzzaman, 2023).

Circuit breakers form a great part of electrical power systems for protection against overcurrent, short circuits, or faults that may cause damage to electrical circuits. Essentially, circuit breakers are automatic switches that open and interrupt the flow of electricity in case of abnormalities, hence preventing possible hazards such as fire, equipment damage, and power outage. Conventional circuit breakers, while effective, often require manual intervention and provide limited data about system performance or fault detection.

In addition to their primary role in fault detection, the balance of electrical power systems largely relies on the critical role of circuit breakers (Gupta, 2014). They forestall widespread power outages and prevent serious damage to equipment by isolating those sections of a network that develop overcurrent or short-circuit conditions. A circuit breaker operates in conjunction with protective relays, which provide accurate and timely disconnection of faulty circuits to protect the entire system. They are also vital in high-voltage systems, where their dependability might save large-scale outages. For instance, in industry, they safeguard sensitive machinery from electrical faults that can cause huge losses financially. Recent advancements in the modeling and estimation of electrical and solar parameters, such as temperature-based solar radiation analysis for optimizing energy systems in regions like Ilorin, Nigeria (Y. B. Adediji et al., 2021), further underscore how accurate energy prediction and system reliability go hand in hand in modern electrical networks.

Furthermore, circuit breakers also save energy by facilitating better load management and reducing unnecessary energy wastage(Saleri, 2018). Advanced circuit breakers allow smart load-shedding mechanisms, which help in optimizing energy distribution during periods of peak demand. The residential environment contains the vital safety characteristic of circuit breakers, namely preventing accidents due to electrical faults, and thereby complies with all safety regulations and standards.

The Internet of Things (IoT) can be defined as a system of physical devices that are connected through some advanced technologies like software and sensors to communicate with one another over internet (Adediji, 2022). IoT has made a revolutionary impact in many fields like energy and power management. The devices of IoT have made the process of interaction between different connected systems extremely smooth and have helped in intelligence-based decisions and automation. The utilization of IoT in power has contributed in many aspects like smart meters, demand response systems, and power grid management. The application of IoT in circuit breakers has increased their capabilities as it provides information in a real-time scenario regarding energy consumption, fault level status, and health status of the system. In addition to that, improvements in material science and its related researches like electronic properties of twisted van der Waals materials are accompanying innovative developments in IoT to provide efficient and compact electronic devices for better performance and enhanced sensitivity of power devices that are connected to each other.

IoT helps integrate renewable energy sources into the grid through better coordination and management of distributed energy resources. IoT-based platforms allow both utilities and end-users to monitor and control energy usage remotely, leading toward smart demand-side management and, hence, cost savings. The use of IoT in electrical power management represents one of the major steps toward greener, more reliable, and more efficient energy systems.

Modern circuit breakers use advanced materials and technologies, such as vacuum and SF6 gas, to enhance their performance under extreme conditions. The integration of digital technology and Internet Of things (IoT) into electrical systems has paved the way for smart circuit breakers. Unlike conventional circuit breakers, smart circuit breakers are equipped with advanced features such as real-time monitoring, remote control, and data analytics. These devices make use of sensors, microcontrollers, and communication modules to enhance functionality, including predictive maintenance, fault detection and diagnosis, and energy management. This integration enables a proactive approach to electrical safety and efficiency, with respect to the demands of modern power systems. By applying data analytics and machine learning, smart circuit breakers are able to forecast faults before they happen, thus proactive maintenance reduces downtime(Hoffmann et al., 2020).

2. Literature Review

2.1 The Need for Improved Power Management and Safety

In the ever-changing environment of present-day electrical systems, great importance still lies in improving the management of power supply as well as ensuring safety. Sturdy and stable electricity is essentially a need in day-to-day living, industrial applications, and the functioning of modern societies. Interruptions in the supply of electricity may arise from faults, overloading, or external factors, often resulting in significant financial losses and inconvenience. Consequently, the management of power systems must ensure a constant and consistent flow of electricity with minimal interruptions to enhance system stability. Similar to how fluctuations in stock market indicators reflect broader economic conditions, the dynamics of power systems also mirror the health of national infrastructure and productivity—an interrelation observed in studies linking energy stability and economic performance in Nigeria (Adediji et al., 2024).

Safety remains an inherent guiding principle behind innovations in power management, as electrical faults, such as short circuits, overcurrents, and equipment failure, become serious threats to infrastructure, human safety, and ecological integrity. Today's circuit breakers, sporting the latest safety features, automatically isolate the flawed portions of the electrical distribution grid, thereby averting further maladies and securing assets. At the same time, the expanding need for electricity, fueled by urban growth, industrialization, and technological growth, has escalated the need for effective power management that best utilizes resources, minimizes waste, reduces expenditure, and minimizes environmental impacts (lui & kong, 2015).

Intelligent technologies allow precise monitoring and control while also embracing variable energy sources like solar and wind, whose intermittent nature requires fault-tolerant systems to stabilize energy supply and demand. Better power management also addresses the rising pressures on infrastructure through the use of the Internet of Things (IoT) to optimize distribution of the burden, prevent overloading, and enhance overall availability. Aside from considerations related to efficiency, active maintenance and predictive fault identification gained ascendance, taking systems from reactive to preventive measures that minimize downtime and related repair costs (Zhang et al., 2023). At the end, compliance with standards is still the key, as high-tech solutions help organizations meet strict safety and efficiency standards, minimize legal liability, and engender public trust.

Finally, the resilience of the power systems to externalities, such as natural disasters, cyberattacks, as well as malfunctions of equipment, is a more critical issue. Advanced power management systems enhance resilience by ensuring quick recovery and dynamic reactions to unintended events. This capability is necessary to maintain stability as well as protect vital infrastructure as the globe becomes increasingly interdependent and vulnerable.

2.2 Faults in Electrical Power Systems

Faults in a power system can be considered anomalies whose occurrence disrupts the normal flow of current, resulting in damage to equipment, power outages, and safety concerns (Abubakar & Abdulkareem, 2022). Circuit breakers play significant roles in identifying these faults and halting any further problems. The knowledge gained from the growth of dielectric materials, with the latest being the synthesis of lead-free $BaTiO_3$-based ceramic capacitors with efficient energy storage capabilities (Y. Adediji et al., 2023), further underscores the significance of adequate fault management and sustained energy security in modern power systems. Of the most widespread faults in power systems, the short circuit fault is the most prevalent where two or more conductors accidentally touch each other. Its occurrence creates a spurt of extra current which can overheat the conductor to the point of equipment damage and even fires. The circuit breaker automatically acts to break the current in the event of phase-to-phase faults, phase-to-ground faults, and in the case of three-phase faults.

Another significant fault is overload, which forms when circuits draw more current than they can handle. While short circuits build up instantly, overloads build up slowly, creating insulation breakdowns and heat over time. Smart circuit breakers are always watching current flow and interrupt power during long-lasting overcurrents to avoid danger. They also sense arc faults, where broken insulation, loose contacts, or worn-out wires create unintended electrical discharges. These arcs produce great heat and fire hazards, but sophisticated devices such as Arc Fault Circuit Interrupters (AFCIs) recognize peculiar arcing signatures and disconnect the circuit before fires occur (El-Sherif & Domitrovich, 2023).

Figure 1 Burning of Electrical Wire Outlet due to Fault

Additional faults are earth faults, where live conductors inadvertently touch the ground, normally due to insulation breakdowns. Even minor current leakages can lead to shocks or fires, so there are devices like Residual Current Circuit Breakers (RCCBs) and Ground Fault Circuit Interrupters (GFCIs) that automatically disconnect the supply. Overvoltage faults, caused by incidents such as lightning or flawed regulators, also threaten systems; while surge protectors are common, smart breakers today come with voltage monitoring so that they disconnect during long-term surges (Othman et al., 2019). In addressing the faults, circuit breakers conform to safety requirements, minimize downtime, and enhance the integrity of power systems.

2.3 Internet of Things in Power Systems

The Internet of Things (IoT) refers to a network of devices that collect, transfer, and analyze information to improve decision-making capabilities (Khan & Yuce, 2019). Recently, it has received widespread attention and has become one of the quickest growing areas in the automation of home and industrial applications. Devices connected through IoT are network-capable and hence can communicate with each other through a network that enables real-time information acquisition, defect detection, and distant control. Various research works have revealed that IoT has a promising role in the power management sector in relation to energy conservation and security. The integration of IoT-based applications in power systems has altered many power generation and usage approaches. Devices like smart meters, sensors, and smarter controllers are a few IoT-based technologies that have recently been made a part of power systems for smooth interaction between different devices. By allowing real-time monitoring of voltage level information transfer, power absorption level monitoring, and entire system performance monitoring, devices like this have contributed significantly to enhanced efficiency and reliability (Saleem et al., 2017). Furthermore, bi-innovations in sustainable materials like “The Advances in Sustainable Materials and Their Application in Carbon Neutral Packaging” and “An Overview of Mechanical and Chemical Recycling Methods for Polyethylene Terephthalate Plastics” in this publication (Y. Adediji & Adediji, 2024a) are strengthening IoT development capabilities for making more robust and sustainable device components that balance technological feasibility and sustainability.

The foremost benefit of the Internet of Things (IoT) in power systems lies in its capability to facilitate predictive maintenance. IoT-driven frameworks, through the utilization of machine learning algorithms and analytical data processes, are proficient at detecting anomalies in equipment functionality and anticipating potential failures before they occur (Ahluwalia, 2024). By adopting a proactive approach, unforeseen outages can be averted, thus minimizing maintenance costs by addressing issues before they escalate into more serious problems. Furthermore, IoT is instrumental in the management of demand on the consumer side. Intelligent metering devices and home automation technologies furnish users with immediate feedback regarding their energy consumption, enabling them to optimize their usage and curtail waste. In addition, utility companies can leverage this data to execute demand-response initiatives, which adjust electricity consumption according to grid conditions to avert overloads and bolster system reliability. Another pivotal function of IoT in power systems pertains to the integration of renewable energy resources. IoT-based energy management solutions can effectively align supply with demand by incorporating solar photovoltaic systems, wind generation units, and energy storage solutions into the electrical grid (Mbelu et al., 2024; Saleem et al., 2017). This integration promotes a more sustainable and dependable framework for energy distribution.

In conclusion, IoT has transformed the power sector by introducing smart solutions that enhance efficiency, reliability, and sustainability. The continuous advancement of IoT technologies will further improve grid resilience, energy optimization, and fault management, making power systems more intelligent and responsive to future challenges

2.4 Smart Circuit Breakers

The significance of smart circuit breakers over traditional circuit breakers is evident in digital monitoring and control capabilities that ensure enhanced safety and efficiency (Agbese et al., 2024). In contrast to traditional circuit breakers that are totally dependent on mechanical and thermal trippable devices for function and safety, smart circuit breakers are equipped with advanced technologies like sensor devices and processors that enable monitoring and predictive tripping. The integration of Internet of Things (IoT) technology enables enhanced electrical safety and efficiency in domestic as well as industrial and business settings. Moreover, developments in fields like structural improvements in wind-wave-loaded solar photovoltaic systems have highlighted the intensifying relationship between AI-enabled electrical devices and renewable resources (Y. Adediji, 2022). The integration of traditional safety features and digital capabilities has made smart circuit breakers a leading candidate for participation in future aspects of power management and a key step toward sustainable power distribution (Gonen, 2014; Hauer & Bartonek, 2016).

At the core of the smart breaker is a microcontroller, which manages data acquisition, decision-making, and external system communication. A microcontroller called ESP8266 was used in this project because it has a built-in Wi-Fi capability, small size, and affordable price. It is very appropriate for applications requiring real-time monitoring and wireless communication because of the integration of processing capability, availability of GPIO, and energy conservation. It does not need any external wireless module, as opposed to previous boards like the Arduino Uno, so the complexity of the hardware is minimized, making it easier to integrate into the system.

The determination of electrical current is a crucial function of a smart circuit breaker since overload and short circuits are primarily identified through unusual currents. In this context, a Current Transformer (CT) sensor is used. CTs have some notable characteristics in AC mains current measurement in relation to their provision of galvanic isolation. The provision of galvanic isolation can primarily improve user safety while offering an exact current value. Hence, in a similar fashion that a revolution in material sciences has made possible biodegradable metal alloying in biomedicine for making biodegradable Mg-based alloys that place a large emphasis on exactness and malleability in different critical systems like biomedicine (Adediji & Adediji, 2024), the appropriateness of CT current sensor technology reveals a similar concern for excellence in electrical systems. In contrast to Hall Effect-based devices like ACS712 CTs have a distinct role in AC current measurement and perform better in overload current detection. It is even easier to install without interrupting much of the circuit while implementing. Thus, CTs can easily and reliably function as continued sources in domestic as well as industrial contexts.

The relay and Tripping mechanism form the core protection units of the circuit breaker. Standard circuit breakers employ electromechanical switches, but newer versions employ relays that are controlled by microcontroller logic to achieve faster and more precise action. Under this system, the relay is triggered automatically when the current transformer (CT) detects current magnitudes exceeding a set limit. This approach not only provides a safer approach by limiting dangers of overheating and mechanical damage to equipment but also allows remote control through wireless commands. By comparison to older passive trip units, this active monitoring and control immensely improve the circuit breaker's reactivity and adaptability.

IoT integration is what elevates the breaker beyond traditional protection devices. With the ESP8266's built-in Wi-Fi module, the system communicates directly with a web-based interface, enabling users to remotely monitor load conditions, receive notifications, and control breaker operations in real-time. Such connectivity supports predictive maintenance, allowing users to anticipate failures before they escalate. In larger networks, these features can be extended to support smart grid initiatives, providing load balancing, demand-side management, and enhanced energy efficiency (Othman et al., 2019). Apart from fault protection, smart circuit breakers are strong in energy management. As they monitor current usage all the time, they provide an indication of patterns of usage which can result in better usage of energy and less wastage.

Phone or web-based remote-control features are a boost in that users can control and even remotely reset the circuit breaker. The significance of smarter systems is that they enable better utilization of renewable power sources in that they ensure a safe and stable control of distributed power sources like solar panels and inverters while keeping the whole power grid stable (El-Sherif & Domitrovich, 2023). Just like how there is a rising trend in relation to renal innovations that are quite complementary to smarter electrical systems for enhanced and more efficient utilization of power in smarter infrastructure systems (Adeyinka et al., 2023), innovations in relation to more efficient development of thin-film solar cells keep rising in that they are more efficient and much more adaptive when it comes to power utilization in smarter electrical systems.

The whole system is made more effective through additional components like resistors and capacitors that contribute to a stabilized signal and critical circuitry safety. Apart from the ESP8266 microcontroller and CT sensor and relay circuit components as mentioned above for a smarter electrical system setup that can provide safety and monitoring through internet connection capabilities that offer more advanced functionalities and capabilities in relation to power circuit safety and monitoring in relation to IoT sensored devices and capabilities in smarter electrical system infrastructure that connects safety and monitoring to internet-based power monitoring and control devices for a more advanced electrical system setup for a smarter and more advanced electrical setup for safety and monitoring needs through internet connections and capabilities in that setup without going beyond the required parameters as mentioned. The whole system is more effective in that it ensures safety in that overload detection and faulty circuit segregation through smarter infrastructure capabilities and is more directly adaptive to internet connection capabilities for more advanced monitoring and control.

3. Methodology

3.1 Research Design

The study adopted an applied experimental research design to derive a working IoT-based smart circuit breaker. The design combined hardware prototyping and software integration to attain a sensing-layer, processing-layer, actuating-layer, and user-interface-layer system. The design facilitated simulation of real-world electrical faults, like overloads, to determine the system's accuracy, response speed, and dependability. By using a controlled laboratory experiment setup, the research could verify safety attributes, communication effectiveness, and remote-control functionality. The design process further facilitated iterative testing and refinement to determine that the system could function efficiently, integrating with IoT platforms, and delivering applicable solutions to domestic and industrial power management. The experimental design guaranteed that outcomes were data-driven, repeatable, and directly applicable to the modern power systems.

3.2 System Architecture

The system architecture forms the backbone of the IoT-enabled smart circuit breaker, defining how the sensing, processing, actuation, and application layers interact to ensure safety, reliability, and remote control. At the sensing layer, a current transformer (CT) was used to measure current levels. The CT was chosen for its high accuracy, galvanic isolation, and suitability for AC measurements, allowing safe and reliable monitoring without direct electrical contact with the mains. Its analog output was conditioned using a burden resistor and routed to the ESP8266 microcontroller’s ADC pin for real-time data acquisition, forming the basis for overload detection and fault monitoring.

The processing layer was managed by the ESP8266 microcontroller, which was selected because of its compact size, low power consumption, and integrated Wi-Fi functionality. Serves both to process the data and act as the communication interface, the ESP8266 continuously checked measured current readings against defined thresholds and activated relay commands after observing any abnormal conditions. This helped eliminate the need for auxiliary communication modules, thus reducing system complexity and costs.

The actuating layer contained a tripping and relay mechanism, and this segregated the circuit during faults. Unlike the traditional mechanical breakers, this relay was driven by digital inputs coming from the microcontroller, and this allowed fast, programmable, and accurate disconnection. The application of solid-state switching devices increased switching speed, minimized mechanical wear, and overall system reliability.

At the application layer, a web-based interface enabled the user to access real-time current readings, breaker positions, and fault alerts remotely through smartphones, tablets, or computers. It further provided remote control functionality such that circuits can be switched on and off and historical energy consumption can be viewed by management. This layer represented the IoT capability of the system, facilitating integration with home automation solutions and wider smart grid applications.

The overall architecture facilitated smooth communication between all elements to allow proper monitoring of available levels, immediate fault identification, and local remote control. The system design was customizable and could be implemented and utilized both commercially and industrially and paves the way to future IoT-based energy management system designs.

3.3 Hardware Design

The IoT-driven smart circuit breaker's design incorporated all elements into a single system that merged conventional protection schemes with smart IoT capabilities. The center of the design was the ESP8266 microcontroller, selected due to its small size, in-built Wi-Fi, low power requirement, and affordability. The microcontroller acted as the processing and communication entity with real-time data measurement, fault detection based on threshold, and control of relays, while relaying system data to the web-based program for observation and teleoperation.

The current transformer (CT) sensor was the main sensing component, facilitating precise, non-intrusive measurement of alternating current. The output was conditioned by a burden resistor and taken to the microcontroller's ADC pin, facilitating effective monitoring to determine overload and fault conditions. The galvanic isolation of the CT sensor safeguarded the operator and prevented damage to the microcontroller being driven by high voltages, thus being suited to residential and commercial usage.

The relay and tripping mechanism served as the actuating component, with the responsibility of breaking the circuit on sensing of abnormal conditions of current. Unlike conventional electromechanical relays, the system made use of solid-state switching devices, thus improving response speed, decreasing mechanical wear and tear, and facilitating programmable disconnection thresholds. The arrangement allowed rapid isolation of faults, minimized possible damage to equipment, and increased overall dependability.

Supportive components, including resistors, capacitors, and connectors, were included to achieve proper signal conditioning, voltage stabilization, and stability of the circuits. The conventional breaker was considered the starting point to combine these devices to achieve a common and reliable foundation to the IoT-enhanced functionality. The electronics units collectively established a reliable, safe, and fully operational prototype that is able to demonstrate the practical benefit of IoT-enabled smart breakers.

3.4 Software Design

The software part of the smart circuit breaker was created to enhance the hardware to achieve real-time monitoring, fault detection automation, and remote control. The ESP8266 microcontroller was programmed with the Arduino IDE that offered ease of use libraries to handle Wi-Fi communication, reading ADC, and hosting a web server. Firmware procedures repeatedly retrieved the current data through the CT sensor, checked against preset overloads thresholds, and activated the relay on detection of abnormal conditions.

A Web-based interface was the primary control and monitoring system. Powered by the ESP8266, the interface showed real-time current readings, breaker conditions, and fault notifications over smartphones, tablets, or computers. The interface could remotely turn circuits on or off and view historical energy usage, with the ability to control multiple breakers with proper scaling to higher systems. The interface had IoT features to provide integration with home automation systems and future smart grid integration.

The system design also prioritized maintainability and scalability. The modular code of this software enabled the integration of new features such as predictive maintenance, energy analytics, or intercommunication between multiple network nodes post-design. Data logging further enabled historical analysis to learn patterns and enhance energy management practice. All these software modules collectively boosted the functionality, accessibility, and flexibility of the smart circuit breaker and therefore made it a contemporary and useful solution to power protection both in residences and industries.

3.5 System Implementation

The implementation stage included integrating all the developed components into a working and integral prototype. The conventional circuit breaker constituted the basic foundation onto which the current transformer (CT), ESP8266 microcontroller, and relay system were integrated. Auxiliary elements, such as resistors, capacitors, and connectors, were added to ensure proper signal conditioning, stable power delivery, and system reliability. The interconnection of the CT to the microcontroller was achieved through a burden resistor to allow safe harvesting of current readings without direct involvement with the mains supply.

The ESP8266 acted both as the processing and communication module, running scheduled routines while also hosting the web interface through which users would interact. The relay module was connected to the load circuit and was electronically switched by the microcontroller to allow safe disconnection during cases of overload. The combination of these elements left us with a compact but solid architecture that fused traditional electrical protection with modern IoT functionality.

Extreme care was taken with respect to the safety of the circuit and hardware arrangement during the process of assembly. Sufficient insulation and gap were maintained to avoid leakage currents or short circuits, and facilities for heat dissipation were adopted by the relay unit. The hardware was powered by a regulated supply with alternate schemes being considered to maintain continuous operation during power failure instances. The software was then transferred to the ESP8266 and calibration testing conducted to fine-tune sensor outputs and establish the effectiveness of communication.

The ultimate prototype exhibited a flawless amalgamation of sensing, processing, actuation, and application layers, indicating that the design was capable of consistently identifying overloads, disconnecting the circuit, and relaying real-time data to users. Through the combination of economical components and sophisticated programming, the execution of the system affirmed the feasibility of creating an IoT-enabled smart circuit breaker appropriate for contemporary power systems.

3.6 Experimental Setup and Testing

To determine the effectiveness of the smart circuit breaker, a series of planned experiments were conducted with different operating conditions. The prototype was connected to a test bench with various domestic loads, including incandescent bulbs, fans, and small appliances, to mimic real-world electrical consumption scenarios. To provide increased measurement accuracy, a reference ammeter was implemented alongside the current transformer during sensor reading calibration. The calibration was necessary to confirm that the output of the current transformer, after being conditioned through the burden resistor, accurately matched with the actual true current readings.

The testing procedure was executed in several phases, commencing with the overload detection trial. The applied loads were systematically elevated beyond the specified rating to evaluate the ESP8266's ability to activate the relay. The system effectively identified overload situations and activated the breaker with minimal latency, thus validating its protective capabilities. In a similar manner, consecutive switching evaluations were conducted under standard operating conditions and underload scenarios to examine the reliability of relay performance and to investigate any potential mechanical or electronic degradation over numerous cycles.

Additional tests were conducted on the reliability of communication and functionality of the web interface. The ESP8266 was set up to provide data over Wi-Fi, allowing users to access current values and breaker conditions remotely using a smartphone or computer. Real-time access was confirmed by comparing measured data with actual load variations, and control operations such as breaker toggle by hand were similarly tested. The link's performance was analyzed with mixed signal conditions to confirm system stability over diverse operating environments.

Finally, response times were measured to determine the period between fault detection and breaker actuation, and to analyze data update latency on the web-based interface. The system showed rapid fault detection and isolation potential, with repeat real-time data transfer being recorded during testing. These tests showed that the smart breaker prototype achieved its objectives of offering accurate fault detection, reliable disconnection, and clear remote monitoring, thus proving its potential for deployment within residential and power systems industrially.

4. Results and Discussion

4.1 Introduction

This smart Circuit Breaker system consist of four different functioning part responsible for a specific role in monitoring and controlling the current flow. These units are the Current Sensing Unit, Microcontroller Unit and the relay switching unit, and the web app interface.

The current sensing unit makes use of a current transformer (CT) to measure the current drawn by the load. The signal from the CT is passed through a burden resistor and signal conditioning circuit to produce a voltage that is proportional to the current flowing. This analog signal is then fed into the ESP8266's analog input pin for monitoring and reading. The microcontroller unit is powered by the ESP8266-12F, which is responsible for reading the sensor data, performing logic decisions, and controlling other components. When the microcontroller detects a current above or below the safe threshold (indicating an overload and under respectively), it sends a control signal to the relay module, which acts as a switch to immediately disconnect the load from the power source.

The relay switching unit consists of a 3.3V relay module connected to one of the ESP8266's digital output pins. This relay is used to break the circuit whenever an overload condition is detected. The switching action is automated and based on the microcontroller's real-time analysis of sensor input.

4.2 Testing

To evaluate the performance and reliability of the smart circuit breaker system, a series of controlled tests were conducted using both **solar power** and **AC power** sources. The load configuration consisted of **three 10W bulbs**, strategically used to simulate different current load conditions:

One bulb represented an **underload** condition,

Two bulbs indicated a **normal** operating state, and

Three bulbs signified an **overload** situation.

Upon starting the system, the ESP8266-12F microcontroller initializes by the user starting the **time** of operation. As the system runs, it continuously measures the **current drawn** through the load using the current transformer and checks the voltage level using the ZMPT101B voltage sensor. These readings, along with the **status of the relay** (whether tripped or active), are transmitted to a **web application interface** for real-time monitoring, **data logging**, and documentation.

Testing was carried out on **three separate occasions** under varying conditions:

8th July, 2025 – 12:00 PM:
Test performed using **AC power supply**.

15th July, 2025 – 12:30 PM:
System powered via a **solar power setup**.

16th July, 2025 – 2:30 PM:
Final test conducted again using **AC power supply**.

All tests were conducted at the **University of Ilorin**, Kwara State and in each case, the system responded as expected that is accurately detecting the load condition and taking action by tripping the relay during overload and underload. The real time data was successfully sent to the web application, validating the wireless communication and logging features.

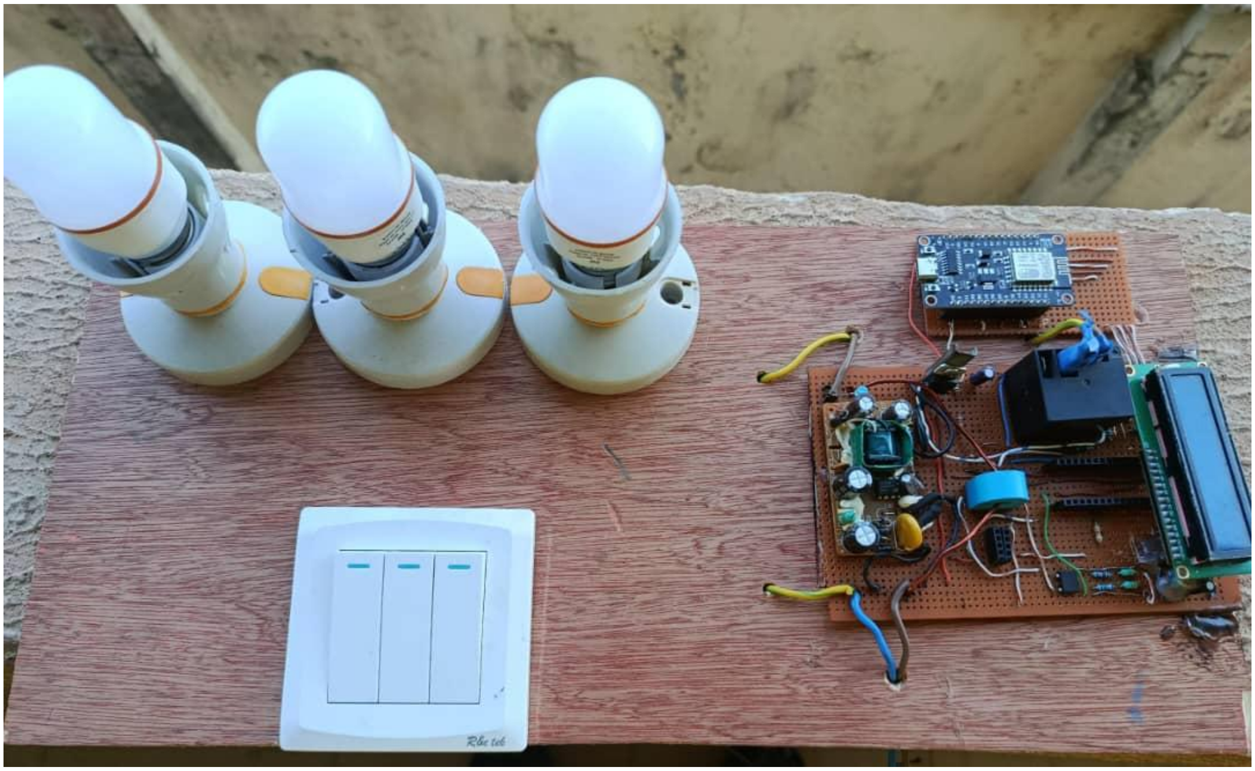

Figure 2 Smart Circuit Breaker System

4.3 Results

Based on the design, the complete operational experimental model of a smart circuit breaker has been constructed. The results obtained from tests were obtained on 8th, 15th, 16th of July, 2025 in University of Ilorin using both AC power as well as solar power and the load being three 10W Bulbs. The readings are shown below

Table 1 Table for Result of Test 1

S/N	Date and Time of Trigger	Reason for Trigger	Measured Current(A)
1	2025/7/16 12:39:36	Insufficient Load Protection	0.007692
2	2025/7/16 12:39:49	Normal Operation Resumed	0.056908
3	2025/7/16 12:40:22	Insufficient Load Protection	0.038452
4	2025/7/16 12:40:40	Normal Operation Resumed	0.056908
5	2025/7/16 2:42:32	System Overload Protection	0.076901

Table 2 Table for Result of Test 2

S/N	Date and Time of Trigger	Reason for Trigger	Measured Current(A)
1	2025/7/16 2:36:36	Insufficient Load Protection	0.007692

2	2025/7/16 2:37:2	Normal Operation Resumed	0.055370
3	2025/7/16 2:37:4	Insufficient Load Protection	0.037683
4	2025/7/16 2:37:36	Normal Operation Resumed	0.056908
5	2025/7/16 2:37:52	System Overload Protection	0.0899749

Table 3 Table for Result of Test 3

S/N	Date and Time of Trigger	Reason for Trigger	Measured Current(A)
1	2025/7/18 12:6:36	Insufficient Load Protection	0.007692
2	2025/7/18 12:7:2	Normal Operation Resumed	0.043066
3	2025/7/18 12:9:4	Insufficient Load Protection	0.022303
4	2025/7/18 12:9:36	Normal Operation Resumed	0.046053
5	2025/7/18 12:10:52	System Overload Protection	0.086899

4.4 Discussion

The tests clearly show that the smart circuit breaker performed remarkably in recognizing underload, normal load, as well as overload situations. Measured current values during each test corroborated the system's expected behavior. Under underload situations, the breaker identified poor load protection and then tripped the relay. Under normal operating condition, the breaker allowed current flow within set safety margins, although under overload situations, the system appropriately tripped the circuit to prevent impending damage.

Real-time operating status transmission and instantaneous reading to the web program confirm the system's IoT functionality as well as its future application in intelligent homes and green energy networks. However, the variance in the value of the current in the three experiments evidences minor calibration variations in the sensors as well as impacts by the weather condition such as the strength of the sun during the solar-powered experiment.

In summary, the findings affirm the operational effectiveness, reactivity, and dependability of the intelligent circuit breaker. This system not only offers safeguards against irregular load scenarios but also empowers users to observe events from a distance, indicating a noteworthy advancement compared to traditional circuit breakers.

5. Conclusion

The project set out on designing and developing an IoT-enabled smart circuit breaker that can provide real-time monitoring, automatic protection, as well as remote control over electrical loads. With an integration of hardware prototyping as well as software integration, the system was able to blend the traditional protective function of circuit breakers with the advanced intelligence offered by IoT innovations harmoniously.

The implementation of a current transformer for the purpose of load assessment facilitated secure and precise oversight, whereas the ESP8266 microcontroller contributed both computational capabilities and integrated wireless communication. The relay switching unit consistently carried out tripping commands in response to the identification of atypical load conditions. By means of a web-based application, users gained the ability to monitor current values in real-time, receive notifications, and exercise remote control over the circuit breaker.

Experimentation under laboratory conditions confirmed that the system worked as intended, rightly identifying underload, normal load, and overload conditions and taking the proper action by sustaining supply or disconnecting the circuit accordingly. The web page interface also proved the IoT module by providing easy remote access as well as event recording without physical contact.

In a nutshell, the novel smart circuit breaker introduced here demonstrates the ability to improve electrical safety, offer user convenience, and maximize energy management in modern dwellings and clean energy settings. Unlike conventional circuit breakers that operate on purely mechanical principles, this product combines protective attributes with data-driven intelligence as well as over-air connectivity. Future studies might explore system extension for inclusion of voltage monitoring, compatibility with mobile apps, fault prediction, as well as scalability for commercial use.

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