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IoT-Based Electrical Protection and Monitoring System for Real-Time Detection of Current and Voltage Faults in Residential Electrical Installations

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Abstract

Electrical disturbances such as overcurrent and overvoltage in residential electrical installations can lead to equipment damage, reduced operational efficiency, and increased safety risks if not addressed promptly. Conventional protection mechanisms are generally limited to localized interruption and lack real-time monitoring and remote communication capabilities. This study presents the design and implementation of an IoT-based electrical protection and monitoring system for real-time detection of current and voltage faults in residential electrical installations. The proposed system integrates a NodeMCU ESP8266 microcontroller, a PZEM-004T sensor module for measuring electrical parameters, a relay module for automatic load disconnection, and a mobile-based notification platform for remote monitoring. The system continuously measures voltage, current, power, and energy consumption while executing protective actions when abnormal thresholds are exceeded. An experimental approach was employed, including hardware design, prototype development, and performance evaluation under various load conditions. The results indicate that the system is capable of detecting electrical anomalies in real time with an average response time of 1 second and measurement accuracy reaching 98%. The relay mechanism successfully disconnected the load during fault conditions, while remote notifications enhanced user awareness and system accessibility. The proposed system demonstrates practical applicability as an intelligent protection framework for improving electrical safety and monitoring efficiency in residential environments.

Keywords: Internet of Things, electrical protection, real-time monitoring, fault detection, residential electrical installation

1. Introduction

The digital transformation has resulted in major changes in the operation of electrical systems especially in the domestic sector. The use of the Internet of Things (IoT) enables the creation of electrical systems into smarter systems by connecting monitoring, control and protection systems [1], [2]. There is a growing demand to have efficient protection systems with the rising utilization of electronic appliances that are vulnerable to electrical shocks. Possessing conditions like overcurrent, overvoltage can damage equipment and create safety hazards in case they are not addressed in time [3], [4]. Thus, the usage of smart technology in electrical safety systems becomes a more topical need in the contemporary age.

Traditional systems of protection in domestic applications usually continue to use equipment like fuses and Miniature Circuit Breakers (MCB). These gadgets do a good job of disconnecting the power in case there is a disturbance, however, they are merely a rudimentary protection [5]. The primary drawback of traditional systems is that they do not have a real-time monitoring ability of electrical parameters. Moreover, the immediate information about the current electrical conditions is not provided to the users. This renders the disruption management process reactive and less encouraging of early prevention initiatives .

With the creation of IoT technology, new opportunities have appeared in the creation of more adaptive and integrated smart home systems [6], [7]. Different research has indicated that the PZEM-004T sensor andNodeMCU ESP8266 microcontroller can be used to obtain accurate electrical parameters data [8]. The majority of past applications were oriented towards energy use monitoring and electrical load control [9], [10] . But the part of active protection against current and voltage disturbances was not a major area of concern in most studies. Nevertheless, with the introduction of monitoring and automatic protection systems, the stability of the household electrical systems can be improved.

The proposed research is intended to design and construct an IoT-based electrical protection and monitoring system of household electrical installations. The system created employs the NodeMCU ESP8266 as the control center and the PZEM-004T as the sensor to measure electrical parameters. Relay The relay is an actuator that is automatic and can be used to disconnect the load in case of an abnormal condition. Moreover, the system is linked to a mobile notification system to facilitate remote monitoring. In this way, the system will be able to respond fast to disturbances, as well as improve the accessibility of information to users.

The primary value addition of this study is that it created a smart protection system which combines monitoring capabilities, early-detection, and automatic responses into one system. The suggested system is not only able to improve the safety of electrical installations but also increase the possibilities of users to control the state of electrical processes in real-time. Assessment was done by testing accuracy of sensor, response time, and efficiency of the protection mechanism. It is believed that the findings of the research can offer a viable substitute solution in the creation of newer household electrical infrastructure. Moreover, this study lays the groundwork to future enhancement of a safe and sustainable smart home system.

2. Material and methods

This study uses an experiment as a research design to build, test, and analyze the performance of an Internet of Things (IoT)-based electrical protection and monitoring system in residential electrical systems. This method was selected as it is possible to directly test the hardware-software integration under the conditions of the operational environment and that is as close to actual implementation as possible. The phases of the research are system architecture design, component integration, prototype development, and performance testing based on the quantifiable technical parameters. The evaluation is focused on the precision of the reading of electrical parameters, the speed of protection reaction, and the dependability of the system to deliver notifications in real-time. This research methodology will produce empirical findings on whether the system is an effective intelligent protection system in a home setting or not.

Figure 1 below is a system architecture designed on the integration of sensors, controllers, actuators and user interfaces. The system involves the PZEM-004T module to constantly monitor voltage, current, active power, energy, frequency, and power factor. Measurement data can be handled by the microcontroller based on a microprocessor ESP8266, the control center, and the Wi-Fi-based communication module. A protection actuator is a relay that switches off power supply automatically when the parameters measured are above the set limit. The data concerning the state of the system is then sent to a Telegram-based notifying service to ensure users are able to observe the state of the electrical system remotely.

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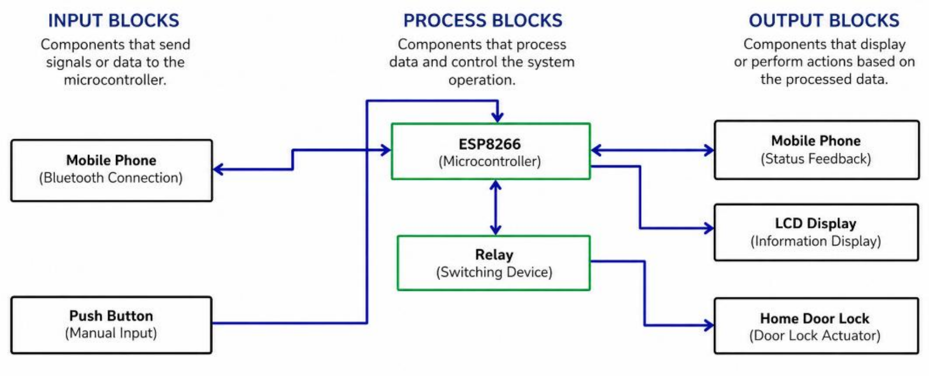

Figure 1. Blok Diagram System

The main components used in this research are summarized in Table 1. The selection of components is based on feature availability, interface compatibility, and implementation efficiency at the household scale.

Tabel 1. Main Components in The System

Component	**Function**	**Main Specification**
NodeMCU ESP8266	Main controller and data communication	Wi-Fi 2.4 GHz, 80 MHz
PZEM-004T	Electric parameter sensor	80–260 VAC, 100 A
Relay Module	Relay Module Automatic load	10 A / 250 VAC
LCD I2C 16x2	Local display	Antarmuka I2C
Stepdown Converter	Voltage reducer	220 VAC ke 5 VDC
Push Button	Manual control	Normally Open

The operational logic of the system will be designed as a protection algorithm as in Figure 2. During the first step, the system will conduct pin and Wi-Fi connection and synchronization with the Telegram bot. Then, the sensor reads current and voltage data periodically. The obtained values are compared with the protection limits, which include a maximum of 1.5 A current, a voltage higher than 220 VAC, and a low voltage higher than 150 VAC. When the parameters are greater than the safe limits, the relay will be turned on to de-energize the load and relay trip notification will be sent to the user by the system. In the other case, when the conditions are normal, the system will keep on providing information on the electrical parameter status, but will not disconnect the load.

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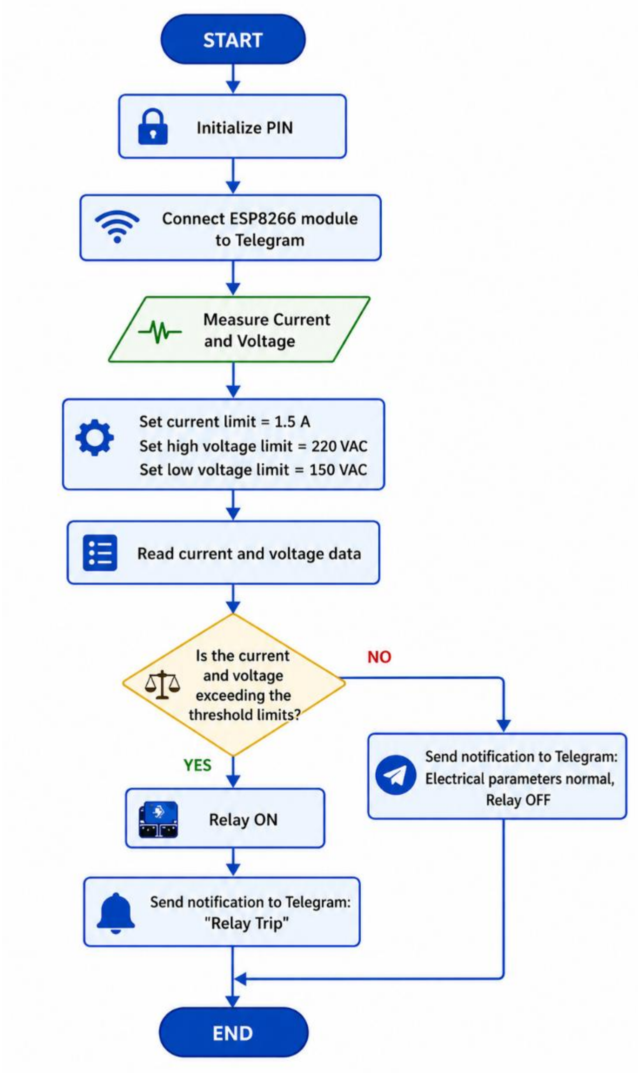

Figure 2. Flowchart System

The prototype was implemented by fitting all the parts on a test panel which is a small scale household installation as illustrated in Figure 3. System program was created in Arduino IDE and C/C++ language and it incorporated sensor reading functions, decision making logic, relay control and data communication to Telegram. Three general scenarios were tested, which included normal conditions, overcurrent simulation, and abnormal voltage simulation. Five tests were carried out on each scenario to ensure the reliability of the performance of the system. The results of the test in form of measurement value, relay status, response time and success of notification were noted.

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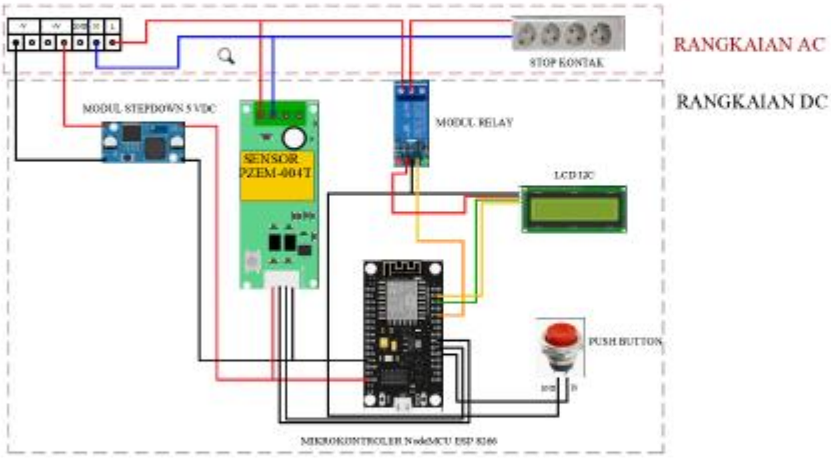

Figure 3. Schematic of the System Circuit

System performance testing is done using three primary measures, which include sensor accuracy, protection response time and communication reliability. The percentage error against a standard reference measuring instrument is used to determine the sensor accuracy by the equation:

$$\text{Error}(\%) = \frac{X_{Sensor} - X_{Referensi}}{X_{\text{Referensi}}} \text{x } 100$$

Response time is determined by the duration of time taken between the time that the parameter has exceeded the threshold and the time that the relay has been able to disconnect the load. The reliability of the communication is assessed in terms of the proportion of successful deliveries of Telegram notifications during each of the test conditions. Data were all analyzed quantitatively-descriptively to determine the overall system performance in assisting IoT-based electrical protection and monitoring.

3. Results and discussion

Results

The implementation results show that the IoT-based electrical protection and monitoring system has been successfully built and operates according to the established design. The system is capable of reading electrical parameters in real-time thru the PZEM-004T sensor, then processing the data using the NodeMCU ESP8266 to determine normal or abnormal conditions. The measurement results are displayed locally via an LCD and sent to users thru the Telegram platform. In addition, the relay automatically disconnects the load when the detected parameters exceed the threshold. In general, the integration between sensors, microcontrollers, actuators, and notification systems worked well without significant issues during testing.

a. Results of Electrical Parameter Measurements

The testing was conducted to evaluate the accuracy of the sensor readings against the reference measuring instrument. The parameters tested include voltage and current under several load variations. The measurement results show that the PZEM-004T sensor has a high level of accuracy compared to standard measuring instruments. The reading differences are within a relatively small range, making them acceptable for household monitoring needs. Thus, the sensor is deemed suitable for use as a main component in the protection and monitoring system.

Tabel 2. Comparison of Sensor Measurement Results and Reference Instrument

Parameter	Sensor	Reference	Error (%)
Voltage	219.6 V	220.0 V	0.18
Voltage	218.9 V	219.5 V	0.27
Current	1.42 A	1.45 A	2.07
Current	1.36 A	1.39 A	2.16

Based on the data, the average voltage measurement error is below 1%, while the current measurement error is below 3%. These values indicate that the sensor performance is quite accurate for household protection applications. A high level of accuracy is an important factor to ensure that load disconnection decisions can be made precisely. This result confirms that the system has a reliable measurement basis.

b. Results of Automatic Protection Testing

Protection testing is conducted to assess the system's ability to respond to overcurrent and overvoltage conditions. When the current exceeds the threshold of 1.5 A or the voltage is outside the safe range, the relay automatically cuts off the power supply. The test results show that the protection mechanism operates according to the programd logic. All disturbance scenarios were successfully identified correctly. No load disconnection failures were found during the testing process..

Tabel 3. Protection System Testing Results

Scenario	Detected Value	Relay Status	Notification
Kondisi Normal	219 V / 1.20 A	ON	Sent
Overcurrent	220 V / 1.72 A	OFF	Sent
Overvoltage	231 V / 1.10 A	OFF	Sent
Undervoltage	148 V / 0.95 A	OFF	Sent

The data shows that the system is capable of consistently performing protective functions under all testing conditions. The relay only activates to cut off the load when the parameters exceed the safe limit. Under normal conditions, the power supply remains connected without intervention. This pattern indicates that the decision-making logic is functioning stably.

Figure 4. Result Overvoltage Testing

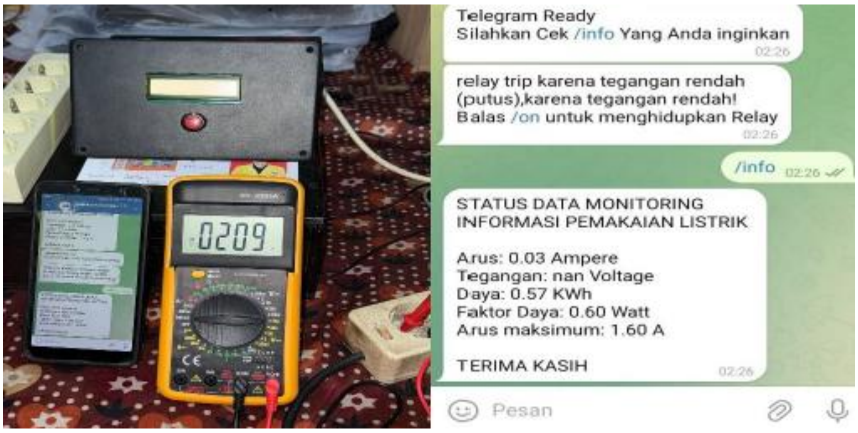

Figure 5. Result Undervoltage testing

c. System Response Time

Response speed becomes an important indicator in electrical protection systems. The measurement is conducted by calculating the time interval from when the disturbance is detected until the relay disconnects the load. Based on the test results, the average system response time is around 1 second. This value indicates that the system is quite fast in preventing potential damage to electrical equipment. The response is also influenced by the stability of the Wi-Fi connection and the processing time of the microcontroller.

Tabel 4. System Response Time

Testing	Response Time
Test 1	0.98 s
Test 2	1.02 s
Test 3	1.01 s
Test 4	0.99 s
Test 5	1.00 s

An average response time of 1.00 seconds indicates that the system is sufficiently responsive for domestic protection needs. In the context of household installations, this time is considered adequate to minimize the risk of prolonged disruptions. Thus, the system is not only accurate but also quick to act.

d. Reliability of Notifications and Remote Monitoring

The Telegram-based notification option enables users to get current data regarding electrical conditions. The testing conditions were all successful in terms of message delivery without pronounced delays. Moreover, the electrical parameters may be tracked by users using the corresponding real-time interface. This option increases monitoring flexibility even in absence of the user at the point of installation. The reliability in communication is another value addition appreciated in the development of IoT-based systems.

In general, research findings point to the designed system being able to achieve the primary goal, which consists in offering an automatic protection and IoT-based electrical monitoring to household installations. The precision of the sensors, protection response, and the success of providing the notification evidences the fact that the system can be introduced as a viable solution. IoT technology applied in the security system makes the system efficient, easily accessible, and safer. These results prove the possibility of the further evolution of a more widespread smart protection system.

Disscussion

The results of this study underline that the implementation of the Internet of Things (IoT) technology in the household electrical protection systems can result in a more responsive monitoring and protection system than the traditional ones [10], [11]. The system that is designed is not only a tool of real-time monitoring electrical parameters, but also can undertake automatic protective measures when overcurrent, overvoltage or undervoltage are observed [12]. These features show a transformation of protective functions, which was a passive approach to an intelligent system based on data. This ability is very applicable to domestic installations since disturbances in electricity usually have no pre-warnings that can be detected by users. Thus, IoT-based systems are strategically valuable in contributing to safety and operational efficiency of household installations [13], [14].

In the context of measurement accuracy, the results of the research indicate that the PZEM-004T sensor can generate measurements with a low error rate as compared to the reference instrument [15]. The mean error in voltage below 1% and current below 3 percent means that the sensor is reliable enough to be used in monitoring and making protection decisions [16]. These results are consistent with other prior works that place the PZEM-004T as a cost effective solution to microcontroller-based energy measurement systems. The accuracy obtained is suitable in the practical application despite the fact that it is not tailored to laboratory calibration functions. In this way, the validity of sensor data may be regarded as good enough to trigger the automatic protection logic.

The fact that the system manages to react to any disturbance situation proves the efficiency of the implemented protection algorithm. The fact the system can make its own decisions without the involvement of a user is shown by automatic shutdown of the load when they go outside the range [17], [18]. This feature turns out to be the key point of distinction over traditional monitoring devices that typically just give information without any corrective measures. Such self-response ability is essential in the situation of electrical safety to minimize the harm to electronic equipment and the possibility of accidents related to the prolonged disturbances. Thus, the study increases the role of IoT as not only an active component of the protection system but also as a communication medium.

Based on the temporal performance aspect, an average response time of approximately 1 second signifies that the system is low enough in latency to be used in the home setting. This fast reaction can be taken as the evidence that the process of sensor reading, data processing and relay activation can be done effectively. In homes protection systems, such a time is found to be adequate to avoid the amplification of disturbances before they can influence a broader area. Nonetheless, with the application in industrial settings or in critical systems with sensitive loads, additional optimization is necessary to achieve a response time down to the milliseconds. This implies that the scalability of the system is yet to be closed but it needs to be adjusted to the design of the system depending on the complexity of the application.

Besides the technical features, the great contribution of this work is that remote notifications have been integrated via Telegram, enabling users to get disruption information first-hand. This feature improves situational awareness of users about the state of the electrical installation remotely. This solution is indicative of a new dynamic in the sphere of energy management i.e. the interdependence of physical machines and users with the help of the internet. Real-time communication capabilities are more flexible and controllable compared to traditional local systems of protection. In this way, the research will provide technical solutions and also assist in changing the shift to a safer and more responsive smart home ecosystem.

In spite of the positive performance demonstrated by the research results, several limitations should be mentioned. The experiment was performed at prototype level using few situations, and therefore, before concluding to true installation environments, additional testing is necessary. The system is also not immune to the reliability of the internet connection to deliver notifications, which may also impact reliability in places with poor network coverage. It is suggested that future studies be conducted to understand how to integrate it with artificial intelligence to create a better predictive tool of the electrical disturbances. Through this advancement, IoT-based protection systems can mature into proactive systems that are able to identify possible disruptions even before they happen.

4. Conclusion

This study was able to both design and deploy an Internet of Things (IoT)-based electrical protection and monitoring system that could identify current and voltage disrupts on household electrical installations in real time. The system exhibits a good performance with an adequate accuracy of measurements, fast protection response time, and remote notification that is delivered successfully to users. The combination of the PZEM-004T sensor, the NodeMCU ESP8266, the relay, and the Telegram platform demonstrate that the IoT technology can be used practically to increase the safety and efficiency of the management of domestic electrical energy. Along with the role of a monitoring tool, the system can also serve as an active protection device since it can automatically break the load in case of abnormal conditions. Therefore, the study has a practical impact on the creation of an adaptive, safe, and possibly scalable smart electrical system to implement on a larger scale.

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