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Internet of Things (IoT)-Based Overvoltage Protection and Monitoring System for Single-Phase Electrical Networks

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ABSTRACT: Voltage quality in single-phase electrical power networks for residential applications does not always remain at nominal conditions and is prone to fluctuations caused by load variations and distribution network conditions. Repeated or sustained overvoltage conditions can reduce equipment lifespan and damage electrical and electronic devices. Therefore, this study aims to design and implement an overvoltage protection and monitoring system for single-phase power networks based on the Internet of Things (IoT). The proposed system employs a PZEM-004T 10A module for electrical parameter measurement, an ESP32 microcontroller as the main controller, and a Solid State Relay (SSR) as the protection actuator. The system is designed to detect overvoltage conditions, automatically disconnect and reconnect the load based on predefined voltage thresholds and time delays, and provide real-time monitoring through the ThingSpeak IoT platform. Experimental results indicate that the measured line voltage ranged from approximately 196 V to 235 V, with an average value of about 203 V. The maximum recorded current was 2.48 A with a maximum active power of approximately 466 W, while the system frequency remained stable around 50 Hz. The measured power factor varied between 0.27 and nearly 1.0. The protection mechanism operated reliably without significant false trips, and the IoT-based monitoring system successfully logged and visualized real-time data. These results demonstrate that the developed system is effective as an IoT-based solution for overvoltage protection and monitoring in single-phase electrical power networks.

KEYWORDS: Overvoltage, Electrical protection system, Monitoring, Internet of Things (IoT), Single-phase power network.

INTRODUCTION

Over-voltage can be caused by various factors, including load imbalance in the distribution network, power delivery system faults, and fluctuations in electrical energy sources, including renewable energy-based systems such as solar power plants [1]. This condition has the potential to cause negative impacts in the form of accelerated degradation of electronic components, reduced equipment lifespan, and operational failures of household electrical systems.

Although effective in protecting the network from overcurrent faults, Miniature Circuit Breakers (MCBs) are not designed to specifically detect and respond to over-voltage conditions or voltage fluctuations. Consequently, when an over-voltage occurs, electrical equipment remains connected to the network without an automatic disconnection mechanism based on voltage parameters [2].

IoT-based systems enable the integration of automatic protection functions, real-time electrical condition monitoring, and historical data logging for power quality analysis and evaluation purposes [3] [4]. Through IoT platforms, electrical parameters such as voltage, current, and power can be monitored remotely via the internet network, thereby enhancing the safety, convenience, and efficiency of electrical installation management.

The development of protection systems against over-voltage faults had been carried out long before the concept of the Internet of Things expanded widely. Designed and realized a microcontroller-based over-voltage protection device capable of detecting abnormal voltage conditions and automatically disconnecting the load [5].

Based on these problems and supported by findings from previous studies, there is a need for a system capable of providing automatic over-voltage protection while simultaneously offering an Internet of Things (IoT)-based monitoring facility for single-phase electrical network conditions. This system is expected to enhance the safety of electrical equipment, minimize the risk of damage due to over-voltage, and provide the convenience of real-time electrical condition monitoring.

METHODOLOGY

Tools and Materials

1. Tools

   The equipment used in this research includes:

   1. Laptop/PC

2. Digital multimeter
3. Variac
4. Screwdrivers, pliers, and other mechanical tools
5. Internet connection

2. Materials

The main materials used in this research are:

1. ESP32 microcontroller
2. PZEM-004T 10A sensor
3. SSR 10DA actuator
4. Buzzer
5. System power supply
6. Cables and supporting components
7. ThingSpeak IoT platform

System Design

Hardware design includes the integration of the PZEM-004T module with the ESP32 microcontroller as the measurement and data processing unit. Voltage and current from the single-phase electrical network are measured by the PZEM-004T module, and the data is then sent to the ESP32 via serial communication. The ESP32 controls the SSR circuit, which functions as an actuator to disconnect and connect the load. A buzzer is used as an alarm indicator when the protection system is active. The entire circuit is designed to operate on a low-voltage, single-phase electrical network.

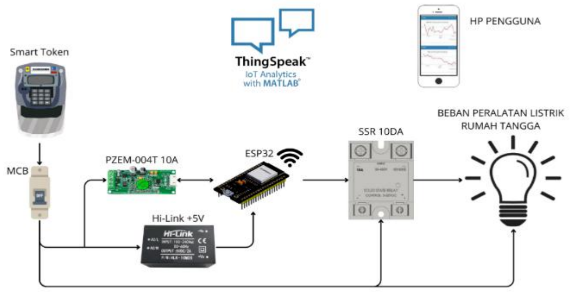

Figure 1 System block diagram

The system block diagram illustrates the architecture of the Internet of Things (IoT)-based overvoltage protection and monitoring system for a single-phase power grid. This system is designed to measure electrical parameters, execute automatic protection decisions, and monitor the electrical network status in real-time via the internet.

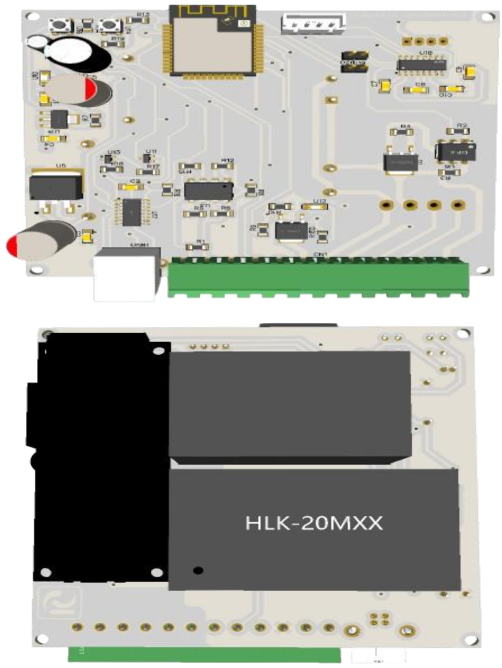

Figure 2 PCB design of the IoT-based overvoltage monitoring and protection device

The single-phase power source originates from the household electrical grid, passing through a prepaid kWh meter (smart token) and a Miniature Circuit Breaker (MCB).

The MCB functions as the primary protection against overcurrent and short-circuit faults. After passing through the MCB, the electrical power is distributed to the designed monitoring and protection system. At this stage, conventional protection systems are incapable of handling overvoltage faults, thereby requiring an additional protection system.

The ESP32 microcontroller acts as the central control unit of the system. The ESP32 receives measurement data from the PZEM-004T module and then processes this data based on the pre-designed overvoltage protection algorithm. If the measured voltage exceeds the designated threshold, the ESP32 activates the protection mechanism by controlling the load-disconnecting actuator. Additionally, the ESP32 transmits the monitoring data to the IoT platform via a WiFi connection.

The monitoring data sent by the ESP32 is forwarded to the ThingSpeak platform as the IoT medium. This platform functions to display electrical parameters and protection status in real-time graphical formats, as well as to store historical data. Through ThingSpeak, the data can be accessed and analyzed at any time as part of the protection system's performance evaluation.

Figure 3 Overvoltage monitoring device and enclosure

Users can monitor the electrical network conditions and protection status via mobile devices or other internet-connected equipment. Thus, the system enables remote monitoring without requiring physical presence at the installation site, while simultaneously enhancing the safety and reliability of household electrical installations.

Figure 3 illustrates the physical implementation of the overvoltage monitoring and protection device following the fabrication stage. The PCB utilizes a double-layer FR4 type. To ensure the safety of the PCB and its components, it is securely mounted inside a waterproof enclosure. A total of 3 electrical outlets used to supply power to electrical appliances are positioned on the side of the device casing, with a maximum power capacity of 1000VA.

The system software was developed using the C++ programming language on the Arduino IDE platform. The program on the ESP32 includes:

- Sensor data reading from the PZEM-004T,
- Data processing and voltage condition determination,
- Threshold-based and delay-time-based overvoltage protection algorithms,
- Control of the protection actuator,
- Periodic data transmission to the ThingSpeak platform.

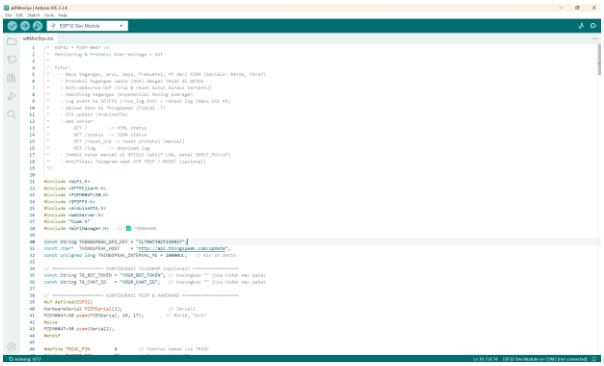

Figure 4 Arduino IDE

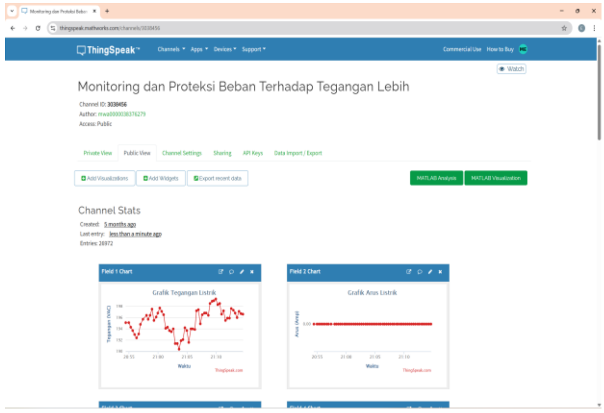

Figure 5 ThingSpeak IoT Web Platform

The data used in this testing consists of monitoring data of electrical parameters from a single-phase power grid, recorded continuously by the Internet of Things (IoT)-based protection and monitoring system. The data was obtained from the PZEM-004T 10A module integrated with the ESP32 microcontroller and transmitted periodically to the ThingSpeak platform. The data tabulation shows the recording of electrical parameters at relatively constant time intervals; thus, the acquired data is time-series in nature and can be utilized to comprehensively analyze the dynamics of household electrical network conditions. The analyzed parameters include voltage, current, active power, frequency, and power factor, each recorded in standard electrical power system units.

RESULTS AND DISCUSSION

Based on the tabulated monitoring data, the voltage values of the single-phase electrical network exhibit fluctuations over time. The measured voltage does not remain at a constant value but changes according to the load conditions and the grid supply.

Table 1 Voltage Monitoring on the Electrical Network

No.	Time and Date	Tegangan (VAC)
1	2025-12-06T12:03:31+07:00	234,4
2	2025-12-06T12:03:51+07:00	234,5
3	2025-12-06T12:04:11+07:00	234,5
4	2025-12-06T12:04:31+07:00	234,1
5	2025-12-06T12:04:51+07:00	234
6	2025-12-06T12:05:11+07:00	233,9
7	2025-12-06T12:05:31+07:00	233,9
8	2025-12-06T12:05:51+07:00	233,7
9	2025-12-06T12:06:11+07:00	233,7
10	2025-12-06T12:06:31+07:00	233,8

From all the recorded data, the voltage has a minimum value of approximately 196 V and a maximum value reaching around 235 V, with an average value in the range of 203 V.

This fluctuation remains within the tolerance range of a low-voltage distribution system; however, during certain time intervals, it approaches the upper limit, which potentially poses a risk of causing disturbances to electrical appliances.

These results indicate that household electrical networks possess dynamic voltage characteristics, thereby making a voltage monitoring system highly essential for the early detection of abnormal conditions.

The current data tabulation reveals significant variations in current over time. The recorded current values range from a minimum value of approximately 0.05 A to a maximum value of about 2.48 A, with an average value of around 0.4 A.

Table 2 Observation of Load Current over Time

No.	Time and Date	Current (Amp)
1	2025-12-06T12:03:31+07:00	0
2	2025-12-06T12:03:51+07:00	0
3	2025-12-06T12:04:11+07:00	0
4	2025-12-06T12:04:31+07:00	0
5	2025-12-06T12:04:51+07:00	0
6	2025-12-06T12:05:11+07:00	0
7	2025-12-06T12:05:31+07:00	0
8	2025-12-06T12:05:51+07:00	0
9	2025-12-06T12:06:11+07:00	0
10	2025-12-06T12:06:31+07:00	0

These changes in current reflect the variation in loading within the household electrical installation, such as the operational activities of low to medium-power electrical appliances. The fluctuating pattern of the current indicates that the connected loads are dynamic and non-constant.

The recorded current data demonstrates that the monitoring system is capable of sensitively recording load changes in real-time, thereby serving as a basis for energy consumption analysis and electrical system condition evaluation.

Based on the tabulated active power data, the measured power values exhibit fluctuations that follow the changes in current and voltage. The minimum active power recorded is in the range of a few watts, while the maximum power reaches approximately 466 W, with an average value of around 80–90 W.

This fluctuation in active power indicates a non-uniform pattern of household electrical energy usage. An increase in active power at certain times indicates the operation of higher-power electrical appliances, whereas low power values represent light load or standby conditions. These results prove that the system is capable of accurately and continuously monitoring electrical power consumption, as well as providing essential historical data for evaluating energy efficiency.

Table 4.1 presents the measured active power data over time recorded by the monitoring system. The displayed data represents a portion of the overall testing data, while the complete dataset is provided in the appendix.

Table 3 Observation of Active Load Power over Time

No.	Time and Date	Power (Watt)
1	2025-12-06T12:03:31+07:00	0
2	2025-12-06T12:03:51+07:00	0
3	2025-12-06T12:04:11+07:00	0
4	2025-12-06T12:04:31+07:00	0
5	2025-12-06T12:04:51+07:00	0
6	2025-12-06T12:05:11+07:00	0
7	2025-12-06T12:05:31+07:00	0
8	2025-12-06T12:05:51+07:00	0
9	2025-12-06T12:06:11+07:00	0
10	2025-12-06T12:06:31+07:00	0

Over-voltage testing was conducted to evaluate the system's capability to detect voltage conditions that exceed the designated threshold and to respond to such conditions by activating the protection mechanism. Since continuous over-voltage conditions do not always occur naturally in household electrical grids, an over-voltage simulation was performed in this test by gradually increasing the source voltage using a VARIAC.

The system's over-voltage threshold was set at 245 V, with a trip delay time of 3 seconds before the system disconnects the load. The protection status is expressed as OVP = 0 for normal conditions and OVP = 1 for active protection conditions.

Table 4 Over-Voltage Testing Table against OVP Status

No	Time and Date	Voltage (VAC)	Status OVP
1	08/12/2025 14:20	228,5	0
2	08/12/2025 14:20	231,2	0
3	08/12/2025 14:20	234,8	0
4	08/12/2025 14:21	238,5	0
5	08/12/2025 14:21	241,7	0
6	08/12/2025 14:21	244,2	0
7	08/12/2025 14:22	246,8	0 *(delay)*
8	08/12/2025 14:22	248,3	1
9	08/12/2025 14:22	247,9	1
10	08/12/2025 14:23	246,5	1
11	08/12/2025 14:23	242,8	1 *(delay reset)*
12	08/12/2025 14:23	239,6	1 *(delay reset)*
13	08/12/2025 14:24	238,2	0
14	08/12/2025 14:24	236,9	0
15	08/12/2025 14:24	235,4	0

Based on the simulation table, the system begins to detect an overvoltage condition when the voltage value exceeds the 245 V threshold. When the voltage reaches 246.8 V, the OVP status remains in the normal condition because the system is still within the trip delay phase. This indicates that the system does not immediately disconnect the load due to a transient voltage spike.

After the voltage remains above the threshold for the specified duration, the system activates the protection and changes the OVP status to active (OVP = 1). In this condition, the Solid State Relay (SSR) disconnects the power supply to the load as a safety measure for the electrical appliances.

When the voltage begins to drop back below the safe limit, the system does not immediately reconnect the load, but instead applies a reset delay. The load is only reconnected after the voltage stabilizes below the reset value for a specific period. This mechanism prevents false resets caused by momentary voltage fluctuations.

Based on the overall data tabulation and analysis results, the designed overvoltage protection and monitoring system is capable of recording electrical parameters consistently and in real-time. The observed fluctuations in voltage, current, and power indicate that household electrical networks experience dynamic conditions and have the potential to cause disturbances if not equipped with an adequate protection system.

The monitoring data also shows that the protection system operates selectively, without significant false trips, thanks to the implementation of thresholds and time delays. Integration with the IoT platform enables continuous data storage and visualization, allowing the system to function not only as a protection device but also as a means for analyzing electrical network conditions.

The overvoltage simulation test results demonstrate that the protection system operates according to the design. The system is able to distinguish between transient voltage spikes and continuous overvoltage conditions through the application of thresholds and time delays. Consequently, the risk of unnecessary load disconnection can be minimized.

This testing proves that the integration of the PZEM-004T measurement module, the ESP32 microcontroller, and the SSR actuator is capable of producing a reliable overvoltage protection system. The recorded OVP status data also demonstrates that the IoT-based monitoring system can be used to document protection events as part of the system's performance evaluation.

CONCLUSION

1. Based on the monitoring results during the testing period, the measured electrical network voltage ranges from a minimum of approximately ±196 V to a maximum of ±235 V, with an average value of around ±203 V. This voltage fluctuation indicates that the household electrical grid does not always operate at nominal voltage, making overvoltage detection crucial for protecting electrical appliances.
2. The system is capable of automatically disconnecting the power supply to the load when the measured voltage exceeds the predetermined threshold, and automatically reconnecting the load once the voltage returns to a safe condition by applying a time delay. The test results demonstrate that this mechanism successfully prevents false trips caused by transient voltage fluctuations and operates stably throughout the testing period.
3. Electrical parameters such as voltage, current, active power, frequency, power factor, and protection status can be monitored in real-time via the internet. The measurement data was successfully transmitted and stored periodically at intervals of approximately 20 seconds, thereby generating historical data that can be utilized for system performance analysis.
4. The maximum current recorded during the testing reached approximately 2.48 A, with a maximum active power of around 466 W, while the system frequency remained relatively stable at around 50 Hz. The measured power factor values varied between ±0.27 and nearly 1.0, reflecting the predominantly non-linear characteristics of household loads.

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