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Design of a Selective Load Protection System for Households Using Node-RED with Priority-Based Load Shedding Method

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ABSTRACT

Overvoltage and undervoltage are electrical disturbances in household) s that can damage electronic equipment. The use of excessive loads, especially compressor-based devices that are vulnerable to on-off cycles due to conventional MCB trips, can shorten equipment life. This study aims to design and build a selective load protection system based on IoT using the Priority-Based Load Shedding method with Node-RED integration. The system uses ESP32, three PZEM-004T sensors, relay module, and DFPlayer Mini for local audio alerts, with MQTT protocol via HiveMQ broker for real-time communication. Test results show the PZEM-004T sensor has voltage error 0.35%–0.49%, active power 3.6%, and current 6.19%. Voltage protection successfully interrupts power flow in less than 2 seconds. The load shedding mechanism successfully unloads non-priority loads sequentially when total current exceeds the safe limit. The Node-RED dashboard can monitor all electrical parameters in real time and send direct control commands to hardware.

INTRODUCTION

Electricity is a fundamental necessity that underpins nearly all activities in modern life. The dependence on electrical power demands reliable and safe installation systems. Overcurrent, or overload, is a commonly encountered problem in which excessive load usage can cause damage to electronic equipment [1]. In addition to overcurrent, overvoltage and undervoltage disturbances also pose serious threats. According to SPLN 2013 (Indonesian National Electricity Standard), voltage conditions are considered abnormal when they rise or fall beyond 10% of the nominal voltage of 220V. Voltage disturbances that go undetected or receive a delayed response can increase the risk of equipment damage, reduce energy efficiency, and raise maintenance costs [2]. Furthermore, undervoltage and overvoltage disturbances in power networks can lead to voltage collapse or complete blackouts [3].

In general, the public relies on MCBs (Miniature Circuit Breakers) as the standard protection device capable of automatically disconnecting the circuit when an overcurrent occurs [4]. However, conventional MCBs have significant limitations: they are unable to detect overvoltage and undervoltage conditions, and they disconnect the entire load when an overcurrent event occurs. This total power disconnection is particularly detrimental to compressor-based appliances (such as air conditioners and refrigerators), which are vulnerable to repeated on-off cycling, thereby shortening the equipment's operational lifespan [5]. Several prior studies have developed microcontroller-based protection systems. Sinulingga [6] designed an overcurrent relay system using NodeMCU and an ACS sensor limited to a single load channel. Hasibuan et al. [7] developed a 220V protection system using ESP8266 and PZEM-004T; however, it focused solely on total disconnection of a single load. Kiswantono et al. [8] designed an overvoltage monitoring system using an Over Voltage Relay (OVR). Panggabean et al. [9] designed a digital OCR (Over Current Relay) using ATmega8535 with a timer mechanism to handle inrush current. Although these studies have successfully created automated protection systems, they generally still apply total disconnection to all loads and have not yet implemented a selective disconnection mechanism based on load priority. To address these limitations, this study proposes the implementation of a Priority-Based Load Shedding method. Load shedding is a strategic action aimed at preventing total blackouts by disconnecting non-priority loads in order to maintain priority loads [10]. The designed system utilizes an ESP32 as the data processing unit, three PZEM-004T sensors for electrical parameter readings, relay modules as selective load disconnectors, a DFPlayer Mini module for local audio alerts, and IoT integration using the MQTT protocol with Node-RED serving as the monitoring and control dashboard. The system is also equipped with a thermal MCB curve simulation using a heat accumulation model to anticipate inrush current.

The key contributions of this study are as follows:

1. Development of a priority-based load shedding mechanism for selective load disconnection in household electrical systems.
2. Implementation of real-time voltage and current monitoring utilizing three PZEM-004T sensor modules with a dynamic pin remapping method on the ESP32.
3. Integration of undervoltage and overvoltage protection with automatic auto-recovery capabilities.
4. Development of a thermal MCB curve simulation employing a heat accumulation model to anticipate inrush currents.
5. Application of an IoT-based monitoring and control architecture utilizing a Node-RED dashboard with the MQTT protocol for remote monitoring, as well as local audio alerts via the DFPlayer Mini.

Unlike conventional MCB-based protection systems that only perform total disconnection of all loads during overcurrent events without any voltage monitoring capabilities, the proposed system integrates selective load shedding, undervoltage/overvoltage protection, and real-time IoT-based monitoring within a single integrated embedded platform.

RESEARCH METHOD

A. Research Design / Experimental Setup

This study employs an experimental method utilizing a design-and-build approach. The research workflow begins with a literature study, problem formulation, development of working schematics, hardware preparation, staged component testing (individual components, serial communication, undervoltage/overvoltage simulation using a voltage regulator, and Node-RED integration), data collection, and concludes with report preparation.

B. System Architecture

The protection system consists of several main subsystems that are mutually integrated using a combination of various components. The primary hardware components include the ESP32-WROOM-32 as the microcontroller, three PZEM-004T V3.0 sensor modules equipped with 100A Current Transformers (CTs), three SRD-05VDC-SL-C relay modules (10A/250VAC), a DFPlayer Mini with a 2W speaker, and a Hi-Link HLK-10M05 as the 5V DC power supply. The software platforms used are the Arduino IDE (C++) and Node-RED. The overall system architecture is shown in Figure 1.

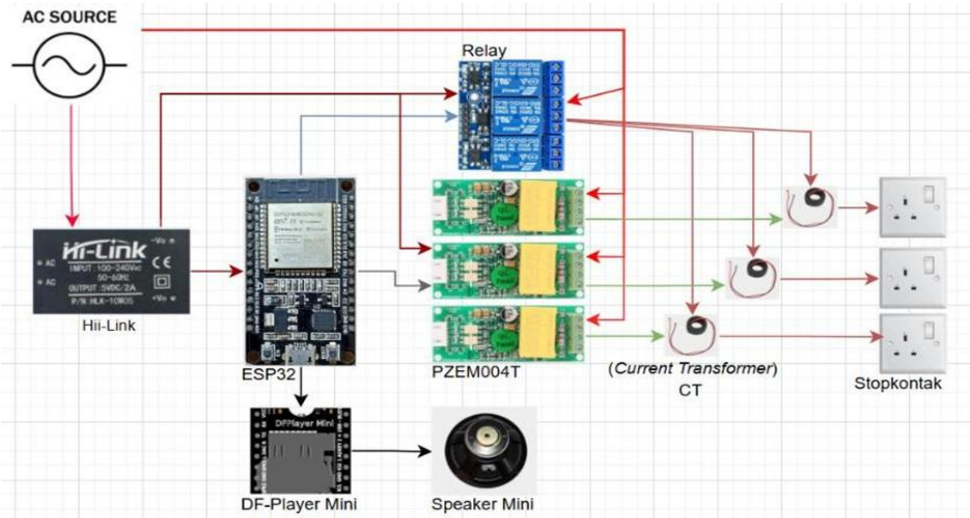

Figure 1. System Workflow

a) Sistem Data: All parameters, including voltage, current, and active power, are read by three PZEM-004T sensors via serial UART communication. Due to the limited UART pins on the ESP32, a Dynamic Pin Remapping method is implemented to alternate readings every 750 ms using a single shared TX pin.

b) Communication System: Local communication between hardware components utilizes UART interfaces (PZEM-004T on UART2, DFPlayer Mini on UART1). Remote communication employs the MQTT protocol via the HiveMQ broker (broker.hivemq.com, port 1883) for transmitting real-time data to Node-RED.

c) Control and Protection System: The ESP32 processes the sensor data and automatically executes three types of protection:
   1. Undervoltage (<198V) and overvoltage (>242V) protection, which disconnects all loads and features an auto-recovery mechanism once the voltage returns to normal.
   2. Priority-based load shedding, which sequentially disconnects loads starting from the smallest current draw when the total current exceeds the pre-defined threshold.
   3. A thermal MCB curve simulation utilizing a trip-time multiplier factor based on C2 MCB curve data [11] to anticipate inrush currents.

d) Audio Alerts: The DFPlayer Mini module plays local audio messages to notify users of undervoltage, overvoltage, overload, and load shedding conditions, as well as the on/off status of the outlets. A 4-second delay is programmed between audio playbacks to prevent overlapping sound outputs.

C. System Capacity and Safety Limit Analysis

The capacity of the protection system is determined based on the specifications of its primary components. The SRD-05VDC-SL-C relay module has a maximum capacity of 10A at 250VAC per channel. Theoretically, by utilizing three relay modules, the system is capable of handling a total current of up to 30A. However, the power distribution cable used is a NYAF 0.75 mm2 wire. According to the PUIL 2000 (Indonesian General Electrical Installation Regulations) Table 7.3-1, a NYAF cable with this cross-sectional area has a current-carrying capacity (CCC) of 7A at a maximum operating temperature of 70◦C. Therefore, the safe total current limit for the entire load is set at 7A, with a default testing threshold of 2A per outlet.

D. Hardware and Software

The primary hardware components include: the ESP32-WROOM-32 (38-pin) as the microcontroller, three PZEM-004T V3.0 sensors with 100A CTs, three SRD-05VDC-SL-C relay modules (rated at 10A/250VAC), a DFPlayer Mini module with a 2W speaker, a Hi-Link HLK-10M05 as the 5V DC power supply, and three electrical outlets acting as load distribution points. The software setup utilizes the Arduino IDE for programming the ESP32 (C++ language) and Node-RED for the monitoring dashboard and control interface using Visual Programming Language (VPL). The power distribution wiring employs NYAF 0.75 mm2 cables (with a safe current-carrying capacity of 7A based on PUIL 2000).

E. Testing Phase

The testing procedures comprise:
1. An accuracy test of the PZEM-004T sensor by comparing its readings against standard measuring instruments (voltmeter, ammeter, and wattmeter);
2. An undervoltage and overvoltage protection test utilizing a voltage regulator;
3. A Node-RED performance test to ensure the consistency of the displayed data;

4. A test of the load shedding mechanism under varying load conditions; and
5. A response test of the DFPlayer Mini audio module.

The experiments were conducted at Building A8 of the Department of Electrical Engineering, Faculty of Engineering, Universitas Negeri Surabaya, and a private residence. The measurement error for accuracy is calculated using the following formula:

RESULTS AND DISCUSSION

A. System and Accuracy Testing

Research results, research results, research results, research results, research results, research results, research results.

Table 1. PZEM-004T Sensor Accuracy Test Results

Parameter	Outlet 1	Outlet 2	Outlet 3
Average Voltage Error (%)	0,361	0,356	0,298
Average Current Error (%)	0	0	0
Average Power Error (%)	10	9,3	9,3

The results indicate that the voltage reading error ranges from 0.298% to 0.361%, which is well below the accuracy specification of the PZEM-004T datasheet (0.5%). The current readings across all three outlets show an error of 0%, with a discrepancy of 0.007A under load variations (0.14A, 0.8A, and 0.18A). The active power error of 9.3% to 10% is influenced by the load power factor and the wattmeter's own power consumption of 1W under no-load conditions. Overall, the PZEM-004T sensor is highly suitable for use as an electrical parameter measurement unit

B. Undervoltage and Overvoltage Protection Testing

Testing was conducted using a voltage regulator to simulate undervoltage (<198 V) and overvoltage (>242 V) conditions. The test results are presented in Table 2.

Table 2. Voltage Protection Response Speed Test Results

Disturbance / Fault	Threshold	Result	Response Time (ms)
Normal Voltage	198V – 242V	On	-
Undervoltage	< 198V	Off	1440
Overvoltage	> 242V	Off	-

The protection mechanism successfully disconnected the load in less than 2 seconds. The system is also equipped with an auto-recovery feature that automatically reactivates the load once the voltage returns to the normal range.

The testing was conducted by evaluating the trip time. Based on Table 1, the test results show that the disconnection was successfully executed at 1,440 ms for undervoltage and

1,820 ms for overvoltage. Therefore, this disconnection mechanism can operate within a maximum limit of 2 seconds

C. Node-RED Testing

The test results show that the data displayed on the Node-RED dashboard matches the data sent from the Arduino IDE serial monitor in real-time. The data updates every 2 seconds (3×750 ms PZEM-004T polling cycle). The relay control feature via Node-RED successfully transmits On/Off commands to the ESP32, which are executed immediately. The Status Log on the dashboard successfully displays notifications for undervoltage, overvoltage, and load shedding conditions.

D. Node-RED Testing

The testing utilized four types of loads: a large fan (0.18A), a small fan (0.14A), a soldering iron (0.59–0.09A), and an incandescent lamp (0.09A). The test results are shown in Table 3.

Table 3. Load Shedding Test Results

Scenario	Outlet 1	Result
3 active loads, A < Limit	0,5	All on
2 outlets, A > Limit	0,4	Outlet with the smallest current turned Off (shedding)
2 outlets, A > Limit	0,3	Outlet with the smallest current turned Off (shedding)
2 outlets, A > Limit	0,3	Outlet with the smallest current turned Off (shedding)
1 outlet, A > Limit	0,5	Overload (Immediate Off)

The load shedding mechanism successfully disconnected loads based on the smallest current order to maintain the priority load (largest current draw). When only a single load exceeded the limit, the system detected an overload condition and disconnected that specific load immediately.

E. DFPlayer Mini Audio Testing

The test results indicate that the audio response ranges from 0.56 to 1.06 seconds with a playback duration of 2 to 3 seconds. The delay between audio playbacks is set to 4 seconds to prevent overlapping sound outputs. The audio module successfully provides voice alerts for all protection conditions (undervoltage, overvoltage, overload, and load shedding) as well as the on/off status of the outlets.

F. Thermal MCB Characteristic Curve Simulation

The thermal curve simulation was evaluated by varying the load current to generate different multiplier factors. The test results recorded a trip time of 105.21 seconds at a

1.3× multiplier (minor overload) and 4.25 seconds at a 6.3× multiplier (severe overload). This tripping response demonstrates consistency with the characteristic curve of a Type C2 MCB [11]. This validates that the software-based heat accumulation algorithm in the system successfully responds to overcurrent dynamically and adaptively to accommodate transient inrush currents.

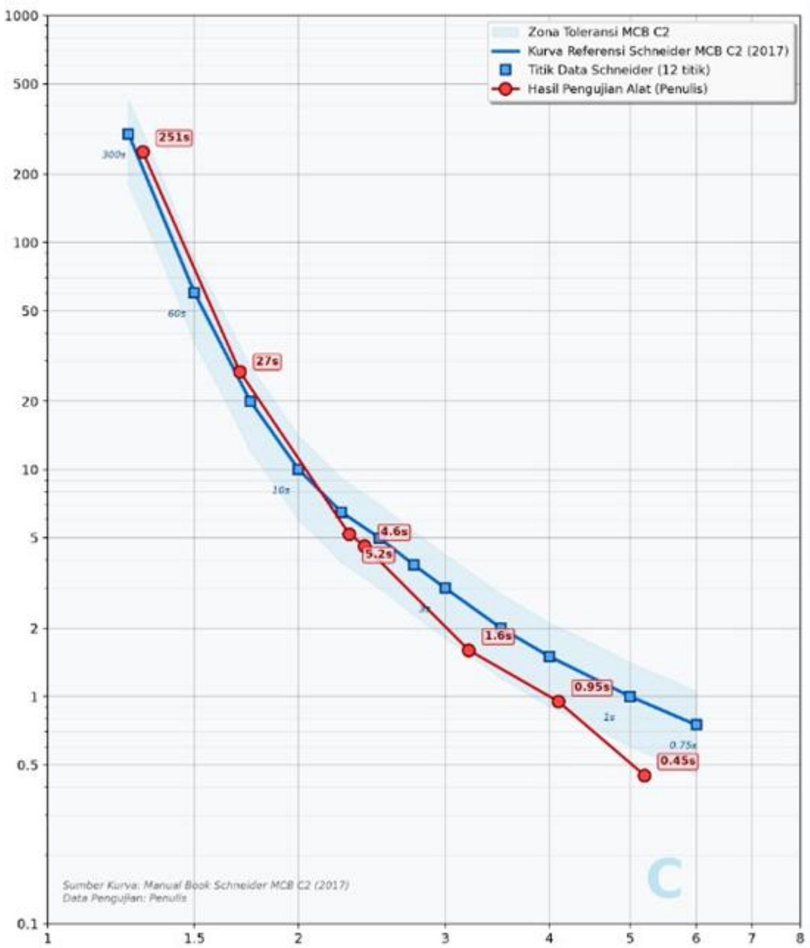

Figure 2. Load Shedding Testing

CONCLUSION

Based on the test results and analysis, an IoT-based selective load protection system utilizing the Priority-Based Load Shedding method has been successfully designed and implemented. The PZEM-004T sensor proved to be accurate with a voltage reading error of 0.35%–0.49%, an active power error of 3.6%, and a current error of 6.19% (with a discrepancy of 0.007A), making it highly suitable for electrical parameter measurement.The undervoltage and overvoltage protection mechanisms successfully disconnected the loads in less than 2 seconds (1,440 ms for undervoltage and 1,820 ms for overvoltage), complemented by an auto-recovery feature. The load shedding mechanism successfully disconnected loads selectively starting from the lowest current draw to maintain priority loads. The Node-RED dashboard, integrated via the MQTT protocol, successfully displayed real-time data and transmitted control commands. The DFPlayer Mini provided local audio alerts with a response time of 0.56–1.06 seconds. For future development, it is recommended to use a private MQTT broker for data security, add a historical database, integrate Telegram/WhatsApp notifications, optimize the auto-recovery feature for load shedding, upgrade to a three-phase system, and incorporate voltage sag detection.

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