

## Design of Arduino-based Overvoltage Type Time-lag Relay

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**Abstract** – Voltage stability is a fundamental requirement to ensure that electrical equipment operates safely, efficiently, and with minimal risk of permanent damage. Overvoltage disturbances, whether caused by distribution system anomalies, switching operations, or transient surges, can significantly reduce equipment lifespan and potentially result in system failure. Therefore, implementing a reliable and responsive protection mechanism is essential in low-voltage electrical installations. This research presents a comprehensive design and development of a single-phase overvoltage protection system utilizing an Arduino Uno microcontroller combined with a time-lag relay scheme. The proposed system continuously monitors input voltage using a PZEM-004T AC sensor capable of measuring 80–260 V AC with precise UART data transmission to the controller. The microcontroller executes real-time evaluation of the voltage profile against adjustable protection thresholds, specifically set around 192 V and 231 V, to detect abnormal voltage conditions. A selective time-delay algorithm is implemented to ensure that the relay only disconnects the load when an overvoltage condition persists beyond a defined duration, thereby filtering out short-term transient spikes. In order to enhance user interaction and configurability, the prototype is equipped with a 16×2 I2C LCD display and three push-buttons that allow the user to set the overvoltage limit, time delay, and calibration offset. The inclusion of a calibration feature enables the compensation of minor measurement deviations from the PZEM-004T module when compared to a higher-accuracy reference meter. Experimental evaluation confirms that the system operates as intended, with load disconnection and reconnection following the defined parameters. The measured trip time exhibits a deviation of less than 10% from the configured delay, and the voltage reading accuracy error is reduced to below 1% after calibration. These results demonstrate that the developed prototype delivers dependable protection performance despite its use of low-cost and widely available components. Overall, this work contributes a practical, affordable, and educational solution for understanding overvoltage relay behavior in electrical protection systems. The findings highlight the system's potential as a learning platform in vocational and undergraduate engineering environments, while also offering an applicable framework for further improvement such as integration with IoT-based remote monitoring capabilities.

**Keywords** – overvoltage; time-lag relay; arduino; voltage monitoring; relay protection.

### I. INTRODUCTION

THE stability of the electrical supply is a critical aspect that must be ensured in the operation of modern power systems. Voltage abnormalities, such as overvoltage and undervoltage, have the potential to disrupt the continuity of power delivery and lead to premature degradation or permanent damage to sensitive electrical equipment [1–3]. Overvoltage refers to a condition in which the system voltage exceeds the permissible upper limit of the nominal value, whereas undervoltage refers to a condition in which the system voltage drops below the allowable lower threshold [4–6]. Both conditions pose significant risks to

equipment performance and user safety.

Based on the State Electricity Company Standard (SPLN T6.001: 2013) and the International Electrotechnical Commission Standard (IEC 60038), voltage tolerance limits under normal service conditions should remain within  $\pm 10\%$  of the nominal system voltage [7–9]. Any deviation beyond this threshold is considered unsafe and may trigger equipment malfunction, overheating, insulation failure, or even fire hazards. To prevent such incidents, an automatic protective device is required to continuously monitor input voltage conditions and disconnect the load in the event of persistent overvoltage occurrences. To avoid unnecessary disconnection caused by transient disturbances, a time-delay mechanism must be applied before executing the trip action [10–12].

Commercially available protection relays equipped with time-delay mechanisms are widely used

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in the industry. However, these products generally come at a high cost and operate as closed systems, limiting their educational exposure to students [13–15]. From an academic perspective, it is crucial for electrical engineering students to not only recognize such protection devices but also understand their internal functional principles, control strategies, and component interactions [16–18].

Therefore, this research introduces the design and development of a one-phase overvoltage protection relay based on the Arduino Uno microcontroller platform. Supported by the PZEM-004T AC voltage measurement module, a 5 V DC relay, and a 16×2 I2C LCD interface, this system provides real-time voltage monitoring, configurable voltage threshold limits, utilization of programmed time delays, and system calibration features. The proposed design serves as an affordable and customizable learning medium that simulates industrial relay protection behavior while remaining easily reproducible using commercially available electronic components [19].

This study further provides guidance for future enhancements, including testing with real electrical appliances under varying load conditions to validate the performance robustness, improve measurement accuracy, and minimize error variation. Data obtained from this prototype implementation will serve as a foundation for future system refinement and development of more advanced protection strategies [20].

## II. RESEARCH METHODS

This section elaborates the complete design methodology of the proposed time-lag overvoltage protection relay, including system architecture, operational workflow, software development, and physical implementation steps.

### i. System Design

The complete system architecture is illustrated in Fig. 1. The design incorporates multiple hardware components to ensure reliable sensing, processing, control, and visualization of supply voltage conditions. The system consists of six main elements:

1. **Voltage Input, AC 220 V.** The mains voltage serves as the primary supply source. It is fed to the PZEM-004T for measurement and also to an SMPS module for conversion to DC supply. This measurement is the primary basis for determining system protection status.
2. **DC Power Supply.** The SMPS module converts 220 V AC into regulated DC output (5–12 V) required for the operation of Arduino Uno, relay mod-

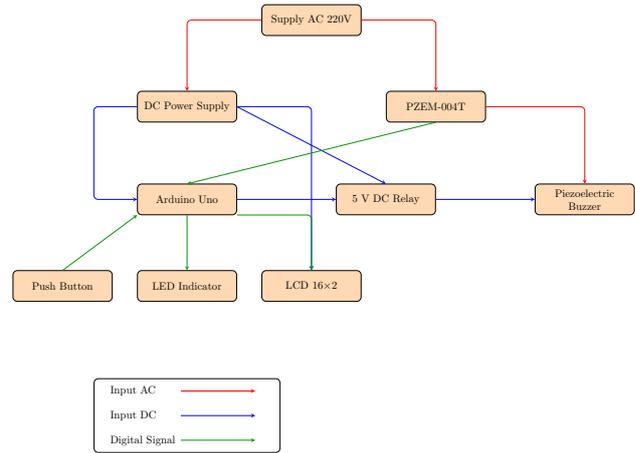


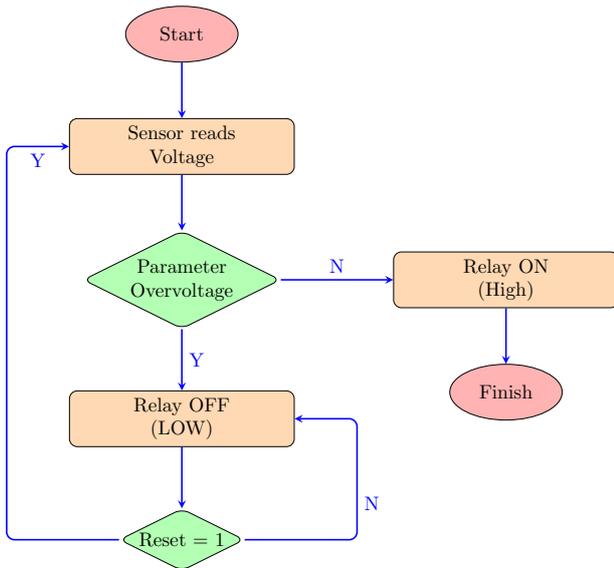
Figure 1: Block diagram of the proposed protection system

ule, LCD, buzzer, and indicators. Its compact design and superior efficiency make it compatible for embedded relay protection systems.

3. **PZEM-004T Voltage Sensor.** This module continuously measures AC voltage within the rated range of 80–260 V and transmits acquisition data to Arduino Uno via UART. It acts as the core sensing unit for fault identification.
4. **Arduino Uno (Microcontroller).** Arduino Uno performs real-time data processing, executes comparison logic against threshold limits, controls relay activation timing, and updates visual feedback through LCD and indicators. Push-buttons are configured as interactive elements for setting voltage thresholds, delay times, and calibration.
5. **5 V DC Relay.** The relay operates as the disconnection switch. It responds based on the microcontroller logic to isolate the protected load when abnormal voltage persists beyond the selected trip delay timing.
6. **16×2 I2C LCD Display.** The LCD provides user feedback regarding measured voltage values, threshold settings, system mode, and trip status.

### ii. System Workflow

Fig. 2 illustrates the complete workflow logic executed by the Arduino controller. The overall process begins with continuous voltage measurement, which serves as the primary reference for the subsequent decision-making stage. Once the acquired voltage value is compared against the predefined threshold limits, the controller determines the appropriate response. If the voltage is detected to be outside the acceptable operating range, the relay is activated to disconnect the load. Conversely, when the voltage returns to a safe and normal condition, the relay is instructed to reconnect the load, ensuring stable and reliable system operation.



**Figure 2:** Operational workflow of AC overvoltage relay protection

If the measured voltage exceeds 231 V, the controller activates a programmed delay time counter. Once the counter runs out, the load is disconnected. If the voltage returns to normal during the countdown, the timer resets automatically, avoiding false trips. Once tripped, the system requires the RESET operation to resume monitoring.

*iii. User Interface Logic*

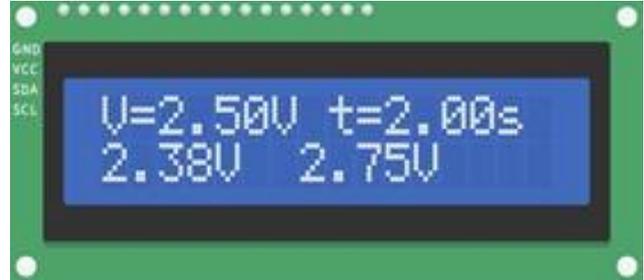
A user-friendly menu system is displayed on the LCD to facilitate direct interaction between the user and the protection device. As shown in Fig. 3, the main menu interface provides clear navigation options, allowing users to view real-time voltage information, configure threshold settings, and monitor system status. This structured interface ensures ease of use, enabling operators to quickly understand the current operational state and access essential control features without requiring advanced technical knowledge.



**Figure 3:** Main menu interface

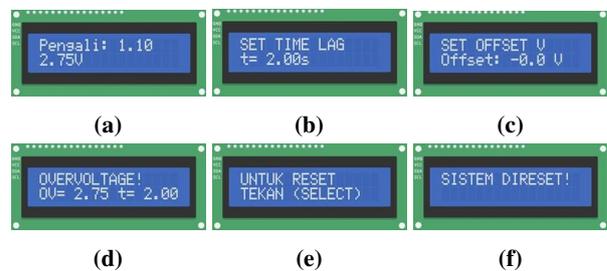
The monitoring display offers comprehensive real-time feedback of the input voltage, along with the currently configured voltage limits and delay settings, as

illustrated in Fig. 4. This screen enables the user to continuously observe the protection status and confirm that the device parameters remain within the desired operating range. With this information accessible at a glance, users can easily detect abnormal voltage conditions and verify that the system responds correctly according to the programmed protection logic.



**Figure 4:** Voltage monitoring interface

The Setting submenu includes several configurable parameters that allow the user to adjust the protection behavior according to specific operating requirements. Through this menu, users can modify the upper and lower voltage thresholds, set the delay time for relay activation, and reset system parameters to default values when necessary. These customization options enhance the flexibility of the device, ensuring that it can be adapted to various electrical environments while maintaining reliable protection performance.



**Figure 5:** (a) Overvoltage limit configuration interface (b) Time delay configuration interface (c) Voltage offset calibration interface (d) Overvoltage status and delay process display (e) Reset command display (f) Display after relay reset

*iv. Protection Relay Simulation*

Relay operation is simulated to visually demonstrate the tripping behavior when an overvoltage condition occurs, as shown in Fig. 5(d). During this state, the system intentionally disconnects the load to prevent potential equipment damage and ensure electrical safety.

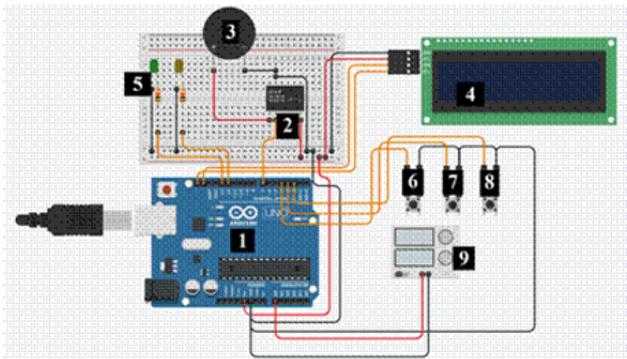
After the voltage returns to a stabilized and acceptable level, a manual Reset action is required to restore the system to normal operation, as illustrated in Fig. 5(e). This reset mechanism serves as an additional

safety measure to confirm that the user acknowledges the previous fault condition.

Once the reset process is successfully performed, the relay automatically returns to its normal monitoring mode and continues to supervise the voltage input for any further abnormalities, as depicted in Fig. 5(f).

#### v. Wiring Diagram

The wiring diagram illustrated in Fig. 6 was designed and generated using TinkerCAD software. This schematic provides a clear visual representation of all electrical connections between the Arduino controller, sensors, relay module, and supporting components. By utilizing a virtual prototyping platform, the circuit configuration can be validated prior to physical implementation, reducing potential wiring errors and ensuring a more efficient and reliable assembly process.



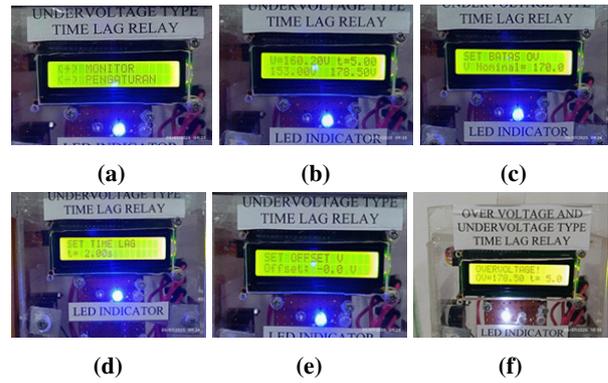
**Figure 6:** System wiring diagram simulation

The interconnection consists of sensor input, regulated DC supply, relay switching path, push-button command interface, and buzzer indicator to ensure system operation feedback.

### III. RESULTS AND DISCUSSION

The primary interface displayed on the 16×2 I2C LCD presents two main menu options: (+) MONITOR for real-time voltage observation and (-) SETTINGS for parameter configuration when the device is initially powered. This interface allows the user to interact using push-buttons to navigate through the available menu options. The visualization of the main interface display is shown in Fig. 7(a).

When the Monitor menu is selected, relevant operational information such as the real-time measured voltage, the programmed time-lag value, and the upper voltage threshold is displayed to provide users with full visibility of the current protection status. This display helps the operator quickly assess whether the system is functioning within the desired limits, as illustrated in Fig. 7(a).



**Figure 7:** Menu interface (a) Main menu interface (b) Voltage monitoring interface and protection parameters (c) Overvoltage limit configuration interface (d) Overvoltage limit configuration interface (e) Time delay configuration interface (f) Voltage offset calibration display

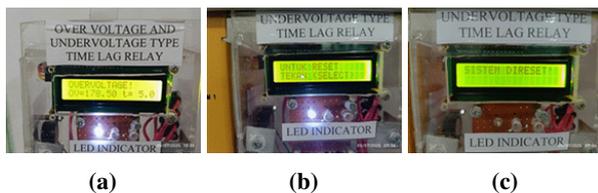
In the Settings submenu, users can configure three primary protection parameters to match specific application requirements. These include adjustment of the allowable voltage limits, modification of the relay delay time, and restoration of the system to default configurations when needed. Through these adjustable settings, the protection device can be optimally tailored for various electrical conditions while ensuring safe and reliable performance.

- 1. Overvoltage limit setting.** The threshold voltage is defined relative to the nominal voltage using multiplication-based scale factors. The system will disconnect the load once the measured voltage exceeds the set limit. The interface layout for this parameter is depicted in Fig. 7(b).
- 2. Time-lag delay configuration.** Users can adjust the relay activation delay after selecting the overvoltage limit. This helps prevent mistaken tripping due to temporary voltage spikes. Fig. 7(e) shows the delay time setting interface.
- 3. Voltage offset calibration.** This feature compensates for sensor reading deviations compared with a calibrated reference voltmeter, improving measurement accuracy. The calibration menu display is shown in Fig. 7(f).

#### i. Simulation of Protection Relay

A simulation scenario demonstrates how the system responds to overvoltage conditions. When the measured voltage exceeds the upper threshold and the delay counter reaches zero, the relay disconnects the load. The trip status display is shown in Fig. 8(a).

If the supply voltage returns to normal within the delay period, the system automatically cancels the countdown and continues in monitoring mode, effec-



**Figure 8:** (a) Relay trip condition after time delay threshold reached (b) Reset instruction display after protection event (c) System recovery and reset success display

tively preventing false tripping due to transient disturbances.

After a fault trip event, the system will instruct the user to press the SELECT button to reset the protection logic, as illustrated in Fig. 8 (b). Upon successful reset, the system acknowledges the recovery status as shown in Fig. 8(c). The relay remains inactive until the user re-enters monitoring mode.

It is important to note that after reset, users may reconfigure parameters or choose to resume monitoring operation immediately. This represents a safe and controlled recovery process ensuring human acknowledgment before re-energizing loads.

### ii. Design Testing Results

In the testing stage, measurement data were obtained for the trip (release) voltage from the comparison between voltage readings on the PZEM-004T module and the reference voltmeter, as well as the relay trip time. The calculated trip voltage values were derived based on the multiplication of the system voltage with the selected overvoltage percentage parameters. The complete relay test data are summarized in Table 1.

**Table 1:** Relay Operating Data

Parameter	Voltage Value (V)	Time Delay (s)	PZEM (V)	Voltmeter (V)	Trip Time (s)
105%	178,5	0,5	178,6	179,6	0,53
110%	187	0,5	187,1	188,0	0,55
115%	195,5	0,5	195,6	196,5	0,57
120%	204	0,5	204,1	205,1	0,56
125%	212,5	0,5	212,5	213,4	0,51
130%	221	0,5	221,1	222,1	0,51
105%	178,5	1	178,6	179,6	1,53
110%	187	1	187,1	188,0	1,55
115%	195,5	1	195,6	196,5	1,57
120%	204	1	204,1	205,1	1,56
125%	212,5	1	212,5	213,4	1,51
130%	221	1	221,1	222,1	1,51
105%	178,5	2	178,6	179,6	2,53
110%	187	2	187,1	188,0	2,55
115%	195,5	2	195,6	196,5	2,57
120%	204	2	204,1	205,1	2,56
125%	212,5	2	212,5	213,4	2,51
130%	221	2	221,1	222,1	2,51

### iii. Testing Analysis

The test utilized a system voltage of 170 V due to limitations of the laboratory power supply, which op-

erates within the range of 0–231 V. Using a nominal voltage higher than 170 V may reduce the feasibility of simulating overvoltage events under all configured setting parameters, considering the maximum voltage capability of the supply. Meanwhile, operating below 170 V would result in measurement inaccuracies due to sensor limitation where the PZEM-004T supports only 80–260 V measurement range.

### iv. Overvoltage Testing Response

The overvoltage tests show that when the supplied voltage approaches or exceeds the threshold limit, the microcontroller initiates protection logic. If the abnormal voltage persists until the countdown reaches zero, the relay disconnects the load. However, if voltage stabilizes before the delay expires, the command is cancelled and the system returns to normal state—preventing false trips due to transient fluctuations.

### v. Voltage Offset Accuracy

For reference comparison, a Fluke 179 True-RMS voltmeter was used with a measurement accuracy of  $\pm(1.0\% + 3 \text{ digits})$  at 45–500 Hz [9]. Differences observed between PZEM-004T and Fluke readings arise from each instrument's accuracy tolerance of  $\pm 0.5\%$  (PZEM-004T) and  $\pm(1.0\% + 3)$  (Fluke 179), as well as calibration conditions. To compensate for this deviation, a voltage offset calibration feature was implemented, improving reading consistency with the reference voltmeter.

### vi. Time-Lag Relay Performance

The relay trip time deviations observed in testing are influenced by microcontroller processing delay associated with reading sensor data, executing the protection algorithm, and energizing the relay coil. Additional latency may result from manual stopwatch trigger error. However, the deviation remained below 10%, which is considered acceptable for educational and prototype applications.

## IV. CONCLUSION

Based on the experimental testing and analysis conducted, the Arduino Uno-based overvoltage and undervoltage protection relay with a time-lag mechanism has successfully demonstrated operational performance in accordance with standard protection relay characteristics. The system is able to detect abnormal voltage conditions and initiate automatic load disconnection, while also restoring normal operation once the voltage

returns to permissible limits. This ensures that temporary fluctuations do not lead to unnecessary power isolation.

The measurement performance of the protection system shows a strong correlation with the reference measuring instrument (Fluke 179 True-RMS multimeter), maintaining a voltage reading error of less than 1% after calibration. The implementation of a voltage offset adjustment feature effectively improves accuracy by compensating measurement deviations from the PZEM-004T module. In addition, the trip time readings indicate that the time-delay logic operates consistently, with deviations recorded at less than 10% of the configured delay settings, thus validating the reliability of the protection mechanism.

Considering its low-cost components, simple architecture, and flexibility in parameter configuration, the proposed prototype provides a beneficial educational medium for students and practitioners to understand protection concepts in low-voltage electrical systems. Furthermore, the design structure offers ample potential for future development, including integration with IoT-based monitoring, enhancement of relay response performance, extension to multi-phase systems, and incorporation of surge protection features to broaden practical application.

Overall, this work demonstrates that the developed system is not only technically feasible but also economically advantageous, making it suitable for implementation in laboratory exercises, small-scale protection applications, and further research in microcontroller-based electrical safety systems.

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