Design and Implementation of Microcontroller-based Voltage Monitoring and Protection Device with user-Defined Threshold levels

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Abstract
In this work, a microcontroller-based voltage monitoring and protection device with user-defined threshold levels is developed. In many developing regions, frequent fluctuations in AC supply and interruptions caused by transient conditions such as lightning strikes, switching surges, and heavy load variations often result in damage to electrical and electronic equipment, and in extreme cases, fire hazards. These irregularities pose a serious reliability challenge in both residential and industrial environments. The proposed design utilizes an Arduino microcontroller to monitor the supply voltage and provide low-cost protection by disconnecting the load whenever voltage levels exceed or fall below user-defined limits. The protection limits can be adjusted by the user according to equipment specifications. The system includes a regulated DC power supply, voltage sensing circuit, control logic, and relay switching stage for isolation of unsafe voltages. Compared with available commercial protective devices that are often expensive and lack user configurability, the developed system offers a more flexible and economical solution. Prototype tests confirm that the system performs effectively, meeting all design objectives for safe operation and equipment protection.

Keywords: Microcontroller, AC Mains, Regulator, Rectifiers, Voltage Sensor,

I. Introduction
In many developing regions, including Nigeria, reliable mains electricity remains a challenge due to frequent fluctuations, interruptions, and surges caused by lightning, switching transients, and variable load demand. These voltage irregularities often damage electrical and electronic devices, reduce their operational lifespan, and in severe cases may result in fire hazards. Traditional protective systems are typically configured with fixed threshold limits for over-voltage and under-voltage cut-offs, which restrict flexibility and may not align with the specific voltage tolerance of individual equipment [1], [2].

This study presents the development of an affordable microcontroller-driven voltage protection and monitoring unit that enables users to set custom upper and lower voltage thresholds according to the requirements of connected devices. Based on an Arduino microcontroller platform, the system continuously samples the AC supply voltage, compares each reading with the user-defined thresholds, and disconnects the load automatically when abnormal voltage conditions occur. In contrast to existing solutions [3],[5] which are generally expensive and operate with factory-fixed protection values, the proposed design provides improved flexibility, adaptability, and cost efficiency.

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The main contributions of this work include:

1. Provision of user-adjustable voltage limit settings in real time;
2. Reliable protective response achieved with minimal hardware resources; and
3. Experimental validation of the prototype's performance.

II. Related Work

Researchers have proposed several approaches to voltage monitoring and protection, but most systems rely on fixed thresholds or pre-configured protection settings.

In **[1]**, a programmable protective device was developed for low-voltage distribution systems using microcontrollers to monitor under-voltage, over- voltage, and over-current conditions. While effective, the system does not allow dynamic user input of voltage limits. Similarly, **[2]** presented an IoT-enabled over-voltage and under-voltage protection device, but threshold configuration is performed during setup rather than by end-users at run time.

A novel system for industrial and domestic applications was described in **[3]**, providing tripping mechanisms for mains fluctuations; however, it relied on fixed design thresholds.

In **[4]**, a methodology for monitoring voltage supply in public buildings was proposed using ITIC curves. While it offered valuable analysis of sags and swells, it focused on evaluation rather than protective switching.

Commercial devices are also available **[5]**, but they tend to be relatively expensive and rarely provide user-friendly threshold input. More recent developments have expanded voltage monitoring and protection concepts using modern controller technology. For instance, Thentral *et al.* **[6]** implemented an over-voltage and under-voltage protection circuit using operational amplifiers and voltage regulator ICs, while Simatupang *et al.* **[7]** demonstrated a prototype Arduino-based protection system capable of responding to voltage fluctuations in real time.

In addition, Singh and Gupta **[8]** introduced an IoT- based voltage monitoring framework that integrates predictive analytics for smart grids, and Adewale and Moyo **[9]** proposed a Wi-Fi–enabled voltage supervision system with cloud-based logging for predictive maintenance. These recent studies highlight the progression from static protective devices toward adaptive, programmable, and connected systems. However, there remains a need for a low-cost, user-configurable design that can be locally implemented using accessible components— an objective that this work achieves.

III. Methodology

A. System Overview

The proposed system is designed to ensure reliable protection and continuous monitoring of electrical equipment against abnormal AC voltage conditions such as overvoltage, under-voltage, and transient surges. It utilizes an Arduino-based control unit that provides a cost-effective and flexible platform for implementing voltage regulation and protection functions. The system allows users to set custom voltage limits for both upper and lower thresholds through dedicated input keys, enabling adjustment according to the rated tolerance of specific appliances or installations. The voltage level of the AC supply is measured using a ZMPT101B voltage sensor module, which generates a corresponding analog signal proportional to the mains voltage. The Arduino continuously processes this signal, compares it with user-defined threshold values, and initiates protection actions when the voltage exceeds or drops below these limits. A short startup delay is incorporated to prevent false triggering during transient switching or power restoration after outages. The user interface includes four control buttons for threshold adjustment, a buzzer and LED indicators for audible and visual fault alerts, and an LCD display for real-time voltage status monitoring.

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A relay driver circuit provides electrical isolation and automatically disconnects the load whenever unsafe voltage conditions are detected. Overall, the design offers a simple, low- cost, and adaptable approach to voltage protection suitable for residential and small-scale industrial applications.

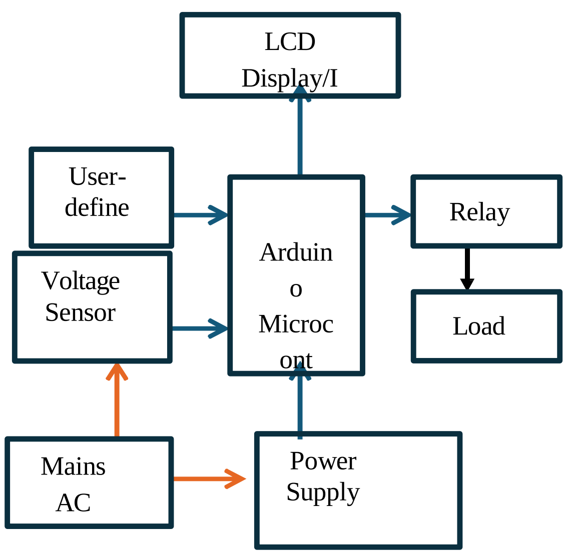

Fig. 1 depict the block diagram of the system

1. Power Supply Unit (PSU)

The power unit provides a regulated DC supply required for the control circuitry. It comprises a 230/12V step-down transformer, a bridge rectifier, filter capacitors, and a voltage regulator (LM7805) that delivers a stable 5V DC output for the Arduino and peripheral components.

2. Voltage Sensing Circuit

A ZMPT101B single-phase voltage sensor module is employed to sample the mains supply. The module outputs a scaled analog signal proportional to the input AC voltage, which is then fed into the Arduino's analog input for processing. The sensor operates at 5V DC and can safely monitor line voltages up to 250V at 50/60Hz. Its internal circuitry uses an LM358 operational amplifier and an adjustable multi-turn potentiometer for fine calibration of the measured signal.

3. Microcontroller Unit (MCU)

The system is controlled by an Arduino-Nano based on the ATmega328 microcontroller. It operates at 5V with a 16 MHz clock frequency and provides fourteen digital I/O pins six of which support PWM output and eight analog input channels. It includes 32kB of flash memory (2kB reserved for the boot- loader), 2kB of SRAM, and 1kB of EEPROM. The board can be powered either through the Mini-B USB connector or via an external 6–20V supply. The microcontroller reads voltage data from the sensor, compares it with user-defined limits, and triggers the protective relay when thresholds are exceeded.

4. User Input and Display Unit

The system interface comprises four push-buttons

ADD, DEC, SET, and MENU used to adjust and store the desired upper and lower voltage limits. A

16×2 LCD display provides real-time voltage

a buzzer and indicator LEDs alert the user to abnormal operating conditions.

□□□□□□□□ □□□□□□□□ (□)□□□ (□)

$$\square_{pp} - \square_{rms} = \frac{\square_{dc}}{2\square\square}$$

$$\text{Therefore, } \square = \frac{I_{dc}}{2f(V_{pp} - V_{rms})}$$

□□□□□ □□ □□□□□□□□ I_{DC} = 450mA, f = 50Hz, V_{pp} = 7.07V, a□□ $\square_{rms}$ = 5□.

$$\text{Therefore, } \square = \frac{450 \text{ X} 10^{-3}}{2 \text{ X } 50 \text{ X } (7.07–5)}$$

$$= 2174\square\square$$

5.Protection Switching Circuit

Arduino detects unsafe voltage conditions, it

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energizes or de-energizes the relay coil through a transistor driver, thereby connecting or disconnecting the load. This ensures that the protected equipment operates only within the definedvoltagerange.

For good filtering, the capacitor used must not be less than 2174µF. For this work, 2200µF capacitor was used. Because capacitors with higher values filter better than capacitors with lower values

Transformer Selection

Transformer is used. Assuming unity power factor (ideal situation),

□□□□□□ □□□□□□□ ($□_{out}$) = 5□

□□□□□ □□□□□□□ ($□_{in}$) = 240□

□□□□□□□□□ □□□□□□□ □□□□□□□ ($□_{rms}$) = □□

So, □□ □□□□□□□ □□□□ □□□□□□□□□,

$I_{DC} = \underline{2 \times I_{rms} \times \sqrt{2}}$

$□_{rms}$ □□ □h□ □□□□□ □□□□□□□□□ □□□□□□□ □□ □h□

□□□□□□□□□□

$2 \times 500 \times 10^{-3}$ x $\sqrt{2}$

= □□□□□

□

□□ □□□□□□□ □□□, $□_{DC} = \sqrt{2} \times □ = \sqrt{2} \times 5 =$ **7V**

Fig. 2 Depict the circuit Diagram of system

Selection of Rectifiers(Bridge)

The peak Inverse Voltage(PIV) of a diode is the maximum reverse voltage a diode can tolerate before it breaks down. Since the output voltage of the transformer is

12.7 3V, diodes of PIV above 12.73

that can handle 450mA is selected. For this work, a bridge rectifier using four IN4001 diodes encapsulated in a chip is use

B. Power Supply Design

Design of the DC Power Unit

The power supply converts the AC mains voltage to a

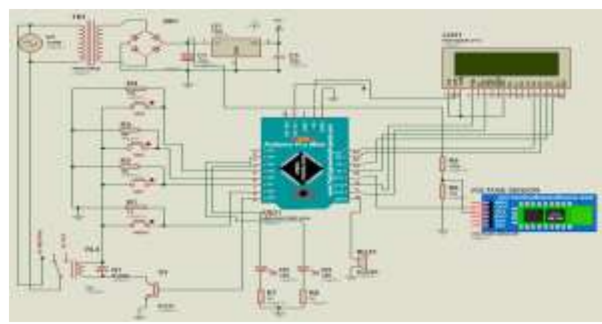
suitable DC level for the electronic circuitry. The

step-down transformer reduces the 220–240V inpu

to approximately 12V RMS and also provides

galvanic isolation to enhance operator safety. The bridge rectifier then converts the AC waveform into a pulsating DC signal. Silicon rectifiers are preferred for their robustness and low cost. A filter capacitor smoothes the ripples, and an LM7805 voltage regulator produces a constant 5V output that can handle450mA is selected. For this work, a bridge rectifier using four IN4001 diodes

encapsulatedinachipisuse



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Design of the Filter Capacitor

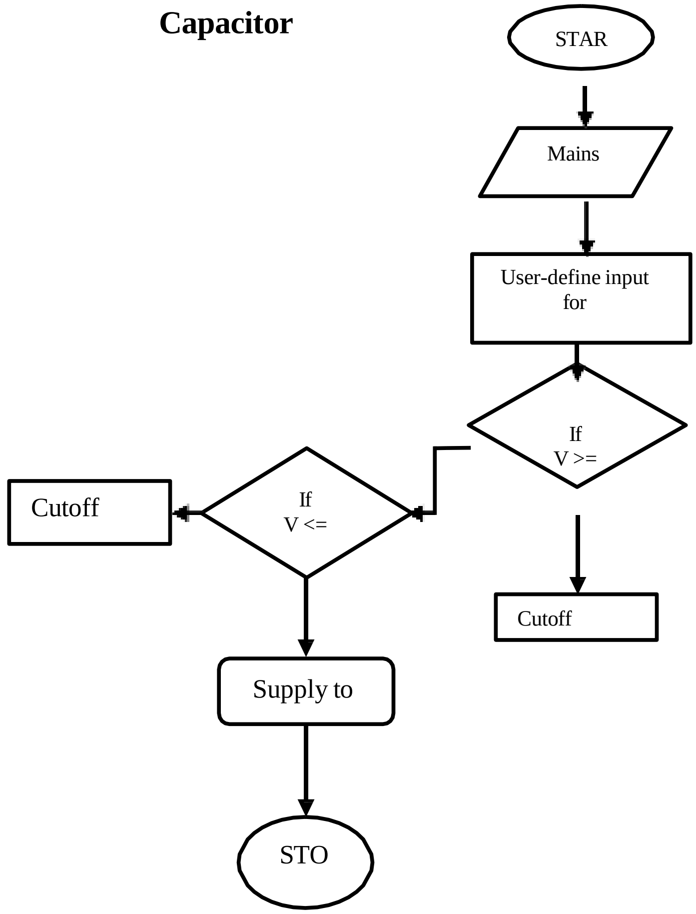
The output of the bridge rectifier has ripples, whose voltage is calculated,

$\square_R = \square_{pp} - \square_{rms}$----------------------------- (a

$\square h\square\square\square\ \square_{pp}\ \square\square\ \square h\square\ \square\square\square\square - \square\square$

$- \square\square\square\square\ \square\square\square\square\square\square\square\ \square\square\ \square h\square$

Fig.3 Depict flowchart of the system



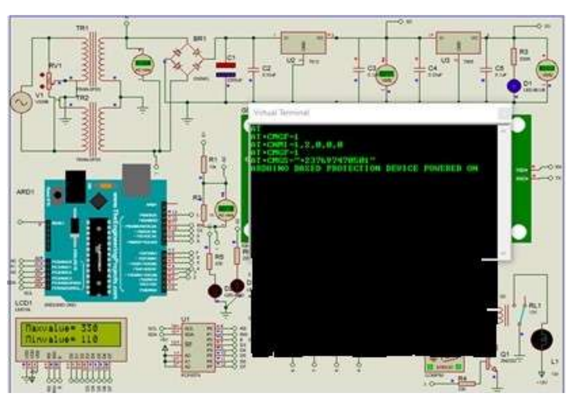
IV.Results

A. **SystemStartupandInitialization** when the system is powered on, all modules are first initialized by the Arduino controller. During this brief startup process, the LCD display activates and performs an internal check before showing the main configuration menu. The user is then prompted to set the desired upper and lower voltage thresholds through the control buttons. Once these limits are entered, the values are stored in the microcontroller's memory to ensure persistence even after power is removed. After initialization, the system begins continuous voltage monitoring through the ZMPT101B sensor. The real-time line voltage is displayed on the LCD screen, and the system responds automatically based on the measured values relative to the programmed thresholds.

- When the supply voltage drops below the lower limit, the relay is de-energized, disconnecting the load and activating both the buzzer and the "UNDER-VOLTAGE" indicator on the LCD.
- When the voltage exceeds the upper threshold, the relay is again disengaged and the display shows "OVER-VOLTAGE" together with an audible alert.
- Under normal operating conditions, the relay remains energized, the load stays connected, and the display shows "NORMAL" status with the actual voltage reading.

Observation of Performance

Simulation and bench-testing confirmed that the system correctly identifies all three operating conditions under-voltage, normal, and over-voltage. The response time from fault detection to relay switching was observed to be less than 200ms, ensuring prompt protection. The LCD interface provided clear and stable feedback during voltage variations, and stored settings were retained after multiple power cycles.



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B. Costruction

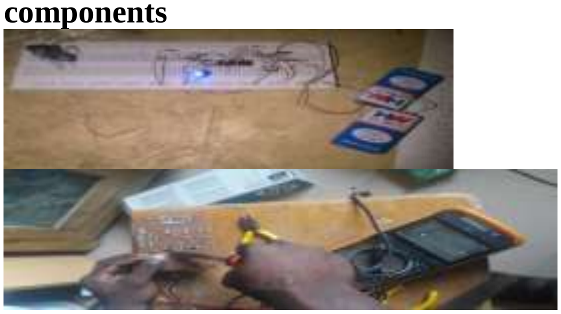
All electronic components and hardware required for the prototype were sourced locally to minimize cost and ensure availability for replication. Before soldering, the circuit was first simulated on Proteus software to confirm correct functionality and logic flow.

A preliminary hardware test was then performed by assembling the circuit on a breadboard to validate the design concept and verify voltage readings, switching action, and display response. After confirming satisfactory operation on the breadboard, all components were systematically transferred to a Vero board for permanent construction. Proper soldering techniques were applied to maintain electrical integrity and mechanical strength of each joint.

During assembly, care was taken to avoid overheating sensitive components and to prevent adjacent tracks from bridging. The soldering iron tip was cleaned and tinned regularly to ensure neat connections, and only a minimal amount of solder was used at each joint.

The completed prototype was visually inspected and tested for continuity and short circuits before powering the system. Figures 5a and 5b illustrate the intermediate breadboard stage and the final soldered Vero board assembly, respectively. The finished hardware demonstrated stable operation and reproduced the expected output behavior observed
during simulation.

Fig 5a depict bread-board connections and 5b depict Vero-board soldering of components



C. Testing and Result Analysis

I. System Testing

The prototype was evaluated by supplying its input through a variable AC transformer (Variac)
connected to the mains. This adjustable source allowed the input voltage to be varied gradually between 145V and 210V AC, which corresponds to the intended operating range of the system. The output stage of the controller drives a relay module wired in series with a demonstration load a 230V incandescent lamp connected through the relay's normally-open (NO) contact.

When the line voltage dropped below approximately 145V, the Arduino logic de-energized the relay, isolating the lamp to prevent under-voltage operation. Likewise, when the input exceeded about 210V, the relay again opened the circuit to disconnect the load, providing overvoltage protection. In each abnormal case, the LCD display presented an alert message indicating the fault type and measured voltage level. The approximate tripping period for the relay was determined from the mains frequency using

$$T = \frac{1}{f}$$

where $f = 50Hz$, hence $T = 20ms$. representing the nominal response interval of one supply cycle.

This value was confirmed during testing with negligible additional delay introduced by the control logic.

II. Result Analysis

After integrating all subsystems and enclosing the prototype in its casing, the device successfully performed both under-voltage and over-voltage protection in accordance with user-defined limits. When powered, the system continuously displayed the instantaneous supply voltage and automatically switched the output relay within the calculated 20 ms period whenever the input exceeded the preset limits. The variable AC

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source was adjusted across multiple values within 145–209V AC, and the corresponding readings shown on the LCD matched the measured voltages from a calibrated multi-meter within ±2 %. Each disconnection and reconnection event occurred smoothly without contact chattering, confirming the stability of the control algorithm and the adequacy of the 5 V regulated supply.

Overall, the prototype achieved reliable operation throughout the test range, validating its capability to safeguard domestic appliances from mains fluctuations while allowing end-users to configure protection thresholds as required. The table is shown below.

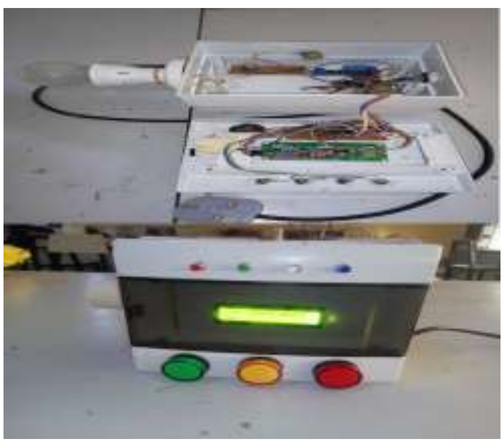

Table 1. Depict output

S/N	VARIA B LE SUPPL Y	LED INDICATO RS	LCD READ O UT	LOA D
1	209V	Red=ON Amber=OFF Green=OFF/ ON	Overvolt a ge	OFF
2	190V	Red=OFF Amber=ON Green=OFF	Normal	ON
3	170V	Red=OFF Amber=ON Green=OFF	Normal	ON
4	150V	Red=OFF Amber=ON Green=OFF	Normal	ON
5	<145	Red=ON Amber=OFF Green=OFF/ ON	Unde r- voltag e	OFF

The test above and the result demonstrate that the circuit achieved its design aim and purpose. The system worked according to specification and quite satisfactorily.

Conclusion

This work presented the design and implementation of a microcontroller-based voltage monitoring and protection system capable of safeguarding single- phase electrical loads against over-voltage and under- voltage conditions. The system was built around the Arduino Uno platform, integrating both hardware and firmware components that were developed, tested, and validated experimentally. Laboratory evaluation under various supply conditions demonstrated reliable detection and isolation of abnormal voltages, with accurate real- time readings displayed on the LCD interface. The system allowed users to set and adjust voltage thresholds as desired, thereby providing a flexible and cost-effective protection approach suitable for domestic and small-scale industrial applications.

The principal contribution of this research lies in developing an accessible, low-cost protection device that combines real-time voltage measurement with user-configurable control logic. The simple implementation makes it adaptable for further modification or integration into more advanced power management systems.

For future enhancement, a higher-capacity controller such as the Arduino Mega or Raspberry Pi may be adopted to expand memory and processing capability. Additionally, incorporating a non-volatile memory backup such as a CMOS battery or serial EEPROM would ensure that preset threshold values are retained even after a power interruption. These improvements would extend the system's reliability and operational scope for real-world deployment.

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