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Intelligent Power Quality Monitoring and Protection System

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Abstract : *The Intelligent Power Quality Monitoring and Protection System is designed to monitor voltage and current parameters in real time using an INA219 sensor and ESP32 microcontroller. The system displays measured values on a 0.96-inch I2C OLED display and detects voltage variations beyond predefined limits. When the voltage exceeds 4.1 V or falls below 3.8 V, a buzzer provides an audible alert, while LEDs indicate the system status. A relay module and fuse are incorporated to support protective operation. This system offers a simple, low-cost approach to power monitoring and electrical protection.*

Keywords: ESP32 (Espressif Systems 32-bit Microcontroller), INA219 (Voltage and Current Sensor Module), IoT (Internet of Things), OLED (Organic Light-Emitting Diode), I²C (Inter-Integrated Circuit) and IDE (Integrated Development Environment).

I. INTRODUCTION

Power quality monitoring is important for maintaining the safe and reliable operation of electrical and electronic equipment. Voltage fluctuations and abnormal electrical conditions can affect equipment performance and may cause damage if they are not detected promptly. Therefore, monitoring electrical parameters and providing timely warnings are essential for improving system reliability.

The proposed Intelligent Power Quality Monitoring and Protection System uses an INA219 sensor to measure voltage and current and an ESP32 microcontroller to process the measured data. A 0.96-inch I2C OLED display shows the readings, while a buzzer and LEDs provide alerts when abnormal voltage conditions occur. The buzzer is activated when the voltage rises above 4.1 V or drops below 3.8 V. A 5 V relay module and fuse are also included to support the protection mechanism.

Previous research has explored various methods for electrical power monitoring and protection. Artono et al. [1] developed an IoT-based voltage protection system for railway passenger information displays using ESP32 and INA219 sensors. Rizqi and Hartoyo [2] proposed an ESP32-based electrical disturbance monitoring system using PZEM-004T and DHT11 sensors for monitoring and automatic load protection. Mallala et al. [3] presented an IoT-based Smart Power Quality Analyzer with remote data access and GSM alert notifications to monitor electrical fluctuations. Similarly, Aloni et al. [4] developed an Arduino-based over-voltage and under-voltage protection system for single-phase AC supplies. These studies demonstrate the importance of microcontroller-based electrical monitoring and automatic protection in different applications.

From the review of previous research papers, it is observed that existing systems mainly focus on specific applications such as railway monitoring, household electrical protection, and remote power quality analysis. Some systems require internet connectivity, cloud platforms, GSM communication, or multiple sensing modules, which can increase hardware complexity and overall cost. Other systems are designed for AC applications rather than simple low-voltage DC monitoring. Therefore, there is a need for a compact, economical, and easy-to-use monitoring and protection system that can operate locally without depending on internet connectivity.

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To address these limitations, the proposed Intelligent Power Quality Monitoring and Protection System aims to develop a low-cost DC monitoring prototype using an ESP32 microcontroller and INA219 sensor for continuous voltage and current measurement. The system displays real-time readings on a 0.96-inch OLED display and uses green and red LEDs to indicate normal and abnormal voltage conditions. When the voltage falls below 3.8 V or rises above 4.1 V, the buzzer provides an audible warning and the relay automatically disconnects the connected load. The main objective is to integrate monitoring, fault indication, and automatic protection into a single simple and reliable system with minimum hardware requirements.

II. PROPOSED SYSTEM

A. Hardware Components Used

The proposed system consists of hardware components that shown in figure1 work together to measure electrical parameters, display readings, detect abnormal voltage conditions, and provide alerts.

[1] ESP32 Microcontroller

The ESP32 is the main controller of the system. It receives voltage and current readings from the INA219 sensor, processes the data, and controls the OLED display, buzzer, LEDs, and relay module according to the programmed logic

[2] INA219 Voltage and Current Sensor

The INA219 is a digital sensor used to measure bus voltage and current. It communicates with the ESP32 through the I2C interface and provides electrical measurements for monitoring and detecting abnormal voltage conditions.

[3] 0.96-Inch I2C OLED Display

The OLED display presents the measured voltage, current, and system status. Its I2C communication interface reduces the number of connections required between the display and the ESP32.

[4] 5 V Relay Module

The relay module acts as an electrically controlled switch. It can connect or disconnect a circuit according to the control signal from the ESP32, provided that the relay is wired and programmed for automatic protection.

[5] Fuse

A fuse is a protective component that interrupts the circuit when excessive current flows through it. It helps reduce the risk of damage caused by overcurrent or short circuits when correctly selected and installed.

[6] Buzzer

The buzzer provides an audible warning when the monitored voltage exceeds 4.1 V or falls below 3.8 V. It alerts the user to abnormal voltage conditions detected by the controller.

[7] LEDs

LEDs provide visual indications of system status. Different LEDs can be programmed to indicate normal operation, abnormal voltage, or a protection event.

[8] Power Supply

The power supply provides the electrical energy required to operate the ESP32 and the connected components. Appropriate voltage regulation and current capacity are necessary for stable and safe operation.

Component	Main function
ESP32	Processes data
INA219	Measures voltage/current
OLED (0.96″)	Displays readings
5 V Relay	Circuit switching
Fuse	Overcurrent protection

Table 1. Hardware components

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Component	Main function
Buzzer	Audible alert
LEDs	Status indication
Power supply	Provides power
Arduino IDE	Code development
C code	Controls system logic

Table 2. Indicators and software



Figure1: Components Used

B. System Architecture

The proposed Intelligent Power Quality Monitoring and Protection System consists of an INA219 sensor, ESP32 microcontroller, OLED display, relay module, buzzer, LEDs, and a fuse. The INA219 measures voltage and current and sends the readings to the ESP32 through the I2C communication interface. The ESP32 processes the measured data and compares the voltage with predefined threshold values. The OLED displays the readings, while the buzzer and LEDs provide alerts about abnormal voltage conditions. The relay module can be used to switch the monitored circuit according to the programmed control logic.

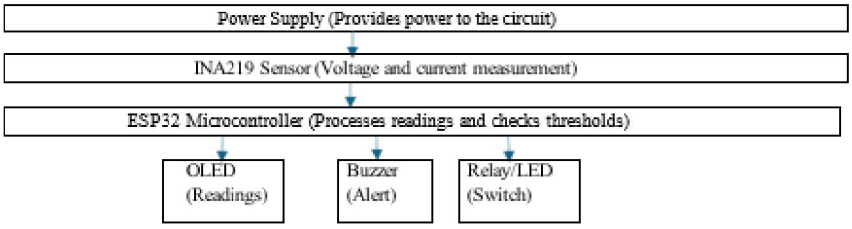


Figure 2: Block Diagram of Proposed System

C. Working Principle

The system operates through the following steps:

[1] **Power Supply:** The supply provides the required power to the circuit.

[2] **Parameter Measurement:** The INA219 sensor measures voltage and current.

[3] **Data Processing**: The ESP32 receives and processes the sensor readings.

[4] **Voltage Comparison:** The measured voltage is compared with the programmed limits of 3.8 V and 4.1 V.

[5] **Audible Alert:** The buzzer turns ON when voltage falls below 3.8 V or rises above 4.1 V.

[6] **Display and Indication**: The OLED displays the readings, and the LEDs indicate the programmed system status.

[7] **Protection:** The relay switches the connected circuit if the corresponding protection logic is implemented. The fuse provides overcurrent protection.

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Voltage condition	System response
Below 3.8 V	Buzzer ON
3.8–4.1 V	Within defined range
Above 4.1 V	Buzzer ON

Table 2: Voltage threshold conditions.

D. Software Implementation

The proposed system is programmed using the Arduino IDE, which provides an environment for writing, compiling, and uploading code to the ESP32 microcontroller. The program is developed using Arduino C, which is based on C programming concepts. It enables the ESP32 to communicate with the INA219 sensor and OLED display through the I2C interface and control the buzzer, LEDs, and relay module through digital input/output pins.

[1] Arduino IDE

Arduino IDE is used to develop and upload the program to the ESP32 board. The required ESP32 board package and sensor/display libraries are installed to support communication with the connected hardware components. The program is compiled to identify errors before being uploaded to the microcontroller.

[2] Programming Logic

The program follows a continuous monitoring process. First, the ESP32 initializes the sensor, OLED display, and output pins. It then reads the voltage and current values from the INA219 sensor and compares the measured voltage with the predefined threshold limits.

The voltage thresholds are set at 3.8 V and 4.1 V. When the voltage falls below 3.8 V or rises above 4.1 V, the ESP32 activates the buzzer and indicates the abnormal condition through the LEDs. The relay is controlled according to the protection logic to disconnect the monitored supply during an abnormal voltage condition. Under normal conditions, the measured values and system status are displayed on the OLED.

[3] Software and Hardware Integration

The software connects the measurement and protection functions into a single monitoring system. Sensor readings are processed by the ESP32, while the OLED, buzzer, LEDs, and relay respond according to the programmed conditions. This integration enables continuous monitoring and automatic response to abnormal voltage levels.

E. Hardware Implementation and Result

The Intelligent Power Quality Monitoring and Protection System is implemented using an ESP32 microcontroller, INA219 voltage and current sensor, 0.96-inch I2C OLED display, 5 V relay module, fuse, buzzer, and LEDs. The system is programmed using the Arduino IDE with C code. The INA219 sensor measures voltage and current, and the ESP32 processes the readings to identify abnormal voltage conditions. The measured parameters and system status are displayed on the OLED screen. When the voltage exceeds

4.1 V or falls below 3.8 V, the buzzer is activated to alert the user, while the LEDs indicate the operating condition. The relay is intended to disconnect the monitored supply when the voltage exceeds the predefined limits, provided that the protection logic is implemented and correctly wired. The fuse provides additional protection against excessive current.

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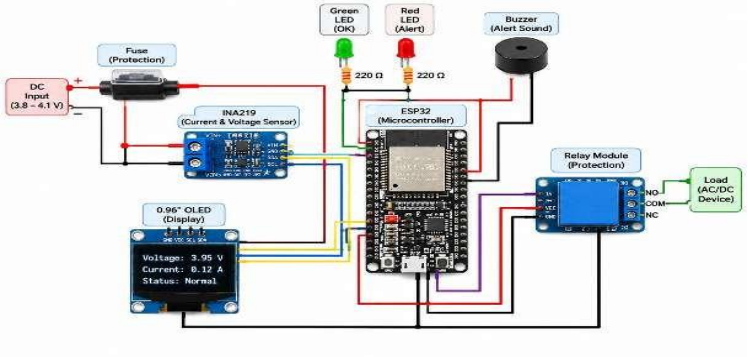


Figure 3: Circuit diagram of Hardware Prototype of the Intelligent Power Quality Monitoring and Protection System.

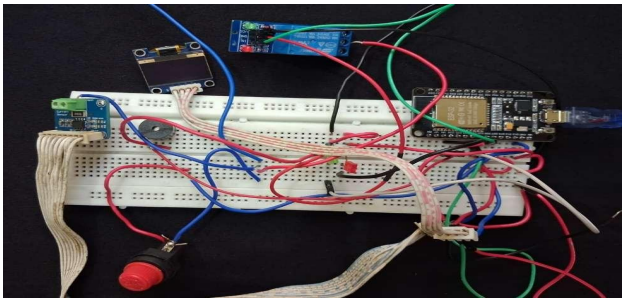


Figure 4: Hardware Prototype of the Intelligent Power Quality Monitoring and Protection System.

Voltage condition	Expected response
Below 3.8 V	Buzzer ON
3.8–4.1 V	Normal-range indication
Above 4.1 V	Buzzer ON

Table 4. Expected response under different voltage conditions

F. Limitations

The proposed system is designed to detect voltage variations based on predefined threshold values. Its accuracy depends on sensor calibration, circuit connections, and the reliability of the power supply. The present design does not measure all power-quality parameters, such as harmonic distortion and frequency variations. The relay-based protection function also requires proper wiring and testing to ensure reliable disconnection during abnormal voltage conditions.

III. CONCLUSION AND FUTURE SCOPE

The Intelligent Power Quality Monitoring and Protection System presents a simple and economical approach to monitoring voltage and current using an INA219 sensor and ESP32 microcontroller. The system displays the measured parameters on a 0.96-inch I2C OLED display and provides an audible warning when the voltage exceeds 4.1 V or falls below 3.8 V. The integration of a buzzer, relay module, and fuse supports abnormal-voltage indication and additional circuit protection. The use of Arduino IDE and C programming makes the system convenient to develop and modify.

The system can be improved by adding data logging, wireless monitoring through Wi-Fi, and mobile notifications. Additional sensors and signal-processing techniques could be incorporated to measure parameters such as frequency, voltage ripple, and harmonic distortion. An improved protection mechanism with fault history recording and automatic recovery could also be developed.

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