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Microcontroller-Based Real-Time Energy Monitoring and Voltage Protection System Using ESP32

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Abstract: This research concentrates on the creation of an intelligent energy monitoring and voltage protection system utilizing the ESP32 microcontroller. The system's main goal is to help people keep track of how much electricity they use and protect their electrical appliances at the same time. It is common for household electrical systems to have sudden changes in voltage and too much current. Because of this, appliances might not work right and their life span might be shorter. In some cases, it can also make things unsafe. The proposed system keeps an eye on the main electrical quantities, such as voltage, current, power, and total energy used, to deal with this problem. A voltage sensing circuit detects the supply voltage, and a current transformer measures the load current. After being measured, these signals are used for more processing and monitoring. The ESP32 takes these signals and figures out the real-time power usage of the load by calculating the RMS values. The system has a relay mechanism built in to keep it safe. The relay automatically disconnects the load if the voltage or current goes above a certain safe level to protect it. A 16×2 LCD screen shows the measured values and the status of the system, making it easy for the user to see how much energy is being used and how the system is doing overall.

Keywords: Energy Monitoring, Voltage Protection, ESP32, Relay Control, Current Transformer, IoT-Based System

I. INTRODUCTION

Electrical power is used every day in homes and small shops for running different appliances. In many cases, the supply voltage is not stable and problems like high voltage, low voltage, or excessive current can occur. Because of this, electrical appliances may get damaged or their performance may reduce over time. Sometimes these issues also create safety risks. Normal energy meters only record total energy for billing and do not show detailed information about voltage condition or load behavior. So most users come to know about the problem only after equipment failure or a sudden increase in the electricity bill.

Due to the growth of embedded systems and IoT technology, it has become easier to design small and affordable monitoring systems. In this project, an ESP32-based energy monitoring and voltage protection system is developed. The circuit measures AC voltage and load current using appropriate sensing components. The measured signals are analyzed by the controller to obtain RMS voltage and current values, along with the real-time power and total energy consumption. For protection, a relay circuit is included in the design. Whenever the voltage or current exceeds the preset limit, the relay cuts off the supply to the load. In this way, the system not only protects appliances from damage but also allows users to keep track of their energy usage regularly.

II. OBJECTIVES

The primary aim of this research is to design and implement a Smart Energy Monitoring and Voltage Protection System based on the ESP32 microcontroller for household applications. The system is intended to continuously observe key electrical parameters and ensure automatic protection when abnormal voltage or current conditions occur. In addition to enhancing electrical safety, the system seeks to promote greater awareness of energy consumption among users.

The specific objectives of this work are as follows:

1) To measure and monitor real-time AC voltage and load current.
2) To calculate instantaneous power and cumulative energy consumption accurately.
3) To display voltage, current, power, and energy values on a 16×2 LCD interface.

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4) To implement automatic load disconnection under overvoltage, under voltage, and overload conditions using a relay mechanism.
5) To provide a low-cost, reliable, and efficient solution for domestic energy monitoring and protection

III. RELATED WORK

Some researchers have designed systems to safeguard domestic appliances against electrical disturbances such as overload, overvoltage, and undervoltage. An overload protection system based on Arduino was demonstrated in [1], where a relay system was employed to switch off the load during high current flow. Likewise, an overvoltage and undervoltage protection system was designed in [2], which sensed the supply voltage and switched off the load whenever the threshold was violated. These designs enhanced electrical safety; however, they were primarily designed for protection purposes and lacked the integration of real-time energy monitoring.

Real-time energy monitoring in smart home settings has also been extensively researched. A smart home energy consumption monitoring system was designed in [3], where electrical quantities were measured to enhance user knowledge. An Arduino-powered energy monitoring system was designed in [4] to locally display voltage and current readings. Although these designs enabled real-time monitoring, they lacked the integration of automatic protection against voltage instability. Moreover, home-scale energy monitoring and management systems have been investigated in [5], which primarily focused on supervisory control and home-scale energy optimization.

As ESP32 and IoT technology continue to evolve, more compact and intelligent monitoring systems have been developed. A smart energy monitoring system based on ESP32 was designed in [6], which enabled real-time measurement and cloud-based data transfer. IoT-based microgrid monitoring and protection systems were further explored in [8], where relay modules were employed for load switching. However, most existing designs either focus on monitoring or protection, and there is a lack of integration of real-time RMS calculation, embedded decision-making, relay-controlled load switching, and local display in a unified low-cost domestic system.

Accordingly, the purpose of this research is to develop an ESP32-based embedded system that integrates both energy monitoring and voltage protection functions..

IV. BLOCK DIAGRAM

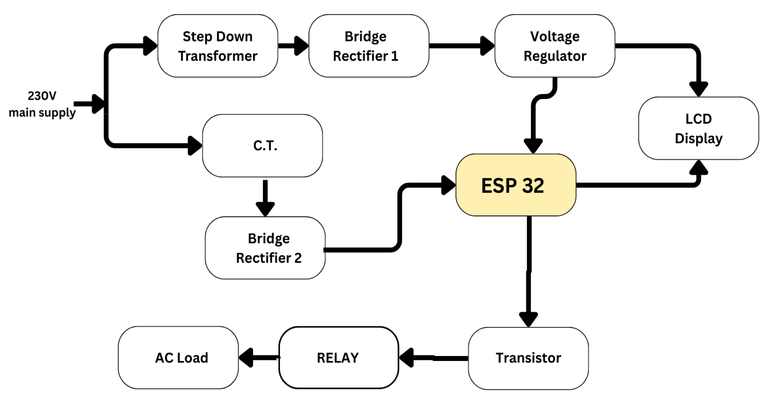

Fig. 1 Block Diagram of the Proposed Energy Monitoring and Voltage Protection System

The design of the proposed Smart Energy Monitoring and Voltage Protection System is shown in Fig. 1. The proposed system comprises a number of functional blocks, such as voltage sensing, current sensing, signal processing, display, and protection, which are managed by the ESP32 microcontroller.

First, the incoming AC mains is stepped down to a lower voltage using a step-down transformer. The stepped-down AC mains is then converted to DC using the first bridge rectifier and is then regulated using a voltage regulator circuit to supply a stable DC voltage to the ESP32 microcontroller and the LCD module. To measure the load current, a current transformer (CT) is used to isolate the current measurement from the high-current line. The CT output is then rectified using a second bridge rectifier before being sent to the ESP32 microcontroller for processing.

The ESP32 microcontroller is the main control and processing unit of the proposed system. It runs embedded algorithms to calculate the voltage, current, power, and total energy consumption. The microcontroller continuously monitors the measured values against the preset safety thresholds. Once an overvoltage, undervoltage, or overload condition is detected, the ESP32 microcontroller activates a transistor driver circuit that switches on the relay module. The relay module then switches off the AC load to avoid any damage. At the same time, the system displays all the measured values and system status information on the LCD display for real-time monitoring by the user.

V. SYSTEM OVERVIEW

The Smart Energy Monitoring and Voltage Protection System is essentially a highly advanced digital bodyguard for your home's electrical system. At its heart lies the ESP32 microcontroller, a high-speed "brain" that is responsible for all calculations from data acquisition to decision-making. However, since the raw power from a wall socket is simply too intense for sensitive electronics, the system first "domesticates" the electricity by passing it through a step-down transformer, which reduces the voltage to a safe level. The signal is then purified by a bridge rectifier and smoothed by capacitors, with a final voltage regulator to ensure that the ESP32 microcontroller is supplied with a rock-solid, flicker-free, and constant DC current. It is this foundation that prevents the system from crashing when it is monitoring the very power fluctuations it is supposed to detect.

To monitor the amount of power being consumed without actually having to come into contact with high-voltage wires, the system uses a Current Transformer (CT). This sensor "senses" the current flow through induction, adding an essential safety feature by ensuring that the high-voltage mains are always kept well and truly separate from the control circuitry. Once the ESP32 has received these isolated signals, it proceeds to perform lightning-fast calculations to derive real-time values for RMS voltage, current, and total power consumption. These values are then transmitted to a 16×2 LCD display, giving you a real-time readout of your home's performance. Most importantly, the ESP32 microcontroller acts as a highly proactive sentry: if it senses a potentially life-threatening surge or a voltage spike that crosses pre-set safety thresholds, it instantly sends a signal to a relay to physically switch off the load. In a matter of a fraction of a second, your precious appliances are protected from damage, making it a flawless combination of high-tech data analysis and automated home protection.

Fig. 2 ESP32 Development Board Used in the System

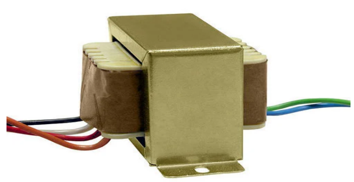

Fig. 3 Step-Down Transformer for Voltage Reduction

Fig. 4 Current Transformer for Load Current Measurement

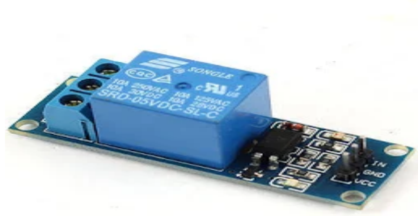

Fig. 5 Relay Module for Load Isolation

Fig. 6 16×2 LCD Display Module

VI. METHODOLOGY

The system's methodology is based on a seamless pipeline of real-time sensing, signal processing, and protection. It all begins with the high-voltage AC supply, which is initially "tamed" by a step-down transformer to make it safe and measurable. However, since raw AC is too random for a digital brain, this processed signal is further rectified and filtered to convert it into a smooth, proportional DC voltage that the ESP32 can easily detect via its analog-to-digital converter (ADC).

At the same time, the system also monitors the load current via a Current Transformer (CT). The main benefit of this setup is its safety feature, wherein the CT uses magnetic induction to "sense" the current, creating a physical isolation barrier between the high-power lines and the control electronics. The current signal is processed before being input into the ESP32. By continuously sampling these two signals, the ESP32 can compute accurate electrical values in real-time, enabling it to function with it as a high-speed calculator and a vigilant safety guardian.

The RMS voltage and RMS current values are calculated using the standard root mean square formula:

$$V_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} v_i^2}$$

$$I_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} i_i^2}$$

where $\boldsymbol{v_i}$ and $\boldsymbol{i_i}$ represent sampled voltage and current values respectively, and N is the total number of samples

The instantaneous power is calculated as:

$$P = V_{RMS} \times I_{RMS}$$

The cumulative energy consumption is computed using:

$$\text{Energy (kWh)} = \frac{P \times T}{1000}$$

where t represents time in hours.

The results are shown on the 16×2 LCD display. The system continuously monitors the voltage and current readings and compares them with the threshold values. If the voltage reading goes beyond the upper limit or falls below the lower limit, or if the current reading goes beyond the overload limit, the ESP32 sends a control signal to the transistor circuit. The transistor turns on the relay, which turns off the AC load.

As soon as the voltage and current readings fall within the normal range, the relay can turn on automatically according to the logic programmed in the system. This helps to continuously monitor the system and provides automatic protection and electrical safety.

VII. RESULTS

The Smart Energy Monitoring and Voltage Protection System was tested in a series of rigorous tests under various operating conditions to ensure the accuracy and reliability of the system. In each test, the system was found to be highly effective in monitoring the RMS voltage, current, instantaneous power, and cumulative energy consumption in real-time. These values were displayed on the 16×2 LCD display module with no lag whatsoever, ensuring a seamless user experience. Under normal operating conditions, the system kept a vigilant eye on the circuit, providing stable and consistent values that remained well within the acceptable accuracy levels required for contemporary applications.

The system's robustness under adverse operating conditions was put to the test when electrical anomalies were introduced into the circuit. As soon as the supply voltage exceeded the safe limit on the higher side or fell below the minimum limit, the ESP32-based relay system instantly switched off the power supply to the circuit, protecting it from potential damage. The same was true for overload conditions, where the system instantly switched off the circuit as soon as it sensed excessive current flow, thus preventing hardware failure or burning out. By utilizing the ESP32's onboard ADC, the system efficiently processed the incoming analog signals, ensuring that the protection circuit remained operational and uninterrupted even under continuous usage.

In the end, the system performed flawlessly, proving that it could effectively bridge the gap between real-time energy monitoring and automatic hardware protection. The relay system's response time was quick enough to protect the connected appliances from being exposed to potentially hazardous electrical conditions for an extended period of time, thus making the system a highly useful tool for residential power management. By providing users with a real-time energy consumption dashboard while also serving as a high-speed digital guardian, the project successfully accomplished all its set objectives related to energy efficiency and automated household security.

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