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ESP32-Based IoT Smart Energy Monitoring and Intelligent Load Control System Using MQTT and Cloud-Based Remote Supervision

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Abstract
The rapid growth of the Internet of Things (IoT) has transformed conventional electrical monitoring systems by enabling intelligent, real-time, and remotely accessible energy management solutions. This study presents an **ESP32-based IoT Smart Energy Monitoring and Intelligent Load Control System** designed to monitor electrical parameters and facilitate efficient energy supervision through cloud-based communication. The proposed system employs voltage and current sensing modules to measure AC voltage, current, and power consumption, while RMS-based calculations ensure accurate and stable measurements under varying load conditions. The ESP32 microcontroller serves as the central processing unit, integrating sensor data acquisition, relay-based load control, and wireless communication. MQTT protocol is utilized to transmit real-time data to the Adafruit IO cloud platform for remote visualization and continuous monitoring. Additionally, Telegram Bot integration enables users to receive instant notifications and retrieve live electrical parameters through mobile devices, while an I2C LCD provides local display of system status. Experimental evaluation demonstrates reliable Wi-Fi connectivity, accurate electrical parameter measurement, synchronized relay operation, stable MQTT communication, and effective remote monitoring across different load conditions. The proposed system offers a low-cost, scalable, and user-friendly solution for residential, commercial, laboratory, and small industrial applications. By combining cloud connectivity, intelligent communication, and automated load management within a single platform, the developed architecture enhances energy awareness, improves operational efficiency, and provides a flexible foundation for future advancements, including predictive energy analytics, smart billing, fault detection, renewable energy integration, and AI-assisted energy management.
Keywords: IoT, ESP32, Smart Energy Monitoring, MQTT, Adafruit IO, Telegram Bot

1. INTRODUCTION

1.1 Introduction

The increasing demand for efficient energy utilization and intelligent monitoring systems has led to the rapid development of Internet of Things (IoT)-based smart energy management technologies. Traditional electrical monitoring systems require manual observation and lack real-time accessibility, making them inefficient for modern residential, commercial, and industrial applications. With the advancement of embedded systems and wireless communication, smart monitoring solutions have become an effective approach for improving energy awareness, reducing wastage, and enabling remote supervision of electrical devices.

IoT-based energy monitoring systems provide continuous measurement of electrical parameters such as voltage, current, and power consumption through connected sensors and microcontrollers. These systems enable users to remotely access energy usage information using cloud platforms, thereby enhancing convenience and operational efficiency. Among various microcontroller platforms, the ESP32 has gained significant attention due to its integrated

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Wi-Fi capability, low power consumption, high processing speed, and cost-effectiveness. These features make it highly suitable for real-time monitoring and automation applications.

1.2 Problem Statement

Efficient monitoring and management of electrical energy consumption have become critical challenges in residential, commercial, and industrial environments due to the increasing demand for electricity and the need for energy conservation. Conventional energy monitoring systems generally rely on manual meter readings and standalone measuring instruments, which do not provide real-time data accessibility, remote monitoring, or automated load control. Such traditional approaches often lead to delayed fault detection, inefficient power utilization, and increased operational costs.

Existing electrical monitoring solutions are frequently limited by the absence of integrated communication systems that allow users to access energy parameters remotely. In many cases, users are unable to continuously observe voltage, current, and power consumption levels, making it difficult to identify abnormal conditions such as overload, energy wastage, or device malfunction. Additionally, conventional systems lack intelligent notification mechanisms that can instantly inform users about the status of connected electrical loads.

1.3 Objectives

The primary objective of this project is to develop an IoT-based smart energy monitoring and load control system capable of measuring and monitoring electrical parameters in real time using an ESP32 microcontroller. The system is designed to provide efficient energy supervision, remote accessibility, and intelligent communication features for improved electrical management.

The specific objectives of the proposed system are as follows:

1. **To design and develop a real-time energy monitoring system** capable of measuring AC voltage, current, and power consumption using appropriate sensing modules connected to the ESP32 platform.
2. **To implement accurate RMS-based electrical parameter calculation** for reliable measurement of voltage and current values under varying load conditions.
3. **To establish IoT-based cloud communication** using MQTT protocol and Adafruit IO for remote monitoring and visualization of electrical parameters through an online dashboard.
4. **To integrate relay-based load control mechanisms** for switching and monitoring multiple electrical loads within a smart monitoring environment.
5. **To provide local monitoring capability** through an I2C LCD display for displaying voltage, current, power, and relay status in real time.
6. **To implement Telegram Bot communication** for sending relay status notifications and allowing users to request real-time voltage, current, and power data remotely.
7. **To improve energy awareness and operational efficiency** by enabling users to monitor electrical consumption patterns and load conditions continuously.
8. **To develop a low-cost and scalable smart monitoring architecture** suitable for residential, laboratory, and industrial energy management applications.
9. **To create a platform for future enhancements**, such as energy billing, overload protection, smart alerts, and predictive energy analysis.

2. ANALYSIS & DESIGN

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2.1 System Overview

The proposed smart energy monitoring and load control system is designed to provide real-time measurement, monitoring, and communication of electrical parameters using IoT technology. The system combines sensing modules, wireless communication, cloud monitoring, and relay-based appliance management into a unified framework. The primary purpose of the analysis phase is to identify system requirements, operational flow, hardware interactions, and communication architecture necessary for achieving reliable energy monitoring.

The system continuously acquires analog signals from the voltage and current sensors connected to the ESP32 microcontroller. The voltage sensor measures AC supply voltage, while the current sensor measures the total current consumed by connected loads. These analog signals are processed using RMS calculation methods to obtain accurate electrical parameter values.

The ESP32 acts as the central processing unit responsible for data acquisition, sensor calibration, cloud communication, relay monitoring, and Telegram-based interaction. Real-time measurements are displayed locally using an I2C LCD and remotely through Adafruit IO dashboards using MQTT communication.

The relay modules provide appliance switching functionality, enabling load control and monitoring. Telegram Bot integration serves as an additional communication channel, allowing users to request system status and receive updates regarding relay conditions and electrical measurements.

2.2 COMPONENTS USED
2.2.1 ESP32 PINOUT
One of the advantages of the ESP32 is that it has a lot more GPIOs than the ESP8266. You won't have to juggle or multiplex your IO pins. However, there are a few things to keep in mind, so please read the pinout carefully.

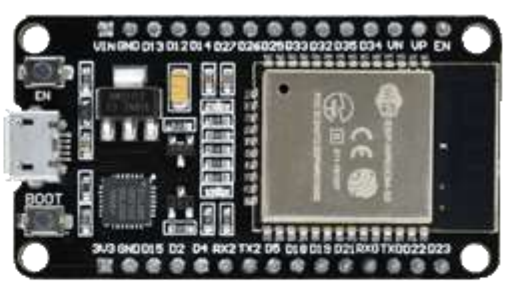

Fig: 2.2.1 **ESP32 Pinout Reference**

The ESP32 is a low-cost, incredibly versatile microcontroller series with integrated Wi-Fi and Bluetooth, developed by Espressif Systems. Often considered an "Arduino on steroids," it is the industry standard for IoT projects, smart home devices, and wireless robotics due to its robust processing power and low power consumption.

ESP32 Peripherals and I/O

Although the ESP32 has 48 GPIO pins in total, only 25 of them are broken out to the pin headers on both sides of the development board. These pins can be assigned a variety of peripheral duties, including:

15 ADC channels	15 channels of 12-bit SAR ADC with selectable ranges of 0-1V, 0-1.4V, 0-2V, or 0-4V

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2 UART interfaces	2 UART interfaces with flow control and IrDA support
25 PWM outputs	25 PWM pins to control things like motor speed or LED brightness
2 DAC channels	Two 8-bit DACs to generate true analog voltages
SPI, I2C and I2S interface	Three SPI and one I2C interfaces for connecting various sensors and peripherals, as well as two I2S interfaces for adding sound to your project
9 Touch Pads	9 GPIOs with capacitive touch sensing

Thanks to the ESP32's pin multiplexing feature, which allows multiple peripherals to share a single GPIO pin. For example, a single GPIO pin can act as an ADC input, DAC output, or touch pad.

ESP32 Pinout

The ESP32 DevKit V1 development board has 30 pins in total. For convenience, pins with similar functionality are grouped together. The pinout is as follows:

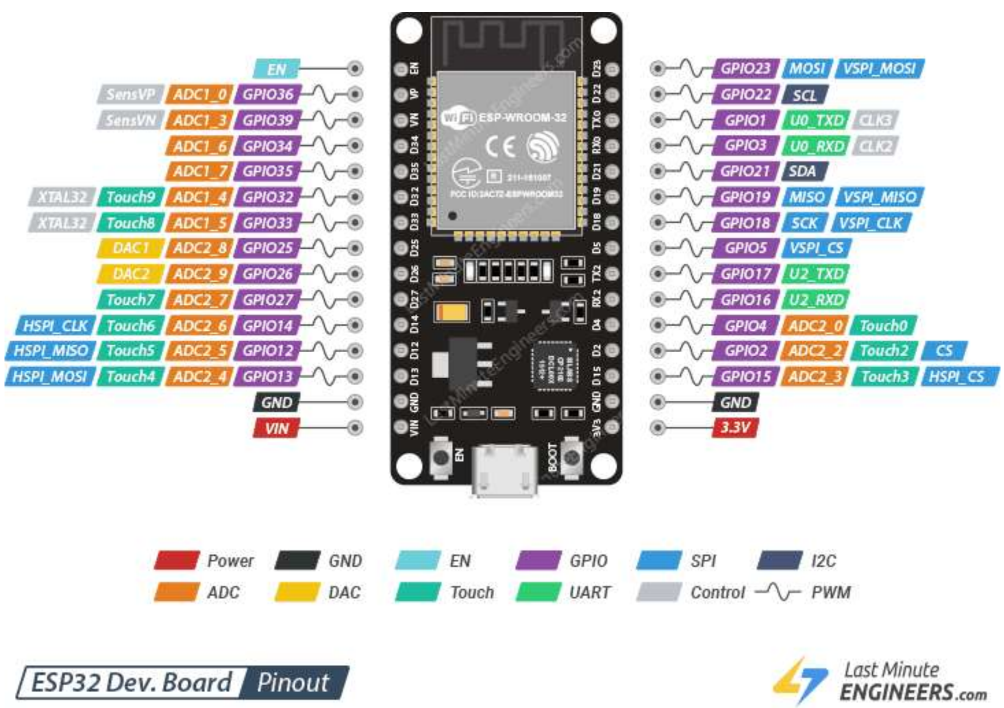

Fig: 2.2.2.1

GPIO Pins

The ESP32 development board has 25 GPIO pins that can be assigned different functions by programming the appropriate registers. There are several kinds of GPIOs: digital-only, analog-enabled, capacitive-touch-enabled, etc. Analog-enabled GPIOs and Capacitive-touch-enabled GPIOs can be configured as digital GPIOs. Most of these digital GPIOs can be configured with internal pull-up or pull-down, or set to high impedance.

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PWM Pins

The board has 21 channels (all GPIOs except input-only GPIOs) of PWM pins controlled by a PWM controller. The PWM output can be used for driving digital motors and LEDs.

The PWM controller consists of PWM timers, the PWM operator and a dedicated capture sub-module. Each timer provides timing in synchronous or independent form, and each PWM operator generates a waveform for one PWM channel. The dedicated capture sub-module can accurately capture events with external timing.

Power Pins

There are two power pins: the VIN pin and the 3V3 pin. The VIN pin can be used to directly power the ESP32 and its peripherals, if you have a regulated 5V power supply. The 3V3 pin is the output from the on-board voltage regulator; you can get up to 600mA from it. GND is the ground pin.

Enable Pin

The EN pin is the enable pin for the ESP32, pulled high by default. When pulled HIGH, the chip is enabled; when pulled LOW, the chip is disabled.

The EN pin is also connected to a pushbutton switch that can pull the pin LOW and trigger a reset.

3. LITERATURE REVIEW

The Internet of Things (IoT) has emerged as a promising technology for developing intelligent monitoring systems by enabling seamless communication among connected devices. IoT-based architectures facilitate real-time data acquisition, cloud connectivity, and remote accessibility, making them suitable for smart energy management applications. However, existing frameworks provide limited emphasis on practical implementation using low-cost embedded platforms. **[1]**

Cloud-integrated IoT architectures have significantly improved data collection, storage, and visualization for smart monitoring applications. By combining sensing devices with cloud computing, these systems enhance accessibility and support real-time decision-making. Nevertheless, comprehensive implementations for electrical energy monitoring and intelligent load control remain limited. **[2]**

Wireless communication technologies have enabled efficient monitoring of industrial and residential electrical systems through IoT platforms. Existing approaches demonstrate the advantages of remote supervision and automation but require affordable and scalable embedded hardware for widespread deployment. **[3]**

IoT-based smart energy meters have been developed to transmit electrical consumption data to cloud platforms, allowing users to monitor energy usage remotely. Although these systems improve energy awareness, they generally lack intelligent load control and real-time user notification features. **[4]**

Cloud-enabled electrical monitoring systems using Wi-Fi-based microcontrollers have demonstrated effective remote measurement of voltage, current, and power consumption. However, these systems do not provide integrated relay control or interactive communication with end users. **[5]**

Residential energy monitoring systems based on wireless microcontrollers have enabled real-time visualization of power consumption through cloud dashboards. While these solutions offer improved accessibility, their measurement accuracy under varying electrical loads requires further enhancement. **[6]**

Smart home energy management systems have incorporated wireless communication to automate electrical appliance control. Although these systems improve user convenience, they are constrained by limited processing capabilities and insufficient support for advanced IoT services. **[7]**

MQTT-based communication frameworks have gained popularity in smart energy monitoring due to their lightweight protocol and efficient data transmission. These systems reduce communication overhead and improve cloud connectivity; however, they generally lack integrated remote notification services. **[8]**

ESP32-based smart monitoring systems have demonstrated reliable real-time acquisition of electrical parameters and cloud-based visualization. Despite these advantages, many implementations do not include intelligent relay switching or messaging-based user interaction. **[9]**

Cloud-supported electricity monitoring platforms have enhanced remote accessibility through mobile applications and online dashboards. However, several existing solutions lack accurate RMS-based calculations for reliable measurement of voltage and current under different operating conditions. **[10]**

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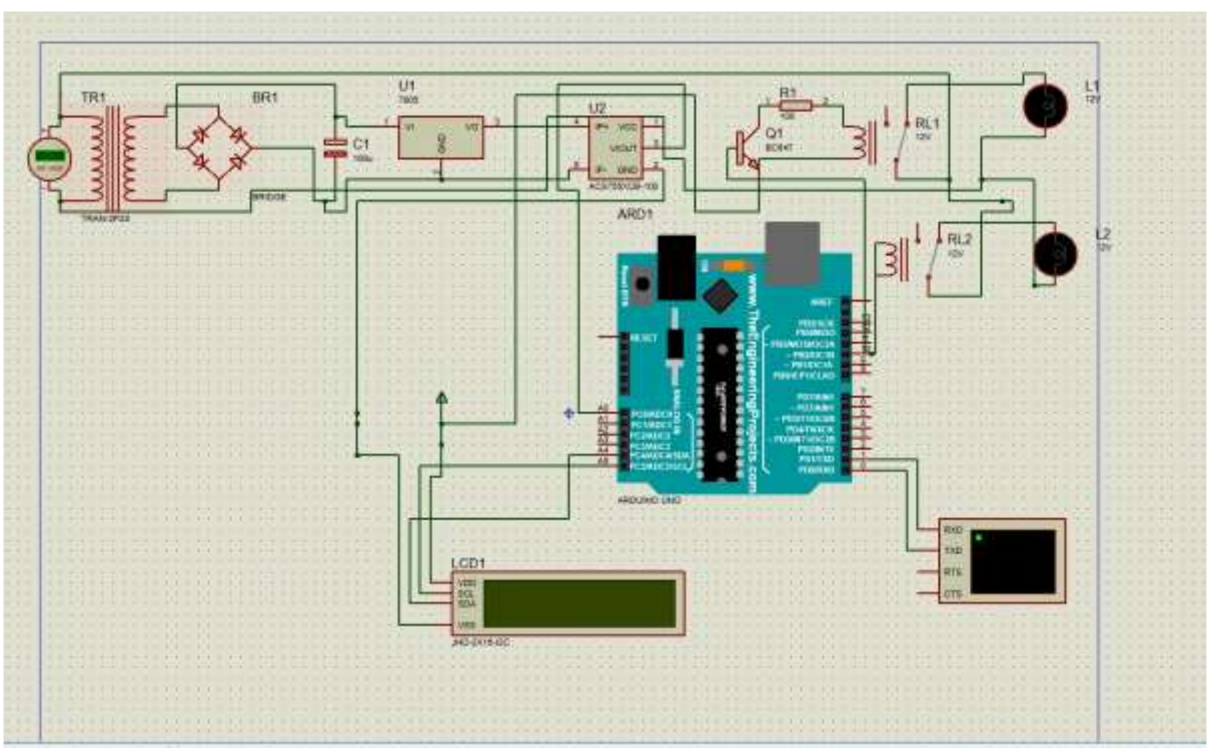
Intelligent IoT-enabled energy management systems have improved the monitoring of electrical power consumption using wireless sensor networks. Nevertheless, many existing approaches do not support multiple load control or standardized MQTT-based cloud communication. **[11]**
Recent real-time energy monitoring systems integrating ESP32 with cloud services have demonstrated improved scalability and operational efficiency. However, interactive notification mechanisms for informing users about system status remain largely unavailable. **[12]**
Advanced IoT-based energy management frameworks utilizing cloud computing and edge processing have significantly enhanced monitoring performance and reduced communication latency. Despite these benefits, system complexity and implementation cost remain major challenges for small-scale applications. **[13]**
Modern IoT frameworks have successfully integrated MQTT communication for reliable real-time monitoring of electrical parameters. Although communication efficiency has improved, many systems still lack user-friendly messaging platforms for instant alerts and remote interaction. **[14]**
Recent developments in smart energy monitoring have focused on integrating ESP32, MQTT, cloud dashboards, and intelligent communication services into unified platforms. However, existing solutions rarely combine accurate RMS-based electrical parameter measurement, cloud visualization through Adafruit IO, relay-based load control, local LCD display, and Telegram Bot communication within a single low-cost architecture. This research addresses these limitations by proposing an integrated IoT-based smart energy monitoring and load control system. **[15]**

4. IMPLEMENTATION

The implementation of the proposed smart energy monitoring and load control system involves the integration of hardware components, sensor interfacing, IoT communication, and software programming using the ESP32 microcontroller. The system is designed to measure electrical parameters, display information locally, transmit data to a cloud platform, and provide real-time user interaction through Telegram notifications.

4.1 CIRCUIT DIAGRAM



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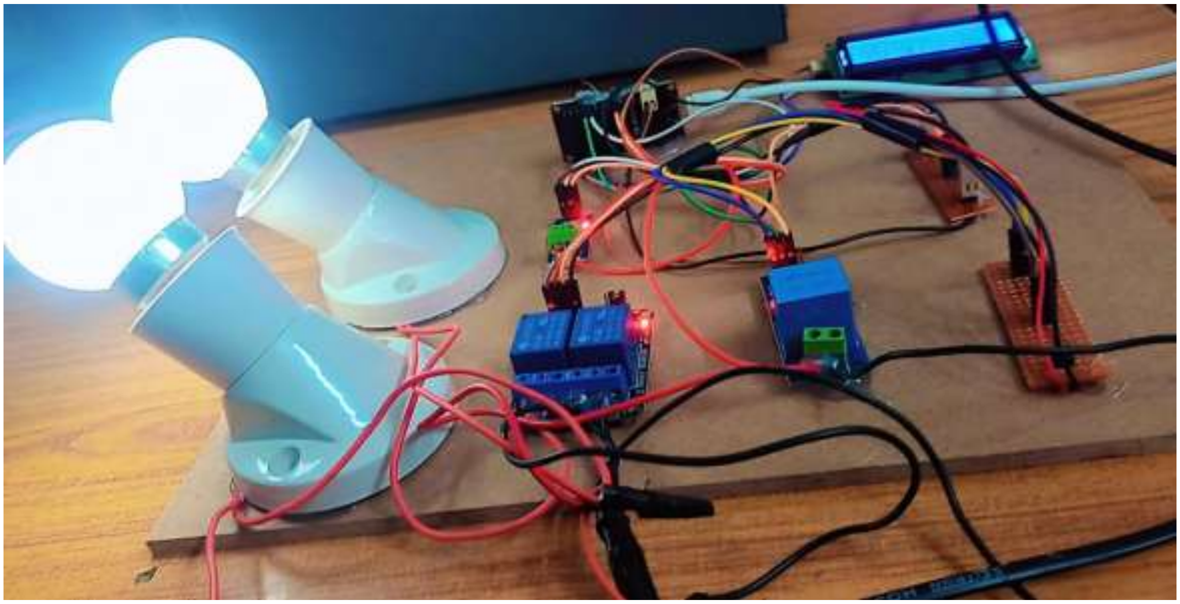
4.2 Hardware Implementation

The hardware implementation consists of sensors, communication modules, relay interfaces, and display components connected to the ESP32 DevKit.

PRACTICAL IMPLEMENTATION



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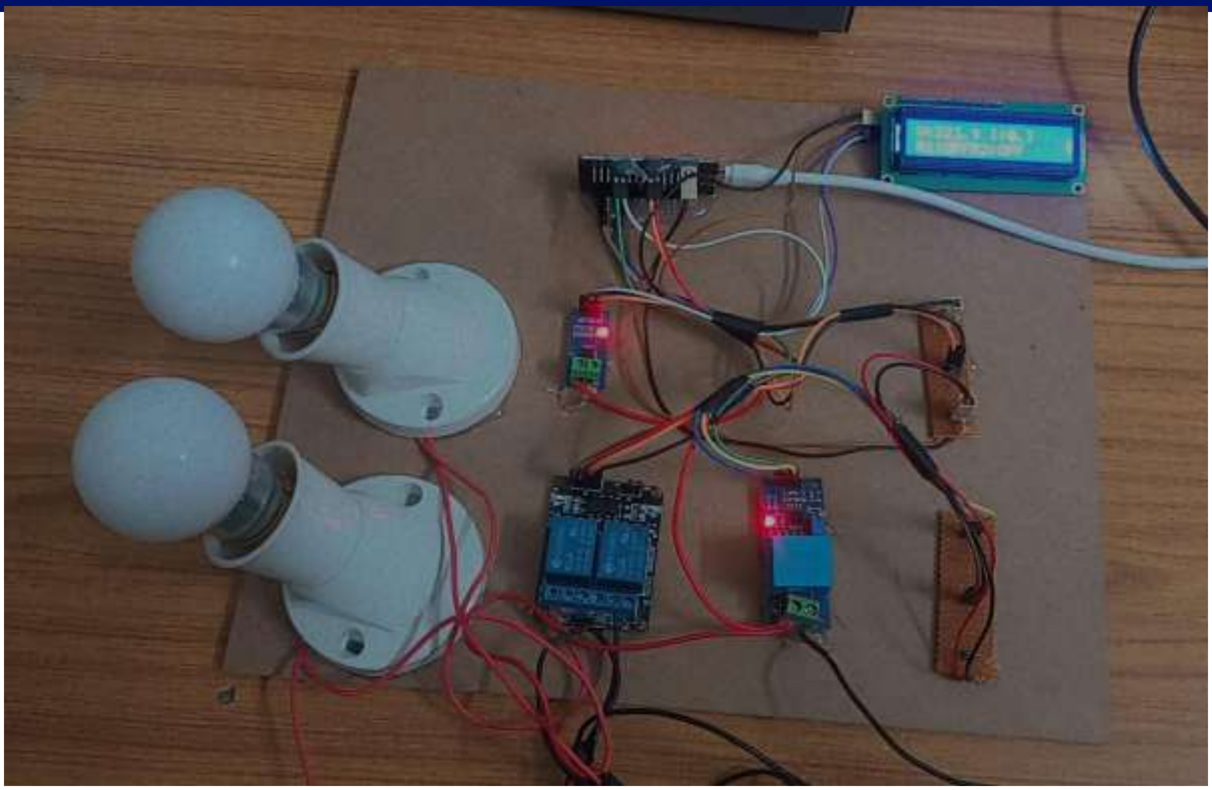

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5. Results and Discussion

The proposed smart energy monitoring and load supervision system was successfully implemented and tested using an ESP32 microcontroller, voltage sensor, current sensor, relay modules, MQTT cloud communication, LCD display, and Telegram Bot integration. The system demonstrated reliable performance in measuring electrical parameters, displaying local information, and transmitting data remotely. Experimental testing confirmed that the system can monitor voltage, current, and power consumption while providing real-time relay status updates through cloud and messaging platforms.

5.1 Performance Evaluation and Testing Results

The system performance was evaluated by testing each module individually and then validating complete integrated operation.

Voltage Measurement Testing

The voltage sensor was tested under AC supply conditions to verify accurate voltage monitoring. The measured values were compared with a standard multimeter.

Parameter	**Measured Value**	**Reference Value**	**Accuracy**
AC Voltage	228–232 V	230 V	High

The RMS-based algorithm improved measurement stability and reduced noise fluctuations.

Current Measurement Testing

The current sensor was tested using multiple load conditions such as bulbs and electrical appliances.

Load Type	**Current Measured**
No Load	~0.00 A
LED Bulb	0.05–0.10 A
Incandescent Bulb	0.35–0.50 A
Multiple Loads	Increased proportionally

The system successfully measured current changes depending on load variation.

Power Calculation Testing

Power values were calculated using voltage and current measurements.

P=V×IP=V\times IP=V×I

The calculated power closely matched expected theoretical values.

MQTT Communication Testing

Adafruit IO dashboard communication was tested for:

- Real-time parameter updates
- Relay synchronization
- Data publishing stability

Results showed successful MQTT communication with optimized update intervals to avoid throttling.

Telegram Communication Testing

Telegram Bot integration was validated using command-based interaction.

Commands tested:

- /status
- /data

The system successfully transmitted:

- Relay status
- Voltage values
- Current values
- Power values

LCD Display Testing

The I2C LCD displayed real-time system parameters.

Example Display:

V:230.5 I:0.42

R1:ON R2:OFF

The display updated continuously without flickering.

5.2 Observations

During testing and experimentation, several important observations were recorded.

1. The ESP32 maintained stable Wi-Fi connectivity during operation.
2. RMS calculations improved measurement consistency.
3. Voltage sensor readings required calibration for improved accuracy.
4. Current sensor performance depended on correct wire placement.
5. MQTT cloud updates worked efficiently after optimizing data intervals.
6. Telegram communication required proper connection handling for reliable messaging.
7. Relay status synchronization worked correctly between Adafruit IO and ESP32.

LCD provided quick local monitoring without dependency on internet connectivity

Conclusion

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The proposed **ESP32-based IoT Smart Energy Monitoring and Intelligent Load Control System** successfully demonstrates an efficient, reliable, and cost-effective solution for real-time electrical energy monitoring and remote load management. By integrating voltage and current sensing modules with the ESP32 microcontroller, the system accurately measures electrical parameters using RMS-based calculations and continuously monitors voltage, current, and power consumption. The incorporation of the MQTT protocol and Adafruit IO cloud platform enables seamless real-time data transmission, remote visualization, and continuous supervision of energy usage. Furthermore, Telegram Bot integration enhances user interaction by providing instant notifications and on-demand access to system information, while the I2C LCD offers convenient local monitoring of system parameters and relay status. Experimental evaluation confirmed stable Wi-Fi communication, reliable sensor performance, accurate power computation, synchronized relay operation, and effective cloud connectivity under different load conditions. Compared with conventional monitoring systems, the proposed architecture offers improved accessibility, enhanced operational efficiency, and intelligent load control within a low-cost and scalable framework. The developed system is well suited for residential, commercial, laboratory, and small industrial applications where continuous energy supervision is essential. Future enhancements may include automatic energy billing, overload and fault detection, machine learning-based energy consumption prediction, renewable energy integration, and mobile application support to further improve the intelligence, scalability, and practicality of the proposed smart energy management system.

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