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IOT Based Assisted Adaptive Control of Multilevel Inverter for Grid Tied Renewable Energy System

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Abstract: ***This study presents an IoT-assisted adaptive control approach for a multilevel inverter used in grid-connected renewable energy systems, where maintaining stable and efficient power delivery is critical despite fluctuations in input sources and load variations. The proposed system integrates the multilevel inverter within a smart grid environment, utilizing IoT-based sensors and communication technologies to continuously monitor grid conditions, renewable energy generation, and load requirements in real time. To improve system performance, an advanced adaptive control strategy is employed, which dynamically modifies parameters such as modulation index, switching sequences, and control gains based on real-time feedback obtained through the IoT network. This approach enhances the system's transient behavior, minimizes voltage and current distortions, and ensures effective regulation of both active and reactive power, overcoming the limitations of traditional linear control methods. Additionally, the inverter supports multiple modes of operation, including constant voltage, constant current, and constant power control, making it adaptable for applications involving solar photovoltaic systems, wind energy integration, and hybrid energy storage systems within smart grids.These results highlight the potential of combining multilevel inverter technology with IoT-enabled adaptive control to meet the demands of modern grid-tied renewable energy systems.***
Keywords: IoT-assisted adaptive control, multilevel inverter, grid-connected renewable energy, smart grid systems.

I. INTRODUCTION

The increasing need for clean and sustainable energy has significantly accelerated the adoption of renewable sources such as solar and wind in modern power systems. However, the inherent variability of these energy sources introduces challenges in maintaining grid stability, ensuring power quality, and achieving efficient energy conversion [1]-[3]. Multilevel inverters have become an effective solution for converting DC power from renewable sources into high-quality AC power suitable for grid integration, as they offer lower harmonic distortion, higher efficiency, and improved output voltage waveforms compared to traditional inverter designs [4]-[6]. such as proportional–integral (PI) controllers, often exhibit limited performance when dealing with sudden variations in input power and load demand, resulting in slower dynamic response and reduced overall efficiency [7]-[10].

To overcome these limitations, the incorporation of Internet of Things (IoT) technology offers a promising solution by enabling continuous monitoring of key system parameters, including voltage, current, frequency, and load conditions, through interconnected sensors and communication networks [11]-[12]. This adaptive approach enhances transient performance, minimizes harmonic distortion, and ensures effective control of both active and reactive power [13]-[15].

II. FLOW CHART

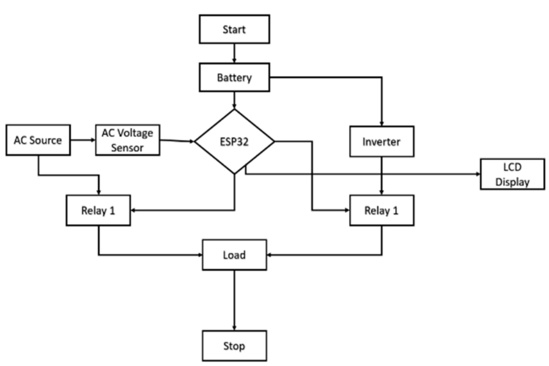


Fig.1. Flow Chart

1) Start
- The process begins with system initialization.
- All components are powered up and configured, ensuring that the control sequence is ready for operation.

2) Battery
- The battery serves as an energy storage unit, providing backup power when the main supply is unavailable.
- It ensures uninterrupted operation of the inverter during outages.

3) AC Source
- This is the primary power supply obtained from the utility grid.
- Under normal conditions, it delivers electricity directly to the load.

4) AC Voltage Sensor
- The AC voltage sensor continuously monitors the input voltage level.
- It transmits real-time voltage data to the ESP32 and helps detect any fluctuations or faults in the supply.

5) ESP32
- The ESP32 acts as the central controller of the system.
- It processes data received from the voltage sensor and makes decisions to control relays and manage inverter operation accordingly.

6) Relay 1 (AC Side)
- Relay 1 connects the AC source to the load during normal conditions.
- It is controlled by the ESP32 and disconnects the supply if a fault or voltage drop is detected.

7) Relay 2 (Inverter Side)
- Relay 2 switches the load connection from the AC source to the inverter output when required.
- This ensures a seamless transition and continuous power supply.

8) Load
- The load represents electrical appliances or devices that consume power.
- It receives electricity either from the AC source or the inverter depending on system conditions.

9) LCD Display
- The LCD module provides real-time system information.
- It displays voltage values, system status, and indicates whether the power is supplied from the main source or the inverter.

III. PROBLEM STATEMENT

The integration of renewable energy sources such as solar and wind into grid-connected power systems introduces several technical challenges due to their variable and unpredictable behavior. Fluctuations in energy generation, primarily caused by changing environmental conditions, can lead to instability in voltage, frequency, and overall power quality, thereby affecting the reliable operation of the grid. Multilevel inverters are commonly employed to connect these renewable sources to the grid, but their effectiveness largely depends on the control strategy used. Traditional approaches, including proportional–integral (PI) controllers, often fail to respond efficiently to rapid changes in input power and load demand, resulting in slower system dynamics, higher total harmonic distortion (THD), and inadequate control of active and reactive power. In addition, the absence of real-time monitoring and intelligent decision-making capabilities further restricts system performance. Without continuous feedback from the grid and connected sources, the inverter is unable to adapt its operation to changing conditions in an optimal manner. This limitation can lead to inefficient energy conversion, increased power losses, and reduced lifespan of system components.

IV. PROPOSED SYSTEM

The proposed system utilizes an ESP32 microcontroller to develop an intelligent and automated control solution for a grid-connected renewable energy application. An AC voltage sensor is employed to continuously monitor the grid voltage in real time. During normal operating conditions, Relay 1 remains activated, allowing the load to be powered directly from the main AC supply.
When the system detects a voltage drop or any abnormal condition, the controller responds immediately by turning Relay 1 OFF and activating Relay 2, thereby switching the power source to the inverter. This ensures a continuous and reliable power supply without interruption. A 16×2 LCD display is incorporated to provide real-time feedback, including AC voltage readings and the operational status of both relays (ON/OFF), enabling effective local monitoring.

Furthermore, the system is integrated with the Adafruit IO platform, where voltage data and relay status are transmitted via Wi-Fi. This allows users to perform remote monitoring, maintain data records, and implement efficient energy management strategies.

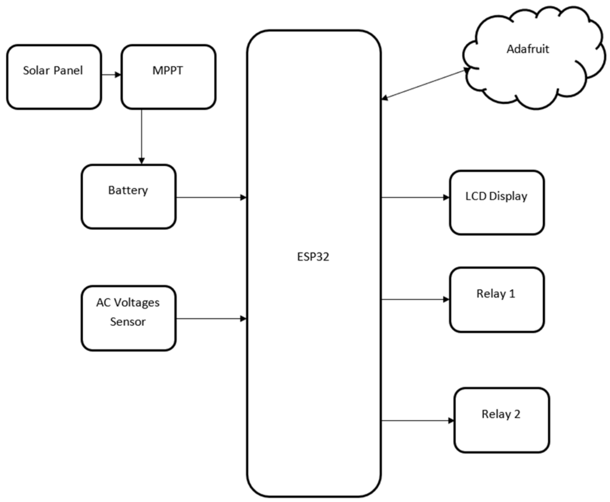


Fig.2. Block Diagram

V. HARDWARE IMPLEMENTATION

A. ESP32

The ESP32 microcontroller is widely recognized for its integrated Wi-Fi and Bluetooth capabilities, including both Classic Bluetooth and Bluetooth Low Energy (BLE). These built-in features remove the need for additional communication hardware, making the ESP32 highly suitable for wireless data transfer, remote monitoring, and cloud-based IoT applications. It is frequently used with platforms such as Blynk and MQTT to enable real-time data exchange and system control.

Fig.3. ESP32

In addition to its connectivity features, the ESP32 provides a wide range of input and output interfaces. It includes multiple GPIO pins that support digital input/output operations, as well as advanced functionalities such as Pulse Width Modulation (PWM), Analog-to-Digital Conversion (ADC), and Digital-to-Analog Conversion (DAC).

B. AC Voltage Sensor

An AC voltage sensor is an electronic module designed to measure alternating current (AC) voltage and convert it into a safe, low-level signal that can be read by microcontrollers such as the ESP32 or Arduino. This allows high-voltage electrical signals to be monitored without directly exposing the control circuitry to dangerous voltage levels.

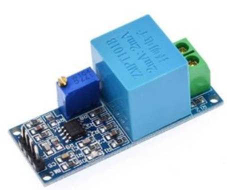


Fig.4 AC Voltage Sensor

C. LCD Display

An LCD with an I2C interface is widely used in embedded systems to display text information while minimizing the number of required microcontroller pins. It typically combines a standard 16×2 LCD (16 columns and 2 rows) with an I2C communication module, making it easy to interface with development boards such as the ESP32 or Arduino.

Fig.5. LCD Display

D. Relay Module

A relay module is an electrically controlled switching device that allows low-voltage circuits to operate high-voltage or high-current loads. It is commonly used with microcontrollers such as the ESP32 or Arduino to enable safe and efficient control of electrical appliances in automation systems. One of its key advantages is electrical isolation, which protects the control circuit from high-power signals.

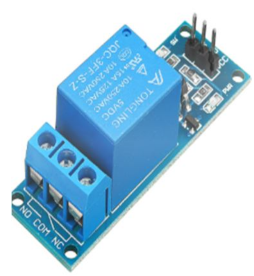


Fig.6. Relay Module

A typical relay consists of an electromagnetic coil, a mechanical switching arm, and three terminals known as Common (COM), Normally Open (NO), and Normally Closed (NC).

E. Solar Panel

A solar panel is a device designed to convert sunlight into electrical energy through the photovoltaic effect. It is one of the most commonly used technologies for producing clean and renewable power. A standard solar panel is composed of multiple solar cells, typically made from silicon, which acts as a semiconductor material.

Fig.7. Solar Panel

F. MPPT (Maximum Power Point Tracker)

Maximum Power Point Tracking (MPPT) is an advanced control technique used in solar energy systems to ensure that a solar panel operates at its highest possible efficiency. Since the power output of a solar panel changes with variations in sunlight intensity, temperature, and load conditions, it does not deliver constant power throughout the day.

Fig.8. MPPT (Maximum Power Point Tracker)

G. 12v Battery

A 12V battery is a commonly used energy storage device that delivers a nominal voltage of 12 volts and is essential in various applications such as automotive systems, solar power setups, backup supplies, and embedded systems using controllers like the ESP32. It is typically constructed by connecting multiple electrochemical cells in series; for example, a standard lead-acid battery consists of six cells, each producing about 2 volts, which together provide a total output of 12 volts.

Fig.9. 12v Battery

Lead-acid batteries are widely used due to their low cost and reliability, although they are relatively heavy and may require regular maintenance. In contrast, lithium-based batteries are lighter, more efficient, and provide a longer service life, making them suitable for advanced applications such as renewable energy systems and portable electronics.

H. Inverter

An inverter is an electrical device that converts direct current (DC) into alternating current (AC), enabling DC sources such as batteries and solar panels to power conventional AC appliances like fans, lighting systems, televisions, and refrigerators.

Fig.10. Inverter

Due to this capability, inverters are widely used in backup power systems, renewable energy installations, and portable energy solutions. The operating principle of an inverter involves rapidly switching the DC input to produce an alternating output waveform. This is typically achieved using power electronic components such as transistors, MOSFETs, or IGBTs, which switch on and off at high frequencies. As a result, the inverter generates an AC waveform that may be a square wave, modified sine wave, or pure sine wave depending on the design. Among these, pure sine wave inverters are considered the most suitable for sensitive electronic equipment, as they provide a smooth and stable output similar to the utility grid supply.

I. Adafruit IO

Adafruit IO is a cloud-based Internet of Things platform developed by Adafruit Industries that enables users to connect hardware devices such as ESP32, Arduino, and Raspberry Pi to the internet. It allows data to be collected, monitored, and controlled remotely, making it highly useful for IoT applications and smart systems.

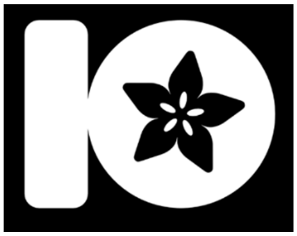


Fig.11. Adafruit IO

The platform operates using two main concepts: feeds and dashboards. A feed acts as a data channel where devices can send or receive information, including sensor readings like temperature, humidity, or voltage. A dashboard provides a visual interface where this data can be displayed using elements such as graphs, gauges, buttons, and sliders. For instance, sensor data from a DHT11 can be visualized in real time using charts, or a relay can be controlled remotely through an interactive button using a smartphone or computer.

VI. CIRCUIT DIAGRAM

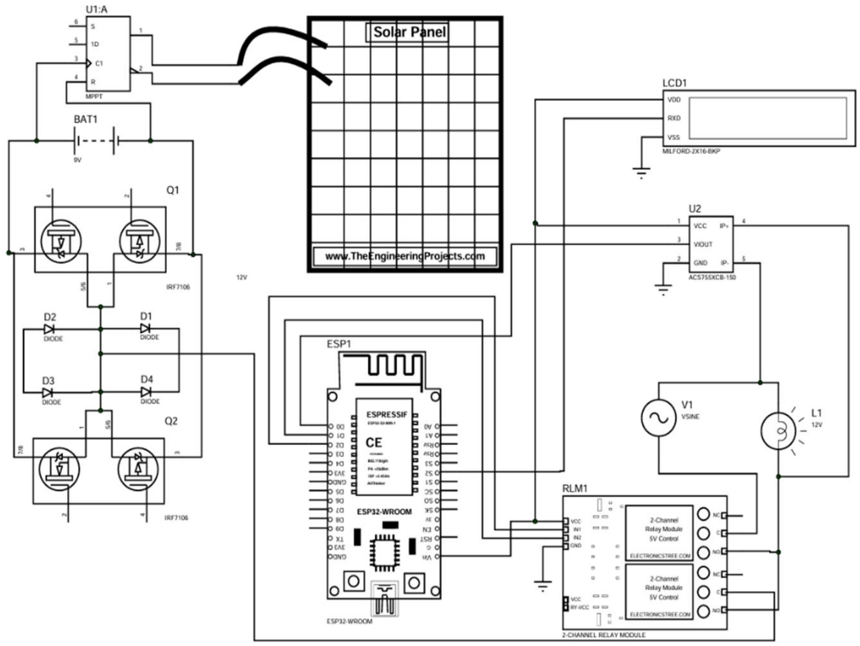


Fig.12. Circuit Diagram

VII. WORKING METHODOLOGY

The system begins by continuously sensing the grid voltage through an AC voltage sensor interfaced with the ESP32 controller. The ESP32 processes the incoming voltage data in real time and checks it against preset threshold limits to evaluate supply conditions.

During normal operation, when the voltage is within the safe range:

- Relay 1 stays activated, supplying power from the main AC source to the load
- Relay 2 remains deactivated
- The LCD screen displays live voltage readings along with the status of both relays

If any abnormal condition such as voltage drops, fluctuation, or power failure occurs:

- The controller immediately deactivates Relay 1 to isolate the main supply
- Relay 2 is activated to switch the load to inverter power
- The inverter uses stored battery energy to continue supplying the load

This automatic transition mechanism ensures a smooth and uninterrupted power supply.

At the same time, the ESP32 uploads key system parameters, including voltage values and relay states, to the Adafruit IO through a Wi-Fi connection.

The cloud platform enables remote supervision, real-time data tracking, and historical data analysis.

VIII. HARDWARE OUTCOME

The implemented hardware system effectively showcases an automatic power control setup based on the ESP32 microcontroller. An AC voltage sensor continuously tracks the grid voltage and supplies real-time data for system decisions. When the supply is normal, the load is powered directly from the main source, and during voltage disturbances or outages, the system smoothly shifts to inverter operation using relays. The inverter converts stored DC energy from the battery into AC power to maintain uninterrupted supply. A 16×2 LCD provides live updates of voltage values and relay conditions for easy local observation. In addition, system data is sent to the Adafruit IO over Wi-Fi, allowing remote monitoring and better energy management.

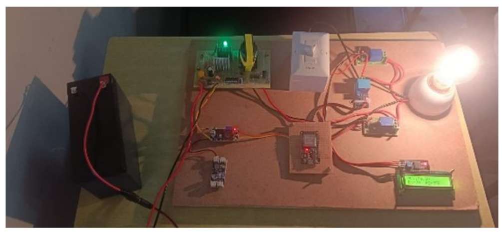
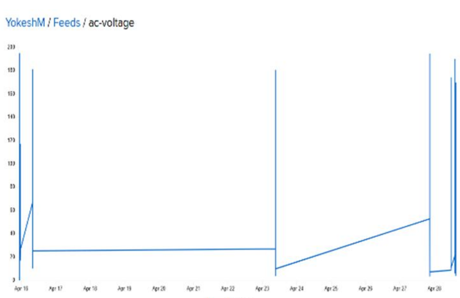


Fig.13. Proto type hardware implementation



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2026/04/28 03:01:53PM	7.407785	0.0, 0.0, 0.0	×
2026/04/28 03:01:42PM	8.556936	0.0, 0.0, 0.0	×
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2026/04/28 03:01:22PM	7.854559	0.0, 0.0, 0.0	×
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2026/04/28 03:01:01PM	7.957238	0.0, 0.0, 0.0	×

Fig.14. Output in Adafruit IO

IX. CONCLUSION

In summary, the proposed IoT-enabled adaptive control system for a multilevel inverter in a grid-connected renewable energy setup offers a dependable and efficient approach for ensuring uninterrupted power delivery under varying conditions. By incorporating the ESP32 microcontroller, the system facilitates continuous voltage monitoring and enables intelligent switching between the main AC supply and inverter backup. The automated relay operation allows smooth transition during voltage disturbances or outages, enhancing system reliability and minimizing interruptions. The inclusion of a 16×2 LCD provides clear real-time display of system parameters for local observation, while integration with Adafruit IO supports remote monitoring, data storage, and effective energy management. Compared to traditional methods, this system improves power quality, reduces the need for manual control, and enhances overall operational efficiency.

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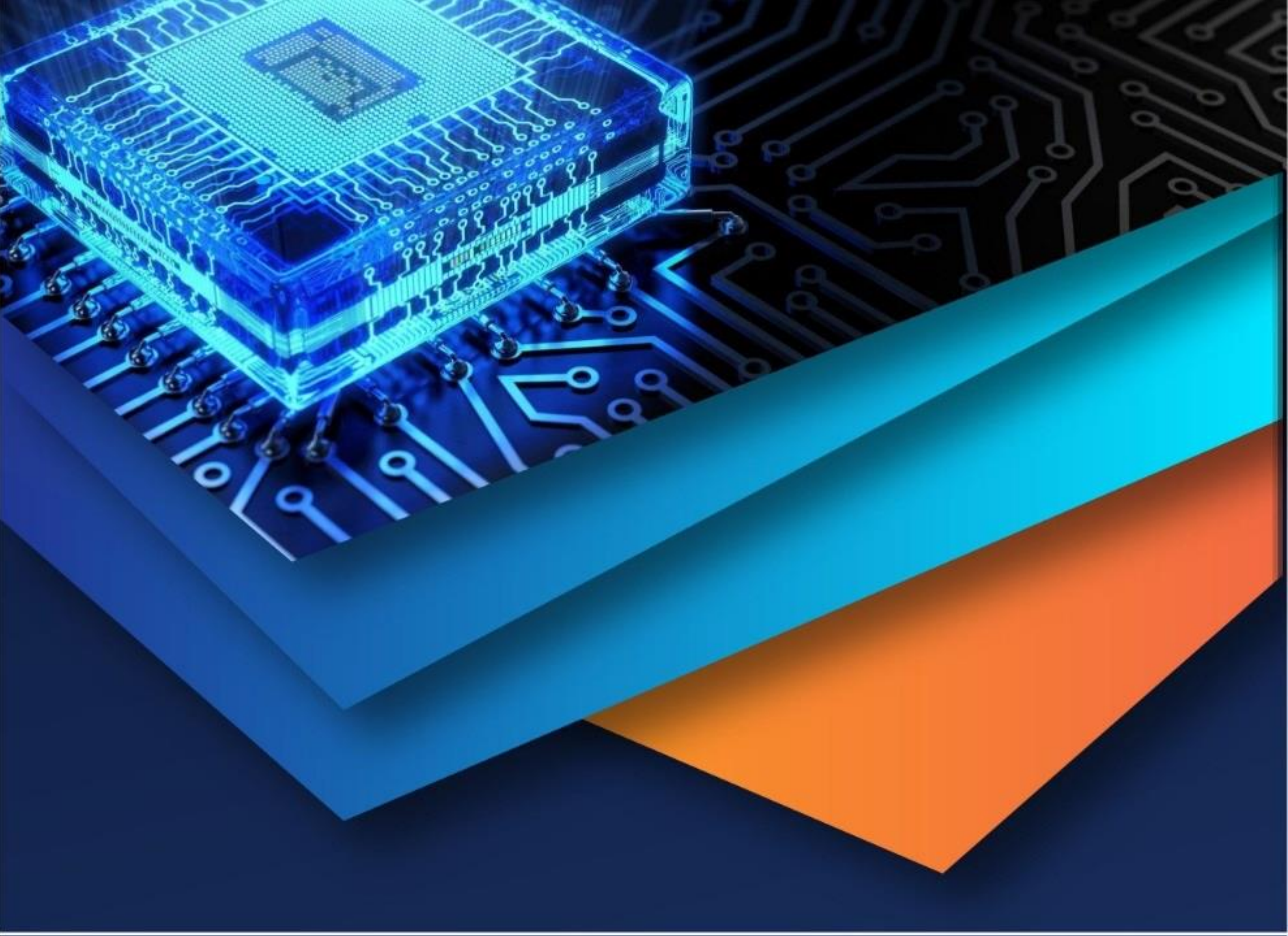

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