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Hybrid Solar and Wind Power Management System with IOT

Shravan Kadam[1], Siddharth Kamble[2], Mayuresh Gajakosh[3], Aniket Kadam[4], Ashwini Khade[5]

Abstract: ***The increasing demand for electricity and the depletion of conventional energy resources have increased the importance of renewable energy systems. Solar and wind energy are two of the most widely used renewable energy sources. However, each source has its own limitations due to environmental dependency. To overcome this limitation, hybrid renewable energy systems are developed by combining multiple energy sources to improve reliability and energy availability. The objective of this project is to design and implement a Hybrid Solar and Wind Power Management System with IoT Monitoring that can intelligently utilize available renewable sources to charge a***
battery. In this system, both solar and wind energy sources are connected to a common battery through charge regulation modules. The solar panel output is controlled using an MPPT charge controller, while the wind turbine output is regulated using a CC/CV module. An ESP32 microcontroller is used as the main controller of the system. It continuously monitors the voltage of both solar and wind sources using voltage sensors and automatically selects the available source based on a predefined voltage threshold. Relay-based switching is used to control the charging path and ensure stable operation. The stored energy in the battery is supplied to the load through an inverter. An ACS712 current sensor is used to monitor the current between the battery and inverter for overload detection. Additionally, the system provides IoT-based monitoring using the Blynk platform, allowing users to remotely observe solar and wind generation data. This project demonstrates an efficient and intelligent approach to managing multiple renewable energy sources for battery charging and power supply. The developed prototype helps in understanding the working principles of hybrid renewable energy systems and their practical implementation.

Keywords: ***Hybrid System , ESP-32 Micro-Controller , IoT Base Monitoring.***

I. INTRODUCTION

The rapid growth in energy demand, along with the depletion of fossil fuel resources and increasing environmental concerns, has led to a global shift toward renewable energy sources. Conventional energy generation methods based on coal, oil and natural gas contribute significantly to greenhouse gas emissions and environmental pollution.

Therefore, renewable energy systems have become essential for sustainable development. Among various renewable energy sources, solar energy and wind energy are the most abundant and widely utilized resources. Solar energy is harnessed through photovoltaic (PV) panels that convert sunlight into electrical energy, while wind energy is generated using wind turbines that convert the kinetic energy of moving air into electrical power.

However, both solar and wind energy have inherent limitations, as solar power generation depends on sunlight intensity and is unavailable during nighttime or cloudy conditions, and wind energy generation depends on unpredictable and variable wind speed. Due to these limitations, relying on a single renewable source reduces system reliability. To overcome this issue, hybrid renewable energy systems are introduced.

A hybrid renewable energy system combines two or more renewable energy sources to improve reliability, stability and efficiency. In a solar-wind hybrid system, solar energy is available during daytime, while wind energy may be available during night or cloudy weather, and their combination ensures better power availability throughout the day. Although hybrid systems improve energy availability, they require intelligent control mechanisms to manage multiple sources effectively.

Without proper control logic, the system may suffer from unstable switching between sources when voltage fluctuates under load conditions, and this frequent switching, also known as relay hunting, reduces system stability and may damage components over time. Therefore, a stable and intelligent power management system is required for efficient hybrid operation.

II. LITERATURE REVIEW

Renewable energy systems have gained significant importance due to increasing energy demand, depletion of fossil fuels and environmental concerns. Among various renewable sources, solar and wind energy are widely used because they are clean,

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sustainable and naturally available.

However, both sources have certain limitations when used independently. Solar photovoltaic (PV) systems convert sunlight into electrical energy. According to John Twidell and Tony Weir [1], solar energy is abundant but its output depends entirely on sunlight availability, as power generation reduces during cloudy weather and completely stops at night. Similarly, wind energy systems convert kinetic energy of wind into electrical power, and as discussed by James F. Manwell, wind energy generation depends on wind speed, which is unpredictable and variable.

To improve reliability, researchers have proposed hybrid renewable energy systems that combine solar and wind energy sources, increasing overall energy availability by utilizing the complementary nature of solar and wind resources. However, early hybrid systems used simple voltage comparison methods for source selection, which often resulted in frequent switching between sources when voltage fluctuated under load conditions. Frequent relay switching, also known as relay hunting, reduces system stability and relay life.

To overcome this issue, hysteresis and latching control techniques have been introduced in microcontroller-based systems, where hysteresis ensures that once a source is selected, it remains active until its voltage falls below a minimum threshold, thereby preventing unstable switching. In addition to source selection, current monitoring is important for system protection, and ACS712 Hall- effect current sensors are commonly used for DC current measurement in renewable systems [6]. Real-time current monitoring helps detect overload conditions and improves system safety.

With the advancement of Internet of Things (IoT) technology, renewable energy systems are now integrated with remote monitoring platforms, allowing real-time monitoring of voltage, current and environmental parameters, which improves system visibility and enables smart energy management. Based on the literature review, it is observed that stable source selection and IoT-based monitoring are essential for modern hybrid renewable systems, as many earlier systems lacked proper latching mechanisms, resulting in unstable switching between sources during voltage fluctuations.

The proposed project addresses this issue by implementing intelligent hysteresis- based control for stable source selection. In addition, IoT integration enables real- time monitoring of solar and wind voltage through graphical visualization. DC current sensing is used only for overload protection of the battery-inverter side to ensure safe system operation.

III. PROBLEM STASTMENT

The increasing demand for electrical energy and the depletion of conventional fossil fuels have created a need for reliable and sustainable renewable energy systems. Solar and wind energy are two of the most widely used renewable sources; however, both sources have inherent limitations when used individually. Solar energy generation depends on sunlight availability and is unavailable during nighttime or cloudy weather, while wind energy generation depends on wind speed, which is unpredictable and variable. As a result, standalone solar or wind systems cannot ensure continuous and stable power supply. To improve reliability, hybrid solar-wind systems are used. Although hybrid systems increase power availability, they introduce new technical challenges such as unstable source switching when voltage fluctuates under load, frequent relay oscillation (relay hunting) between solar and wind sources, lack of an intelligent control mechanism for source selection, absence of real-time monitoring of system performance, and risk of battery damage due to excessive current withdrawal from connected loads.

When load is connected to the system, the source voltage may drop suddenly, and if simple voltage comparison logic is used, the controller may continuously switch between solar and wind sources; this unstable switching reduces system efficiency and affects the lifespan of relays and components. Furthermore, many small-scale hybrid systems do not provide remote monitoring capability, and without monitoring, users cannot observe voltage trends, source behavior, or system status in real time. Another major concern is battery protection, as high-wattage loads connected on the inverter side may draw excessive current from the battery, reducing battery life and affecting system safety.

Therefore, there is a need to design a hybrid solar and wind power management system that selects the most suitable energy source intelligently, prevents unstable switching between sources, ensures stable battery charging, provides real-time IoT- based monitoring, and protects the system against excessive current conditions. The proposed project aims to develop a microcontroller-based hybrid power management system using ESP32 that implements hysteresis-based source selection logic and IoT monitoring, ensuring stable operation under load conditions and providing graphical monitoring of solar and wind generation.

IV. SCOPE OF THE PROJECT

The scope of this project involves the design and implementation of a Hybrid Solar and Wind Power Management System with IoT-based monitoring. The system is developed as a small-scale off- grid renewable energy prototype that demonstrates intelligent

source selection, stable battery charging and real-time monitoring of renewable energy parameters.

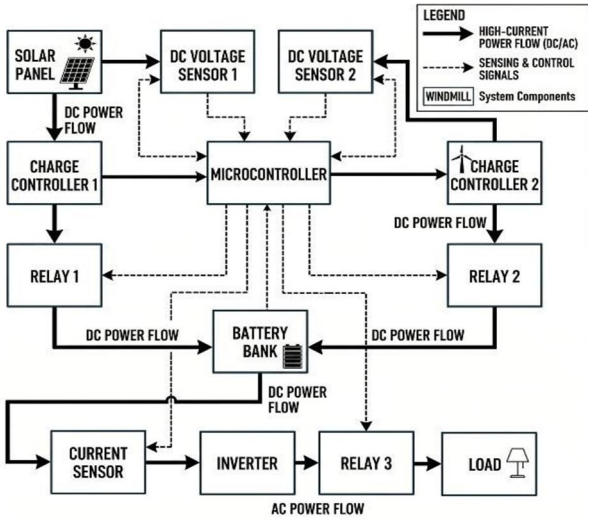
The project focuses on effective integration of solar and wind energy sources using embedded control techniques to ensure reliable operation under varying environmental conditions. In this system, the solar panel is connected through an MPPT controller to optimize power extraction, while the wind turbine output is regulated using a CC/CV module for controlled battery charging. Both sources are used to charge a 12V battery, which acts as the central energy storage and stabilizing unit.

The load is powered through an inverter connected to the battery, ensuring that renewable sources are not directly connected to the load, thereby maintaining system stability and protecting connected devices. The ESP32 microcontroller continuously monitors the voltage levels of both sources and selects the most suitable source using relay-based intelligent control logic.

Hysteresis-based switching is implemented to prevent unstable oscillations during voltage fluctuations. If the active source drops below a defined threshold, the system automatically switches to the alternate available source, ensuring continuous and stable battery charging. The system also incorporates IoT-based monitoring using WiFi connectivity, allowing real-time observation of solar voltage, wind voltage, active source status and system condition through graphical visualization.

DC current sensing is included for battery- side protection to prevent excessive current draw and improve system safety. Overall, the scope of this project covers intelligent hybrid energy management, stable source selection, battery-based power supply architecture and IoT-enabled monitoring within a compact and cost-effective prototype suitable for educational and small-scale off-grid applications.

V. METHODOLOGY

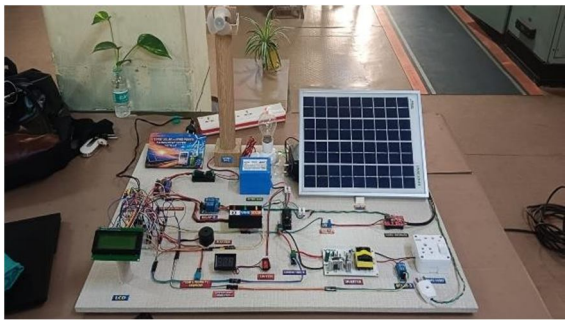


The methodology of the Hybrid Solar and Wind Power Management System involves systematic design, integration, programing and testing of hardware and software components to achieve stable hybrid renewable operation with IoT monitoring.

Initially, the overall system architecture was planned. The solar panel was connected through an MPPT controller to ensure efficient power extraction under varying sunlight conditions, while the wind turbine output was regulated using a CC/CV module to maintain controlled charging voltage. Both sources were connected to charge a 12V battery, which acts as the central energy storage unit, and the AC load is powered through an inverter connected to the battery, following an off- grid configuration.

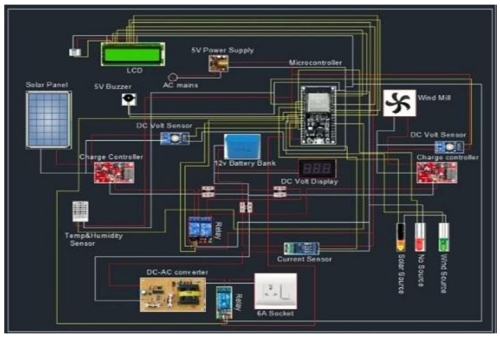
Voltage sensing circuits were implemented to monitor solar and wind voltages using the ADC inputs of the ESP32 microcontroller. The ESP32 was programmed using the Arduino IDE to compare voltage levels and select the most suitable source through relay-based switching, with hysteresis logic implemented to prevent frequent switching during voltage fluctuations and ensure stable battery charging.

A DC current sensor, ACS712, was installed between the battery and inverter to monitor load current and provide protection against excessive current draw, and a load relay disconnects the supply if abnormal conditions are detected. For monitoring purposes, a 20x4 LCD displays real-time system parameters such as solar voltage, wind voltage and active source status.



Additionally, IoT-based monitoring is implemented using ESP32 WiFi connectivity and the Blynk platform to visualize solar and wind voltages remotely through graphical representation. Finally, the system was tested under different operating conditions to verify switching stability, charging performance and IoT data transmission, ensuring proper integration of renewable sources, intelligent source selection and reliable system operation.

VI. WORKING PRINCIPLE AND PROCESS



The Hybrid Solar and Wind Power Management System operates on the principle of intelligent source selection and battery-based energy management. The system integrates two renewable energy sources solar and wind and uses an embedded controller to ensure stable battery charging and controlled power delivery to the load.

The solar panel generates DC power when sunlight is available, and this power is regulated through an MPPT (Maximum Power Point Tracking) controller, which optimizes the operating point of the solar panel to extract maximum possible energy under varying sunlight conditions. The wind turbine generates electrical energy when wind is available, and its output is regulated using a CC/CV (Constant Current/Constant Voltage) module to maintain a stable charging voltage suitable for the battery. Both regulated outputs are connected to a 12V lithium-ion battery, which acts as the central energy storage unit. The battery stores the generated energy and supplies power to the load through an inverter. The load is not directly connected to the renewable sources; instead, the battery serves as a buffer and stabilizer, ensuring continuous and stable power supply even if renewable input fluctuates. The ESP32 microcontroller continuously monitors the voltage levels of both solar and wind sources through analog sensing.

Based on predefined voltage thresholds, the controller determines which source is more suitable for charging the battery. Relay-based switching is used to connect only one source to the battery at a time, and hysteresis logic is implemented to prevent frequent switching when voltages fluctuate under load conditions. If the active source voltage drops below a defined threshold and the alternate source is sufficiently available, the system automatically switches charging to the alternate source.

To protect the system, a DC current sensor, ACS712, is installed between the battery and inverter to monitor the load current. If the current exceeds a predefined safe limit, the controller activates overload protection by disconnecting the load through a relay, preventing excessive current draw from the battery and ensuring safe system operation. A 20x4 LCD is used to display real-time information such as solar voltage, wind voltage, active source status and system condition.

Additionally, the ESP32 connects to WiFi and transmits system data to the Blynk IoT platform, where solar and wind voltages can be monitored graphically in real time. Thus, the working process of the system ensures intelligent source selection, stable battery charging, safe load operation and real-time monitoring, making it an efficient and reliable hybrid renewable energy management solution.

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VII. RESULTS OR APPLICATION

The Hybrid Solar and Wind Power Management System was tested under various operating conditions to evaluate source selection, battery charging behavior, load response and overload protection performance. The system was tested using a 12V, 10Ah lithium-ion battery and a 100W inverter.

A. Solar Source Testing

- Solar panel voltage (no load): 14.2V – 16.0V
- With load connected:
- Solar voltage dropped to 10.0V – 11.0V
- Battery charging remained stable due to MPPT regulation
- Relay selected solar source when solar voltage exceeded wind voltage
- Hysteresis logic prevented frequent switching during voltage fluctuations

B. Wind Source Testing

- Under natural wind conditions:
- Generated voltage: 2.5V – 3.0V
- Confirmed turbine rotation and basic generation
- Voltage insufficient for effective battery charging.
- Simulated high-wind testing (using 14V DC adapter to CC/CV module):
- Regulated wind voltage: 13.5V– 14.5V
- System switched to wind source when solar voltage dropped below threshold
- Wind relay activated successfully
- Battery charging continued without interruption
- Confirmed proper automatic source selection and fallback mechanism
- Validated system under both low-wind and high-wind conditions

C. Load Testing (25W Bulb)

- Measured DC current: 1.90A – 2.50A
- Battery voltage: 12.6V – 12.1V
- No overload condition triggered
- System remained stable
- Measured current matched theoretical calculation (considering 80% inverter efficiency)

D. Load Testing (60W Bulb)

- Measured DC current: 6.0A – 6.8A
- Battery voltage dropped slightly under load
- System remained stable below overload threshold
- Overload demonstration (threshold set to 5A):
- Load relay tripped
- Overload message displayed
- Load supply disconnected successfully
- Verified overload protection logic

E. Overload Protection Testing

- Overload threshold configured at 5A
- When current exceeded 5A:
- Relay disconnected AC supply
- Prevented excessive battery discharge
- Confirmed proper battery-side current protection

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F. IoT Monitoring Results (Blynk Platform)

- Solar voltage graph: 12V – 16V
- Wind voltage graph: 2V – 14.5V
- Active source status updated correctly
- Remote monitoring successful
- Stable data transmission over WiFi

G. Overall System Performance

- Intelligent source selection
- Stable battery-based power architecture
- Automatic switching between solar and wind
- Protection against overload
- Real-time IoT monitoring
- Stable LCD parameter display
- No abnormal heating or instability observed during normal operation

VIII. SOURCE SELECTION AND SWITCHING TESTING

The system was tested under multiple source availability conditions to verify the implemented source selection logic. A voltage threshold of 10V was set for both solar and wind sources, and any source generating voltage above 10V was considered available for battery charging. The system does not permanently prioritize solar or wind; instead, it follows a First- Attempt Mode Selection Logic. Whichever source first exceeds the 10V threshold becomes the active charging source and continues charging the battery until its voltage drops below 10V. If the alternate source is available above 10V at that time, the system automatically switches to it.

1) Case 1: Solar Reaches Threshold First: When solar voltage exceeded 10V before wind voltage, the system activated the solar relay and began charging the battery through the solar path. Even if wind later became available and exceeded 10V, the system did not switch immediately. Solar continued charging until its voltage dropped below 10V. During testing, solar voltage was observed between 14V to 16V under strong sunlight, and the wind relay remained OFF during this period.

2) Case 2: Wind Reaches Threshold First: When wind voltage exceeded 10V before solar voltage, the wind relay was activated first. During simulated high-wind testing using a 14V DC adapter connected to the CC/CV module, wind voltage was observed between 13.5V to 14.5V. The wind source continued charging the battery until its voltage dropped below 10V. If solar became available above 10V afterward, the system switched to solar automatically.

3) Case 3: Only Solar Available: When solar voltage was above 10V and wind voltage remained below 10V, the system activated the solar relay and continued charging normally without switching.

4) Case 4: Only Wind Available: When wind voltage was above 10V and solar voltage remained below 10V, the system activated the wind relay and continued charging through the wind source.

5) Case 5: Both Sources Available Simultaneously: When both solar and wind voltages exceeded 10V simultaneously, the source that first crossed the threshold became active. The system did not alternate continuously between sources. The active source remained selected until its voltage dropped below 10V, preventing unnecessary switching and relay oscillation.

6) Case 6: No Source Available: When both solar and wind voltages were below 10V, the system entered idle mode. Both relays remained OFF and no charging occurred. The battery supplied power to the load through the inverter until renewable sources became available again.

IX. CONCLUSION

The Hybrid Solar and Wind Power Management System with IoT Monitoring successfully demonstrates the practical integration of two renewable energy sources using intelligent control logic and embedded system design. The project achieves stable battery charging through threshold-based source selection, ensuring that only sufficiently strong renewable sources participate in charging.

The implemented first-attempt switching logic allows the system to select whichever source first exceeds the 10V threshold and continue charging until the source voltage drops below the limit, preventing unnecessary relay oscillation and ensuring stable operation under fluctuating environmental conditions. The use of hysteresis control further enhances system reliability. The battery-based architecture ensures that renewable sources are used solely for charging, while the load is powered through an inverter, improving voltage stability and protecting connected appliances. The inclusion of DC current monitoring provides additional safety by preventing excessive current draw from the battery.

Integration of IoT monitoring using the ESP32 and Blynk enables real-time visualization of solar and wind voltages, making the system interactive and suitable for modern smart energy applications. During testing, the system performed reliably under various conditions, including solar-only operation, wind-only operation, simultaneous source availability, and overload scenarios. The results confirm that the system operates efficiently and meets the intended objectives of intelligent hybrid energy management.

Overall, the project demonstrates a compact, cost-effective, and educational prototype of a hybrid renewable energy management system, providing a strong foundation for future enhancements such as parallel charging integration, advanced energy analytics, and large-scale hybrid implementations.

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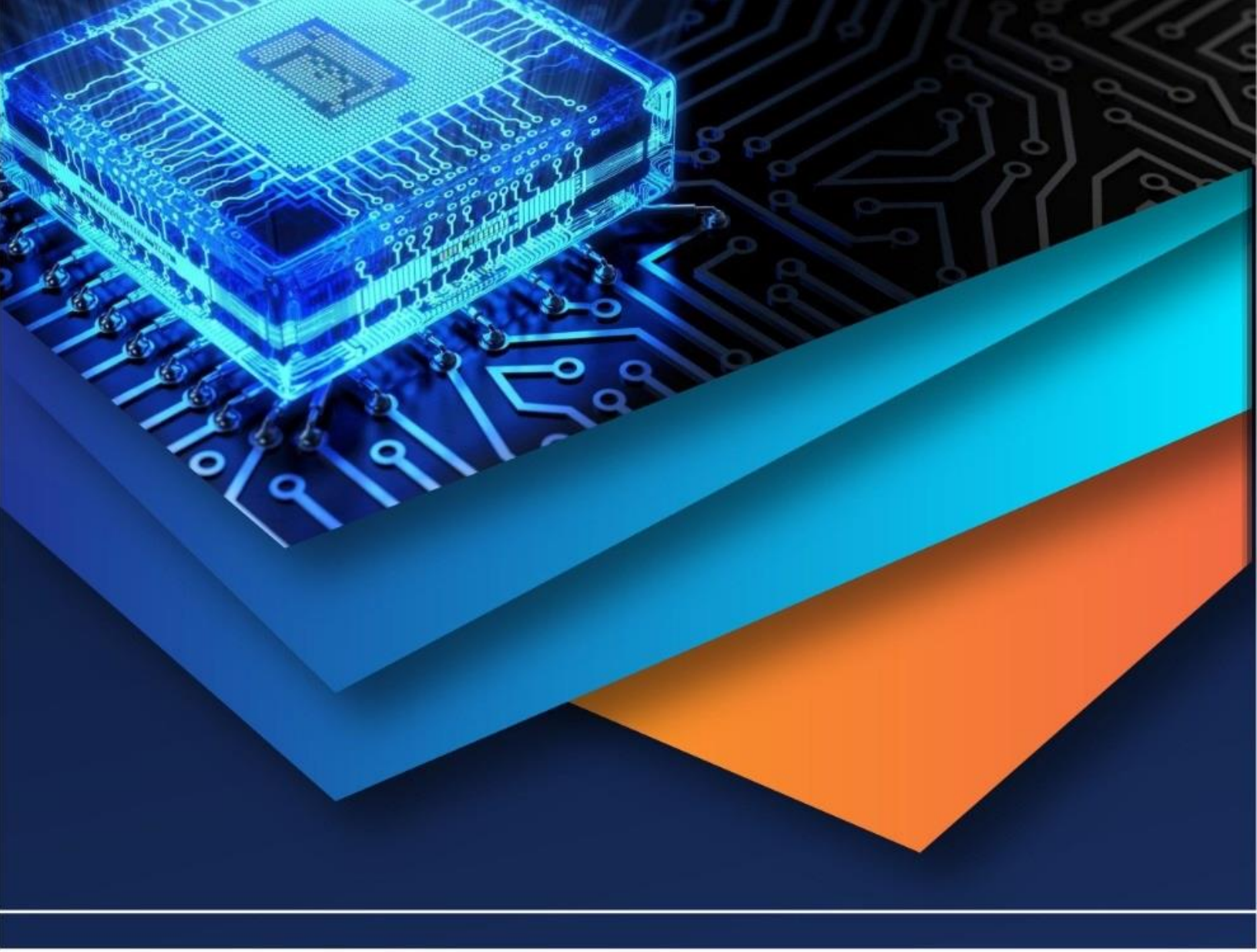
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