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PV and Fuel Cell with Battery DC Microgrid System

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Abstract: ***This paper presents the design and implementation of a hybrid PV–Fuel Cell–Battery based DC microgrid system for reliable renewable energy generation. The proposed system integrates a photovoltaic (PV) source, fuel cell unit, and battery energy storage to ensure continuous power supply under varying operating conditions. Initially, the system is modelled and analysed using MATLAB/Simulink to evaluate power sharing and voltage stability of the DC bus. To validate the simulation results, a small-scale hardware prototype is developed using a solar panel, fuel cell module, battery, DC–DC converters, and a microcontroller. The results demonstrate improved voltage regulation, efficient energy utilization, and enhanced reliability, making the system suitable for renewable energy based microgrid applications.***

Keywords: Photovoltaic System, Fuel Cell, Battery Energy Storage, DC Microgrid, Hardware Prototype, Renewable Energy Integration, Energy Management System, Power Electronics.

I. INTRODUCTION

In recent times, with the growing demand for clean and sustainable energy in the world, renewable energy source integration into modern power systems has been increasing. Traditional methods of generating power from fossil fuels have resulted in environmental degradation through the emission of greenhouse gases and depletion of resources.[1] To address these challenges, microgrids have emerged as reliable and efficient solutions for decentralized power generation and energy management.

A microgrid is a small-scale power network, integrating different types of distributed energy sources, storage systems, and loads. [2] The system can function both in grid-connected mode as well as islanded or standalone operation for uninterruptable power supply even when the grid fails. Among various types of microgrids, [3] DC microgrids have

garnered more attention due to their high efficiency, simple structure, with renewable sources solar

The design and simulation of a PV and Fuel Cell with Battery DC Microgrid System have been done using MATLAB/Simulink in this project.[4] The system integrated three major power sources:

Photovoltaic (PV) array: It converts the solar irradiance into DC power.

Fuel cell: It generates DC power from hydrogen and oxygen through an electrochemical reaction.

BESS - Battery Energy Storage System: It stores excess energy, with backup power provided during the failure of the renewable generation.

Each of these sources is interfaced with the DC bus through DC-DC converters that regulate and stabilize the voltage levels. A maximum power point tracking controller is used for the photovoltaic array to extract the maximum energy at any because the irradiance and temperature are not constant. The overall control strategy would thus seek to maintain stable DC bus voltage and ensure efficient load sharing among the three sources.

[5] The proposed hybrid DC microgrid improves system reliability, power quality, and energy utilization efficiency. It merges the use of renewable sources with an intelligent control approach to provide a sustainable and robust solution for modern energy applications like smart homes, electric vehicle charging systems, and off-grid power supplies.

II. LITERATURE REVIEW

During the last two decades, the concept of microgrids has evolved into a promising solution for integrating renewable sources into a localized power system. Different design, control, and optimization techniques have been explored by researchers all over the world to enhance the stability, efficiency, and flexibility of microgrids, in particular DC- based systems. According to E. Planas et al., in 2015, both AC and DC technologies are usable in microgrids; however, DC microgrids are more efficient because renewable sources of energy, such as solar PV and fuel cells, are naturally DC in nature. As the sources are DC by nature, AC-DC conversions reduce to a minimum to result in fewer losses of energy and less complication in the architecture of the system.

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S. Bacha et al. 2015 ensured that the integration of photovoltaic systems into microgrids would improve grid reliability and enhance power quality with proper energy management and control algorithms. This integration becomes effective with the inclusion of energy storage systems like Lithium-ion batteries, capable of balancing supply and demand during changing conditions of solar irradiance.

Distributed generation within the microgrid enables it to continue in islanded operation mode when the grid is down, according to R. H. Lasseter (2007).

His research established also that islanded operation allows microgrids to offer uninterruptable power; hence, they are suitable for remote applications and those with critical loads.

V.Nasirian et al. propose a distributed cooperative control strategy in DC microgrids to achieve load sharing and voltage regulation among multiple energy sources. Such strategies allow for decentralized control without the need for extensive communication links between converters, thus enhancing system reliability.

A key point that arises from the study of Zhi Na et al. (2013) is the use of DC-DC converters for the integration of renewable sources into DC microgrids. Converters like boost converters and buck converters are important in voltage regulation and power flow control to ensure that each source contributes optimally to the DC bus.

Further, it has been shown by Muntaser et al. (2017) that PID and Fuzzy Logic controllers for hybrid energy systems can be utilized in order to maintain voltage stability and improve power quality. Their work justifies using intelligent algorithms to handle the nonlinear time-varying behaviour of renewable energy sources. In general, prior work emphasizes the potential for overall efficiencies by combining PV, fuel cells, and battery storage into a DC microgrid framework. These results show that a hybrid system can achieve higher energy reliability with greater overall efficiency and lower operational costs compared to single-source systems. Building upon these findings, the present project focuses on simulating and analyzing such a hybrid DC microgrid in MATLAB/Simulink, implementing MPPT control to optimize energy utilization and maintain DC bus stability under dynamic load conditions.

III. METHODOLOGY

1) System Modelling: PV array, Fuel Cell, and Battery are modelled using MATLAB Simscape blocks.
2) Converter Design: These are connected with PV and Fuel Cell via boost converters. The battery is interfaced via a bidirectional buck/boost converter for charging/discharging.
3) Control Implementation: The MPPT perturbation and observation algorithm adjusts the operating voltage of the photovoltaic panels for optimal power. The Fuel Cell supplies base power while the Battery provides transient compensation.
4) Simulation in MATLAB: The hybrid system is then simulated to observe the stability of DC bus voltage and response to the load under various conditions.

IV. EXISTING SYSTEM

In the existing power generation systems, sources like solar photovoltaic (PV) and fuel cells are normally used individually or connected to the grid through AC-based systems. Although these can generate clean energy, they have many limitations.

AC-based interconnection losses: Most of the existing systems use AC microgrids, which involve multiple AC–DC and DC–AC conversions in integrating the renewables. These conversion processes result in appreciable power loss and lowered overall efficiency.

Unstable output under variable conditions: Output from PV and fuel cells varies with incident irradiance, temperature, and fuel supply. Without control systems or energy storage, these variations easily result in voltage instability and power fluctuations.

Lack of hybrid integration: Most of the earlier systems were dependent on either only PV or fuel cell sources. The excess energy could not be stored without a battery storage system and thus supply-demand balance was never maintained during periods of low generation.

Limited control strategies: Conventional systems, on the other hand, employed simple or fixed control schemes that were not adaptive to load variations, thus leading to poor dynamic performance and reduced system stability.

Thus, conventional renewable energy systems failed to maintain the desired DC bus voltage and effective power flow under variable load or environmental perturbations.

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V. PROPOSED SYSTEM

The proposed system, therefore, integrates various renewable sources into a single DC microgrid platform with intelligent control and storage mechanisms to alleviate or overcome these challenges: the "PV and Fuel Cell with Battery DC Microgrid System in MATLAB."

The proposed model includes:

1) Photovoltaic Array (PV): The main source that produces DC power from sunlight.
2) Fuel Cell Stack: A secondary power source that works with an electrochemical process.
3) Li-ion Battery Storage System: Backup power and load fluctuation smoothing.
4) DC-DC Converters-Boost/Buck: These regulate the voltage levels coming from each source before connecting to the common DC bus.
5) MPPT Controller-Perturb and Observe Algorithm: for maximum power extraction from the PV array under variable conditions.

Working Principle of the Proposed System 1. The PV array and Fuel Cell generate DC power, which is boosted using DC-DC converters to maintain the desired DC bus voltage. 2. The Battery serves as both a source and a sink - charging when excess energy is available, discharging when demand goes up or solar/fuel supply diminishes. 3. The MPPT controller continuously monitors the PV voltage and current, tracking where maximum power is obtained. 4. The DC bus collects all the regulated outputs from the various sources and feeds stable power to the connected load.

VI. BLOCK DIAGRAM

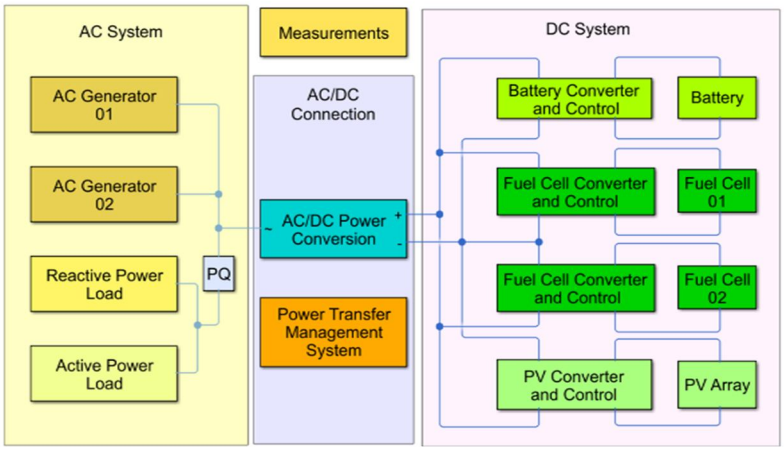


Fig 1- Block Diagram

VII. SYSTEM DESIGN

The proposed system is a PV and Fuel Cell with Battery DC Microgrid System that is designed to integrate renewable energy sources with energy storage and control mechanisms into a single common DC bus network. The system performance is analysed in the presence of different load conditions using MATLAB/Simulink.

The hybrid microgrid has three main sources of energy:

1) Photovoltaic (PV) Array
2) Fuel Cell Stack
3) Battery Energy Storage System (BESS)

Each source is interfaced to the DC bus through an individual DC-DC converter (boost or buck converter), ensuring independent control and voltage regulation. A Maximum Power Point Tracking (MPPT) controller is implemented in order to extract the maximum power from the PV array. The DC bus feeds a variable DC load with a stable and continuous output.

A. Photovoltaic (PV) Array

The PV array directly converts solar radiation into DC power using semiconductor materials, which are usually silicon. Each PV cell produces a small voltage; the cells are arranged in series and parallel to form an array.

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In this project, a 6 kW PV array has been modelled using MATLAB's PV Array block. The output voltage and current depend on the intensity of sunlight and temperature. An MPPT controller has to continuously adjust the operating point for maximum power output for optimal efficiency.

$$I = I_{Ph} – I_0(e^{q(V+IR)/nkT} – 1)\text{-}V+IRS/R_{SH}$$

Whereas,
IPh =Light-generated current
I0 =Diode saturation current
RS, RSh =Series and shunt resistance
V =Output voltage
N =Ideality factor

B. Stack of fuel cells

The Fuel Cell is an electrochemical device that converts hydrogen and oxygen into electricity and water, without combustion. It continuously produces DC power for as long as the fuel is available.

The normal response is:

$$2H2 + O2\ 2H2O + \text{Electrical energy} + \text{Heat}$$

The model used here is a PEM fuel cell. It provides stable voltage output and, when the solar power decreases, serves as a secondary source of energy. Its equivalent circuit involves an activation loss region, ohmic resistance, and mass transport loss in evaluating its efficiency.

C. Battery Energy Storage System (BESS)

Balancing supply and demand through a Lithium-ion battery. It operates in two modes:
Charging Mode: When PV/ Fuel Cell power exceeds the load demand.
Discharging Mode: When generation is insufficient.
The battery provides system stability and continues to deliver power. Its model considers State of Charge, internal resistance, and voltage dynamics.

$$SOC = SOC0 – 1/Q \int ibat(t)\ dt$$

D. DC-DC Converters

The DC-DC converters are crucial for voltage regulation and isolation between the sources of energy and the DC bus. Boost Converter: Used with PV and Fuel Cell to increase the output voltage.

$$VOUT = VI\ N\ /1\ \text{-}D$$

When the switch is ON, energy is stored in the inductor; when OFF, it's released to the output. Buck/Boost Converter: Used w/ Battery for Bidirectional Power Flow, which steps up or steps down the voltage as required during charge/discharge. These converters use MOSFET or IGBT switches, controlled by PWM signals generated in MATLAB.

E. MPPT Controller

A controller with MPPT ensures the PV array operates at its most efficient point. The Perturb and Observe (P&O) algorithm is employed:

1) The controller slightly perturbs the PV voltage
2) If the output power increases, it continues in that direction.
3) If power decreases it reverses the perturbation.

This process repeats continuously, keeping the PV output near the maximum power point.

F. Load

The load represents the electrical demand on the DC bus. In the model, a variable resistive load is used to simulate real- world variations like household or industrial consumption. The performance analysis is conducted under constant, step- change, and variable loads of the system.

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G. MATLAB/ Simulink Environment

All components are modelled in MATLAB/Simulink (PV, Fuel Cell, Battery, DC-DC converters, MPPT, and load). This platform allows: Real-time graphical simulation Power and voltage waveform analysis Performance evaluation in dynamic conditions

VIII. MATLAB/SIMULINK MODEL

The various parts of the MATLAB/Simulink model include:

1) PV Array block with inputs for irradiance and temperature.

2) The boost converter increases and regulates the voltage from the PV array to match the required DC bus voltage of the microgrid. Since PV output varies with solar irradiance and temperature, the converter helps maintain a stable voltage. A Maximum Power Point Tracking (MPPT) algorithm is used to ensure the PV system operates at its maximum power point. The MPPT controller monitors the PV voltage and current and adjusts the converter duty cycle to extract maximum power and improve overall system efficiency.

3) Fuel Cell model using parameters based on Nernst equation with hydrogen flow control

4) Bidirectional DC–DC charge/discharge control. converter for battery

5) The DC bus is the main point where all energy sources and loads are connected in the microgrid system. The DC bus voltage is maintained at a constant level, typically 48V or 120V. Power from the PV array, fuel cell, and battery is supplied to the DC bus through power converters. The load model represents the electrical demand connected to the system.

The performance of the system is simulated for different solar and load conditions.

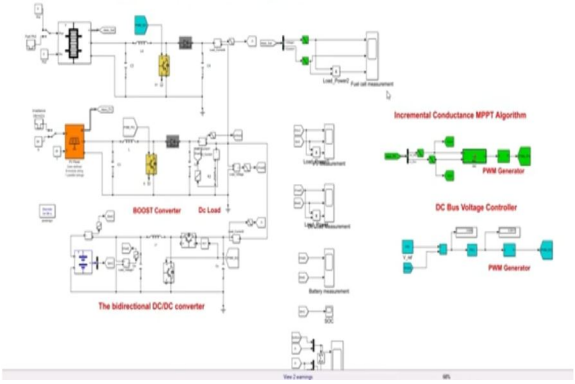


Fig 2- MATLAB Simulation Model

IX. SIMULATION RESULTS

Performance is tested by simulating the system under variable irradiance and load conditions.

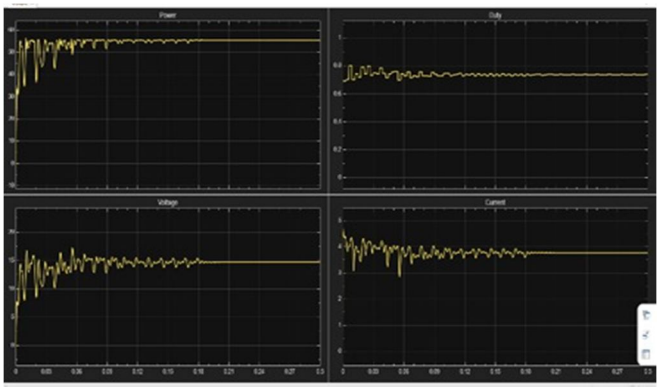


Fig 3- MATLAB Simulation Graph

Case 1: The PV supplies most of the load during high solar irradiance, while excess energy charges the battery.
Case 2: At low irradiance the Fuel Cell begins to supply power in order to maintain DC bus stability.
Case 3: When the load suddenly increases, the battery momentarily discharges to maintain the voltage constant.
Simulation waveforms indicate that the DC bus voltage remains almost constant at 400 V with very minute deviation.

X. HARDWARE KIT

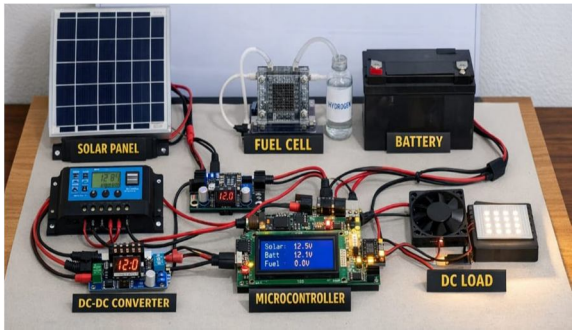


Fig 4- Hardware prototype of the PV–Fuel Cell based Battery DC Microgrid system.

The hardware prototype of the PV and Fuel Cell with Battery DC Microgrid System is shown in Fig. 4. This experimental setup is designed to demonstrate the integration of multiple renewable energy sources with an energy storage system to supply a DC load reliably.

In this system, a solar photovoltaic (PV) panel is used as the primary renewable energy source. The PV panel converts solar radiation into electrical energy and supplies DC power to the system. A charge controller is connected to regulate the voltage and current from the solar panel, ensuring safe charging of the battery and protecting the system from overcharging and reverse current flow.

A fuel cell unit is included as an auxiliary power source to provide additional energy when solar generation is insufficient. The fuel cell generates electricity through an electrochemical reaction between hydrogen and oxygen, producing clean electrical energy along with water as a by-product. This helps improve the reliability and continuity of power supply in the microgrid.

A battery storage unit is incorporated to store excess energy produced by the PV system or fuel cell. The stored energy can be utilized during periods of low generation or high demand, thereby maintaining a stable power supply to the load.

To regulate and stabilize the voltage levels from different sources, DC–DC converters are used. These converters adjust the voltage to the required level and ensure proper power flow between the PV panel, fuel cell, battery, and load.

The entire system is supervised by a microcontroller-based control unit. The microcontroller monitors parameters such as voltage levels of the solar panel, battery, and fuel cell. It also manages the power flow between sources and the load to achieve efficient energy utilization. An LCD display is used to show real-time system parameters.

Finally, the regulated output power is supplied to a DC load, which represents the electrical demand in the microgrid system. The proposed setup demonstrates how renewable energy sources and energy storage can be integrated to form a reliable and sustainable DC microgrid for small-scale applications.

XI. CONCLUSIONS

This work presented the design and analysis of a PV–Fuel Cell–Battery based DC microgrid system for reliable renewable energy utilization. The proposed hybrid configuration combines solar photovoltaic generation, a hydrogen fuel cell source, and a battery storage unit to ensure continuous and stable power supply under varying operating conditions.

Initially, the system was modelled and analysed using MATLAB/Simulink, which demonstrated effective power sharing between the renewable sources and the storage unit. The simulation results confirmed improved voltage regulation, efficient energy utilization, and stable operation of the DC microgrid under dynamic load variations.

To further validate the feasibility of the proposed concept, a small-scale hardware prototype was developed. The prototype integrates a solar panel, fuel cell module, battery storage, DC–DC converters, and a microcontroller-based control system to supply power to a DC load. The hardware setup successfully demonstrates the practical implementation of hybrid energy management in a DC microgrid environment.

The combined simulation and hardware results indicate that the proposed system can effectively enhance the reliability and sustainability of renewable energy-based microgrids. Such hybrid microgrid configurations are particularly suitable for remote locations, distributed energy systems, electric vehicle charging infrastructure, and future smart grid applications.

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XII. FUTURE SCOPE

Although the developed prototype demonstrates the feasibility of the proposed hybrid microgrid system, several improvements can be explored in future research to enhance system performance and scalability.

1) Advanced Hardware Development: The present prototype can be extended into a higher power experimental system using advanced controllers such as DSP or embedded platforms to improve control accuracy and system scalability.

2) Intelligent Control Algorithms: Implementation of intelligent control techniques such as Fuzzy Logic, Artificial Neural Networks (ANN), or Adaptive Control can improve system stability, dynamic response, and energy optimization under varying operating conditions.

3) Hybrid AC/DC Microgrid Expansion: The proposed DC microgrid can be expanded into a hybrid AC/DC architecture capable of interacting with the utility grid, thereby improving flexibility and enabling grid-connected as well as standalone operation.

4) Smart Energy Management System: Integration of an IoT-based monitoring and control platform can enable real-time data acquisition, remote monitoring, and optimal energy management.

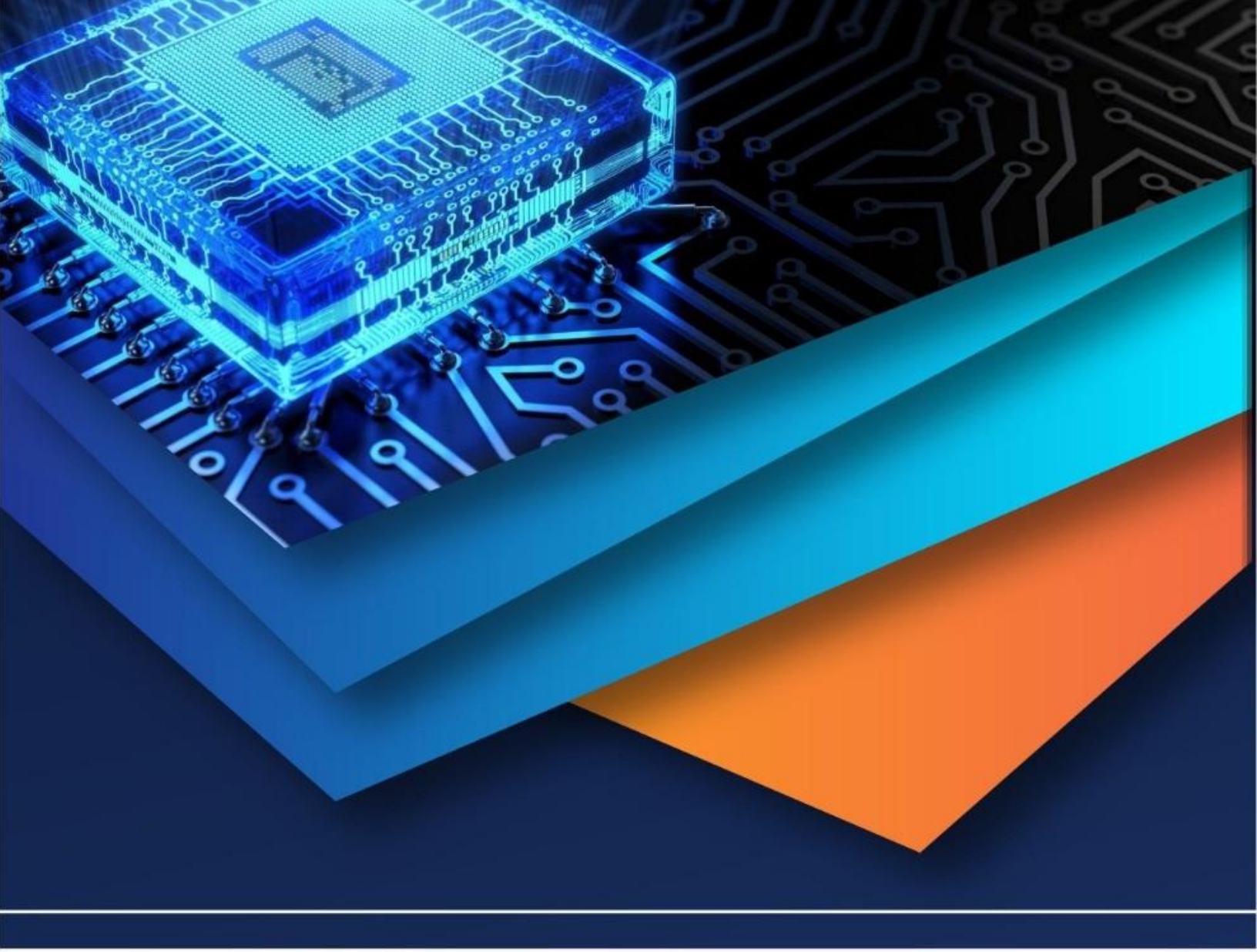
5) Integration of Additional Renewable Sources: Future systems may include other renewable energy sources such as wind turbines, biomass generators, or hydro systems to increase renewable penetration and energy availability.

6) Real-Time Optimization Techniques: The use of machine learning and predictive algorithms for load forecasting and power scheduling could improve long-term efficiency and reduce operational costs.

7) Electric Vehicle Charging Integration: The microgrid can also be adapted to support electric vehicle charging stations, which will become increasingly important in sustainable transportation systems.

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