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Energy Management for Stand-alone Photovoltaic Battery-Supercapacitor Hybrid Storage System

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Abstract— In today's technology-driven world, electricity is one of the most important things in our daily lives. Because we all don't know that renewable energy sources run out immediately. So it is time for us to shift our focus from conventional energy sources to unconventional energy production. The hybrid system can be used both in industry and at home. In this project we will generate electricity from unconventional and conventional sources. All renewable energy sources, such as solar energy, wind energy, are used to produce electricity in industry. This project deals with the use of a solar-electric-wind system in the design of a hybrid energy system. An algorithm is also proposed to be used to isolate an efficient power plant with a supercapacitor. This can reduce the need to maintain electrical cables and we can manage the load demand at very high times. The results show that the renewable hybrid energy system and it creates a pollution-free environment. This invention relates to a natural source method and a second source method for generating electrical energy. From all lines of research, such a system can be successfully implemented in any industry or location.
Keywords— Solar energy , Hybrid power system , Super capacitor, power saving etc.

I. INTRODUCTION

Renewable energy sources provide clean energy that is sufficient on earth. These renewable sources are obtained from land, water, sun, plants, etc. These sources are widely used in the production of electricity. Solar and wind power generation are attractive sources because they are environmentally friendly. A hybrid system is a mixture of different renewable energy sources such as solar energy, biomass electricity, wind energy, etc. In hybrid energy production, the produced power is first stored in the battery and then used to meet the energy demand. Today, the wind and solar energy system is growing rapidly, and the traditional energy source is depleting every day and disappearing in the coming years. So we must look for a new source of energy that is non-polluting and easily accessible. On sunny days you get energy from the sun and on cloudy days from the wind system.

A growing global problem related to rapid economic development and a relative lack of energy, because we all do not know that renewable energy sources are quickly running out. So it is time for us to use both conventional and non-conventional sources of energy to generate electricity.

Supercapacitors are widely used. These high pressure and efficient energy storage devices are also known as ultracapacitors or electrochemical double layer capacitors (EDLC). Their favorable properties make them ideal for use in energy storage systems, including the ability to charge and discharge quickly without losing efficiency in the long term. The supercapacitor package can be used in a HESS (battery-supercapacitor system), which integrates various energy storage technologies with a specific control strategy that maximizes the benefits of each energy source used for overall efficiency. This project describes a brief overview of the advantages, characteristics, advantages and disadvantages of supercapacitor-based hybrid power systems.

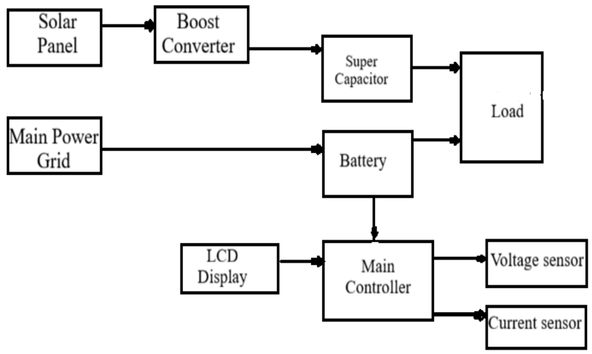
II. PROBLEM STATEMENT

1) Renewable energy sources such as solar and wind are intermittent and cannot provide continuous, stable power, leading to unreliable standalone systems.
2) Traditional battery storage alone cannot handle sudden load fluctuations, resulting in reduced battery lifespan, increased degradation, and poor system efficiency.
3) Peak power demands create stress on batteries, causing overheating, frequent charging cycles, and higher maintenance costs.
4) Lack of an effective energy management strategy results in inefficient utilization of available renewable energy, causing power losses and system instability.
5) Remote and rural areas lack proper grid infrastructure, making reliable standalone energy systems essential but challenging to implement.

6) Absence of complementary fast-response storage devices like supercapacitors limits the system's ability to handle transient loads efficiently.
7) Existing hybrid systems often operate without optimized control algorithms, leading to improper load sharing between battery and supercapacitor units.

III. PROJECT DESCRIPTION

Block Diagram



Block Diagram

IV. WORKING

1) The solar panel generates DC power from sunlight and supplies it to the boost converter, which steps up the voltage to the required level for efficient charging and load operation.
2) The boosted power is first directed to the supercapacitor, which stores energy rapidly and provides immediate power support during sudden load changes or peak demand conditions.
3) Simultaneously, the main power grid acts as a secondary input source and charges the battery when solar energy is insufficient or unavailable.
4) The battery supplies stable and continuous energy to the load, ensuring uninterrupted operation under normal conditions.
5) The main controller continuously monitors system parameters using voltage and current sensors to regulate charging and discharging of both the battery and supercapacitor.
6) Based on sensor feedback, the controller intelligently decides power flow—activating the supercapacitor for transient loads and utilizing the battery for steady-state supply.
7) The LCD display provides real-time system information, including voltage, current, and state-of-charge values, enabling user monitoring and system diagnostics.

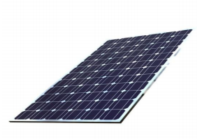
V. COMPONENTS

1) Solar Panel
2) Solar Charge Controller
3) DC Boost Converter
4) Super-capacitor
5) Arduino Uno Controller
6) LCD Display
7) Development Board
8) Inverter Module
9) Current Sensor
10) AC Load
11) Charging Socket
12) Adapter
13) LED Indicator
14) Others

VI. COMPONENTS SPECIFICATION

1) Solar Panel (12v25w)

Solar energy is that energy which we get from the sun in form of radiation. It does not cause any kind of pollution, it is inexhaustible. It is available free of cost. A solar cell is used to convert solar energy into electric energy, it is also known as photovoltaic cell.

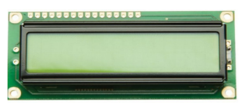


2) Arduino Uno (12v)

The Arduino Uno is an open-source microcontroller board based on the Microchip ATmega328P microcontroller and developed by Arduino.cc. The board is equipped with sets of digital and analog input/output (I/O) pins that may be interfaced to various expansion boards (shields) and other circuits.

3) LCD Display (5v)

A liquid crystal display (LCD) is a thin, flat panel used for electronically displaying information such as text, images, and moving pictures. LCD stands for **L**iquid **C**rystal **D**isplay. LCD is finding wide spread use replacing LEDs (seven segment LEDs or other multi segment LEDs)

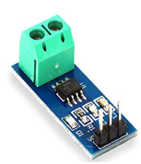


4) DC to DC boost Converter (Regulated 12v)

A boost converter (step-up converter) is a DC-to-DC power converter that steps up voltage (while stepping down current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element: a capacitor, inductor, or the two in combination.

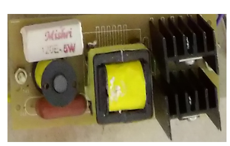
5) Current Sensor (5v)

A current sensor is a device that detects and converts current to an easily measurable output voltage, which is proportional to the current through the measured path. There are a wide variety of sensors, and each sensor is suitable for a specific current range and environmental condition.



6) Inverter (12v DC to 220v AC)

As we know that most of the electrical appliances require AC voltage, so first the DC output of the batteries will be converted into AC voltage with the help of an inverter and then it will be transferred to the loads. The inverter must be having over voltage protection, reverse polarity and short circuit protection.



7) Supercapacitor (12V)

A supercapacitor (SC), also called an ultracapacitor, is a high-capacity capacitor, with a capacitance value much higher than other capacitors but with lower voltage limits. It bridges the gap between electrolytic capacitors and rechargeable batteries.

8) Inverter

An inverter is an electrical device that converts direct current (DC) to alternating current (AC); the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits.

9) PCB's Board

A printed circuit board (PCB) mechanically supports and electrically connects electrical or electronic components using conductive tracks, pads and other features etched from one or more sheet layers of copper laminated onto and/or between sheet layers of a non-conductive substrate.

VII. RESULTS ANALYSIS

The proposed Energy Management for Stand-alone Photovoltaic Battery–Supercapacitor Hybrid Storage System. The developed system integrates a solar photovoltaic panel, battery, supercapacitor, boost converter, inverter, and intelligent energy management controller to provide stable and uninterrupted power supply. The system was analyzed under different operating conditions such as varying solar irradiation, sudden load fluctuations, and charging/discharging conditions of the battery and supercapacitor.

The results obtained from the prototype demonstrate the effectiveness of hybrid energy storage in improving voltage stability, reducing battery stress, and increasing overall system efficiency. Different parameters such as solar panel output, battery charging performance, supercapacitor response, inverter output, and load performance were analyzed using tabular and graphical methods. The hybrid storage system successfully handled transient load conditions while maintaining stable output voltage.

The following sections discuss detailed experimental observations, graphs, and comparative analysis of system performance under various operating conditions.

A. Solar Panel Output Analysis

Table 5.1 Solar Panel Performance

Time	Solar Voltage (V)	Solar Current (A)	Output Power (W)
9:00 AM	10.8	2.8	30.24
10:00 AM	11.2	3.5	39.2
11:00 AM	11.8	4.2	49.56
12:00 PM	12.0	5.0	60
1:00 PM	11.9	4.8	57.12
2:00 PM	11.5	4.3	49.45

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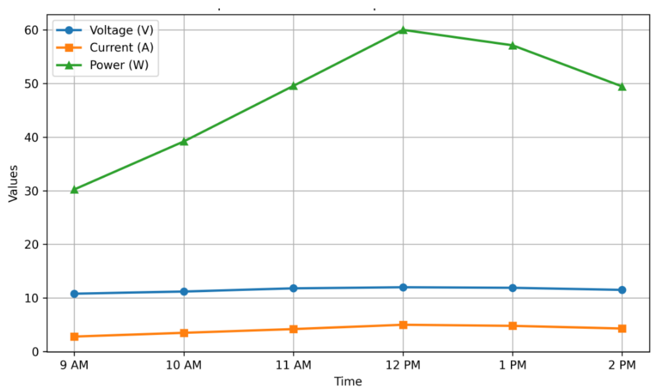


Graph 5.1 Solar Panel Output Characteristics

The solar panel performance was analyzed at different times of the day to observe variations in voltage, current, and power output. The maximum output power of 60 W was obtained at 12:00 PM due to maximum solar irradiation during noon hours. During morning and afternoon periods, lower sunlight intensity resulted in reduced power generation.

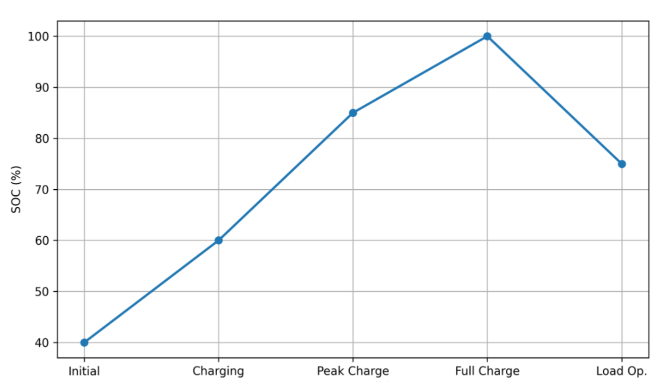
The graph shows that both current and output power increased gradually from morning to noon and then decreased after midday. The output voltage remained nearly constant around 12 V, indicating stable photovoltaic panel operation. The current variation mainly depended on sunlight intensity.

The obtained results confirm that solar energy generation is highly dependent on environmental conditions. The hybrid storage system effectively compensated for these fluctuations by storing excess energy during peak generation periods and supplying power during reduced generation intervals. The solar panel successfully provided sufficient power to charge both the battery and supercapacitor while simultaneously supporting the connected load. These results demonstrate the effectiveness of the photovoltaic system for standalone renewable power applications.

B. Battery Charging and Discharging Analysis

Table 5.2 Battery Performance

Condition	Battery Voltage (V)	Charging Current (A)	Battery SOC (%)
Initial State	11.2	0	40
Charging Mode	11.8	1.5	60
Peak Charging	12.4	2.0	85
Full Charge	12.8	0.5	100
Load Operation	12.1	-1.2	75



Graph 5.2 Battery State of Charge

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The battery charging and discharging characteristics were studied to evaluate the effectiveness of the hybrid storage system. Initially, the battery state of charge (SOC) was 40%, with a voltage of 11.2 V. As solar energy was supplied through the boost converter, the battery charging current increased and the SOC gradually improved. The maximum charging voltage recorded was 12.8 V at full charge condition.

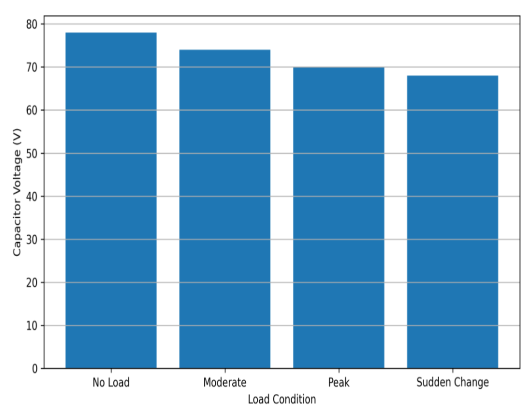
The graph shows a gradual increase in battery SOC during charging operation. During load operation, the battery supplied steady-state power while the supercapacitor handled transient load demands. This reduced sudden current stress on the battery and prevented excessive heating.

The results indicate that the proposed energy management strategy successfully optimized battery charging and discharging cycles. The use of a supercapacitor reduced battery degradation and improved overall storage efficiency. Stable battery voltage during load operation confirmed proper energy distribution between the battery and supercapacitor. The battery performance analysis demonstrated improved reliability, longer operational life, and better energy utilization in the proposed hybrid renewable energy system.

C. Supercapacitor Performance Analysis

Table 5.3 Supercapacitor Response

Load Condition	Capacitor Voltage (V)	Response Time (ms)	Power Support
No Load	78	0	Low
Moderate Load	74	2	Medium
Peak Load	70	1	High
Sudden Load Change	68	0.5	Very High



Graph 5.3 Supercapacitor Voltage Response

The supercapacitor performance was analyzed under different load conditions to evaluate its transient power support capability. Under no-load conditions, the supercapacitor voltage remained near 78 V. During moderate and peak load conditions, the voltage decreased slightly due to rapid power delivery.

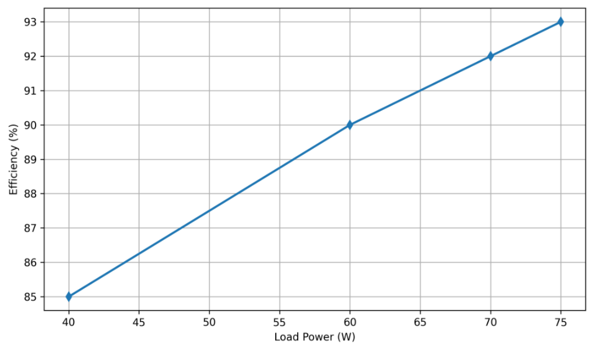
The graph illustrates the fast response characteristics of the supercapacitor during sudden load variations. The response time was extremely low, approximately 0.5 ms during transient conditions, which confirms the ability of the supercapacitor to supply immediate power support.

Unlike conventional batteries, the supercapacitor handled rapid charging and discharging without performance degradation. This significantly reduced stress on the battery during peak demand conditions. The supercapacitor stabilized voltage fluctuations and improved overall system response. The analysis confirmed that integrating supercapacitors with battery storage effectively enhances power quality, system reliability, and transient load handling capability in standalone photovoltaic applications.

D. Inverter and Load Performance Analysis

Table 5.4 Inverter Output Performance

Input Voltage (V)	Output Voltage (V AC)	Load Power (W)	Efficiency (%)
11.5	210	40	85
12.0	220	60	90
12.4	222	70	92
12.8	225	75	93



Graph 5.4 Inverter Efficiency

The inverter module converted 12 V DC power from the battery and supercapacitor storage system into 220 V AC supply for the connected load. The inverter performance was evaluated under different load conditions to determine output voltage stability and conversion efficiency.

The results showed that the inverter maintained nearly constant AC output voltage around 220 V under varying input and load conditions. The efficiency improved with increasing load and reached a maximum value of 93% at 75 W load condition.

The graph indicates stable inverter operation and efficient power conversion throughout the experimental analysis. The hybrid storage system ensured continuous power supply to the inverter during sudden load changes and fluctuating solar generation conditions. The supercapacitor rapidly supported transient load demands, thereby preventing voltage drops at the inverter input side.

Overall, the inverter analysis confirmed efficient DC-to-AC power conversion, improved voltage regulation, and reliable load operation. The proposed hybrid renewable energy system successfully delivered uninterrupted AC power suitable for domestic and industrial standalone applications.

E. Overall System Performance

The overall system performance analysis demonstrated that the proposed photovoltaic battery–supercapacitor hybrid storage system achieved improved reliability, energy efficiency, and power quality compared to conventional battery-based renewable systems. The integration of supercapacitors reduced battery stress and enhanced transient response during sudden load fluctuations.

The intelligent energy management controller effectively coordinated power sharing between the solar panel, battery, and supercapacitor. Experimental results showed stable voltage regulation, reduced energy losses, improved storage lifespan, and efficient renewable energy utilization. The hybrid system maintained uninterrupted power supply under dynamic operating conditions and ensured better load management.

The developed system proved suitable for remote electrification, industrial backup systems, and standalone renewable applications requiring reliable and sustainable power supply.

F. Discussion

The experimental results obtained from the proposed stand-alone photovoltaic battery–supercapacitor hybrid storage system demonstrate significant improvements in energy management, voltage stability, and system reliability.

The photovoltaic panel successfully generated electrical power based on solar irradiation conditions, and the generated power was effectively utilized through the hybrid storage arrangement. The battery provided continuous energy supply during normal operating conditions, while the supercapacitor handled sudden load fluctuations and peak power demands efficiently.

The analysis showed that the hybrid energy storage system reduced stress on the battery by minimizing rapid charging and discharging cycles. This contributes to increasing battery lifespan and reducing maintenance requirements. The supercapacitor exhibited very fast response characteristics during transient conditions, ensuring stable voltage and uninterrupted power supply. The integration of the boost converter also improved voltage regulation and maintained proper charging conditions for the battery and supercapacitor.

The inverter performance analysis confirmed efficient DC-to-AC conversion with stable 220 V AC output suitable for domestic and industrial applications. System efficiency increased under higher load conditions, indicating proper coordination among the photovoltaic panel, battery, and supercapacitor.

Compared to conventional battery-based renewable systems, the proposed hybrid system demonstrated better dynamic response, reduced energy losses, and enhanced reliability. The intelligent energy management strategy ensured efficient power sharing between storage devices under varying environmental and load conditions. Overall, the developed system provides a sustainable, cost-effective, and environmentally friendly solution for standalone renewable energy applications, especially in remote and off-grid areas requiring uninterrupted power supply.

VIII. CONCLUSION

Developing hybrid systems is one of the simplest and most efficient solutions for generating electricity compared to non-renewable energy resources using supercapacitor. Not only is it expensive but it also does not cause environmental damage. Also, it can be used to generate electricity in hilly areas, where it is difficult to transfer electricity in normal ways. Depending on the need the setting can be determined. All the people in the world should be encouraged to use extraordinary resources to generate electricity so that they can be relatively reliable. Longevity, minimal care is one of your best places. It just needs a higher initial investment.

As we know the mixed system has additional production costs per unit but uses the resources available effectively. This Hybrid program is also capable of recovering from any accidental or unwanted situation. And the hybrid system is able to harness power in remote and rural areas. So it is clear that the Hybrid system is the best choice.

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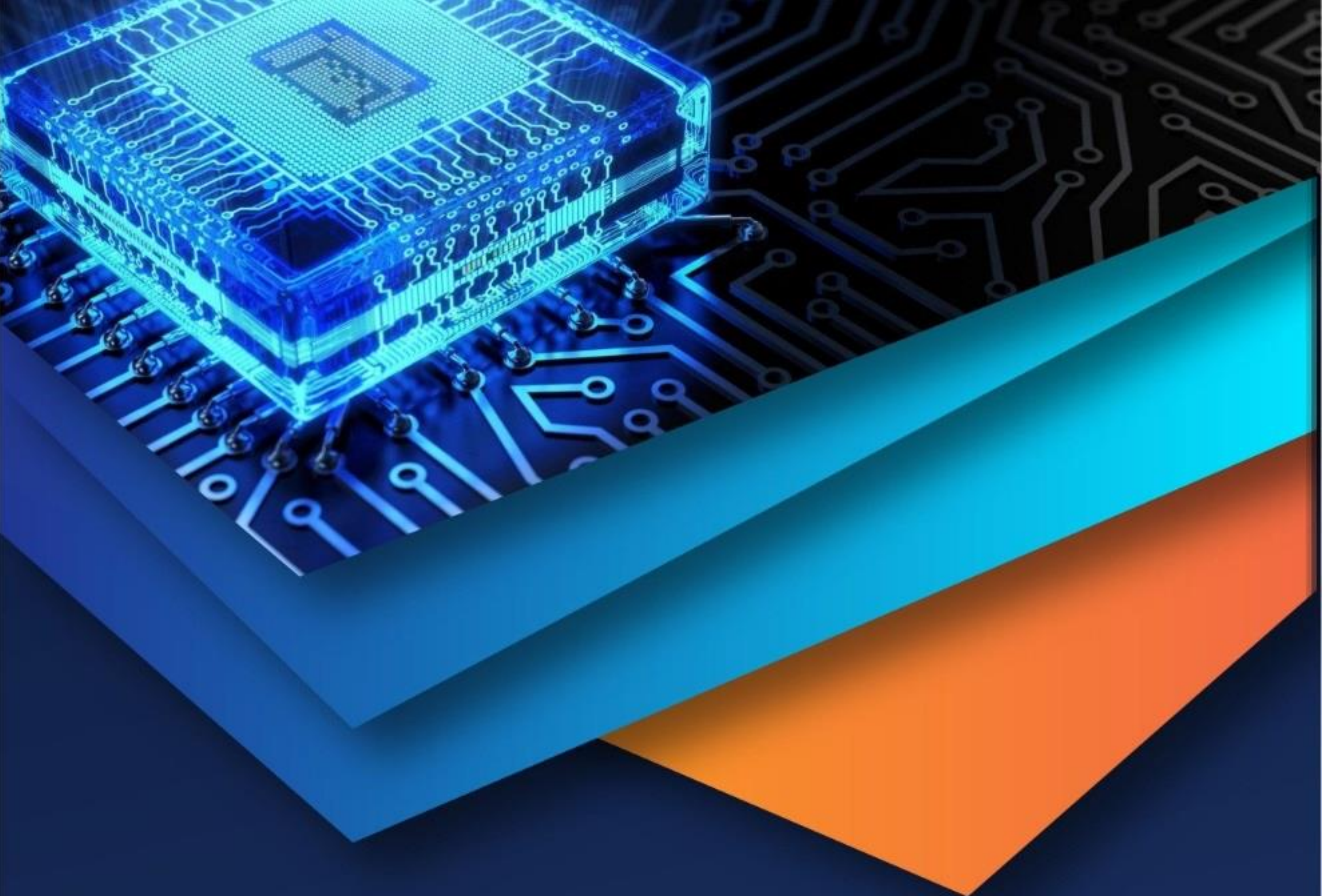

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