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Voltage Sag Control in Hybrid Systems Using SMES-DVR

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Abstract: Hybrid renewable systems combining wind and photovoltaic (PV) sources often experience voltage sags that degrade power quality during grid disturbances. This paper proposes a Fuzzy Logic Controller (FLC)-based Dynamic Voltage Restorer (DVR) integrated with a Superconducting Magnetic Energy Storage (SMES) system for rapid voltage sag mitigation. The system is modelled and simulated in MATLAB/Simulink under symmetrical fault conditions. Simulation results demonstrate that the FLC-based SMES–DVR effectively restores the load voltage with minimal overshoot and oscillations, while also providing a faster response and improved stability compared to conventional DVR approaches.

Keywords: Hybrid PV–Wind System, Voltage Sag Mitigation, SMES-DVR, Fuzzy Logic Control, Power Quality, Renewable Energy.

I. INTRODUCTION

Hybrid renewable energy systems, particularly those combining solar photovoltaic (PV) and wind sources, are increasingly recognized as sustainable solutions for reliable power generation. Despite their potential, integrating these systems with the grid often introduces power quality challenges, with voltage sags being among the most critical due to sudden faults or abrupt load variations. Such voltage dips can adversely affect sensitive industrial equipment and compromise system stability. Dynamic Voltage Restorers (DVRs) have emerged as an effective device to counteract these sags by injecting the required compensating voltage. Additionally, Superconducting Magnetic Energy Storage (SMES) systems offer rapid energy support, which enhances the dynamic response of DVRs. Traditional control strategies for DVRs often struggle to handle nonlinearities and rapid disturbances, prompting the adoption of intelligent approaches like fuzzy logic controllers (FLCs). Fuzzy Logic Controllers (FLCs), known for their adaptability and robustness, can significantly improve the performance of real-time voltage compensation. In this study, an SMES-integrated DVR controlled by an FLC is implemented within a hybrid PV–wind system, and its effectiveness under symmetrical fault conditions is assessed through detailed MATLAB/Simulink simulations.

II. LITERATURE SURVEY

Hybrid renewable energy systems, particularly those integrating photovoltaic and wind power sources, are increasingly used in modern distribution networks. However, these systems are highly susceptible to voltage fluctuations and grid disturbances, which may lead to voltage sags and adversely affect sensitive loads [3]. To mitigate such disturbances, the Dynamic Voltage Restorer (DVR) has been widely adopted as an effective power quality enhancement device due to its fast response and series voltage compensation capability [5]. Despite its effectiveness, a DVR operated with conventional PI control may exhibit slower dynamic response and insufficient compensation performance during nonlinear or rapidly varying operating conditions [5].

To improve control accuracy under such conditions, Fuzzy Logic Controllers (FLCs) have been implemented in DVR systems. FLCs offer superior adaptability and do not require precise mathematical modelling, making them effective for nonlinear and dynamic power system environments [2]. Further enhancement in sag compensation performance has been demonstrated by integrating Superconducting Magnetic Energy Storage (SMES) with DVRs. The SMES unit provides rapid active power injection during voltage dips, thereby improving system stability and reducing the time required for voltage recovery [1]. Studies have shown that DVRs supported by SMES and controlled using fuzzy logic achieve faster restoration and smoother voltage waveforms when compared to conventional DVR systems [4].

Hybrid PV–wind generation supported by DVR–SMES systems has therefore become a promising approach for ensuring reliable and high-quality power delivery in modern power networks [3].

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III. MATERIALS AND METHODS

The proposed system is modelled and simulated in MATLAB/Simulink R2014a to evaluate voltage sag compensation performance in a hybrid renewable energy environment. The proposed hybrid renewable system is modelled and simulated in MATLAB/Simulink R2014a to evaluate voltage sag compensation performance. The system integrates a photovoltaic (PV) array and a DFIG-based wind turbine, interfaced through DC–DC converters and a PWM-based voltage source inverter, supplying regulated power to the grid. MATLAB/Simulink allows detailed modelling of power electronics, renewable sources, and control strategies, while measurement blocks and scopes enable real-time monitoring of load voltage, DVR injection, and ripple levels, ensuring accurate observation of dynamic and steady-state behavior. The hybrid source consists of a photovoltaic (PV) array and a Doubly Fed Induction Generator (DFIG)-based wind turbine, which together supply power to the grid under normal operating conditions. The power output of both renewable sources is interfaced through DC–DC converters and a PWM-based voltage source inverter to maintain regulated power flow.

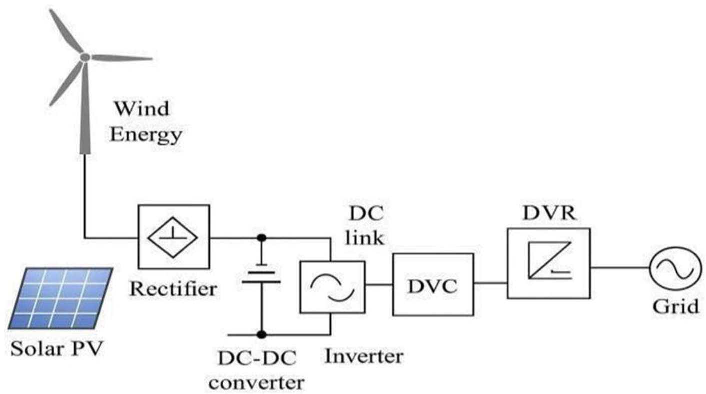


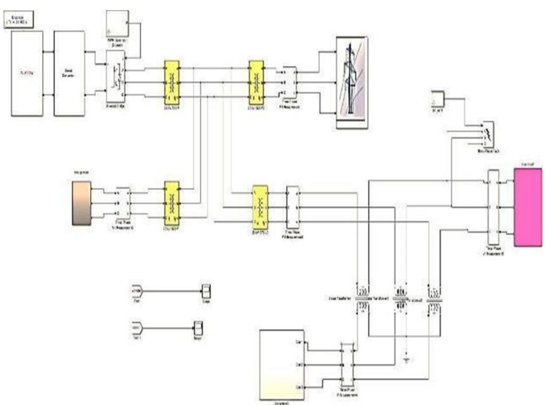
Fig : Hybrid Renewable Energy System

To mitigate voltage disturbances, a Dynamic Voltage Restorer (DVR) is connected in series with the load. The DVR injects the required compensating voltage during fault conditions to maintain the load voltage close to its nominal level. To ensure fast and stable support to the DVR during deep voltage sags, a Superconducting Magnetic Energy Storage (SMES) unit is integrated at the DC link. The SMES provides instantaneous active power, enabling rapid sag compensation and preventing voltage collapse.

A Fuzzy Logic Controller (FLC) is employed to generate the switching pulses for the DVR's voltage source inverter. The input variables of the controller are the voltage error and the change in error, which are processed through fuzzification, rule-based inference and defuzzification. The fuzzy controller enables adaptive and nonlinear control action, improving response time and reducing ripple compared to conventional PI control. To evaluate system performance, symmetrical (three-phase) and asymmetrical (single/dual-phase) voltage sags of 12% and 25% magnitudes are introduced at the point of common coupling. The load voltage waveform, recovery time, and voltage stability are observed to assess the compensation capability. The results show that the SMES-assisted DVR with fuzzy control provides faster voltage restoration, reduced harmonic distortion, and improved stability, especially under unbalanced fault conditions.

IV. RESULTS AND DISCUSSIONS

The suggested method uses a grid-connected hybrid energy system that combines photovoltaic (PV) and wind power sources to provide a steady supply of electricity. A grid-connected hybrid energy system that combines photovoltaic and wind power sources aims to ensure a stable and uninterrupted electrical supply through its integration. This innovative approach not only harnesses renewable energy but also contributes to the resilience and sustainability of the power grid. To improve power quality and keep voltage stable during disturbances, a Dynamic Voltage Restorer (DVR) with a Superconducting Magnetic Energy Storage (SMES) unit is used. A Fuzzy Logic Controller (FLC) regulates the DVR operation, dynamically adjusting the injected voltage based on load conditions and fault severity. The SMES-assisted DVR quickly detects voltage sags and injects the necessary compensating voltage, keeping the load voltage within desired limits. The hybrid PV–wind configuration was developed and simulated in MATLAB/Simulink to analyse its performance under both symmetrical and asymmetrical fault conditions, resulting in voltage sags of 12% and 25%. The proposed SMES-DVR controlled by a fuzzy logic algorithm showed rapid voltage restoration and reliable operation throughout all scenarios.



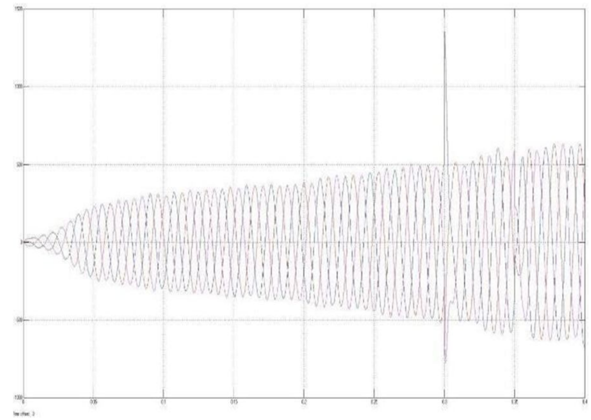
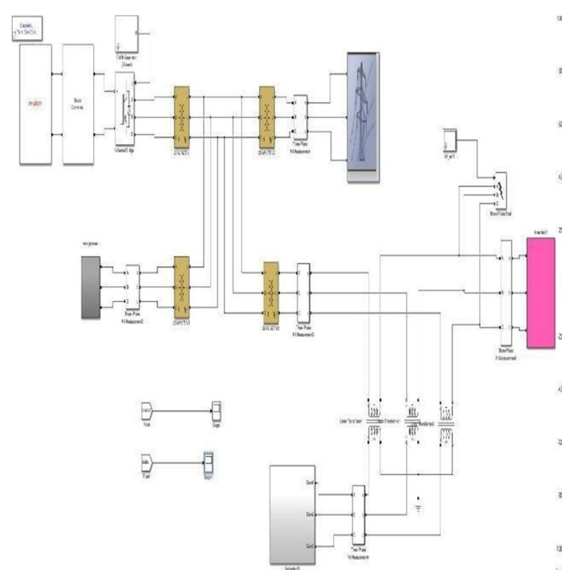


Fig 1: Case of symmetrical fault leading to 25% voltage sag, initiated approximately at this time interval, analyzed without fuzzy logic control

Fig 2: Load voltage during 25% symmetrical voltage sag without fuzzy logic control

Fig 1 shows the voltage drop occurring uniformly across all three phases during a symmetrical fault. Without fuzzy control, the DVR is unable to fully compensate, resulting in a partial sag in the load voltage. Fig 2 During the 25% symmetrical fault (0.20–0.245 s), the load voltage drops to about 270 V and recovers slowly to around 325 V. Without fuzzy control, DVR compensation is insufficient, resulting in 0.045 s recovery time and high ripple in the waveform.



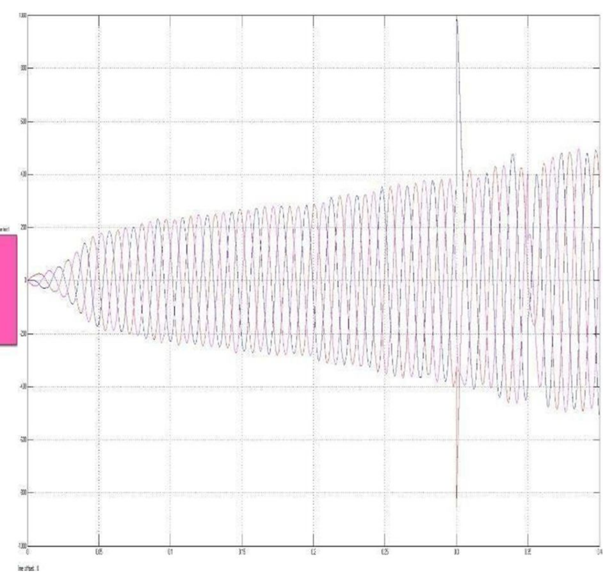
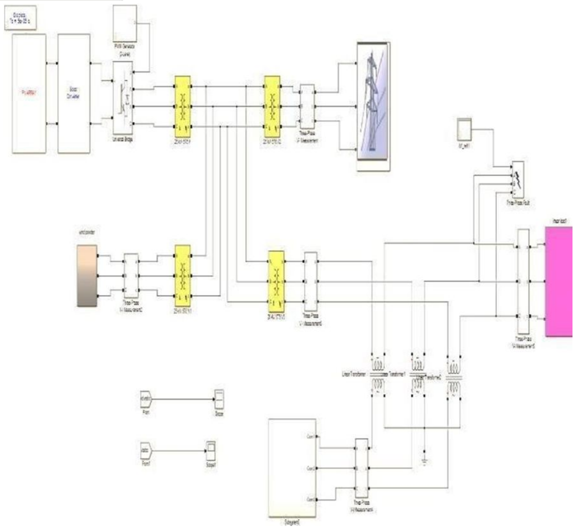


Fig 3: Case of symmetrical fault leading to 25% voltage sag, initiated approximately at this time interval, analyzed with fuzzy logic control.

Fig 4: Load voltage during 25% symmetrical voltage sag with fuzzy logic control.

Fig 3 shows significant drop in voltage is noted across all phases due to the severe symmetrical fault. With fuzzy logic control, the DVR quickly injects the compensating voltage needed to restore the load voltage closer to its nominal value. The waveform becomes more stable with reduced sag and minimized distortion. Fig 4 describes during the 25% symmetrical fault (0.200–0.225 s), the load voltage drops to about 288 V and recovers quickly to around 328 V. With fuzzy logic control, the



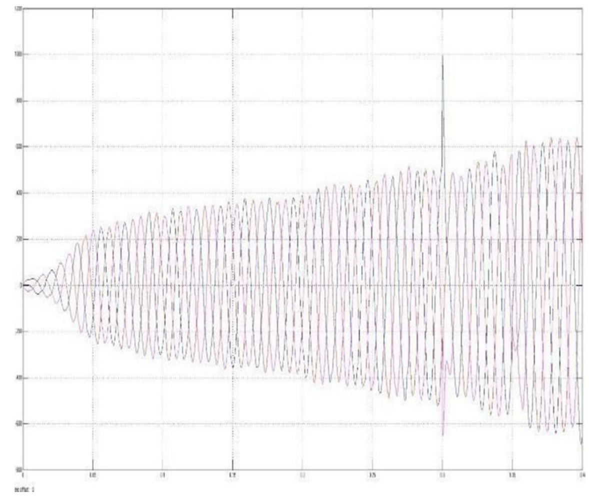
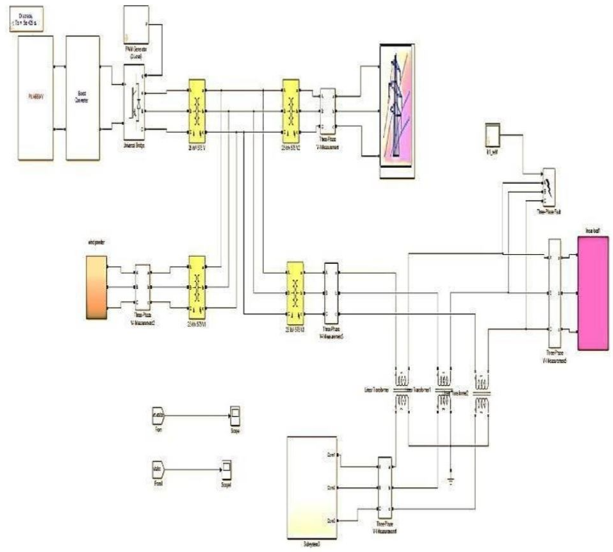


Fig 5: Case of symmetrical fault leading to 12% voltage sag, initiated approximately at this time interval, analyzed without fuzzy logic control

Fig 6: Load voltage during 12% symmetrical voltage sag without fuzzy logic control.

DVR injects 40 V to support the load, achieving rapid recovery in 0.025 s with very low ripple in the waveform.

Fig. 5 shows the load voltage response during a 12% symmetrical voltage sag affecting all three phases. Without fuzzy logic control, the DVR is unable to fully restore the voltage, resulting in a partial sag at the load. Fig 6 shows during the 12% symmetrical fault (0.200–0.240 s), the load voltage drops to about 295 V and recovers to around 328 V. Without fuzzy logic control, the DVR injects 33 V, resulting in a slower recovery of 0.040 s with medium ripple in the waveform.



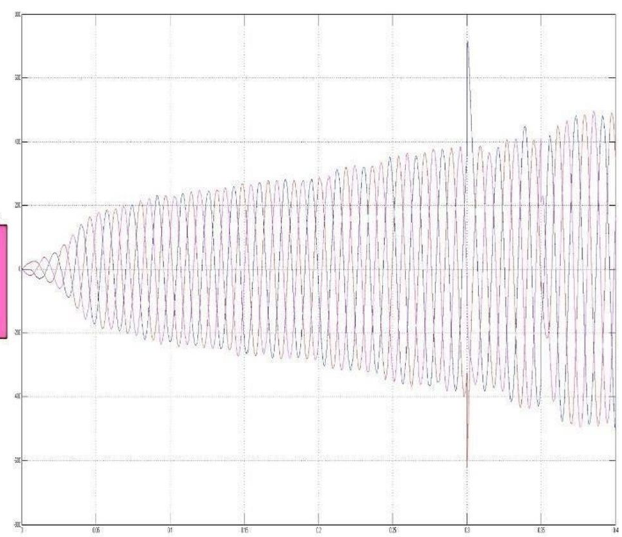


Fig 7: Case of symmetrical fault leading to 12% voltage sag, initiated approximately at this time interval, analyzed with fuzzy logic control

Fig 8: Load voltage during 12% symmetrical voltage sag without fuzzy logic control.

Fig. 7 shows the load voltage response during a 12% symmetrical voltage sag affecting all three phases. Without fuzzy logic control, the DVR is unable to fully restore the voltage, resulting in a partial sag at the load. Fig 8 shows during the 12% symmetrical fault (0.200–0.220 s), the load voltage drops to about 300 V and recovers rapidly to around 330 V. With fuzzy logic control, the DVR injects 30 V, achieving fast recovery in 0.020 s with very low ripple in the waveform.

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To avoid redundancy and maintain clarity in the results, only the symmetrical sag cases (12% and 25%) are presented in waveform form. The asymmetrical sag cases also were analyzed, but their results are summarized in tabulated form in the following section for concise comparison. This approach highlights the key performance improvement while preventing repetition of similar waveform patterns. The results of both symmetrical and asymmetrical voltage sag cases are compared in terms of sag depth, Sag start time, sag cleared, DVR injection start, and load voltage restoration, Recovery Voltage, Injected voltage with and without the fuzzy logic controller. Table 1 summarizes the key quantitative performance metrics, highlighting the effectiveness of the proposed SMES-DVR system with fuzzy logic in mitigating voltage sags across different fault conditions. This comparison clearly demonstrates the improvement in load voltage stability and faster recovery achieved by the fuzzy logic-based control strategy.

Table 1: Simulation results of 25% & 12% Symmetrical and Asymmetrical Faults using without Fuzzy Logic Controller.
The table compares load voltage responses for symmetrical and asymmetrical faults at 12% and 25% sag depths without fuzzy logic control. Higher sag depths and asymmetrical faults result in larger voltage drops, longer recovery times, and higher DVR injection efforts, highlighting the limitations of conventional DVR operation.

Fault type	Controller Used	Sag Depth	Sag Start (s)	Sag Cleared (s)	DVR Injection Start (s)	Sag Voltage (V)	Recovery Voltage (V)	Recovery Time (s)	Injected voltage (v)	Ripple Level
Symmetrical	Without Fuzzy	25%	0.2	0.245	0.205	270	325	0.045	55	High
Asymmetrical	Without Fuzzy	25%	0.2	0.250	0.205	260	320	0.050	60	High
Symmetrical	Without Fuzzy	12%	0.2	0.240	0.205	295	328	0.040	33	Medium
Asymmetrical	Without Fuzzy	12%	0.2	0.245	0.205	290	325	0.045	35	Medium

Table 2: Simulation results of 25% & 12% Symmetrical and Asymmetrical Faults using a Fuzzy Logic Controller
The table shows the load voltage responses for symmetrical and asymmetrical faults with fuzzy logic control at 12% and 25% sag depths. The fuzzy logic controller improves voltage restoration, reducing recovery time, injected voltage, and ripple levels compared to conventional DVR operation, demonstrating enhanced sag mitigation performance

Fault type	Controlled Used	Sag Depth	Sag Start (s)	Sag Cleared (s)	DVR Injection Start (s)	Sag Voltage (V)	Recovery Voltage (V)	Recovery Time (s)	Injected voltage (v)	Ripple Level
Symmetrical	With Fuzzy	25%	0.2	0.225	0.2	288	328	0.025	40	Very low
Asymmetrical	With Fuzzy	25%	0.2	0.230	0.2	285	327	0.030	42	low
Symmetrical	With Fuzzy	12%	0.2	0.220	0.2	300	330	0.020	30	Very low
Asymmetrical	With Fuzzy	12%	0.2	0.225	0.2	298	330	0.025	32	low

V. CONCLUSION

The fuzzy logic simulation results demonstrate that the DVR–SMES system outperforms both PI- controlled and non-fuzzy setups. With fuzzy logic, the recovery time decreased from 0.040–0.055 s (PI) to 0.020–0.030 s, and the injected voltage decreased from 60–78 V to 30–42 V. This reduced the amount of work needed to compensate by almost 40%. Ripple levels also fell by 65–70%, yielding smoother voltage restoration near the nominal 330 V. Overall, fuzzy logic enables faster recovery, lower energy demand, and improved voltage stability, providing a more effective solution for sag mitigation in hybrid renewable systems.

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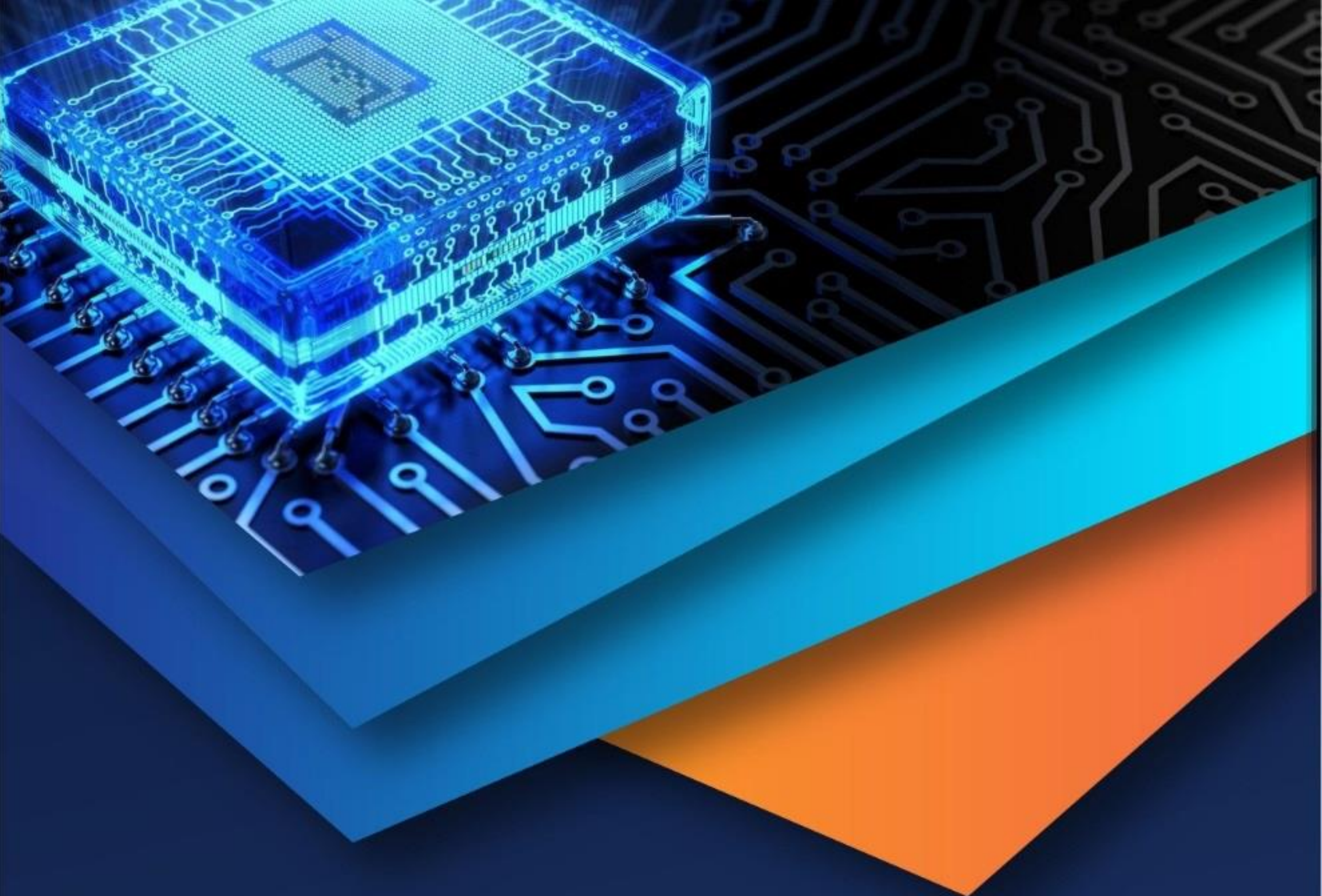

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