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Multi-Level Inverter Modeling and Simulation Using Various and Complex PWM Modulation in MATLAB/Simulink

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Abstract: Thispaperpresentsadetailedcomparisonofseveral multilevel inverter (MLI) topologies, including Neutral Point Clamped (NPC), Flying Capacitor (FC), Cascaded H-Bridge (CHB), and Modular Multilevel Converter (MMC). Application domains, control schemes, modularity, voltage balancing, and structural complexity are the main topics of the analysis. Each topology's component requirements, modulation techniques, and performancetrade-offsareexamined.Simulationresultsvalidate thetheoreticalevaluationandshowhoweachtopologyissuitable forspecificapplicationssuchaselectricdrives,renewableenergy systems, and high-voltage direct current (HVDC) transmission. The study aims to assist researchers and engineers in selectingthe optimal MLI topologies according to the requirements of specific applications.
Index Terms: Multi-level Inverter, PWM, SVPWM, SHE, MATLAB/Simulink, THD, Modeling.

I. INTRODUCTION

The development of power electronic systems has brought about significant changes in power conversion and control. Among these developments, Multi-Level Inverters (MLIs) have gained popularity as a solution for medium- and high- power applications because of their ability to generate a high- quality output voltage with lower harmonic content, lower electromagnetic interference (EMI), and less voltage stress on power semiconductor devices [1], [2].
Conventionaltwo-levelinverters'performanceisoftenlim- ited by high switching losses and harmonic distortion, espe- cially in high-voltage applications. Multi-level inverters such asNeutralPointClamped(NPC),FlyingCapacitor(FC), andCascadedH-Bridge(CHB)improvevoltageresolution by generating a stepped output waveform from multiple DC levels[3].Largefiltersarenolongernecessarythankstothese topologies, which also improve system efficiency.
The effectiveness of MLIs is directly influenced by the modulation technique employed. Although they are easy to use,simplemodulationtechniqueslikeSinusoidalPulseWidth Modulation (SPWM) do not maximize harmonic performance or DC bus utilization [4]. Advanced modulation techniques such as Space Vector Pulse Width Modulation (SVPWM), Level-ShiftedPWM(LSPWM),andSelectiveHarmonicElim- ination(SHE)havebeendevelopedtoaddresstheseissues[5], [6]. These methods enhance waveform quality, reduce switch- ingfrequency,andenableselectivecontrolofharmoniccom- ponents.ModelingandsimulationarekeycomponentsofMLI system design and performance analysis. MATLAB/Simulink provides a comprehensive environment for accurately and flexible modeling inverter circuits and implementing control strategies [7]. It enables a detailed analysis of switching behavior,harmonicdistortion,andthermalperformanceunder various modulation schemes.
This paper focuses on modeling and simulating three- and five-level inverter topologies using multiple PWM techniques in MATLAB/Simulink. The goal is to evaluate the perfor- mance in terms of total harmonic distortion (THD), voltage waveform quality, and control complexity. The rest of the paper is organized as follows: The MLI topologies are ex- plained in Section II, different PWM techniques are described in Section III, the simulation model is presented in SectionIV,resultsandcomparisonarediscussedinSectionV,andthe paper is concluded in Section VI. .

II. OVERVIEW OF MULTI-LEVEL INVERTER TOPOLOGIES

Apowerelectronicconverterknownasamulti-levelinverter (MLI) creates a stepped AC output by combining several DC voltage levels. They use fewer filters, lower electromagnetic interference(EMI)anddv/dtstress,andgreatlyimprove the quality of the output waveform [1], [2]. Diode-Clamped (NPC),FlyingCapacitor(FC),andCascadedH-Bridge(CHB) are the three main multilevel inverter topologies; each has a distinct structure and range of applications.

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A. Diode-Clamped(NeutralPointClamped)MLI

The Diode-Clamped Multilevel Inverter (DCMLI), also known as the Neutral Point Clamped (NPC) inverter, is oneof the earliest and most widely used multilevel topologies. Clampingdiodesareintroducedtoallowtheuseofasingle DC source for multiple voltage levels while reducing the voltage stress on power devices.

1) StructureandWorkingPrinciple: Atypical$n$-levelNPC inverter consists of:

- $2(n-1)$switchingdevicesperphase.
- $(n-2)$clampingdiodesperphase.
- SingleDCsourcesplitinto$(n-1)$equalpartsusing capacitors.

For a three-level NPC inverter, the output voltage (V_o) with respect to the midpoint (neutral) can be represented as:

$$V_o = \begin{cases} +V_{dc}/2 & \text{if } S_1, S_2 = \text{ON} \\ 0 & \text{if } S_2, S_3 = \text{ON} \\ -V_{dc}/2 & \text{if } S_3, S_4 = \text{ON} \end{cases} \quad (1)$$

whereS_1toS_4aretheseries-connectedswitchesperphase.

2) VoltageLevelGeneralization: Foran$n$-levelNPCin- verter, the number of distinct output voltage levels is:

$$L = 2n - 1 \quad (2)$$

However,inpracticalsymmetricdesignusingasingleDC sourcesplitintoequalvoltages,theoutputvoltagelevelsare:

$$V_o = -\frac{(n-1)V_{dc}}{2}, \ldots, 0, \ldots, +\frac{(n-1)V_{dc}}{2} \quad (3)$$

3) SwitchingLogicAlgorithm: Asimplifiedlogictodeter-minetheswitchingstatesbasedondesiredoutputvoltagelevel is shown below:

OutputLevel	S_1	S_2	S_3	S_4
$+V_{dc}/2$	ON	ON	OFF	OFF
0	OFF	ON	ON	OFF
$-V_{dc}/2$	OFF	OFF	ON	ON

4) Advantages and Limitations:

Advantages:

- Reducedvoltagestressperswitch.
- Goodharmonicperformance.
- Suitableformedium-voltageindustrialdrives.

Limitations:

- Unequalcapacitorvoltagebalancinginhigherlevels.
- Diodecountincreasessignificantlywith$n$.
- *Applications:* Thistopologyisextensivelyusedin:
  - Industrialmotordrives.
  - Medium-voltagevariable-speeddrives.
  - UPSsystemsandgrid-connectedinverters

B. FlyingCapacitorMultilevelInverter(FCMLI)

TheFlyingCapacitorMultilevelInverter(FCMLI)topology, which employs capacitors as voltage clamping devices rather than diodes, enables higher voltage levels and more adaptable voltage control. This structure allows for better voltage bal-ancingbetweenswitchingdevices,butatthecostofadditional components and more complex control. [**?**], [**?**].

1) *Structure and Operation Principle:* An n-level FCMLI consists of:
- $2(n-1)$switchingdevicesperphase.
- $(n-1)(n-2)/2$flyingcapacitors.
- AsingleormultipleDCsources,typicallyone. capacitors to synthesize the required output voltage level. The output voltage levels for a phase-leg can be expressed as:

$$V_o = \sum_{i=1}^{n-1} a_i \cdot \frac{V_{dc}}{n-1}, \quad a_i \in \{-1, 0, 1\} \tag{4}$$

where $a_i$is the state of the flying capacitor stage, determining whether it contributes positively, negatively, or is bypassed.

2) *VoltageLevelandCapacitorCount:* Foran$n$-level FCMLI, the total number of distinct output levels is:

$$L = 2n - 1 \tag{5}$$

Thenumberofrequiredflyingcapacitorsperphaselegis givenby:

$$C = \frac{(n-1)(n-2)}{2} \tag{6}$$

3) *BasicSwitchingLogic:* Theswitchingstatesarecare- fully selected to:

- Synthesizethedesiredoutputvoltage.
- Maintainchargebalanceacrossflyingcapacitors.

An example switching table for a 3-level FCMLI is shown below:

OutputVoltage	S_1	S_2	FlyingCapacitorStatus
$+V_{dc}/2$	ON	OFF	Charging
0	ON	ON	Idle
$-V_{dc}/2$	OFF	ON	Discharging

4) *ControlAlgorithm:* Asimplifiedcontrollogicalgorithm for the FCMLI is as follows:
- Measureoutputvoltage$V_o$andcapacitorvoltagesV_{Ci}.
- Determinedesiredoutputlevelbasedonmodulation reference.
- Selectswitchcombinationsthatachievedesired$V_o$while minimizing capacitor voltage error:

$$\min \sum_i |V_{C_i} - V_{ref}| \tag{7}$$

- Unequalcapacitorvoltagebalancinginhigherlevels.

5) *AdvantagesandLimitations:*

Advantages:

- BettervoltagebalancingcomparedtoNPC.
- Increasedredundancyallowsfault-tolerantoperation.
- Capableofgeneratingmorevoltagelevelswithfewer sources.

Limitations:
- Controliscomplexduetocapacitorvoltagebalancing.
- Largenumberofcapacitorsforhigherlevels.
- High switching losses due to frequent balancing opera- tions.

Applications:
- High-performancemotordrives.
- Renewableenergyinterfacesystems.
- Aircraftelectricpropulsionandnavalsystems.

$$N_{FC} = \frac{(n-1)(n-2)}{2} \quad (8)$$

The requirement for dynamic voltage balancing and capacitor pre-chargingaddstothecomplexityofthecontrol[4].Due totheircostandspacerequirements,FCinvertersareless feasibleforsystemsthatneedmultiplelevels,despitetheir superior dynamic performance.

C. .CascadedH-Bridge(CHB)MultilevelInverter

The modular and scalable Cascaded H-Bridge Multilevel Inverter (CHB-MLI) topology consists of several H-bridge cells connected in series per phase. Typically, each H-bridge cell is powered by a different DC source. The CHB topologyisperfectforrenewableenergyintegrationandelectricvehicle (EV) propulsion systems due to its high modularity, fault tolerance, and simplicity of implementation. [16], [17].

1) *Structure and Operation Principle:*Each phase leg ofan m-level CHB inverter is composed of $s = \frac{m-1}{2}$H-bridge cells, with each cell generating three voltage levels: $+V_{dc}$, 0, and $-V_{dc}$.

The output voltage per phase is the sum of voltages pro- duced by each H-bridge cell:

$$V_o(t) = \sum_{i=1} v_i(t) \quad (9)$$

where $v_i(t)$ is the output voltage of the i-th H-bridge cell.Each H-bridge output voltage $v_i$can be:

$$v_i \in \{-V_{dc}, 0, +V_{dc}\} \quad (10)$$

2) *TotalOutputLevels:*ForsH-bridgesperphase,thetotal number of voltage levels m is given by:

$$m = 2s+1 \quad (11)$$

For example, using 3 H-bridges per phase, a 7-level output $(\{-3V_{dc}, -2V_{dc}, \ldots, +3V_{dc}\})$isobtained.

3) *Logic Algorithm for Modulation:* The CHB inverter often uses Phase Shifted Pulse Width Modulation (PS-PWM) or Selective Harmonic Elimination (SHE-PWM) to reduce harmonic distortion. A general algorithm for PS-PWM is:

- Define carrier signals for each H-bridge with equal amplitude and frequency but with phase shifts of:

$$\theta_i = \frac{(i-1)\cdot 180^\circ}{s}, \quad i = 1, 2, \ldots, s \quad (12)$$

- Compareeachcarrierwiththesamesinusoidalreference signal.
- GenerategatesignalsforeachH-bridgeaccordingly.
- Sum the outputs to construct a staircase voltage wave- form.

Selective Harmonic Elimination (SHE-PWM): SHE- PWMcalculatesswitchingangles $\theta_1, \theta_2, \ldots, \theta_s$that eliminate selected harmonics using the Fourier equation of the output voltage:

$$V_o(\omega t) = \sum_{n=1,3,5,\ldots}^{\infty} \left[\frac{4V_{dc}}{n\pi} \sum_{i=1}^{s} \cos(n\theta_i) \right] \sin(n\omega t) \quad (13)$$

wherethegoalistoeliminatespecificharmonics(e.g.,5th, 7th) by solving a system of transcendental equations for θ_i.

4) Advantages:
- Highmodularity—eachH-bridgeisidenticalandinde- pendent.
- Scalabilitytohighervoltagelevels.
- Lowerharmonicdistortionwithpropermodulation.
- Noneedforclampingdiodesorflyingcapacitors.
- Fault-tolerantcapability.

5) Limitations:
- RequiresisolatedDCsourcesforeachH-bridge.
- Increasedcomplexityinbalancingpoweramong DC sources.
- HighercostduetoseparateDCsupplies.

6) Applications:
- Photovoltaic(PV)systems.
- Batteryenergystoragesystems.
- Medium-voltagemotordrives.
- Electricvehicles(EVs)andhybridEVs.

D. Hybrid Topologies
Modern converter systems also explore hybrid topologiesby combining the features of different inverters to improve performance. For instance, CHB led to the development of ModularMultilevelConverters(MMC),whichofferimproved energy balancing and modularity and are suitable for HVDC systems [7].

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E. Comparative Analysis
Table I provides a comprehensive comparison of the major multilevel inverter topologies in terms of component require- ment, voltage balancing, and application suitability.

III. COMPARATIVE TOPOLOGY ANALYSIS
Theparticularapplication,requiredoutputquality,complexity, andcostallinfluencethechoiceofMLItopology.While NPC ispreferredini ndustriamotordrivesbecauseofitssimplicityandresilience,CHBisappropriateforapplication with multiple independent DC sources (such as PV arrays). In situationswhereredundancyanddynamicresponsearecrucial, flying capacitor inverters are employed.

IV. SIMULATIONINMATLAB/SIMULINK
A powerful platform for planning, simulating, and evaluat- ing multi-level inverters with various PWM techniques is of- fered by MATLAB/Simulink. This study used both traditional Sinusoidal PWM (SPWM) and sophisticated Space Vector PWM(SVPWM)techniquestosimulatethree-levelNPCandCHBinverters.

A. SimulationParameters
Theparametersusedinallsimulationsarelisted inTableII
A resistive-inductive (R-L) load was connected at the inverter output to reflect typical industrial conditions.

TABLEI
COMPARATIVEANALYSISOFMULTI-LEVELINVERTERTOPOLOGIES

Characteristic	Neutral Point Clamped (NPC)	Flying Capacitor (FC)	CascadedH-Bridge(CHB)	ModularMultilevelConverter (MMC)
NumberofDCSources	Single	Single	Multiple(isolated)	Multiple(distributed)
SwitchesperPhase	$2(n-1)$	$2(n-1)$	$4s$	$2n$
VoltageBalancingMechanism	Neutralpointclamping	Flyingcapacitors	Self-balancing	Arm-levelcontrol
ComponentCount	Moderate	High(duetocapaci-tors)	High (modular H-bridges)	VeryHigh
ControlComplexity	Moderate	High	Moderate	VeryHigh
Modularity	Low	Medium	High	VeryHigh
CommonApplications	Industrialdrives,UPS	Motordrives,EVs	Renewable energy ,EVs, storage systems	HVDCtransmission, smart grids

TABLEII
SIMULATIONPARAMETERS

Parameter	Value
DCLinkVoltage(V_{dc})	600V
SwitchingFrequency(f_S)	10kHz
FundamentalFrequency(f_O)	50Hz
LoadResistance(R)	10Ω
LoadInductance(L)	20mH
NumberofLevels	3
ModulationIndex(MI)	0.9

B.   SimulinkModelOverview

Simulink's Power Electronics toolbox was used to model the inverter circuit. An IGBT block managed by gating pulses from the PWM generator subsystem was used to implement eachswitch.Asectoridentificationandswitchingtablemethod based on reference vectors was applied to SVPWM.

Figure 1 shows the developed three-level NPC inverter model with SVPWM logic.

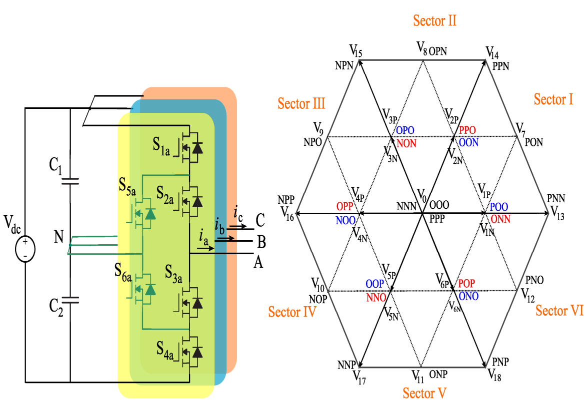

Fig.1.Simulinkmodelof3-levelNPCinverterusingSVPWM

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C. OutputVoltageWaveform

Figure2illustratesthephasevoltagewaveformofthethree- levelinverterusingSPWMandSVPWMtechniques.SVPWM provides a more sinusoidal waveform with fewer switching transitions, improving harmonic performance.

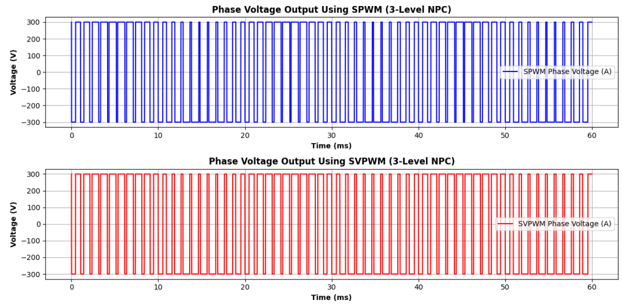

Fig.2.PhasevoltageoutputforSPWMandSVPWM(NPC)

D. TotalHarmonicDistortion(THD)Analysis

The THD was calculated using the Fast Fourier Transform (FFT) tool in MATLAB. SVPWM consistently outperformed SPWM in terms of harmonic reduction.

TABLEIII
THDComparisonofPWMTechniques

PWMTechnique	NPCInverter(%)	CHBInverter(%)
SinusoidalPWM(SPWM)	10.25	8.37
Space Vector PWM (SVPWM)	5.62	4.25

Figure3showstheharmonicspectrumforSVPWMoutput.

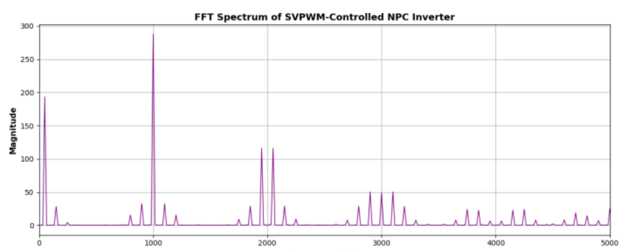

Fig.3.FFTspectrumforSVPWM-controlledNPCinverter

E. Discussion

The simulation results demonstrate that the SVPWM tech- niquehasseveraladvantagesoverSPWM,suchaslowerTHD and better voltage utilization. Furthermore, CHB inverters naturally produce lower THD than NPC due to their modular design and higher number of voltage steps. The results also demonstrate how important it is to select the optimal inverter topology and modulation method to optimize power quality and efficiency.

V. CONCLUSION

In this study, NPC and CHB multi-level inverters were modeled and simulated using MATLAB/Simulink's SPWM and SVPWM techniques. Comparative analysis shows that SVPWM offers better voltage utilization, lower THD, and highervoltagequality.TheCHBtopologydemonstratedbetter harmonic performance due to its modular design, especially when SVPWM was used for control. Future research will focus on enhancing inverter performance in applications such as electric drives and smart grids by fusing experimental validation with advanced control schemes like MPC and AI- based modulation.

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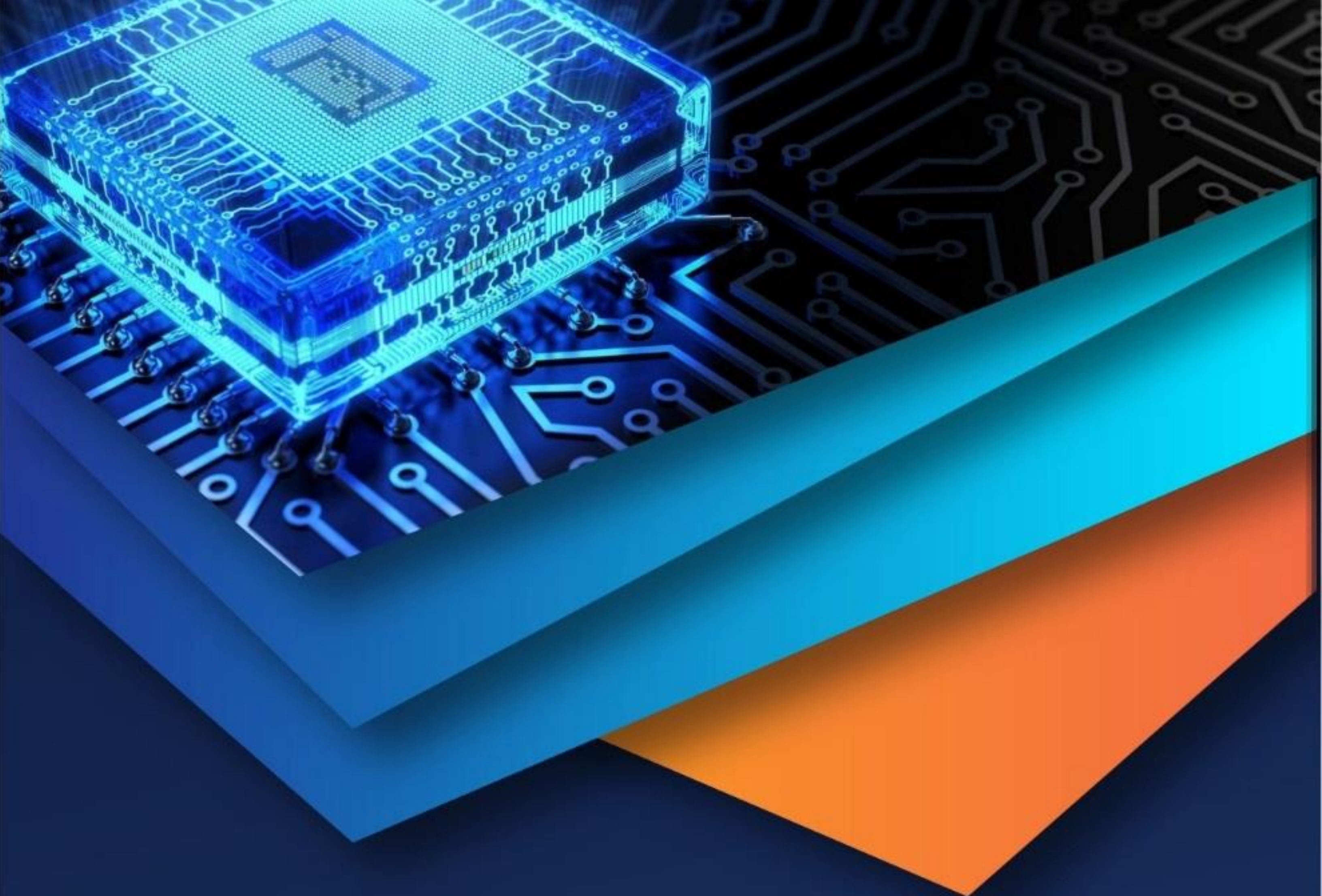

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