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Active and Reactive Power Distribution among Cascaded PV Inverter Modules

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Abstract—Large-scale grid-connected photovoltaic (PV) systems contribute to renewable energy growth, which has inspired the application of cascaded modular multilevel converters due to their unique features such as modular structures, enhanced energy harvesting capability and so on. However, power distribution and control in the cascaded PV system faces tough challenge on output voltage over modulation when considering the non uniform solar energy on segmented PV arrays. This paper presents a decoupled active and reactive power control strategy to improve system operation performance. The relationship between output voltage components of each module and power generation is analyzed with the help of a newly derived vector diagram which illustrates the proposed power distribution principle. On top of this, an effective control system including active and reactive components extraction, voltage distribution and synthesization, is developed to achieve independent active and reactive power distribution and mitigate the aforementioned issue. Simulation results are provided to demonstrate the effectiveness of the proposed control strategy for large-scale grid-connected cascaded PV systems.
Index Terms— Cascaded PV system, decoupled Active and Reactive Power Control, voltage distribution.

I. INTRODUCTION

GLOBAL energy crises from conventional fossil fuels have attracted more renewable energy developments in the worldwide. Among these renewable energy, solar energy is much easier, and delivered to grid by a variety of power converters. In particular, large-scale grid-connected photovoltaic (PV) systems play a major role to achieve PV grid parity and have been put forward in high penetration renewable energy systems [3]. As one type of modular multilevel converters, cascaded multilevel converters share many merits of modular multilevel converters, but also is very promising for the large-scale PV system due to its unique advantages such as independent maximum power point tracking (MPPT) for segmented PV arrays, high ac voltage capability, etc. [5]–[6].

PV systems with cascaded multilevel converters have to face tough challenges considering solar power variability and mismatch of maximum power point from each converter module. In a cascaded PV system, the total ac output voltage is synthesized by the output voltage from each converter module in one phase leg, which must fulfill grid codes or requirements. Because same grid current flows through ac side of each converter module, active power mismatch will result in unsymmetrical ac output voltage of these modules [4]. The converter module with higher active power generation will carry more portion of the whole ac output voltage, which may cause over modulation and degrade power quality if proper control system is not embedded into the cascaded PV system.

Several control strategies have been proposed for the cascaded PV system with direct connection between individual inverter module and segmented PV arrays [2]. But they did not consider the fact that PV arrays cannot be directly connected to the individual inverter module in high-voltage large-scale PV system application due to the PV insulation and leakage current issues. Therefore, those methods in are not useful for a practical large-scale grid-connected cascaded PV system. Moreover, reactive power compensation was not achieved .Proper reactive power compensation can significantly improve the system reliability, and in the meantime help the MPPT implementation for the cascaded module under unsymmetrical condition as well as comply with the system voltage requirement simultaneously. A reactive and active power control strategy has been applied in cascaded PV system with isolated dc–dc converters.

This paper presents a large-scale grid-connected cascaded PV system including current-fed dual-active-bridge (CF-DAB) dc–dc converters and cascaded multilevel inverters as shown in Fig. 1. A decouple active and reactive power control system is developed to improve the system operation performance. Reactive power from each PV converter module is synchronously controlled to reduce the over modulation of PV converter output voltage caused by unsymmetrical active power from PV arrays. In particular, the proposed PV system allows a large low-frequency dc voltage ripple for each PV converter module, which will not affect MPPT achieved by CF-DAB dc–dc converters. As a result, film capacitors can be applied to replace the conventional electrolytic capacitors, thereby enhancing system lifetime.

The following of this paper is organized as follows: Section II gives two-stage large-scale grid-connected cascaded PV system topology and corresponding power flow distribution. Section III gives control design of CF-DAB dc–dc converters, the decoupled active and reactive power control including active and reactive components extraction, voltage distribution and synthesization is executed in multilevel inverter control system to achieve independent active and reactive power distribution. A three-phase 3-MW/12-kV PV system including 12 cascaded PV inverter modules with the proposed decoupled active and reactive power control strategy is modeled in MATLAB/Simulink.

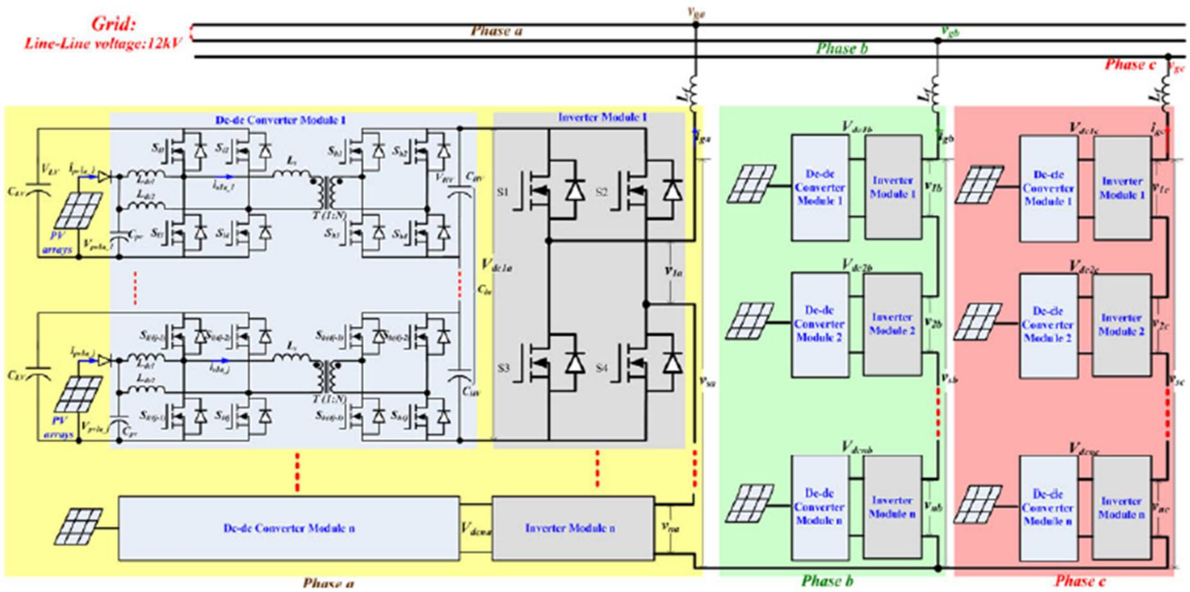

Fig.1. Grid-connected PV system with cascaded multilevel converters

II. SYSTEM CONFIGURATION AND POWER FLOW ANALYSIS

A. *System Configuration*

The proposed large-scale grid-connected PV system is presented in Fig. 1, which demonstrates a three-phase two-stage power conversion system. It includes n cascaded multilevel inverter modules for each phase, where each inverter module is connected to *j* cascaded CF-DAB dc–dc converter modules with high voltage insulation. The cascaded multilevel inverters are directly connected to the grid without big line-frequency transformer, and the synthesized output voltage from cascaded modules facilitates to be extended to meet high grid voltage requirement due to the modular structure. Each dc–dc converter module is interfaced with segmented PV arrays and therefore the independent MPPT can be achieved to harvest more solar energy.

This paper is focused on active and reactive power distribution control of the cascaded multilevel inverters in the proposed PV system. The selected application is a 3-MW/12-kV PV system in this paper. The n is selected to be 4 considering the tradeoff among the cost, lifetime, passive components, switching devices and frequency selection, and power quality. As a result, power rating of each inverter module is 250 kW. The average dc voltage of each inverter module is 3000 V based on the requirement of inverter output voltage, power devices as well as power quality. The second-order voltage ripple on the dc side is allowed to 20% even higher. Hence, film capacitor with 400uF,C_m , is eligible to improve the system lifetime. In addition, the modular structure enables the high-voltage high-frequency SiC power devices for the HVHP PV application. The switching frequency for each power device is 5 kHz. Due to the phase-shift carrierbased phase-width modulation (PWM) control, the PV inverter will generate nine level output voltage and the equivalent output PWM frequency is 40 kHz for each phase. The current ripple of ac inductor is selected to be less than 20% of the rated output current. Therefore, the ac inductor with 0.8 mH, L_f, is acted as the filter. In each dc–dc converter module, L_{dc1} and L_{dc2} are dc inductors, and L_s is leakage inductor. C_{PV} is high-frequency filter capacitor paralleled with PV arrays. High-frequency transformer with turn ration N is connected between low-voltage side (LVS) converter and high-voltage side (HVS) converter. C_{LV} are LVS dc capacitor and C_{HV} are HVS dc capacitor. The detailed parameters have been provided in Table I.

TABLE I

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SYSTEM CIRCUIT PARAMETERS IN SIMULATION

Parameters		Symbols	Value
PV inverter modules in each phase	Number	n	4
	Capacitor voltage	V_{dc}	3000V
	Capacitor size	C_m	400uF
	Filter Inductor	L_f	0.8mH
	Switching frequency	f_{SW}	5kHz
CF-DAB DC-DC converter module	Number	j	5
	Capacitor voltage in low voltage capacitor	V_{LV}	300V
	Capacitor voltage in high voltage capacitor	V_{HV}	600V
	Transformer turn ratio	N	2
	PV arrays output voltage	V_{pvki_r}	100V-200V
	Leakage inductor	L_s	2.5uH
	DC inductor value	L_{dc1},L_{dc2}	12.5uH
	Capacitor in high voltage side	C_{HV}	2mF
	Capacitor in low voltage side	C_{LV}	300uF
	PV arrays output capacitor	C_{PV}	100uF
	Switching frequency	F_{SW_DC}	50kHz
Grid (three phase)	Rated real power	P_g	3MW
	Rated reactive power	Q_g	1.5 MVAR
	Rated phase-ground voltage(RMS)	v_g	12kV

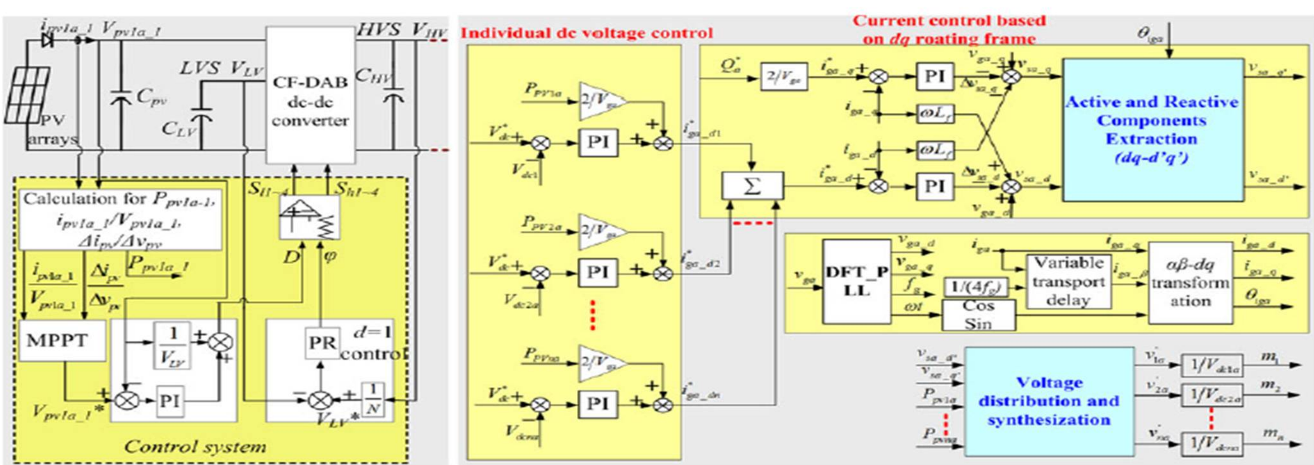

Fig.2. Proposed control system of the grid-connected cascaded PV converters in phase

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III. CONTROL SYSTEM DESIGN

Fig. 2 shows the proposed control system of the grid connected cascaded PV converters including CF-DAB dc–dc converters control and cascaded multilevel inverters control in phase *a*. The same control system can be applied in phase's *b* and *c*.

A. CF-DAB DC–DC Converters Control

Fig. 2 shows the CF-DAB dc–dc converters control for one unit of dc–dc converter module. The same control can be used to other units. Due to the dual-active-bridge structure, this control has two degrees of freedom: the duty cycle D and the phase shift angle ϕ, by which the PV voltage V_{pv1a_1} and LVS dc-link voltage VLV are controlled, respectively. V_{pv1a_1} is directly controlled by the duty cycle D so that it can be well kept at the reference voltage $V^{*}_{pv1a\_1}$ which is generated from MPPT algorithm.

B. Cascaded Multilevel Inverter Control

In cascaded multilevel converter control showing in Fig. 2, active power distribution between cascaded PV converter modules is decided by the individual maximum power available from PV arrays. Considering dc capacitors connected with cascaded multilevel inverter modules have the same capacitance, reactive power from each module can be synchronously controlled to reduce the over modulation risk regardless of active power change. Therefore, the proposed control strategy can be called decoupled active and reactive power distribution control.

IV. SIMULATION VERIFICATION

The following simulation results provide the verification of the aforementioned analysis. The active and reactive power can be independently controlled. Although the solar irradiation on first and second inverter modules is different from one on third and fourth inverter modules after 1 s, the reactive power from them is controlled to be symmetrical. By this proper reactive power distribution, the over modulation caused by the active power mismatch is eliminated. Even when different active power is generated from the four inverter modules after 1.5 s, the effective reactive power compensation can ensure the system with good power quality and stability .It can be seen that THD of *iga* is only 2.532%. The dc voltages on the four modules have good dynamic performance and are controlled to vary with 20% rated voltage but do not affect power quality. Fig.4. shows the simulation results of three-phase cascaded PV system with the proposed control strategy. The solar irradiation for PV inverter modules changes from 200 to 1000 W/m2 at 0.5 s. The total active power to grid, *Pg* , increases from 0.6 to 3 MW. The total reactive power to grid, *Qg*, is controlled to be −1.5 MVAR. At 1 s, solar irradiation appears on these PV inverter modules in phase *b* is different from ones in phases *a* and *c*. Therefore, different active power is generated from three phase. The dc voltages on these modules have good dynamic performance and are controlled to vary with 20% rated voltage.

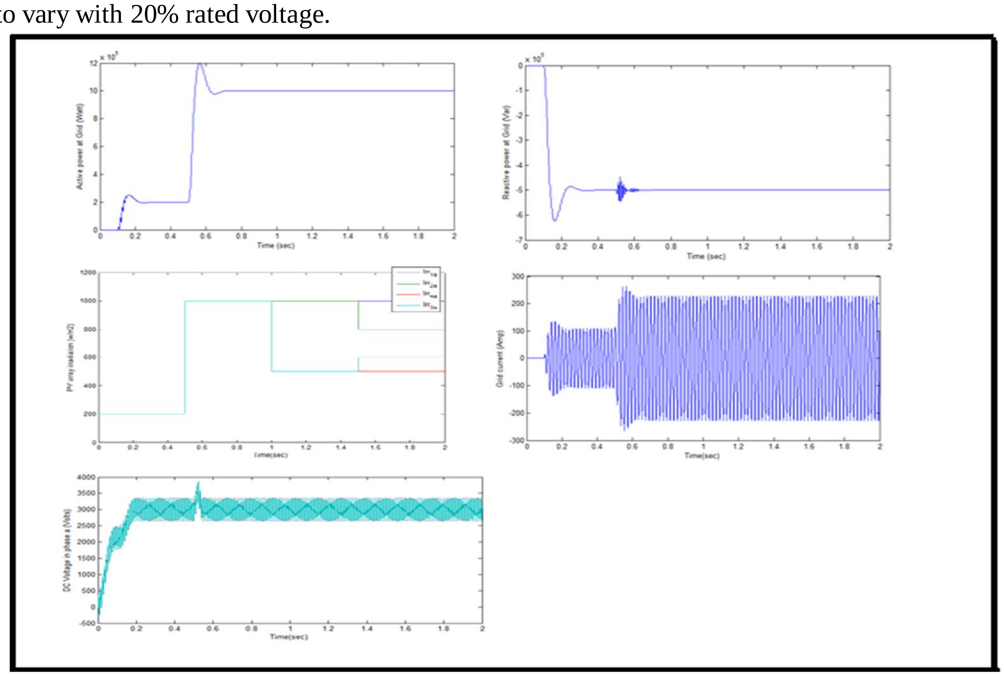

Fig3. Simulation results of PV system with decoupled active and reactive power control in phase a

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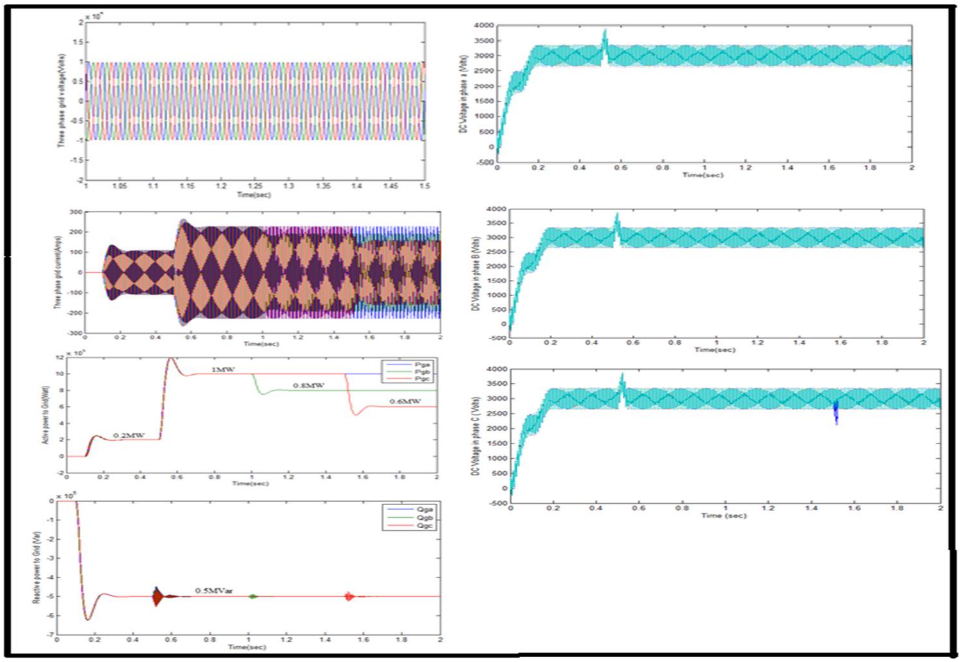

Fig4: Simulation results of PV system with the proposed control in three phases

V. CONCLUSION

This paper gives the active and reactive power distribution among cascaded PV inverter modules and their impacts on power quality and system stability for the large-scale grid connected cascaded PV system. The output voltage for each module was separated based on grid current synchronization to achieve independent active and reactive power distribution. A decoupled active and reactive power control strategy was developed to enhance system operation performance. The proposed control strategy enabled the cascaded PV inverter modules.

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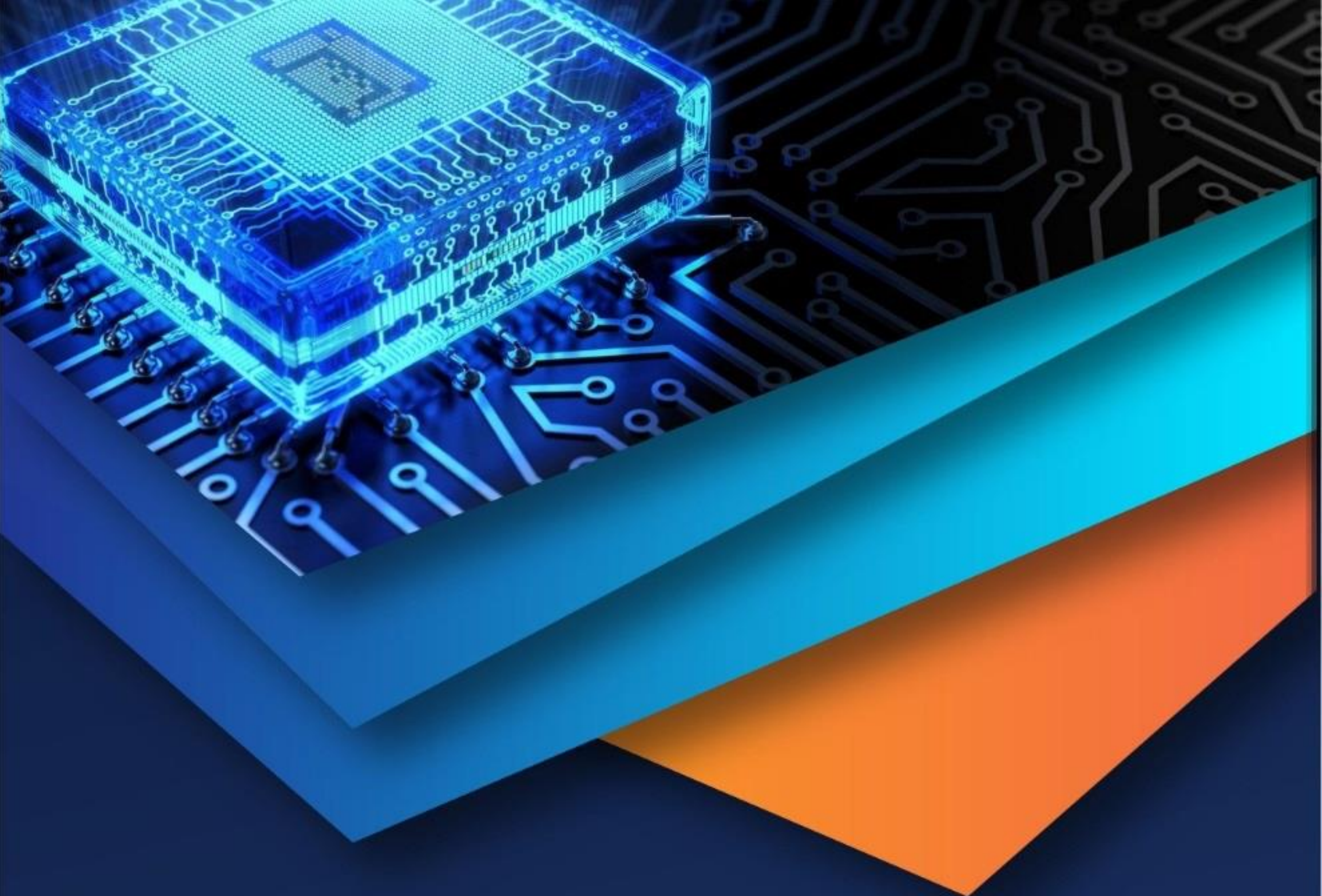

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