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Design of FPGA Controlled Closed Loop Bi-Directional DC-DC (BDC) Converter for Renewable Energy Storage Applications

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Abstract-This paper describes the development of Bi-Directional DC-DC converter (BDC) for solar application. BDC can be used either as a Buck converter or either as a Boost converter. Designed converter in this paper is controlled with PWM techniques. Based on availability of supply BDC can operated in two modes i.e., if supply is available at solar PV side BDC acts as boost converter otherwise acts as buck mode. During day time when sunlight is available Buck Converter is used for charging the battery but during night time when sunlight is not available Boost converter will provide supply with the help of battery. Basically there are three control methods of BDC: current mode control method, voltage mode control method and feed-forward control method. But here in this paper we are controlling BDC by the help of voltage mode control method. This method has several advantages as compared to another method. The main advantages of voltage mode control method are it is easy to control, easy to design, easy to implement and it has less complexity.
Keywords: Bi-Directional DC-DC Converter, Buck converter, Boost Converters.

I. INTRODUCTION

The essential part of the renewable energy system is a storage element. Most of the renewable energy systems include an energy storage element charged by the BDC ,to improve the energy quality. Basic DC-DC Converter have unidirectional power flows capability. In general, a unidirectional dc –dc converter can be tuned into bi-directional dc-dc converter by replacing diode with its controllable switch in its structure. DC-DC Converters are employed in various applications including power supplies for personal computers, office equipment, spacecraft power systems, laptop computers and telecommunications equipment as well as hybrid vehicle, fuel cell vehicle and renewable energy system. To charge and discharge the storage element, BDC is used. Bi-Directional DC-DC Converters converters(BDC) is basically used to transfer power between two networks or we can say in both directions. It is used for DC-DC Power conversion application. To improve the energy quality, most of the renewable energy systems include an energy storage element charged by the bi-directional DC-DC converter. The applications of BDC include energy storage in renewable energy systems, fuel cell energy systems, hybrid electric vehicles (HEV) and uninterruptible power supplies (UPS). The important advantages of BDC are it reduces the cost and improves efficiency, but also improves the performance of the system. In this diagram V1 acts as a solar photovoltaic cell and v2 is a battery. Basically solar photovoltaic cell is a element of solar photovoltaic system which converts solar energy into electrical energy and battery is a storing device.

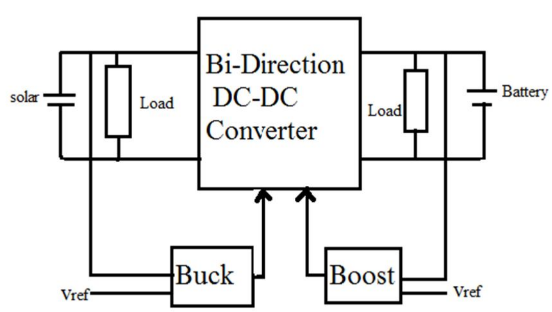

Fig.1: Block Diagram of BDC

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BDC can be used either as a Buck converter or as a Boost converter. If design individually Buck and Boost converters then losses will be increased and it reduces the efficiency, cost, size, capacitor and conductor that why we use BDC in place Buck and Boost converter. If we are not able to design BDC then we have to use two converters that is Buck and Boost converter for uninterrupted power supply for a round of clock. During Day time when sunlight is available Buck Converter is used for charging the Battery while During night time When sunlight is not available Boost converter will provide supply with the help of Battery. If we compare V_{solar} and V_{ref} then it will gives $^{\delta}$ Duty ratio. Duty ratio is Ton/T. T is turn on and turn off time. If change the location of L, Switch and Diode D of Buck converter, it converts into Boost converter. The most important requirements of BDC are high efficiency, light weight, compact size and high reliability. It is highly reliable converter because if one converter will not work on that time than another converter will work.

II. PROPOSED SYSTEM

BDC is basically used for DC-DC power conversion application. BDC has a capability to flow power in both directions, either from the high voltage side to low voltage side (step-down mode), or from the low voltage side to high voltage side (step- up mode).when power is transferred from low voltage side to high voltage side, so BDC operates in step-up mode and when power is transferred from high voltage side to low voltage side, BDC operates in step-down mode.

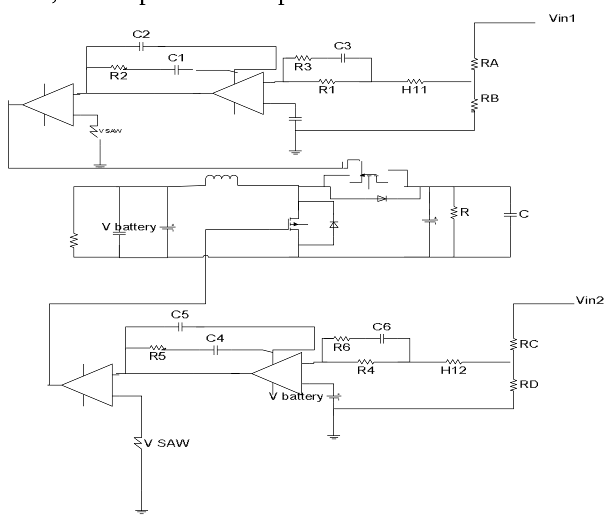

Fig.2: Proposed System of BDC

III. BUCK OPERATION

BDC Converter is act as Buck mode, whenever there is a need to convert high voltage DC to low voltage DC. Even the input of DC-DC converter is unregulated DC it will produces a constant DC voltage or regulated DC voltage under any operating conditions. In this converter the input voltage is greater than output voltage and this converter is known as step-down converter.

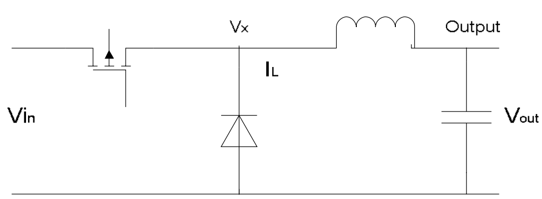

Fig 1.2: Circuit Diagram of Buck converter

To analyse the voltages of this circuit let us consider the changes in the inductor current over one cycle.
From the relations

$$V_x\text{-}V_o=L\frac{di}{dt}$$

the change of current satisfies

$$di=\frac{1}{L}\{\int_0^{Ton}(V_x-V_o)\,dt+\int_{Ton}^{T}(V_x)\ \}$$

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For steady state operation the current at the start and end of a period T will not change. To get a simple relation between voltages we assume no voltage drop across transistor or diode. Thus during the ON time Vx =Vin and in the OFF Vx =0.
Thus

$$0 = \mathrm{di} = \int_0^{ton}(V_{in} - V_o)dt + \int_{ton}^{ton+toff}(-V_O)\,dt$$

which simplifies to

$$(V_{in} - V_o)t_{on} - V_O\, t_{off=0}$$

Or

$$\frac{Vo}{Vin} = \frac{Ton}{T}$$

and defining "duty ratio" as

$$D = \frac{Ton}{T}$$

So the voltage relationship becomes $V_o= DV_{in}$ Since the circuit is lossless and the input and output powers must match on the average $V_o* I_o = V_{in}* I_{in}$. Thus the average input and output current must satisfy $I_{in} = D\, I_o$. These relations are based on the assumption that the inductor current does not reach zero.

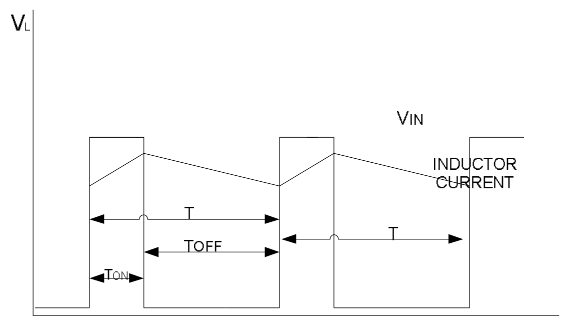

Fig 1.2: waveform of voltage and current changes

IV. BOOST CONVERTER

BDC Converter is act as Boost mode, whenever there is a need to convert low voltage dc to high voltage dc. In this converter the output voltage is greater than input voltage and this converter is known as step-up Converter. Its main application is in regulated dc power supplies and the regenerative braking of dc motor.

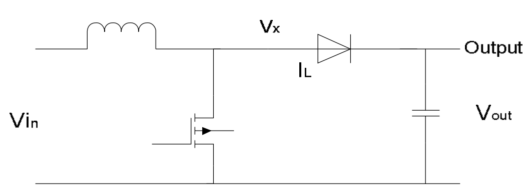

Fig.1.3: Circuit Diagram of Boost converters

When transistor is On $V_x = V_{in}$, and in the Off state the inductor current flows through the
diode giving $V_x = V_o$. For this analysis it is assumed that the inductor current always remains flowing (continuous conduction). The voltage across the inductor is shown in Fig and the average must be zero for the average current to remain in steady state.

$$V_{in\ T_{on}} + (V_{in} - V_o)T_{off} = 0$$

This can be rearranged as

$$\frac{Vo}{Vin} = \frac{T}{Toff} = \frac{1}{(1-D)}$$

and for a lossless circuit the power balance ensures

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$$\frac{Io}{Iin} = (1 - D)$$

When switch is on, the diode is reversed biased, and isolating the output stage. The input supplies energy to the inductor. When switch is off, the output stage receives energy from the inductor as well as from the input.

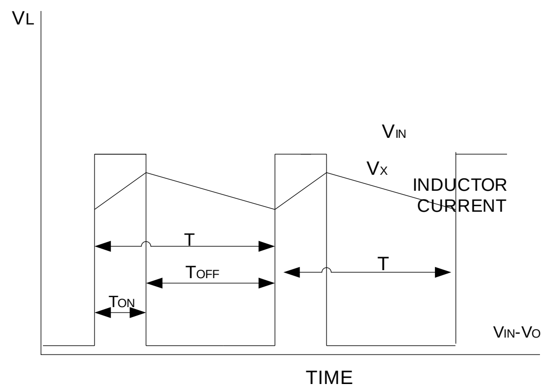

Fig.1.4: waveform of voltage and current

Since the duty ratio "D" is between 0 and 1 the output voltage must always be higher than the input voltage in magnitude. The negative sign indicates a reversal of sense of the output voltage.

V. VOLTAGE MODE CONTROL

Basically there are 3 control methods of BDC that is current mode control, voltage mode control and feed-forward control method. In this paper BDC control by the voltage mode control method. There are several advantages of this method are it is easy to control, it is easy to implement, easy to design and it has less complexity that's why we have used voltage mode control method**.** Traditionally the voltage mode control in designing feedback loop.

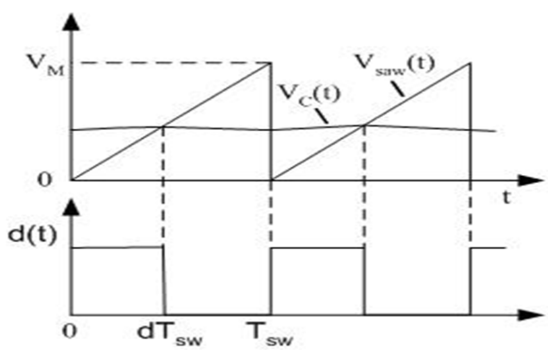

Fig.1.5: PWM Voltage mode control method

VI. CIRCUIT DIAGRAM OF BDC

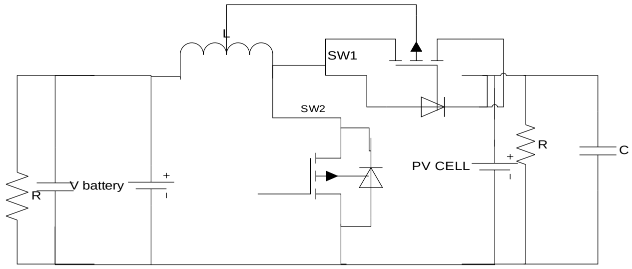

Fig1.5: circuit diagram of BDC

When Switch s_1 is on by that time it acts as a boost converter and When Switch s_2 is on by that time it acts as a Buck converter because of the circuit topology.

VII. FPGA (FIELD PROGRAMMABLE GATE ARRAY)

A field-programmable gate array (FPGA) is an integrated circuit designed to be configured by a customer or a designer after manufacturing—hence "field-programmable." An FPGA is a field programmable device suitable for switching application in power electronics. It can be easily programmed to design a pulse width modulator (PWM) for control applications. Further its fast switching capability and easy implementation of soft computing algorithms make it preferred choice for power control system application and power quality. In this proposed work, the BDC converter will be implemented on FPGA after the simulation in Matlab.

VIII. MATLAB SIMULATION

In this paper, proposed bi-directional converter is designed with 8.33 voltage gain. And then done small signal analysis for bi-directional dc-dc converter to get transfer functions in both the modes and their transfer functions have been presented below.

Buck mode:

Transfer Function

Transfer function with modulator

5887 s + 5.703e08

----

s^2 + 8712 s + 1.408e07

Boost mode:

Transfer Function

Transfer function with modulator

-5.961e04 s + 3.409e07

----

s^2 + 492.2 s + 1.936e05

Type-2 controller is designed to control the Bidirectional dc-dc converter in order to get desired response with following specification PM=57° and GM=14.7dB and its transfer function, bode plot and gate signal generated through it are presented below

controller =

131300 s^2 + 9.321e07 s + 1.654e10

----

s^3 + 25820 s^2 + 1.667e08 s

To verify feasibility of the proposed system in real time implementation results have been verified with the help of Xilinx system interfaced MATLAB Simulink.

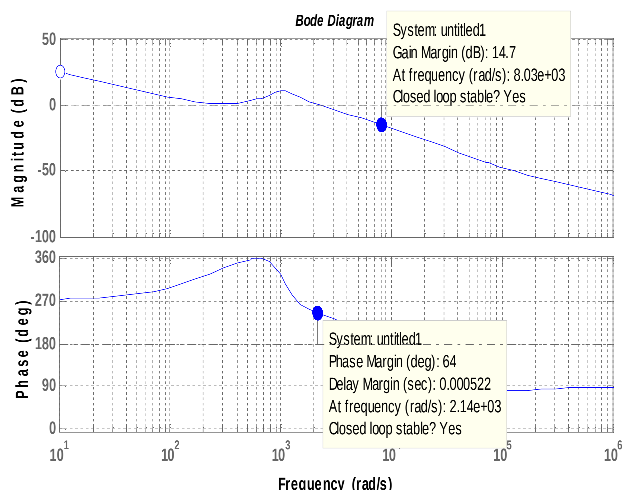

Figure 14.Bode plot of Boost converter loop gain with type-3 controller

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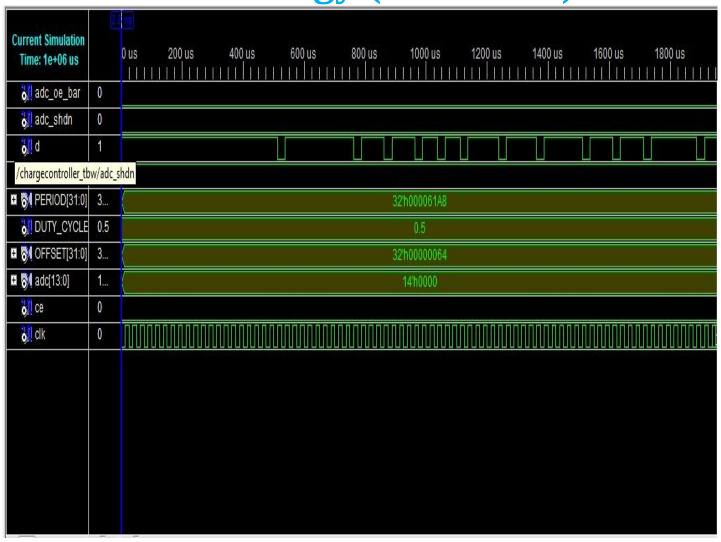

Figure firing pulses to BDC in boost mode

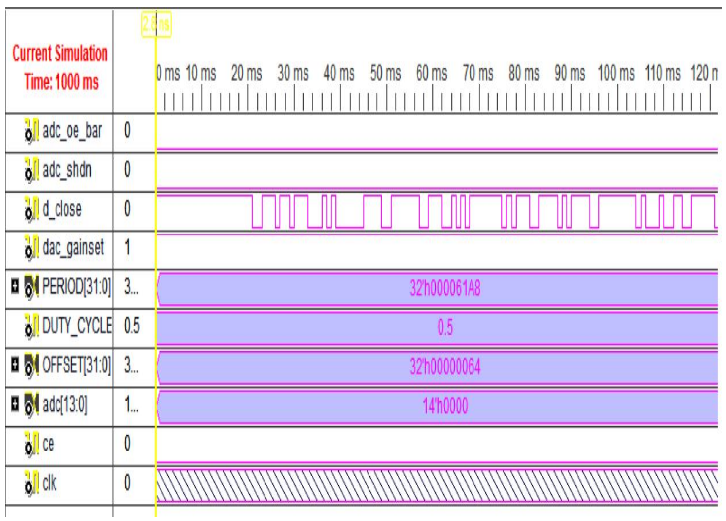

Figure firing pulses to BDC in buck mode

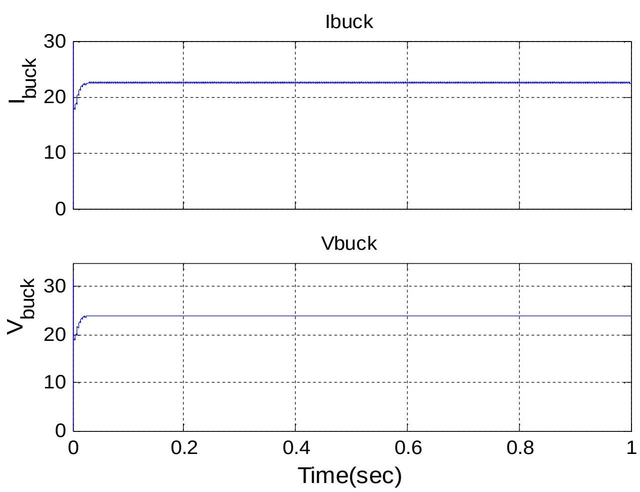

Figure responses of BDC in buck mode

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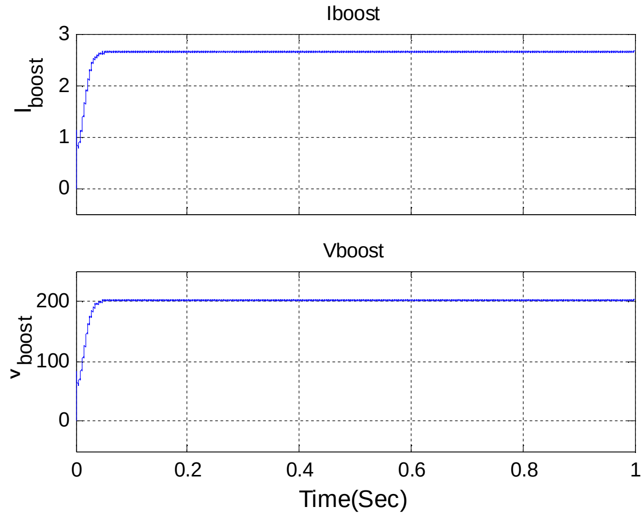

Figure responses of BDC in buck mode

Battery and DC bus voltage and current are shown in following figure to check the charging and discharging of battery.

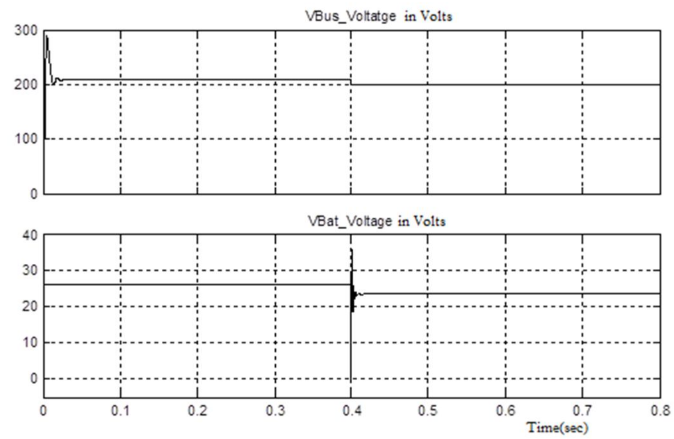

Figure 16. Voltage waveforms of BDC either sides (Bus side and battery side)

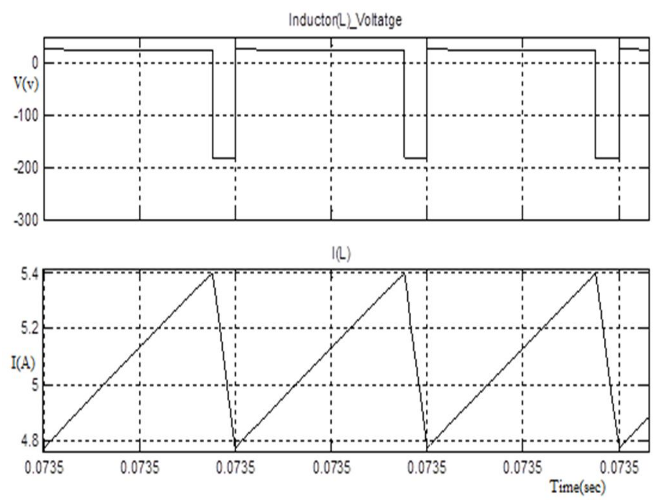

Figure 17. Inductor voltages and currents of BDC

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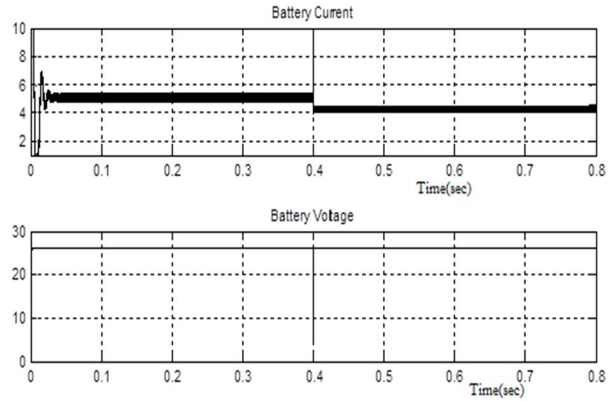

Figure18. Battery side voltage and current

IX. CONCLUSION

In this paper, proposed bi-directional converter is designed with voltage gain of 8.33and also done the small signal analysis to derive transfer functions. Based on transfer function analysis, Type-2 controller is designed to control the Bidirectional dc-dc converter with the specifications of PM=57° and GM=14.7dB and realized in digital domain for the practical implementation of controller in FPGA. And got it verified the design converter is charging the battery when PV power is available and feeding power to dc bus by battery in the absence of sun.

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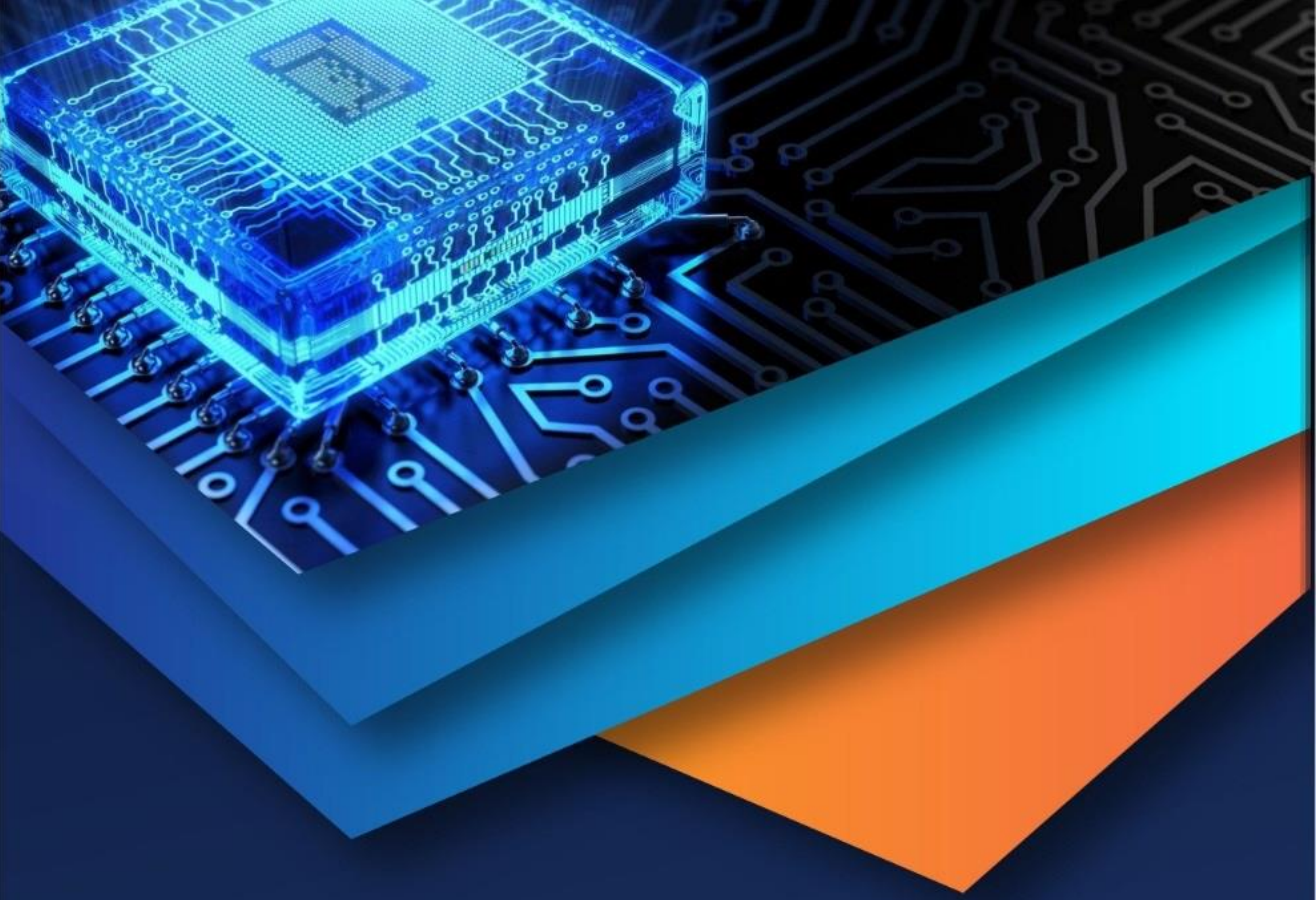

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