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Design and Analysis of ANN Control based LLC Resonant Converter

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Abstract: In this, artificial neural network controller is designed for LLC resonant converter for voltage regulation. The performance of the proposed converter with proportional-integral (PI) controller and ANN controller are analysed from the simulation results. A voltage mode control is provided to get regulated load voltage irrespective of the changes in supply. ANN controller is used for the voltage mode control and the efficiency of the proposed ANN controller is estimated and comparison is made with conventional PI controller. The simulation work is done with MATLAB/Simulink software.
Keywords: Dc-Dc Converters, Resonant converters, Voltage mode Control, PI controller, ANN.

I. INTRODUCTION

In past, the conventional energy sources such as coal, gas, oil, etc, are utilized for power generation until the renewable sources are introduced for electrical power generation. Also, the regulations regarding emission of pollutants and impact on environmental pollution reduction caused the quick growth on these renewable sources. The Photovoltaic (PV) energy was utilized for charging the batteries in isolated areas and wind turbines also used in few occasions. These two energy sources are extended over other applications also and they both get combined to design hybrid system after the idea of grid connected system is introduced. Several new ideas regarding control circuits, design of converters, MPPT (Maximum Power Point Tracking), real and reactive power control and injection, etc, are proposed regarding the hybrid energy resources. The key issue in this is the availability of irradiation in solar and wind speed cannot be predetermined as it relied on the environmental conditions. The wind and solar energies are complement to each other and provides power almost all over the year is the main reason for choosing them for hybrid power generation. Hence these two can be used as main power sources and also it is possible to include an auxiliary power source such as battery, diesel plant, biogas, fuel cell, etc, as backup. As the power generation unit consists of multiple sources, it is more reliable than individual sources irrespective of the location of the power generation unit. It can be utilized in remote villages as the distribution of electrical energy from grid is near to impossible in those locations. A control strategy is important for the hybrid system in order to regulate the variables such as voltage, power, etc. As these renewable sources are volatile in nature voltage control is essential for the reliable power generation and distribution. Various renewable sources are interlinked using dc bus in which the voltage regulation is provided using controllers such as PI control (Proportional Integral), PID control (Proportional Integral Derivative), SM control (Sliding Mode Control), etc, in order to enhance the performance of the HRES.

In this paper, a dc-dc converter system with LLC converter is added to proposed system for providing voltage regulation for dc load. The resonant LLC converter is designed for dc-dc conversion and a comparison is made with conventional controller and proposed controller under varying load conditions. A simple voltage mode control loop is designed with PI and ANN controller and the performance of the proposed system is observed for these two controllers based on simulation results. A hardware prototype model was designed and both buck and boost operations are performed for the output voltage range of 4-20V with input voltage of 12V.

II. LLC CONVERTER

The proposed LLC converter is given in Fig 1 as follows:

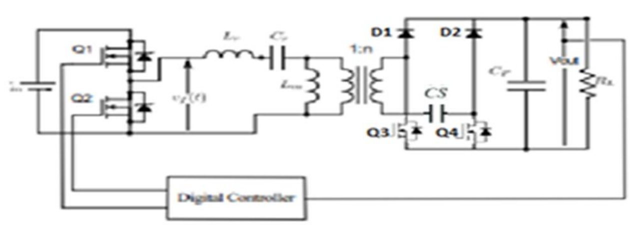

Fig.1. LLC Converter Circuit

In this, when Q1 is ON, the inductor get charged and the capacitor get discharged and provides energy to the primary winding of transformer. In secondary, the energy is utilized by the load with the help of diode rectifier. When Q2 is ON, the inductor starts discharging and provides energy to transformer primary and resonant capacitor. In this also, the load utilizes the energy induced in secondary with the help of diode rectifier.

A. Mode 1

This mode is started at the instant, switch Q2 is off. The I_{Lr} current starts to flow in opposite direction through the body diode of Q1. This will cause the secondary side diode D1 to conduct and Io starts to increase. The magnetizing inductance of the coupled inductor Lm is getting charged with input source voltage.

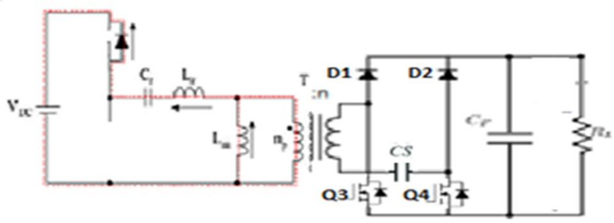

Fig.2. Equivalent circuit of mode 1 of proposed LLC Converter Circuit

B. Mode 2

In this, the Q1 is turned ON and the I_{Lr} current reaches positive. The secondary side diode D1 conducts and the secondary voltage is fixed to Vo. The magnetizing inductance Lm is linearly charged with load voltage, and hence the resonant circuit is not active during this time. When the currents I_{Lr} and I_{Lm} are equal, mode3 starts.

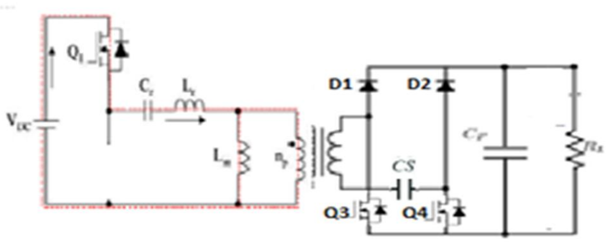

Fig.3. Equivalent circuit of mode 2 of proposed LLC Converter Circuit

C. Mode 3

Mode 3 starts when the I_{Lr} and I_{Lm} are equal. The diodes D1 and D2 are reverse biased and the transformer secondary voltage is less than that of load voltage. When the MOSFET Q1 is turned off, this mode ends.

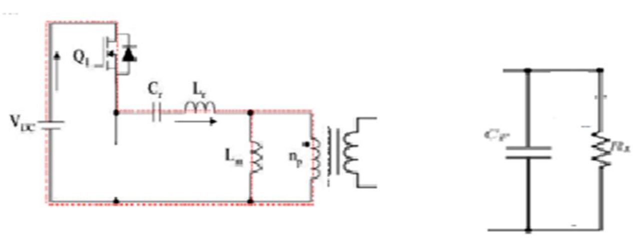

Fig.4. Equivalent circuit of mode 3 of proposed LLC Converter Circuit

The next half cycle is same by turning Q2 ON and OFF.

The procedure of designing the proposed converter is provided below:

- The design of the proposed converter is done based on the rated input source voltage.
- The load regulation is performed with zero loading conditions at maximum possible input source voltage.

1) *Step 1:* The turns ratio of transformer and voltage gain is provided below:

$$M_{nom} = 2n\frac{V_{out}}{V_{dc.nom}} = 1 \quad => \quad n = \frac{1}{2}\frac{V_{dc.nom}}{V_{out}}$$

2) *Step 2:* The maximum and minimum voltage gains is calculated as follows

$$M_{max} = 2n\frac{V_{out}}{V_{dc.min}} \qquad M_{min} = 2n\frac{V_{out}}{V_{dc.max}}$$

3) *Step 3:* The operating (switching) frequency is provided below:

$$f_{n.max} = \frac{f_{max}}{f_r}$$

4) *Step 4:* The equivalent resistance with respect to primary of the transformer is provided below

$$R_{ac} = \frac{8}{\pi^2}n^2\frac{V_{out}^2}{P_{out}}$$

5) *Step 5:* The inductance ratio of the transformer with zero loading conditions and maximum input source voltage is provided below

$$\lambda = \frac{1-M_{min}}{M_{min}}\frac{f_{n.max}^2}{f_{n.max}^2-1}$$

6) *Step 6:* The Q value of resonant converter and full load condition is calculated below:

$$Q_{zvs.1} = 95\% \cdot Q_{max} = 95\% \cdot \frac{\lambda}{M_{max}}\sqrt{\frac{1}{\lambda}+\frac{M_{max}^2}{M_{max}^2-1}}$$

7) *Step 7:* The Q value of resonant converter and no load condition is calculated below:

$$Q_{zvs.2} = \frac{2}{\pi}\frac{\lambda f_{n.max}}{(\lambda+1)f_{n.max}^2-\lambda}\frac{T_D}{R_{ac}C_{zvs}}$$

8) *Step 8: The chosen quality factor within the limits calculated using above relations are*

$$Q_{zvs} \le \min\{Q_{zvs.1}, Q_{zvs.2}\}$$

9) *Step 9:* The lower limit of the switching or operating frequency is provided below:

$$f_{min} = f_r\sqrt{\frac{1}{1+\frac{1}{\lambda}\left(1-\frac{1}{M_{max}^{1+\left(\frac{Q_{zvs}}{Q_{max}}\right)^4}}\right)}}$$

10) *Step 10:* The characteristic impedance values of the resonant circuit is provided below:

$$Z_o = Q R_{ac} \qquad C_r = \frac{1}{2\pi f_r Z_o}$$

$$L_r = \frac{Z_o}{2\pi f_r} \qquad L_m = \frac{L_r}{\lambda}$$

III. CONTROL STRATEGY OF DC-DC CONVERTER

In this, the controlled gate pulses are provided for the dc-dc converter switches. The reference DC voltage (V^*_{dc}) is checked with the measured DC voltage (V_{dc})and the error dc voltage (V_E) is obtained as

$$V_E = V^*_{dc} - V_{dc}$$

The error voltage is then provided to controller, from which the reference controlled voltage V_C is obtained as follows

$$V_C(k) = V_C(k-1) + K_P \{V_E(k) - V_E(k-1)\} + K_i V_E(k)$$

Where k denotes the sampling time period. The pulses generated for the dc-dc converter is of by comparing the control signal V_C with high frequency carrier signal M_C as

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If $M_C < V_{C,}$ pulse is ON

If $M_C \geq V_{C,}$ pulse is OFF

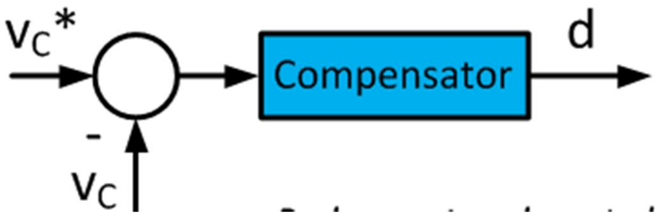

Fig 5 Control loop for the dc-dc converter

IV. SIMULATION SETUP & RESULTS

The Table I consist of the values of the parameters used in simulation which is shown below:

TABLE-I

SIMULATION PARAMETERS

Parameters		Values
Load Voltage (in volts)		600 V
Load Power (in kilo watts)		1 KW
PROPOSED LLC CONVERTER	Lr	0.2mH
	Cr	110µF
	Lm	24mH
Switching Frequency		65 KHz
Input Voltage		300V

The simulation circuit for proposed LLC resonant converter is provided in Fig. 6, which is shown below:

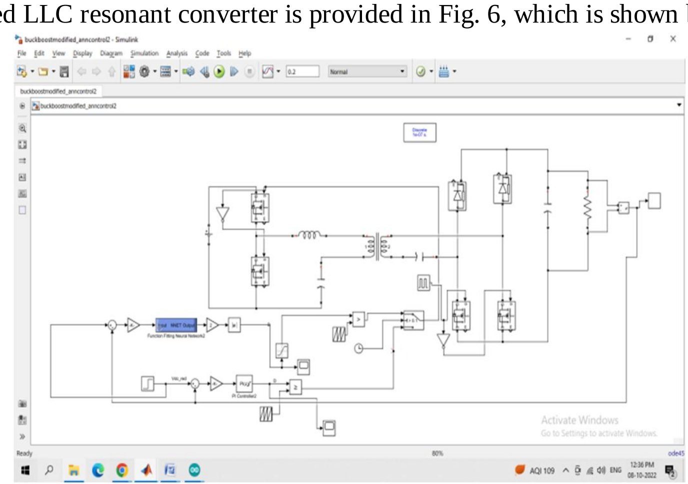

Fig 6. Simulation circuit of proposed System

The load current and voltage (with LLC converter) is provided in Fig 7:

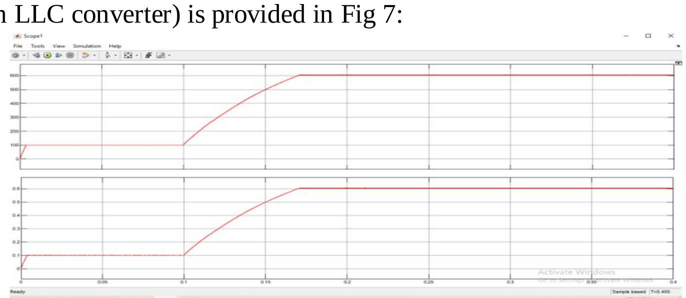

Fig 7 Load current and voltage (with LLC Converter) with PI controller

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The voltage ripple from the LLC converter output is in the range of 4V which is 1% of rated voltage. The efficiency of the LLC converter is provided below in Fig 8:

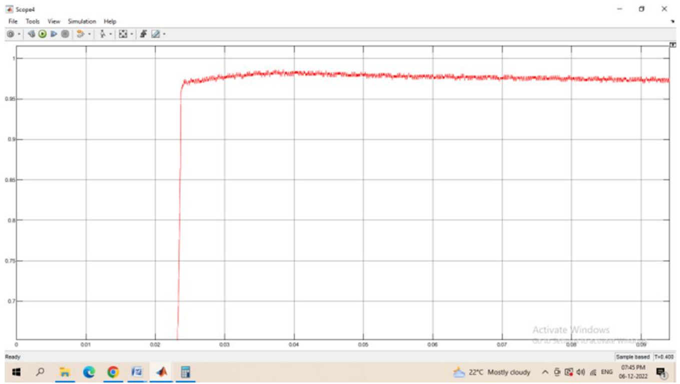

Fig 8 Efficiency of LLC Converter with PI controller

The efficiency of the LLC converter with PI based Voltage mode control is in the range of 97%.

The PI controller is then replaced with the ANN controller. The performance curves of the ANN controller during training is provided below in Fig 9:

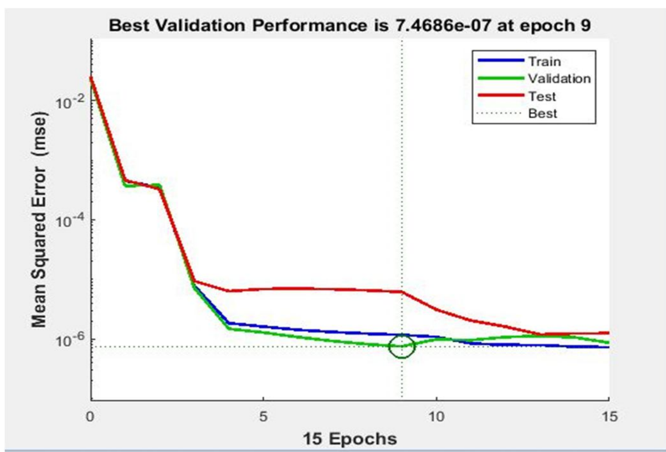

Fig 9 Performance Curves of ANN controller

The mean square error is in the order of 10^{-6} which is same as zero. The regression curves are provided in the Fig 10 as follows:

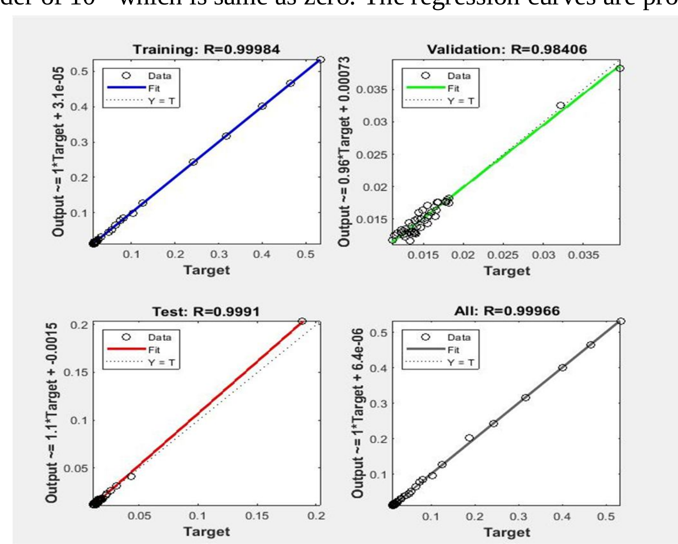

Fig 10 Regression curves of ANN controller

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The regression value is 0.999 where the ideal value for regression is 1.
The load voltage and current (with LLC converter) with ANN control is provided below in Fig 11:

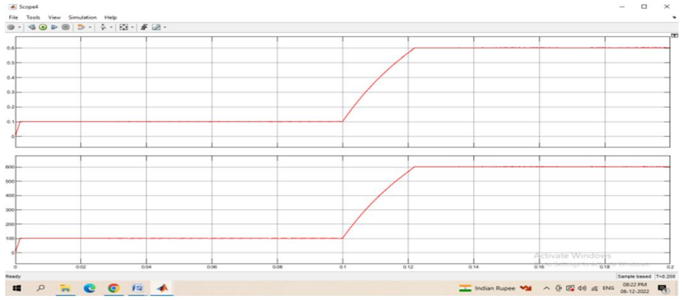

Fig 11 Load voltage and current (with LLC Converter) with ANN controller

In this, the ripple voltage is around 3V which is 0.75% of the rated voltage. The efficiency of LLC converter with ANN controller is provided below in Fig 12:

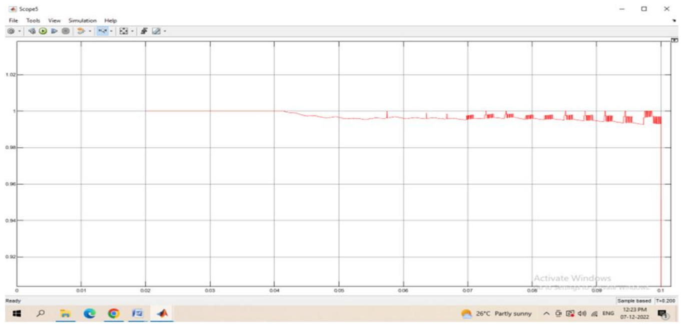

Fig 12 Efficiency waveform of LLC converter with ANN controller

The efficiency of the LLC converter with ANN based Voltage mode control is in the range of 99.6%.

V. HARDWARE SETUP & RESULTS

The Table II consists of the values of the parameters used in hardware which is shown below:

TABLE-II HARDWARE PARAMETERS

<table>
<tr><th colspan="2">Parameters</th><th>Values</th></tr>
<tr><td colspan="2">Load Voltage (in volts)</td><td>4-20 V</td></tr>
<tr><td colspan="2">Load Power (in watts)</td><td>10 W</td></tr>
<tr><td rowspan="2">PROPOSED LLC CONVERTER</td><td>Lr</td><td>32μH</td></tr>
<tr><td>Cr</td><td>1μF</td></tr>
<tr><td colspan="2">Switching Frequency</td><td>62.5 KHz</td></tr>
<tr><td colspan="2">Input Voltage</td><td>12 V</td></tr>
</table>

The hardware circuit is provided below:

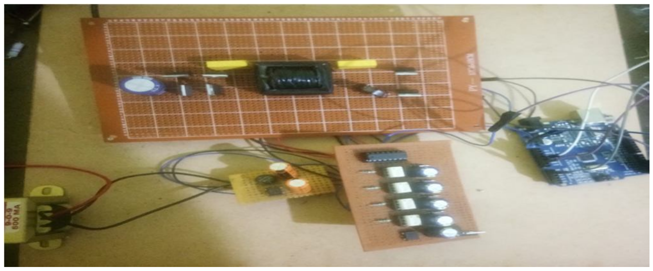

Fig 13. Hardware circuit of proposed System

In this, a 12V dc voltage from regulated power supply of 12V, 1A is connected as source which provides energy to the inductor of the converter for boosting up the dc link voltage which is provided to the primary of coupled inductor which doubles the voltage across the secondary. The secondary is provided to the load via resonant capacitor and dc link capacitor. The secondary voltage is controlled by controlling the primary voltage which is done by controlling the pulse width of S1. A transformer is used to provide supply to the controller and driver circuit. The rectified voltage is provided to 12V regulator and arduino along with driver ics so that the arduino and driver circuit gets the Vcc supply. For buffer ic 5V regulator is used. The arduino generates pulses for converter switches. The pulses for switches S1-S4 are generated in arduino controller and provided with pins 2-5. The reference voltage is varied with the help of a variable resistor which is provided to the input pin A1. The pulses from pins 2 to 5 is provided to buffer ic which isolates the controller and driver circuit and also provides smooth pulses without disturbances. The output of buffer ic is provided to driver ic (individual ic for each switch) through resistance of 1000 ohm and the output of driver ic is provided to the switches.

The gate pulses for the converter switches (S1, S3, S2 and S4 respectively) are provided below in Fig 14:

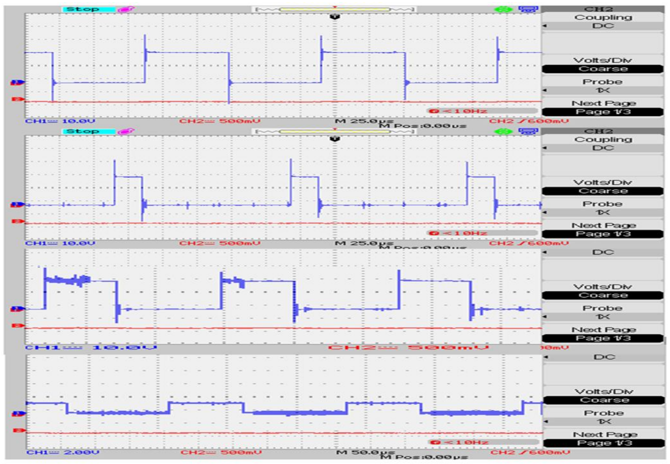

Fig 14. Gate pulses of proposed converter switches

The load voltages measured for various reference voltages (6V – 20V) is provided below in Fig 15:

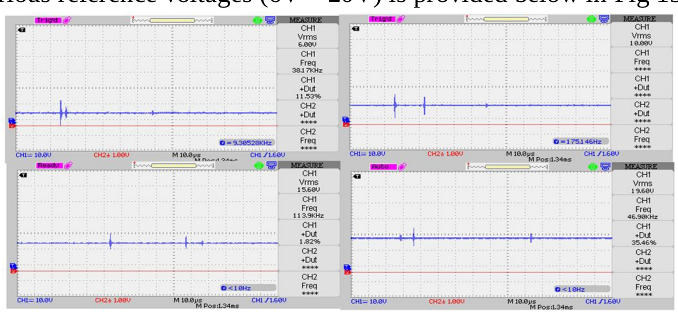

Fig 15. Load voltages of proposed converter in buck and boost mode

In this, both buck mode voltages (6-12V) and boost mode voltages (12-20V) with constant input voltage of 12V are obtained by changing the reference voltage which is provided to the controller. In this, in boost mode, 97.5% of load regulation is achieved for reference voltage of 16V and 98% of load regulation is achieved for reference voltage of 20V.

VI. CONCLUSION

In this paper, a LLC converter is designed with ann based voltage mode control loop and compared with conventional PI controller. The performance of the converters are noted in terms of efficiency and ripple voltages. The LLC converter is more efficient and provides less voltage ripples than that of other converters under study. The PI controller is replaced with ANN controller in voltage mode control loop of LLC converter. This leads to further increase in efficiency and reduction in load voltage ripples. A hardware prototype model is developed for 10W and load voltage is designed for the range of 4V to 20V with input voltage of 12V. Here in boost mode, 98% of load regulation is achieved at full load conditions.

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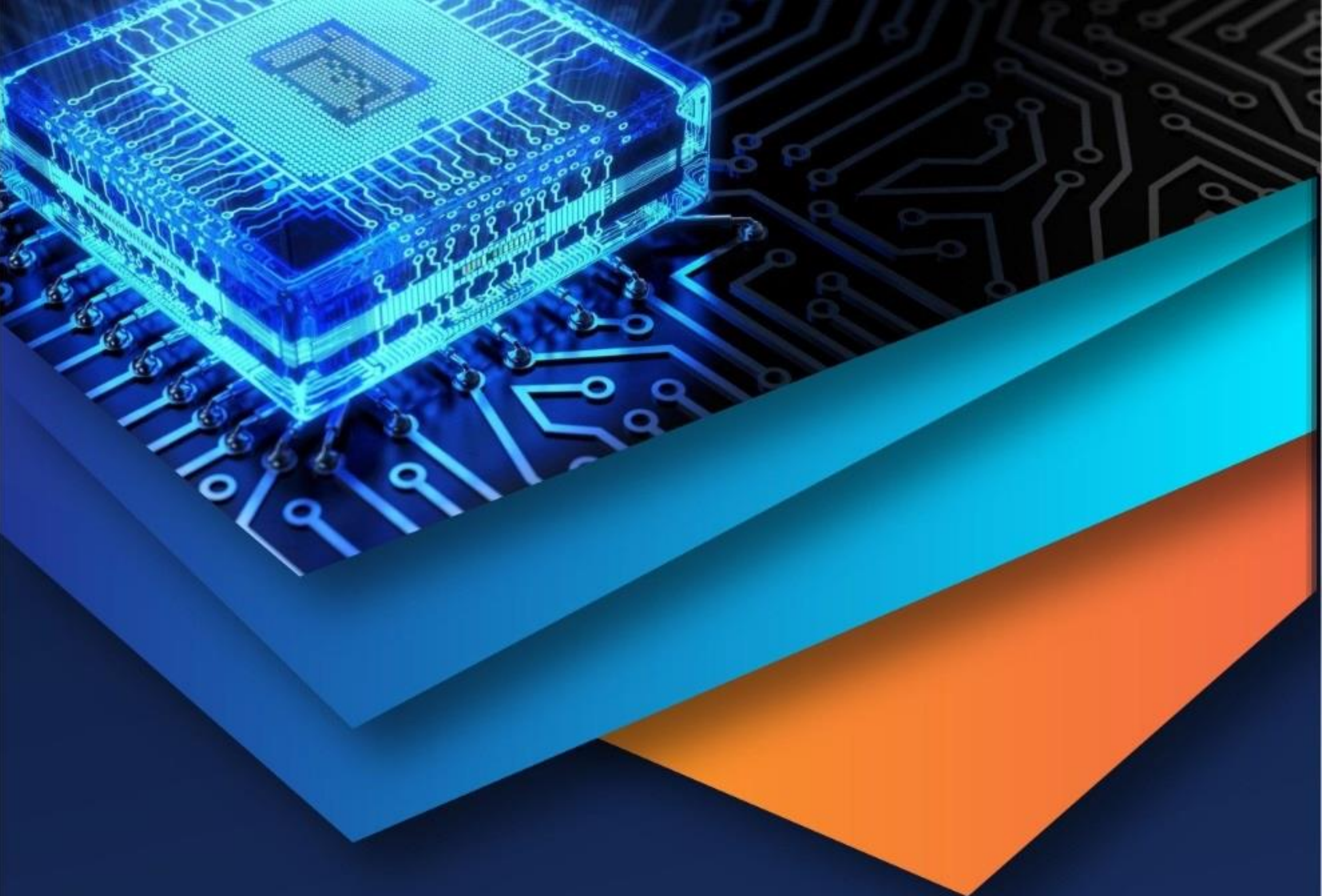

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