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A Predictive Solution to Unbalanced-Voltage Problem in Wind Turbine Using Four-leg Indirect Matrix Converter

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***Abstract*— In this paper, a four leg indirect matrix converter (IMC) is presented for the solution to unbalanced voltage in wind turbines. The wind driven PMSG is used as a generator for the power supply. The four leg indirect matrix converter is eliminates the unbalanced power supply problems that are common in the wind power generation due to variable input parameters. The zero sequence is developed between the output voltage supply of the wind generator thereby the unbalanced voltage levels are balanced and the output power factor is maintained. The zero sequence is generated efficiently as there is no DC link between the two converter stages of the IMC. This produces the zero vector in the inverter voltage thereby the power factor is improved. Simulation using MATLAB is presented and the results are compared.**
***Keywords*— AC-AC Converter, Permanent Magnet Synchronous Generator, Space Vector Modulation, DC Link, Wind Energy**

I. INTRODUCTION

Wind energies are most desired power generation units for more years. Various researches over years have introduced various techniques to improve the power output from the wind turbines. Many industrial applications that are in demand of power consumption have created power crisis in many countries. The power demands are being solved by introducing renewable energy. However the generated power using the renewable energy, wind turbines particularly have a variable output power due to variable inputs which is unavoidable. Solution to this was the power electronics device that converts the variable power to fixed power. Moreover, still problems exists under some constrains of unbalanced power generation. This is very critical issue and challenge to many industries generating power supplies. The solution to unbalanced supply is explained using the four-leg indirect matrix converter [1]. The IMC [3] is an AC-AC converter that is simpler compared to matrix converter. The complexity is reduced in IMC. The four-leg IMC used extra pair of inverter switches that is connected to the neutral of the power supply. The synchronisation is developed such that the neutral link balances the output voltage and current. In the proposed method a PMSG is used as the Wind turbine model. The mathematical modeling of PMSG is done using MATLAB [2], [7].

In the proposed system, the PMSG wind turbine gets the mechanical input. The PMSG is designed to give an unbalanced output voltage. The unbalanced output from PMSG is given to the four-leg indirect matrix converter. The converter output is measured across a RL load. The output obtained is a balanced voltage and current with improved power factor.

II. MATLAB MODELING OF PROPOSED WIND DRIVEN PMSG

The voltage equation of the Permanent Magnet Synchronous Generator (PMSG) is used in the MATLAB for the mathematical modeling. The voltage equations can be represented as,

$$V_a = i_a R_s + p\varphi_a$$
$$V_b = i_b R_s + p\varphi_b$$
$$V_a = i_c R_s + p\varphi_c$$

Where, $p=\frac{d}{dt}$, i_a, i_b and i_c are the phase currents, φ_a, φ_b and φ_c are the flux developed by the phase currents and R_s is the stator resistance.

$$\begin{vmatrix}\varphi_a\\ \varphi_b\\ \varphi_c\end{vmatrix} = \begin{vmatrix} L_{sl} + L_{aa}(\theta_{er}) & L_{ab}(\theta_{er}) & L_{ca}(\theta_{er}) \\ L_{ab}(\theta_{er}) & L_{sl} + L_{aa}(\theta_{er}) & L_{bc}(\theta_{er}) \\ L_{ca}(\theta_{er}) & L_{bc}(\theta_{er}) & L_{sl} + L_{cc}(\theta_{er}) \end{vmatrix} \begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix} + \begin{vmatrix} \varphi_{PMa}(\theta_{er}) \\ \varphi_{PMb}(\theta_{er}) \\ \varphi_{PMc}(\theta_{er}) \end{vmatrix}$$

Where, θ_{er} is the rotor PM axis angle to a axis / electrical angle

For the distributed windings of IPM rotor machines, θ_{er} is more efficiently considered as the self-inductance and mutual inductance mainly depend on it. But the stator inductance is invariant for the surface PM Pole rotors. The additional factor depending on the stator inductance on $N_s\,\theta_{er}$ is due to the existence of slot openings. In consideration with the rotor pole configurations, the stator self and mutual inductance are similar catheterized for the concentrated windings. Contradictorily, the

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distributed windings are larger in values. However, the concentrated windings have smaller end-turn leakage inductance. The space harmonics are also one of the factors to be considered in the fluxes of the permanent magnet machines.

Therefore, with this fact the modeling of the machine takes the assumption that, self and the mutual inductance are either constant or vary sinusoidally with the rotor position ($2\theta_{er}$). In general, the flux linkages $\varphi_{PMa,b,c}(\theta_{er})$ variation in the stator phases are sinusoidal but with θ_{er}. Eventual the time pulsation in the torque and current are observed due to harmonics in the d–q model for the ω_1=ω_2:

$$|L_{abc}\theta_{er}| =$$

$$\begin{vmatrix} L_{ls} + L_0 + L_2\cos 2\theta_{er} & M_0 + L_2\cos(2\theta_{er} + \frac{2\pi}{3}) & M_0 + L_2\cos(2\theta_{er} - \frac{2\pi}{3}) \\ M_0 + L_2\cos(2\theta_{er} + \frac{2\pi}{3}) & L_{sl} + L_0 + L_2\cos(2\theta_{er} - \frac{2\pi}{3}) & M_0 + L_2\cos 2\theta_{er} \\ M_0 + L_2\cos(2\theta_{er} - \frac{2\pi}{3}) & M_0 + L_2\cos 2\theta_{er} & L_{sl} + L_0 + L_2\cos(2\theta_{er} + \frac{2\pi}{3}) \end{vmatrix}$$

$$M = -\frac{L_0}{2} \text{ for distributed windings}$$

Thus the matrix form of the phasor coordinates are given as,

$$|i_{a,b,c}|\,|R_s| - |V_{a,b,c}| = -\frac{d|\varphi_{a,b,c}|}{dt}$$

$$\varphi_{a,b,c} = |L_{a,b,c}\theta_{er})||i_{a,b,c}| + \varphi_{PMa,b,c}(\theta_{er})$$

The Park's transformation from stator to rotor coordinates are given as in the Figure 2 are expressed as,

$$\begin{vmatrix} i_d \\ i_q \\ i_0 \end{vmatrix} = |P(\theta_{er})| \begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix}$$

$$P(\theta_{er}) = \frac{2}{3}\begin{vmatrix} cos(-\theta_{er}) & cos\,(-\theta_{er} + \frac{2\pi}{3}) & cos(-\theta_{er} - \frac{2\pi}{3}) \\ sin(-\theta_{er}) & sin\,(-\theta_{er} + \frac{2\pi}{3}) & sin(-\theta_{er} - \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{vmatrix}$$

The same transformations are valid for φ_{dq0}, V_{dq0}.

Finally, for sinusoidal $\varphi_{PMa,b,c}(\theta_{er})$ distributions,

$$i_d R_s - V_d = L_d \frac{di_d}{dt} + \omega_r L_q i_q$$

$$i_q R_s - V_q = -L_q \frac{di_q}{dt} - \omega_r (L_d i_d + \varphi_{PM1})$$

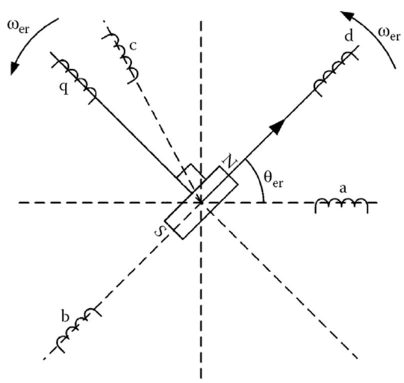

Fig. 2. Three Phase d-q transformation

With

$$\overline{\varphi_s} = \varphi_d + j\varphi_q; = \varphi_d = \varphi_{PM1} + L_q i_d; \varphi_q = L_q i_q$$

$$\overline{V_s} = V_d + jV_q; \overline{\iota_s} = i_d + ji_q$$

From the above equations the space-vector model of the PMSG is obtained as,

$$\overline{\iota_s} - \overline{V_s} = -\frac{d\overline{\varphi}_s}{dt} - j\omega_r\overline{\varphi_s}$$

The torque is obtained as,

$$T_e = p_1\frac{P_e}{\omega_r} = \frac{3}{2}p_1(\varphi_{PM1} + (L_d - L_q)\, i_d)\, i_q$$

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$$L_d = L_{sl}+\frac{3}{2}(L_0-|L_2|);\ L_q = L_{sl}+\frac{3}{2}(L_0 + |L_2|)$$

From the derived expressions the d-q equivalent circuit of the PMSG is given as in the Fig 3.

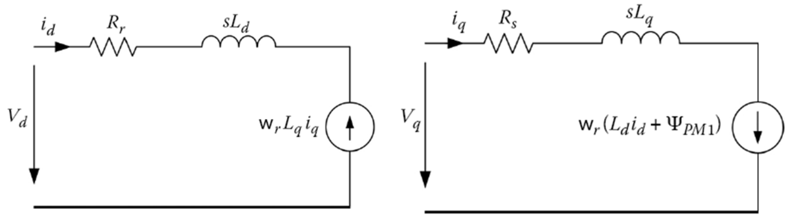

Fig. 3. d-q equivalent circuit of PMSG

The Fig 4 shows the vector representation of the PMSG. The torque value is in negative because of the current i_q which is negative. Under steady state condition, the phase voltages are given as,

$$V_{abc} = V_1\sqrt{2}\cos\left(\omega_r t-(i-1)\frac{2\pi}{3}\right)$$

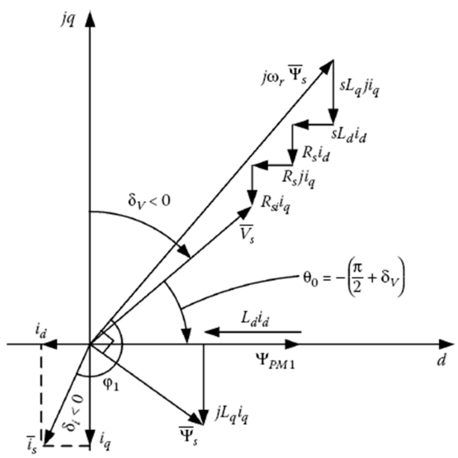

Fig. 4: Vector Representation of PMSG

III. PROPOSED FOUR-LEG INDIRECT MATRIX CONVERTER

The proposed Four-leg Indirect Matrix Converter [1] is shown in the figure 5. The PMSG wind generator is connected to the load through the IMC. The IMC has two stages, one bidirectional rectification and inversion. The inversion stage consists of four-leg unidirectional switches. The weight of the power converter is reduced as the DC link components for the power storage is not present in the IMC.

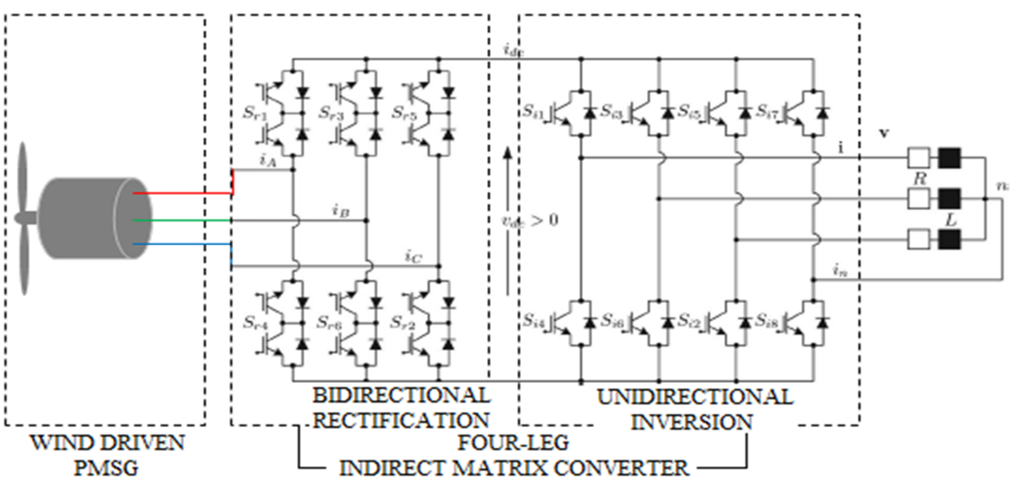

Fig. 5: Proposed Four-Leg Indirect Matrix Converter

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By determining the relationship between the input and the output variables the mathematical modeling in MATLAB can be performed. The DC link voltage is v_{dc} is represented as,

$V_{dc} = T_r v_i$,
Where,
$T_r = [S_{r1} - S_{r4}\ S_{r3} - S_{r6}\ S_{r5} - S_{r2}]$ and
$v_i=[v_A\ v_B\ v_c]$
The DC link current $i_i = [i_A\ i_B\ i_C]^T$ is represented as a function of the output current vector $i = [i_u\ i_v\ i_w]^T$ and as a matrix function of the inversion stage,
$i_{dc} = T_i i$, where $T_i = [S_{i1} - S_{i7}\ S_{i3} - S_{i7}\ S_{i5} - S_{i7}]$
The three phase output voltage, $v = [u_u\ u_v\ u_w]^T$ can be represented as a function of DC-link voltage v_{dc} and the transpose of the matrix T_i
$v = T_i^T v_{dc}$
Using the above equations the controller is used to produce the pulses in a sequence to produce a balanced output at the load side. The firing sequence of the rectifier and the inversion stage is shown in the table I and II respectively.

TABLE I
RECTIFIER STAGE SWITCHING STATE

State	S_{r1}	S_{r2}	S_{r3}	S_{r4}	S_{r5}	S_{r6}
1	1	1	0	0	0	0
2	0	1	1	0	0	0
3	0	0	1	1	0	0
4	0	0	0	1	1	0
5	0	0	0	0	1	1
6	1	0	0	0	0	1
7	1	0	0	1	0	0
8	0	0	1	0	0	1
9	0	1	0	0	1	0

TABLE II
INVERSION STAGE SWITCHING STATE

State	S_{i1}	S_{i2}	S_{i3}	S_{i4}	S_{i5}	S_{i6}	S_{i7}	S_{i8}
1	1	1	0	0	0	1	0	1
2	0	1	1	1	0	0	0	1
3	0	0	0	1	1	1	0	1
4	1	1	1	0		0	0	1
5	1	0	0	0	1	1	0	1
6	0	0	1	1	1	0	0	1
7	1	0	1	0	1	0	0	1
8	0	1	0	1	0	1	0	1
9	1	1	0		0	1	1	0
10	0	1	1	1	0	0	1	0
11	0	0	0	1	1	1	1	0
12	1	1	1	0	0	0	1	0
13	1	0	0	1	1	1	1	0
14	0	0	1	1	1	0	1	0
15	1	0	1	1	1	0	1	0
16	0	1	0	0	0	1	0	1

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IV. PROPOSED SIMULATION MODEL

The proposed system is mathematically modeled of a 4.5kW PMSG system. The wind driven PMSG is modeled to give an unbalanced reference output. The figure 6 shows the unbalanced voltage and current obtained from PMSG.

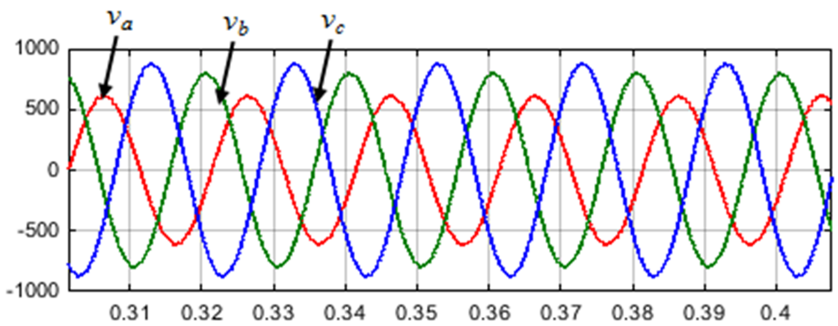
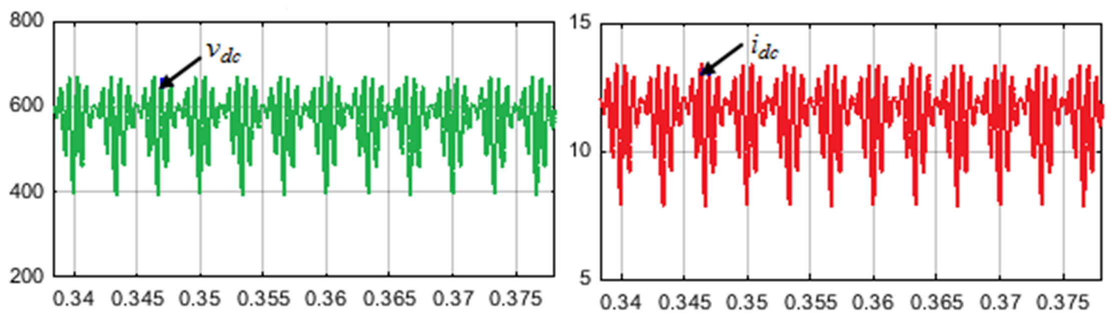


Fig 6. Unbalanced output of PMSG

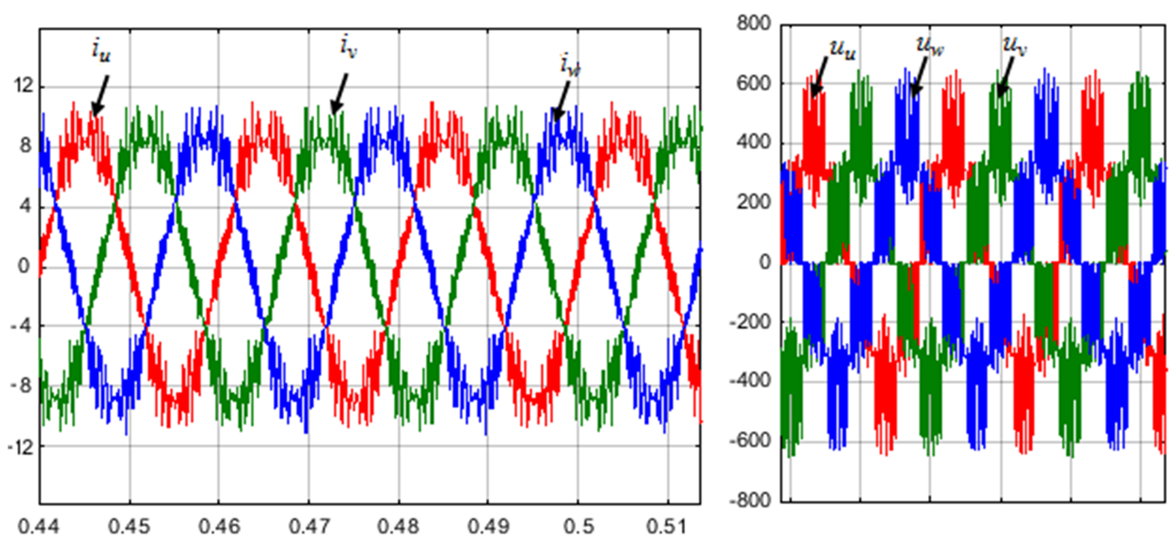
The unbalanced voltage is corrected by the four-leg topology of IMC. The reference values of the current and the voltages are compared with the PMSG output, thereby the error is minimized to produce a balanced output voltage and current. The figure 7 shows the bidirectional DC voltage and current obtained in rectification stage.



(a) (b)

Fig 7. Bidirectional Rectification [M=0.8] (a) Voltage (b) Current

The rectified bidirectional outputs obtained are high level with no losses due to the absence of the dc link elements. The DC supply is then inverted in the inversion stage. The figure 8 shows the inverter balanced output voltage and current at the load side.



(a) (b)

Fig 8: Balanced output [f=50Hz; M=0.7] (a) output load current (b) voltage output across the load

V. CONCLUSION

Most wind turbine connected to weak power systems face the problem of unbalanced voltage conditions. This creates unequal heating in the generators causing damages to the windings. It is necessary to prevent such damages that particularly found in high power wind turbines. The prosed method uses a four leg indirect matrix converter where the three-phase unbalanced power supply is synchronized in two stages of power conversion. The mathematical modeling of PMSG is designed for an unbalanced system. The output of the PMSG wind model is connected to four-leg IMC so as to synchronize the unbalanced input to the balanced output. The output of the IMC is measured across the RL load of 1.5kW. The implementation of the four-leg IMC reduces the stress of unbalanced network thereby increasing the system performance. The system performance can be further improved though the filter circuits, however the cost will be proportionally increased with the filter circuits.

VI. ACKNOWLEDGMENT

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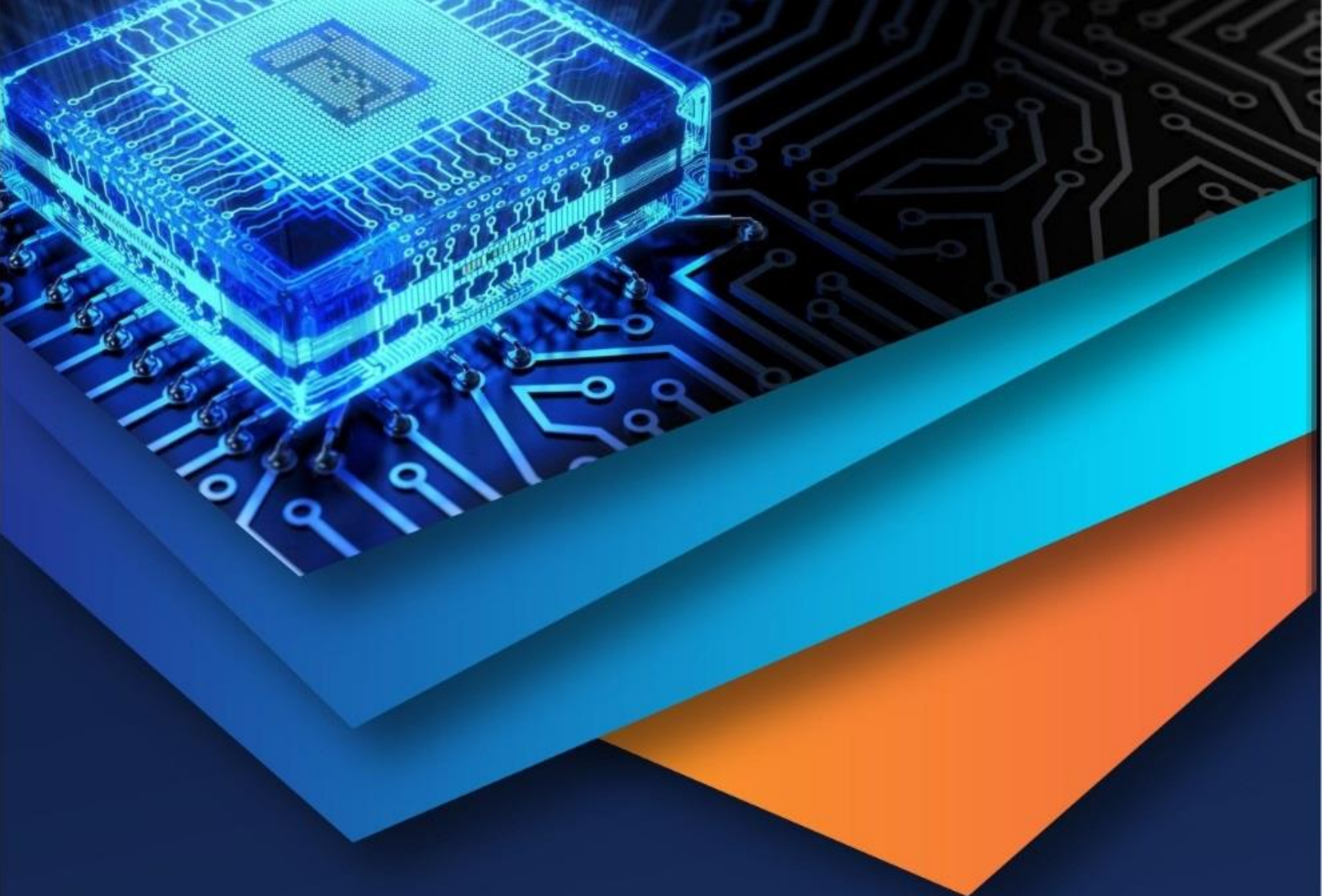

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