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Reduced Torque and Flux Ripple by Hysteresis Band based Bus Clamped Direct Torque Control of Induction Motor

K Durga Devi[1], Jagannadham Lahori[2]
[1]*JNTU, Kakinada, India*
[2]*Associate Proffesor Dept of Eee, Gandhiji Instititute Of Science And Technology, Jaggayapeta*

Abstract: This paper deals with four level torque hysteresis band based bus clamped direct torque control to induction motor. The proposed four level torque hysteresis band based bus Clamped direct torque control to induction machine results in reduction of torque ripple, flux ripple and reduction in harmonic spectrum of current waveforms, further reduction torque ripple and flux ripple can be implemented with duty cycle control of voltage vectors.

Index Terms: Bus clamping direct torque control, direct torque control, harmonic distortion, induction machine motor drives.

I. INTRODUCTION

Direct Torque Control (DTC) strategies of Induction motor drives are mostly used in variable speed applications [2]. The most prominent control objective concerning the induction motor is to keep the electromechanical torque within bounds around its reference; it consists of hysteresis band control for controlling of flux and torque [2, 5 and 6].DTC Strategy is used to compare error between set and estimated flux and torque values. In DTC theory, the machine model is of Stationary Reference frame, due to this demagnetization phenomenon causes direct torque control to affect high flux ripple and torque ripple[15, 12]. This phenomenon commonly affects DTC strategy performance at low speeds as well as at low values of the dc bus voltage. The goal of DTC strategy of induction motor is to reduce torque ripple and flux ripple which can be achieved by bus clamped operation of inverter [7]. Further, the conventional approach of prescribed bands of hysteresis torque control in DTC can be altered with higher order hysteresis band torque control for more reduction of torque ripple. The higher order hysteresis toque controller is operated with duty cycle control, which affects the active time of inverter voltage vectors [8]. By adopting duty cycle control to the higher hysteresis band torque control based bus clamped direct torque control of induction motor makes reduction in torque ripple and flux ripple [8,11]. The proposed duty cycle control based four level torque hysteresis band direct torque control of induction machine (4L THB BCDTC) has low inverter switching losses, low current harmonic distortion to the motor has and torque ripple reduction.

II. MATHEMATICAL MODEL OF IM

The mathematical model of an induction motor defined in the stationary reference frame is widely used for Direct Torque Control (DTC) strategy. The Krause model [1] of induction motor based on impedances in stationary reference frame is given in (1). The generalized expression for torque of the induction motor in terms of stator currents and stator flux linkages is expressed in (3).

$$v_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt} \qquad 1(a)$$

$$v_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt} \qquad 1(b)$$

$$\begin{bmatrix} \dot{\Psi}_{qs} \\ \dot{\Psi}_{ds} \\ \dot{\Psi}_{qr} \\ \dot{\Psi}_{dr} \end{bmatrix} = \begin{bmatrix} 0 & \frac{R_s\,\omega_b}{x_{ls}}\left(\frac{x^*_{ml}}{x_{ls}} - 1\right) & 0 & \frac{R_s\,\omega_b}{x_{ls}}\left(\frac{x^*_{ml}}{x_{lr}}\right) \\ \frac{R_s\,\omega_b}{x_{ls}}\left(\frac{x^*_{ml}}{x_{ls}} - 1\right) & 0 & \frac{R_s\,\omega_b}{x_{ls}}\left(\frac{x^*_{ml}}{x_{lr}}\right) & 0 \\ 0 & \frac{R_r\,\omega_b}{x_{lr}}\left(\frac{x^*_{ml}}{x_{ls}}\right) & -\omega_r & \frac{R_s\,\omega_b}{x_{lr}}\left(\frac{x^*_{ml}}{x_{lr}} - 1\right) \\ \frac{R_r\,\omega_b}{x_{lr}}\left(\frac{x^*_{ml}}{x_{ls}}\right) & 0 & \frac{R_s\,\omega_b}{x_{lr}}\left(\frac{x^*_{ml}}{x_{lr}} - 1\right) & -\omega_r \end{bmatrix} \begin{bmatrix} \Psi_{qs} \\ \Psi_{ds} \\ \Psi_{qr} \\ \Psi_{dr} \end{bmatrix} + \omega_b \begin{bmatrix} I & \Theta \\ \Theta & \Theta \end{bmatrix} \begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} \qquad (2)$$

$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ and $\Theta : 2 \times 2$ null matrix

ω_b : motor angular base frequency

ω_r : rotor angular speed

x_{ls} : stator leakage reactance

x_{lr} : rotor leakage reactance

x_m : mutual reactance

$$x_{ml}^{*} = \frac{1}{\left(\frac{1}{x_m} + \frac{1}{x_{ls}} + \frac{1}{x_{lr}}\right)}$$

Ψ_{ds} : d – axis stator flux linkage

Ψ_{qs} : q – axis stator flux linkage

Ψ_{dr} : d – axis rotor flux linkage

Ψ_{qr} : q – axis rotor flux linkage

$v_{ds}\ v_{qs}$: d and q – axis stator voltages

$v_{dr}\ v_{qr}$: d and q – axis rotor voltages

$$v_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt} \qquad 3(a)$$

$$v_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt} \qquad 3(b)$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{L_r L_s^{'}}(\vec{\Psi}_s \times \vec{\Psi}_r) \qquad 4(a)$$

$$= \frac{3P}{4}(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}) \qquad 4(b)$$

where,

$i_{ds}\ i_{qs}$: stator currents in $d - q$ axis

P : number of poles of the motor

III. DTC OF INDUCTION MOTOR

A. *Switching Table based DTC Strategy*

The stator flux of the induction motor is estimated by integral equation of stator voltage and current as expressed in (5), it is closely related to stator winding voltage drop across R_s. When the induction motor tends to running at their nominal speed range, this voltage drop is ignored as stator input voltage is accounted higher than the voltage drop. Neglecting voltage drop across R_s in (2) and when the estimation sampling period, ΔT_s is small then the change in stator flux and torque can be expressed as in (3) and (4) [2]

$$\vec{\Psi}_s = \int (\vec{V}_s - R_s \vec{I}_s)\, dt. \qquad (5)$$

$$\Delta\vec{\Psi}_s = \vec{V}_s\, \Delta T_s \qquad (6)$$

$$\Delta T_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{\sigma L_s L_r}\left|\vec{\Psi}_r\right|\left|\vec{\Psi}_s + \Delta\vec{\Psi}_s\right| \sin \Delta\delta_{\Psi} \qquad (7)$$

As the sampling period, ΔT_s is very small, the stator flux vector of the induction moves in the direction of voltage and its change is rapid with voltage vector as in (3). The rotor flux vector movement is considerably slower than the stator flux vector due to its higher rotor time constant. The increase or decrease in flux and torque is accountable by the stator voltage. As therefore, the quick change in electromagnetic torque from (4) is mainly affected by the changing torque angle, $\Delta\delta_{\Psi}$ in the desired direction. The inverter switching provides the appropriate active voltage vector to make changes in the flux magnitude and the torque. The application of appropriate voltage vectors torque and stator flux of the motor is controlled directly, which is employed with the help of standard look-up table [1-2] and hence this method control is called direct torque control (DTC) with switching table (ST). The stator flux vector changes and moves in proportion and in the same direction of the stator voltage vector. Hence, the step by step application of appropriate voltage vector changes the flux and torque. In the ST-DTC, the error information of estimated stator flux in (4) and torque in (3) are used in hysteresis controllers as shown in the Fig. 1(a) and Fig1(b)The control scheme for inverter switching is obtained based on increase, decrease or no change in the torque and flux magnitudes. The stator flux and torque are regulated within prescribed bands and the selection of proper switching voltage vectors obtained from (2) and (3), as summarized in Table-I [2,6,12]

$$(\Delta T_e)_{error} = T_e^* - T_e \tag{8}$$

$$(\Delta \Psi_S^*)_{error} = \Psi_S^* - \Psi_S \tag{9}$$

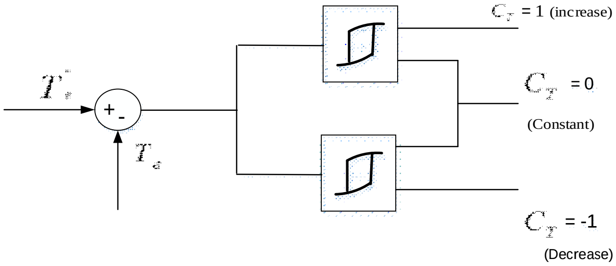


Fig.1(a).Torque 3-level hysteresis comparator

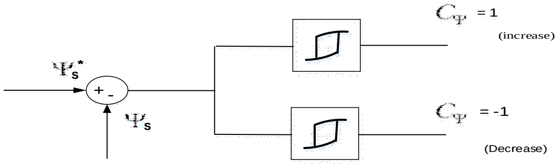


Fig.1(b).Flux 2-level hystersis comparator

B. Bus Clamping based DTC Strategy

The selection of appropriate voltage vectors in ST-DTC strategy is based on switching states of SVM without directly tracing reference voltage vector [7]. The eight switching states of the inverter are shown in the Fig. 2 which are applied to DTC from the switching table given in Table – I. In this strategy the inverter switching in sector – I comprises of voltage vectors. The inverter switches between any two voltage vectors, by applying bus clamping space vector modulation is applied to ST-DTC of induction machine, which makes pole voltages however this switching makes inverter pole voltage +V_{dc} and – V_{dc} constant. Bus clamping SVM (BCSVM) is derived from has two-level torque and two-level flux hysteresis comparator In BCSVM strategies of induction machine has stator flux $\o_s$ where it is logically noted as $c_\o$ taken as 1, to increase $\o_s$ and -1 to decrease it and torque controller is of two level hysteresis control of electromagnetic torque Tem it is logically noted as c_T stated as +1/-1 to increase/ decrease. Voltage Vector selection table can be written as TABLE-II

By considering the switching table, In TABLE-II

Sector

The Voltage vectors are V_2= (+ - -),V_0=(- - -) /V_1=(+ - -),V_3=(+ + -),V_0=(- - -) then lower c-phase dc voltage is clamped.

The overall vector selection table can be written as with comparison of DTC and BCSVM.

TABLE – I: Switching Table: 2L THB DTC Strategy

		Switching Voltage Vector	
T_e	$\vec{\Psi}_s$	2-level DTC Strategy	2-level BC DTC Strategy
↑	↑	V_{k+1}	V_{k+1}
↑	↓	V_{k+2}	V_{k+2}
↓	↑	V_{k-1}	V_k
↓	↓	V_{k-2}	$V_{7,8}$

C. Determination Of Four Level Torque Hysteresis Band Bus Clamping Based Dtc Strategy

Determination of four level torque hysteresis band switching table for BC-DTC strategy, in this proposed Strategy four level torque control and two level flux controller is used. It is synthesized with active switching state. Control of torque can be done from +2 to -2 and control of flux from +1 to -1.as shown in Fig.2[7,16]

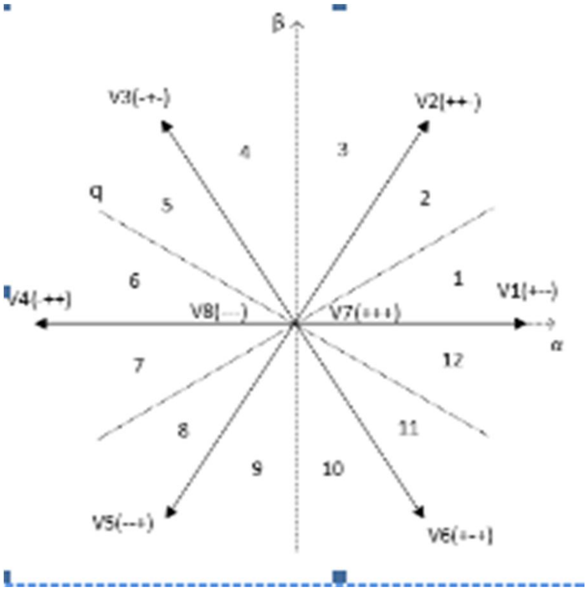


Fig.2.Space vector representation

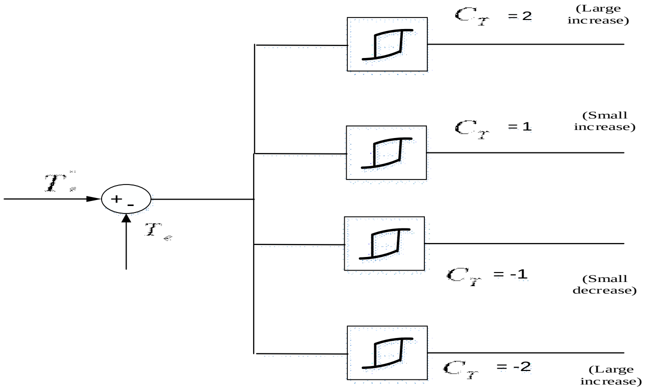


Fig.3.4L THB BCDTC output comparator

D. Novel Switching Strategy Using Duty Cycle

To achieve reduction torque ripple and flux ripple minimization can be done through duty cycle ratio control method. In duty cycle control active voltage vector time period is controlled. This control of duty cycle is taken consideration of flux ripple and torque ripple minimization [8, 11]

Considerations of flux ripple minimization:

$$d_1 = \left| \frac{2(|T_e^*| - |T_e^k|)}{C_T} \right| + \left| \frac{2(|\psi_s^k| - |\psi_s^k|)}{C_\psi} \right| \qquad (10)$$

In the torque ripple minimization can be calculated .the principle of Torque ripple minimization

$$d_2 = \frac{2(|T_e^*| - |T_e^k|)}{2S_{12} - S_0} \qquad (11)$$

The four level toque hysteresis controller is operated with duty cycle control, which affects the active time of inverter voltage vectors.

Vector selection table can be explained for the sector -I

In this 50% duty cycle is applied for reduction of Torque ripple and high level torque control can be implemented.

IV. CALCULATION CRITERIA

Considering the same simulation parameters and for different
reference speed levels, calculation of torque ripple, flux ripple, current THD are selected to evaluate the effectiveness of conventional DTC, 2L THB BCDTC, 4L THB BCDTC.

The calculation of torque ripple can be done as:

Torque ripple formula**:**

$$\text{Torque ripple} = \frac{T_{\max} - T_{\min}}{T_{avg}} * 100 \qquad (12)$$

The calculation of flux ripple can be done as:

Flux ripple formula**:**

$$\text{Flux ripple} = \frac{\psi_{\max} - \psi_{\min}}{\psi_{avg}} * 100 \qquad (13)$$

The calculation of frequency spectrum analysis of three phase stator current can be stated as:

$$THD = \frac{1}{3}\sum_{k=1}^{3} \frac{\sqrt{\sum_{n\neq 1} I_{skn}^2}}{I_{sk1}} \qquad (14)$$

Where I_{sk1} and I_{skn} are rms values of fundamental and nth harmonic currents

V. SIMULATION RESULTS

Induction motor modeling parameters

Stator resistance, R_s= 0.896 ohm.

Stator leakage Inductance, Ll_s=1.94* 10^{-3} H.

Rotor resistance, R_r = 0.896 ohm.

Rotor leakage Inductance, Ll_r=2.45*10^{-3} H.

Mutual Inductance, L_m= 69.75*10^{-3} H.

Moment of Inertia, J=0.225*10^{-3} $kg\text{-}m^2$

Friction coefficient, B = 0 Nm-s

Number of poles, p=4

Motor nominal power P_n, = 150 VA

Motor nominal voltage V_n-RMS = 36 V

Inverter voltage, V_{dc} =50 V

Frequency, f=50 HZ.

Duty cycle upper limit d_{on} = 0.03 (for 4LTHB BCDTC)

Duty cycle lower limit d_{off} = 0.01 (for 4L THB BCDTC)

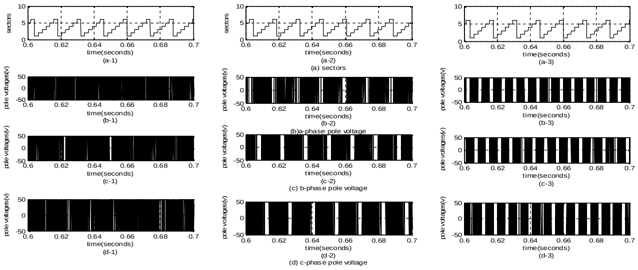
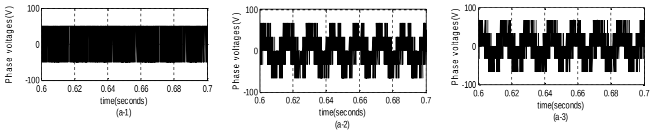
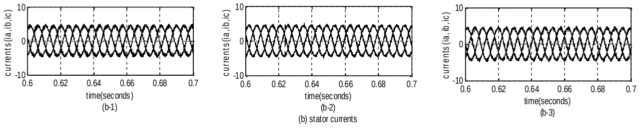


Fig.4.Simulated analysis of conventional DTC, 2L THB BCDTC, 4L THB BCDTC for reference speed Ω_m =157 rad / sec and load torque T_l =0.7 N-m.(a) sectors in $\alpha - \beta$ plain, (b) a-phase pole voltage, (c) b- phase pole voltage, (c) c- phase pole voltage.

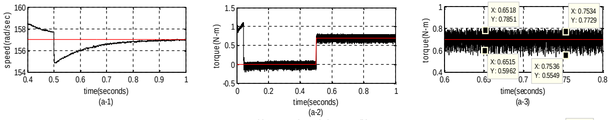


(a) Phase voltages

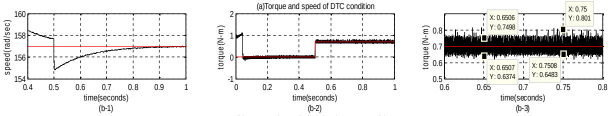


(b) stator currents

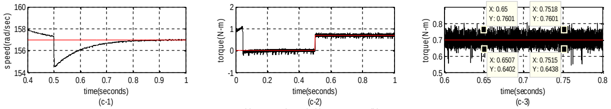
Fig.5.Simulated analysis of conventional DTC, 2L THB BCDTC, 4L THB BCDTC for reference speed Ω_m =157 rad / sec and load torque T_l =0.7 N-m.(a) phase voltage of phase a (b) stator currents.



(a)Torque and speed of DTC condition

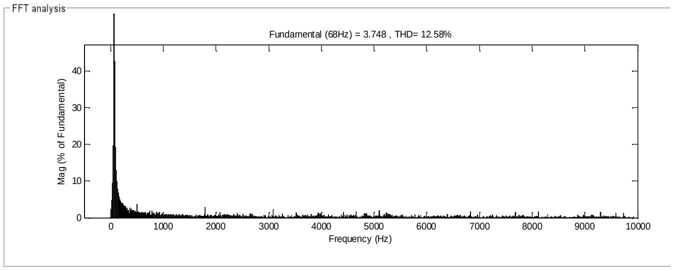


(b)Torque and speed of two level BCDTC condition

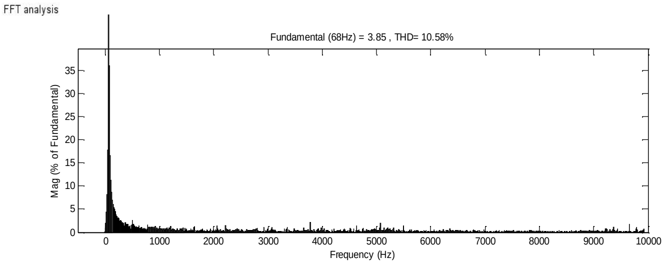


(c)Torque and speed of four BCDTC condition

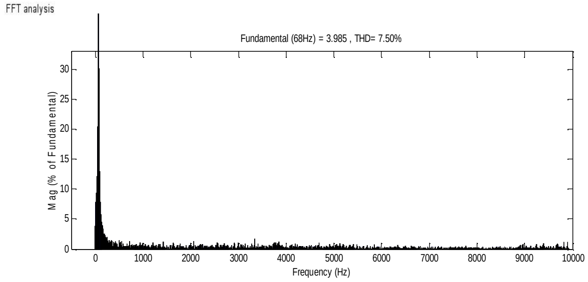
Fig.6.Simulated analysis of conventional DTC, 2L THB BCDTC, 4L THB BCDTC for reference speed Ω_m =157 rad / sec and load torque T_l =0.7 N-m.(a) Torque and speed in conventional DTC strategy (b) Torque and speed in 2L THB BCDTC strategy (c) Torque and speed in 4L THB BCDTC strategy.



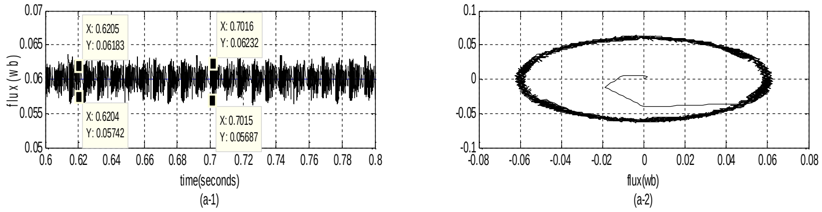
(a) Current THD analysis of CDTC strategy to induction motor drive



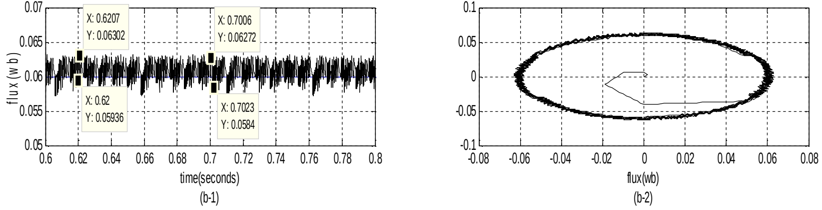
(b) Current THD analysis of 2L THB BCDTC strategy to induction motor drive



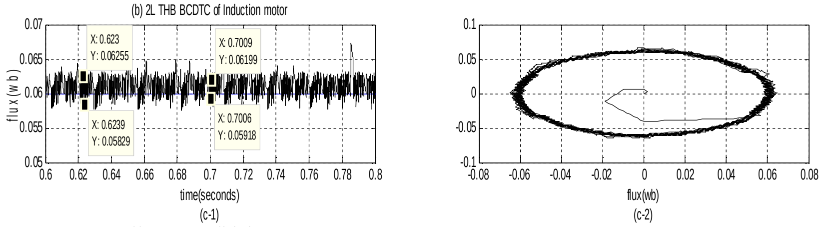
(c) Current THD analysis of 4L THB BCDTC strategy to induction motor drive



(a) CDTC of induction motor



(b) 2L THB BCDTC of Induction motor



(c) 4L THB BCDTC of induction motor

Fig.8.Simulation results of flux responses with CDTC, 2L THB BCDTC, 4L THB BCDTC to induction motor drive.

VI. CONCLUSION

The based on improvement of torque ripple using 4L THB BCDTC. The proposed 4L THB BCDTC strategy can be done in clockwise and anti clockwise direction. Two vector selection table is synthesized according to rotation of three phase induction motor.

In this thesis the performance of conventional DTC (CDTC) and two level torque hysteresis band control based bus clamping DTC (2L THB BCDTC) of induction motor is verified. Another bus clamping based DTC induction motor drive called four level hysteresis band torque control based bus clamping DTC (4L THB BCDTC) is proposed and the performance results are compared.

The performance of induction motor with DTC strategies are analyzed with no load and full load condition. The simulation results of current, electromagnetic torque and flux are presented. In CDTC strategy of induction motor offers high ripple in flux and torque, this effects operation of induction motor. It can be reduced by applying bus clamping strategies. In this clamping of motor phase takes phase which leads to reduction in torque ripple in induction motor. The performance of induction motor can be improved by high reduction of torque ripple, it can be done by increasing the torque hysteresis band of a BCDTC strategy to induction motor and duty cycle control is also implemented. In this project four level torque hysteresis band is proposed to BCDTCIM, This makes reduction in torque ripple, flux ripple and current THD.

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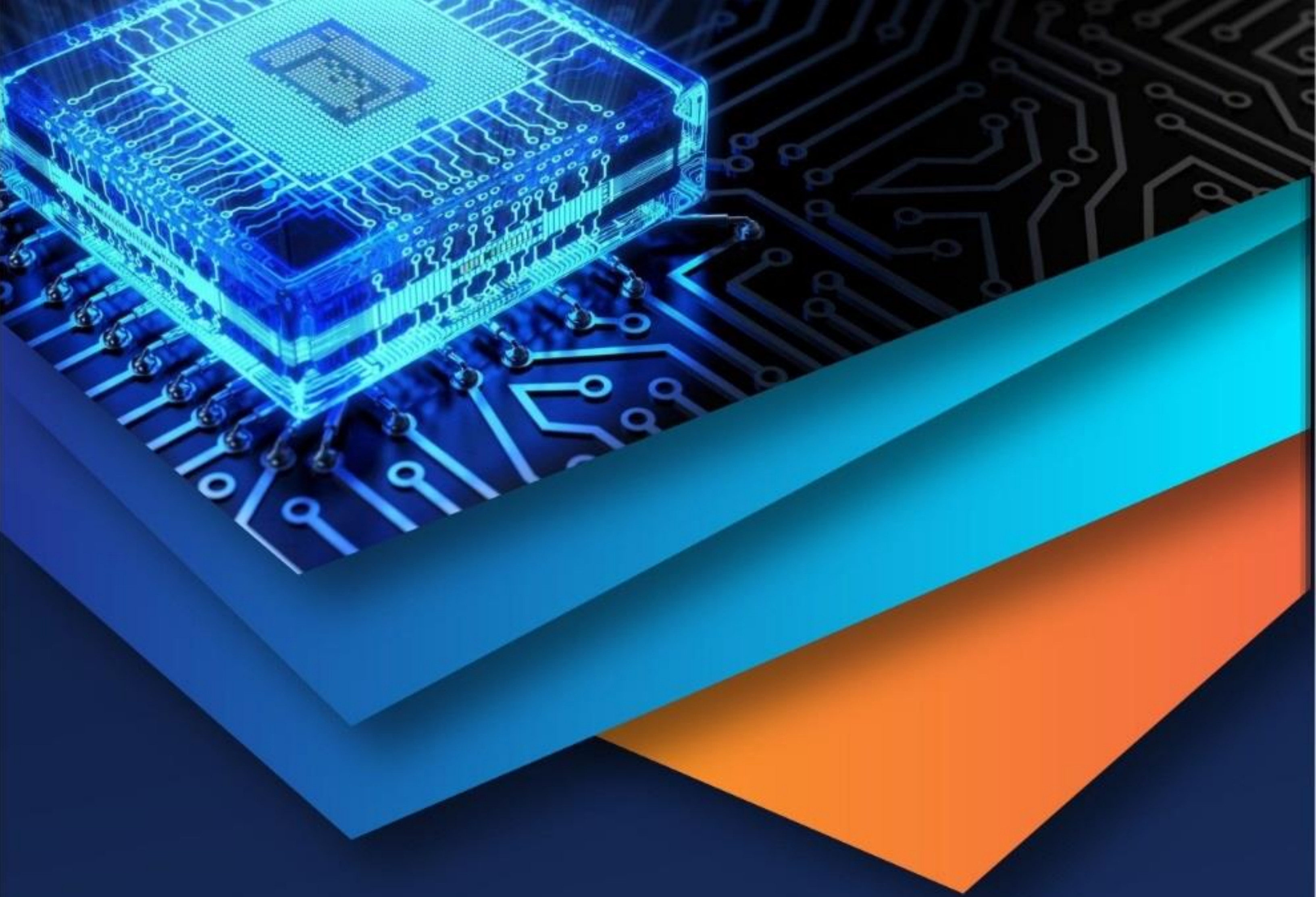

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