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Artificial Neuro-Fuzzy Logic Based Non-Sinusoidal Synchronous Reluctance Motor for Torque Ripple Minimization

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Abstract: ***This paper proposes a new method on adaptive artificial neuro-fuzzy networks for reducing the torque ripple in the non-synchronous reluctance motor. The Lagrange optimization method is used to solve and to calculate the optimal currents in the d-q frames. A control scheme is proposed as an adaptive solution in order to derive the optimal stator currents giving a constant electromagnetic torque and to minimize the ohmic losses. The adaptive learning capacity of neuro-fuzzy networks, the optimal currents can be obtained***.

Index terms- *Non-sinosoidal synchronous reluctance motor, Torque ripple, Optimal currents, Lagrange optimization, AFNline, artificial neuro-fuzzy networks*.

I. INTRODUCTION

Synchronous reluctance motor is gaining more importance in the industries, due to their unique facts such as the fast dynamic response, great efficiency and with low cost. The reluctance motor can deliver a very high speed density at low cost, which makes them ideal for the many applications. Torque smoothness is an essential requirement in many applications. Therefore, many authors have proposed different methods to minimize the torque ripple with this kind of machine. In [1], the authors pointed out that there are two approaches that minimize the torque ripple of synchronous motors. The first one consists of techniques to adjust the machine's stator and rotor design in order to cancel the undesirable torque ripple.

The authors in [2–4] proposed the methods for reducing the torque ripple by adjusting the flux barrier in rotor structure. The effect of rotor skewing to minimize the torque ripple has been studied in detail [5,6]. The authors in [5] and [6] show that the torque ripple is minimized when the rotor is skewed with an angle which is equal to a stator slot pitch. The second approach is based on the active control schemes which modify the stator currents and propose the best currents for cancelling the undesired torque ripple.

The authors in [7] worked in the d–q frame in order to calculate the optimal currents. The copper losses in this method are not minimized because the direct current is forced to be equal to the quadrature one Id= Iq. Also working in the d–q reference frames, the works presented in [8–10] give the expressions of optimal currents to minimize the torque ripple.

The authors of [8] and [9] propose an extended Park transformation to obtain optimal currents in the non-sinusoidal machine, while the authors in [10] obtain optimal currents to achieve a maximum torque-to-current condition which takes into account the effect of magnetic saturation. Based on input–output linearization, the authors in [11] and [12] propose a method to obtain optimal currents that give the constant torque and minimize the losses. Nonlinear controllers are proposed in [11] to regulate the torque by selecting the product of d-axes and q-axes torque currents as one of the output variables. The cross-coupling effects and iron losses are taken into account in [11]. Based on sliding mode control(SMC) [13], the value of the reference current is adjusted in order to keep the speed of the motor constant. Therefore, the torque ripple of the motor is minimized.

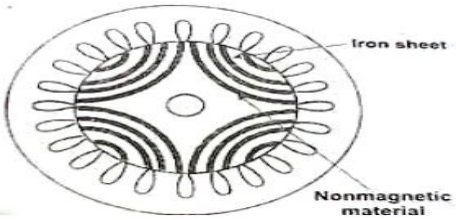

Fig1. Cross section of the SynRM

The injection of current harmonic is proposed in [14], the disadvantage of this method is high torque ripple because the authors optimize the currents only for harmonics of ranks 5 and 7. Recently, based on direct torque control (DTC), the works in [15–18]

have proposed controlling the stator flux and generating the torque. In [16], the amplitude and angle of the commanding voltage vectors were derived from the errors of torque and flux. Therefore, the torque and flux-ripples are minimized.

Based on torque predictive control [17], the optimized voltage is utilized to reduce torque ripple. In that method, the voltage angle vector is determined from the output of torque and flux hysteresis controllers. Another method based on the injection of high-frequency current presented in [18], the MTPA point can be detected because the variation in the torque based on the variation in the current angle is zero at the MTPA points.

In [19], the optimal currents are obtained based on emotional controller and space vector modulation (SVM) under an automatic search of the MTPA strategy.

In [20], the estimated difference of d–q inductance was used to achieve MTPA control and accurate torque control. While all of these authors work only with sinusoidal machines, in this article we work instead with non-sinusoidal SynRMs.

The approaches mentioned above, in this article we use an unique and an adaptive technique base on the artificial neuro fuzzy networks to obtain the optimal stator currents. The optimal stator currents minimizes the copper losses and give the exactly electromagnetic torque desired in non-sinusoidal SynRMs. The ANFs presented in this article is adaptive neuro fuzzy logic.

II. COMPUTATION OF THE TORQUE IN SYNCHRONOUS RELUCTANCE MOTOR

The electromagnetic torque equation is given as follows.

$$T_e = \frac{1}{2} \cdot i^T \cdot \frac{\partial[L(p\theta)]}{\partial\theta} \cdot I \qquad (1)$$

Where $I=[i_a i_b i_c]^T$ is the stator currents vector.

p: the number of pole pairs, and θ: the mechanical angle.

The matrix of inductances $[L(p\boldsymbol{\theta})]$ **is e**xpressed as follows:

$$[L(p\boldsymbol{\theta})] = \begin{bmatrix} La(p\boldsymbol{\theta}) & Ma(p\boldsymbol{\theta}) & Mac(p\boldsymbol{\theta}) \\ Mab(p\boldsymbol{\theta}) & Lb(p\boldsymbol{\theta}) & Mbc(p\boldsymbol{\theta}) \\ Mac(p\boldsymbol{\theta}) & Mbc(p\boldsymbol{\theta}) & Lc(p\boldsymbol{\theta}) \end{bmatrix} \qquad (2)$$

where $L_a(p\boldsymbol{\theta})$, $L_b(p\boldsymbol{\theta})$, $L_c(p\boldsymbol{\theta})$: the self- inductances and $M_{ab}(p\theta)$, $M_{bc}(p\theta)$, $M_{ac}(p\theta)$: the mutual inductances.

The sinusoidal excitation, the current vector is given by:

$$I = \begin{bmatrix} \sqrt{2}.Irms\ .\ \cos(p\theta + \varphi) \\ \sqrt{2}.Irms.\ \cos(p\theta - \frac{2}{\pi} + \varphi \\ \sqrt{2}.Irms.\cos(p\theta + \frac{2}{\pi} + \varphi \end{bmatrix} \qquad (3)$$

With φ: the load angle. Thus, in order to maximize the mean value of electromagnetic torque , the load angle is chosen as: $\boldsymbol{\varphi}$ = 45◦.The accurate measurement of self and mutual inductance calculation is very much necessary for the analysis of the SynRM. Due to the rotor saliency and stator windings distribution. Hence the self and the mutual inductances estimation of SynRM are non-sinusoidal. Electromagnetic torque produced by motor produces ripple when it is fed by the sinusoidal currents.The measurement of the self and the mutual inductances are realized as follows and the expression for the self and the mutual inductances are given by

$$L_a(p\theta) = 0.024+0.113.\cos(2p\theta) -0.0295.\cos(4p\theta) - 0.007\cos(p\theta)$$

$$M_{ab}(p\theta) = -0.093 + 0.0129.\cos(2(p\theta + \frac{2\pi}{3})) + 0.01\cos(4(p\theta + \frac{2\pi}{3})) + 0.006\cos(6(p\theta + \frac{2\pi}{3})) \qquad (4)$$

Therefore, the optimal reference currents are thus required for reducing the torque ripple in this SynRM. For this, in next section, we will present the calculation of optimal currents by means of the Lagrange optimization

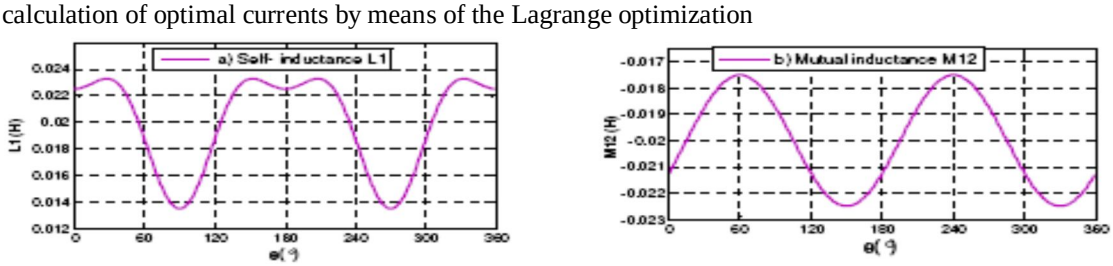

Fig. 2. Self (a) and mutual (b) inductances

III. LAGRANGE METHOD FOR CURRENT OPTIMIZATION

The Park transformation is define by

$$P = \sqrt{2/3}\begin{bmatrix} \cos(p\theta) & -\sin(p\theta) \\ \cos(p\theta - \frac{2\pi}{3}) & -\sin\left(p\theta - \frac{2\pi}{3}\right) \\ \cos(p\theta + \frac{2\pi}{3}) & -\sin(p\theta + \frac{2\pi}{3}) \end{bmatrix} \quad (5)$$

Using park transformation and assuming the zero sequence of the current to zero, we have

$$I = \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} = [P]^T. \quad i_d = i_{d\_opt} = \sqrt{\frac{|T_e|}{\frac{\lambda^2.(a^2.b - a.c^2) + \lambda.(2c^2 - 2.a.b) + b}{\lambda^2.c^2}}} \quad \begin{bmatrix} id \\ iq \end{bmatrix} \quad (6)$$

Where i_d and i_q are the d and q current components.

Replacing (6) in (1), the electromagnetic torque equation is rewritten as

$$T_e = \frac{1}{2}.\begin{bmatrix} id \\ iq \end{bmatrix} T \quad (7)$$

Defining the matrix $[A]$ as follows:

$$[A] = \frac{1}{2}.[P].\frac{\partial[L(p\theta)]}{\partial\theta}.[P]^T = \begin{bmatrix} a(p\theta) & c(p\theta) \\ c(p\theta) & b(p\theta) \end{bmatrix} \quad (8)$$

By replacing eqn (8) in (7) the electromagnetic torque can be rewritten as follow:

$$T_e = a(p\theta).i^2_d + i^2_q + 2.c(p\theta).i_d.i_q \quad (9)$$

In order to minimize the copper loss and obtain the electromagnetic torque, we use Lagrange optimization. The cost function for the copper losses are given by

$$P_j = R_s.(i^2_d + i^2_q) \quad (10)$$

Where P_j: copper losses, R_s are stator resistance.

The Lagrange function is given as

$$L = (i^2_d + i^2_q) + \lambda.(T_e - (a.i^2_d + b.i^2_q + 2.c.i_d.i_q)) \quad (11)$$

With: λ: Lagrange's multiplier,

The derivation of L in terms of i_d and i_q are given as follows

$$\begin{cases} 2.i_q + \lambda.(-2.b.i_q - 2.c.i_d) = 0 & (12) \\ 2.i_d + \lambda.(-2.b.i_d - 2.c.i_q) = 0 & (13) \end{cases}$$

From (12) ,we obtain (14)

(14)

$$i_q = i_{q\_opt} = \frac{(1 - \lambda.id\_opt)}{\lambda.c} \quad (15)$$

Where i_{d_opt}, i_{q_opt} are d and q optimal current components

From (12) and (13) , the Lagrange multiplier is given by:

$$\lambda = \lambda 1 = \frac{(a+b) + \sqrt{(a-b)^2 + 4.c^2}}{2.(a.b - c^2)} \quad \text{with } Te < 0$$

$$\lambda = \lambda 2 = \frac{(a+b) - \sqrt{(a+b)^2 + 4.c^2}}{2.(a.b - c^2)} \quad \text{with } Te > 0 \quad (16)$$

The three phase optimal currents are obtained as

$$\begin{bmatrix} i_{a\_op} \\ i_{b\_opt} \\ i_{c\_opt} \end{bmatrix} = [P]^T . \begin{bmatrix} i_{d\_opt} \\ i_{q\_opt} \end{bmatrix} \quad (17)$$

In order to obtain a desired electromagnetic torque and minimize the cop-per losses in the non-sinusoidal SynRM, the machine stator currents are not sinusoidal to compensate the torque ripple.

We will present a new method based on artificial neuro-fuzzy networks to obtain the optimal currents. Thanks to learning capacity of neural networks, the optimal currents will be obtained online and each machine's parameter estimation errors can be compensated. That is the advantages of ANNs compared with the Lagrange optimization.

IV. ARTIFICIAL NEURO-FUZZY NETWORK FOR TORQUE AND SPEED CONTROLLERS

A. *Idea for the speed control.*

From (14), we can write i_{q_opt} as

$$i_{q\_opt} = \frac{(1-\lambda.a)\,.\; id\_opt\,(Te\,p\theta)}{\lambda.c} = K_{opt}(p\theta)\,.\; i_{d\_opt}\,(T_e\,.p\theta) \qquad (18)$$

$$\text{Where } K_{opt}(p\theta) = \frac{(1-\lambda.a)}{\lambda.c} \qquad (19)$$

The principal idea for the torque and speed controllers comes from the axis q optimal currents in (18). We can observe that this current results from a scalar product of two components: the first one is the optimal function $K_{opt}(p\theta)$, and second one is the axis d optimal current $i_{d\_opt}(Te, p\theta)$.

We can observe that $i_{d\ opt}$ and K_{opt} are the periodic functions, and hence we make possible to Artificial neuro-fuzzy learn and estimate . Therefore, we propose to learn online $i_{dop}t(Te, p\_)$ by one ANF controller and estimate off-line $K_{opt}(p\theta)$ by another AFN with an input vector composed of $\cos(kp\theta)$ and $\sin(kp\theta)$ terms with k varying from 0 to 20 . After convergence, the function $K_{opt}(p\theta)$ is calculated as,

$$K_{op}t(p) \approx i_{d0} + \sum_{i=1}^{K} (i_{da1}\sin(ip\theta) + i_{db1}\cos(ip\theta)) \qquad (20)$$

B. *Torque and speed controller based on artificial neuro-fuzzy networks*

The torque (or speed) errors between the desired torque Tr_{ef} and the calculated torque T_{ein} Fig. 4 is necessary for deriving the optimal current i_{d_opt}. The input vector for AFN line as

$$X = [\,x_0\ \sin(p\theta)\quad \cos(p\theta)\ \ldots\ldots.\sin(Np\theta)\ \cos(Np\theta)]^T \qquad (21)$$

Similarly the weights in AFN line :

$$W = [w_o\ w_{a1}\ \ w_b1\ \ldots..\ w_{aN} w_{bN}]^T \qquad (22)$$

C. *Simulatin Of Artificial Neuro-Fuzzy Network Method*

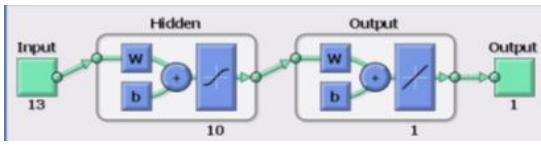

Fig. 3 Fitting function

Matlab/Simulink program is used to simulate for the non-sinusoidal SynRM and the artificial neuro-fuzzy networks. The self and mutual inductances are expressed in (4). The reference speed is fixed at 1200 [rpm] in the simulation. The parameters ofthe machine for simulation and experimental tests are shown in Table 1. The torque and speed controllers based on artificialneuro-fuzzy networks are presented in Fig. 8.

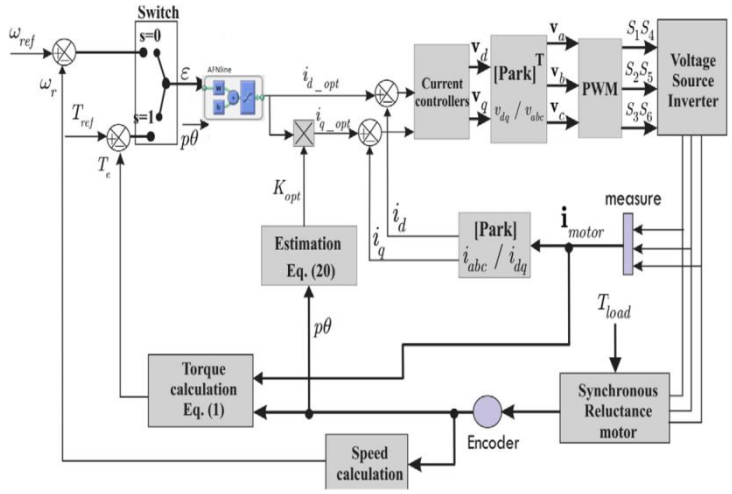

Fig.4. Torque and speed controllers of SynRM based on the artificial neuro-fuzzy networks

The results of neural torque control are shown in Fig. 5 withthe desired torque Tref= 2 [N.m]. The optimal currents obtained by afnline controllers are close to their references as shown to reduce the torque ripple. It can be noticed that the torque ripple obtained with proposed method in Fig. 9b) is not significant (only 0.07% of the desired torque ripples) and the convergence of this strategy takes approximately one electrical cycle (about 25 ms).

A simulation work with a varying torque is presented in order toevaluate the dynamic response of the proposed technique. Fig. 6 shows the obtained results when we change the desired torque to Tref= 5 [N.m] at t = 0.1 s. It can be seen that a good response ofanfline's method with ripple of 0.124% is achieved by observing the optimal currents and the torques obtained in Fig. 6, the converging to the reference values in a short time (about 20 ms). This good result oftorque control is ensured.

V. SIMULATION RESULTS

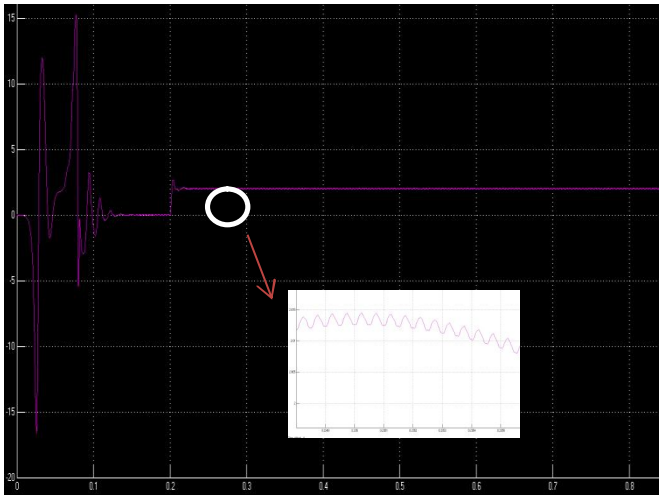

Fig.5 Output waveform of AFNline with torque of 2 N-mt

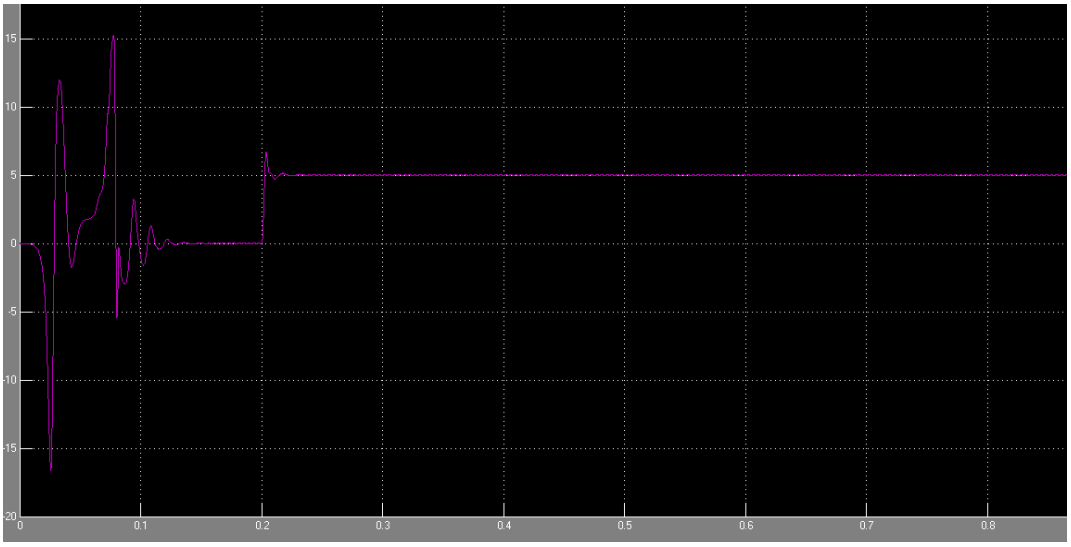

Fig.6 Output waveform of AFNline with torque value of 5 N-

VI. CONCLUSION

We have proposed a new method based on artificial neuro- fuzzy networks for minimizing the torque and speed ripple in non-sinusoidal SynRMs. By this method, we can derive optimal stator currents which are accurately provides electromagnetic torque and minimizing the copper losses. With the learning ability of the AFNline networks we can obtain good stability, short convergence with optimal currents in real time. The afnline controllers take the place of the conventional torque or speed controller to ensure that

the motor's torque or speed con-verge toward the desired ones. Our simulation and experimental results clearly show that the torque and speed ripples have been much reduced and the convergence of the proposed method is achieved within a short time

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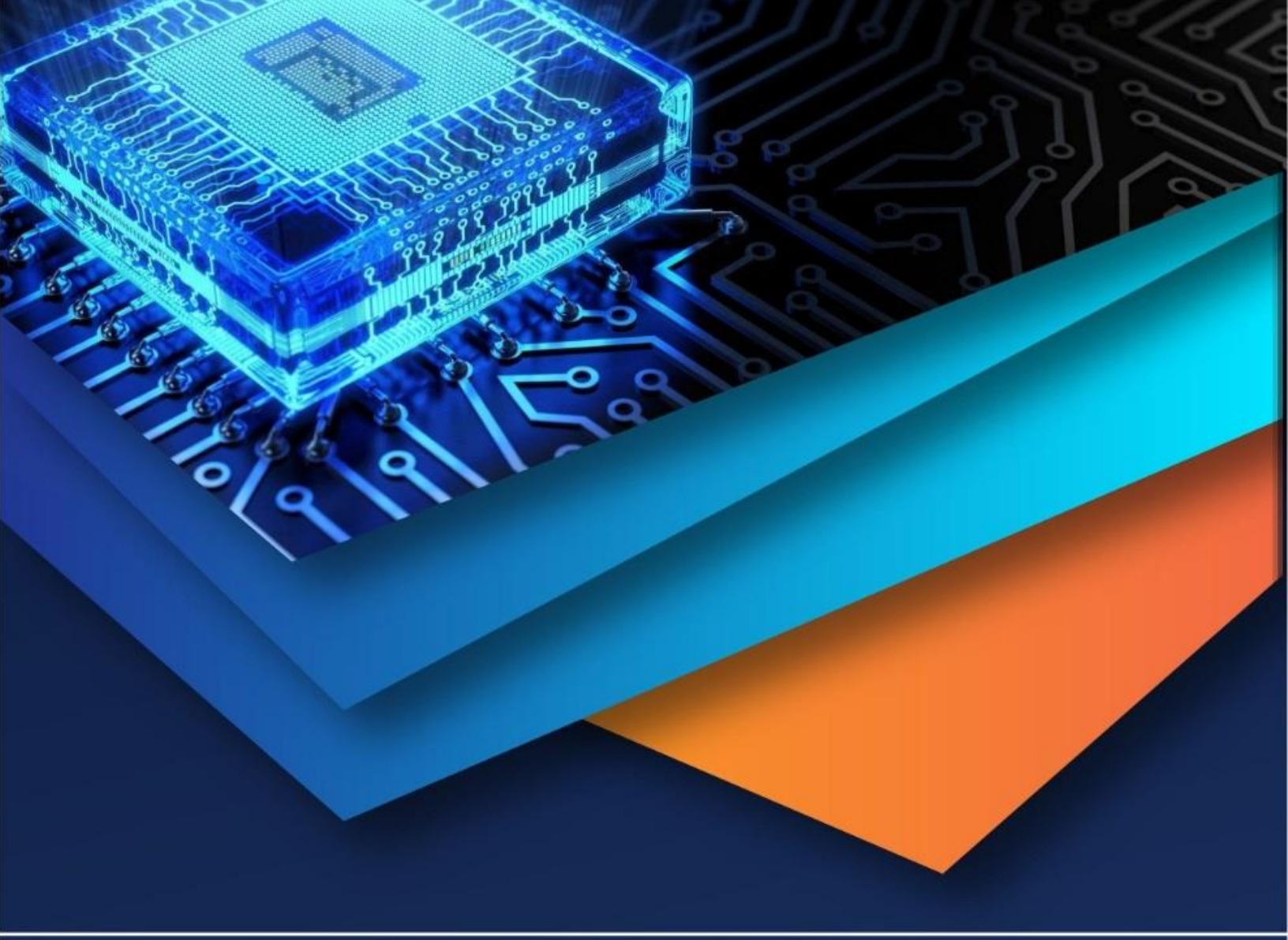

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