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A Review on the Fault-Tolerant Method of PMSM using Finite Element Method by Modifying Phase Angle for EV Applications

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Abstract: The present research reviews a fault-tolerant technique for Permanent Magnet Synchronous Motors (PMSMs) that involves phase angle adjustment. Fault tolerance standards for the motor used in electric vehicles are necessary due to the rapid development of these vehicles. The primary option for electric vehicle drive motors is increasingly being replaced with permanent magnet synchronous motors (PMSM), which have minimal torque ripple, great durability, and other benefits. After comparing a six-phase PMSM to a conventional three-phase PMSM, the performance following a phase open is examined. A fault-tolerant technique for modifying the left phase current's phase angle to reduce torque ripple following a phase open is then described. The finite element simulation indicates that the six-phase PMSM's output torque ripple is reduced, and the fault-tolerant technique that is being described can further reduce the torque ripple.

Keywords: Electric vehicles, Six-phase PMSM, Fault tolerance, Torque ripple, Adjusting phase angle

I. INTRODUCTION

The motor serves as the electrical vehicle drive system's power supply, and multi-phase PMSM motors are typically found in electric buses and other electric vehicles with strict fault tolerance specifications. By increasing the phase number, a multi-phase motor can achieve fault-tolerant operating in the phase-open state by offering a greater degree of control freedom compared to a three-phase motor.

The development of fault detection and diagnostic (FDD) technology is predicated on the use of monitoring systems. The monitoring of motor-related operating parameters, such as current, voltage, flux, speed, temperature, vibration, noise, and partial discharge, and the application of the proper technique to assess the motor's current operating condition are referred to as PMSM driving system fault monitoring and diagnosis technologies.

If the motor is malfunctioning, more information about the kind of failure, its position, its severity, and its development trend must be obtained. To prevent the occurrence of harmful accidents, this enables the site operators to supply the information required for a reasonable arrangement.

Even if a multi-phase motor can continue to operate in a fault-tolerant manner after a phase open fault in the motor drive system, the failure will negatively impact the torque ripple of the motor. The multi-phase induction motor's stator magneto motive force (MMF) in the phase open state is examined, and a non-disturbing rotating MMF approach is suggested to lessen the torque ripple brought on by the phase open. The most effective course of action for current control is suggested to minimize torque ripple. For both single and multiple faults, fault-tolerant control can be achieved with this method. Based on the optimal current calculation, a mathematical model of the motor phase loss is constructed and the decoupling vector control is implemented. In addition, the effects of spatial harmonics and leakage inductance on the torque ripple are examined, and a corresponding suppression technique is suggested to further lessen the torque ripple.

The conventional three-phase PMSM and the one-phase open's performance are first compared. The fault-tolerant technique of lowering the torque ripple by modifying the phase angle of the left phase current is then proposed, based on the analysis theory of MMF. Ansoft, a finite element application, verifies that the fault-tolerant approach is valid.

II. PMSM SIX-PHASE WINDINGS

The two sets of three-phase windings that make up the six-phase windings have an electrical angle difference of 120°, while the corresponding phases have an electrical angle difference of 30°. As illustrated in Fig. 1, the six-phase double Y windings' connecting path and phase electromotive force (EMF) vector diagram have been changed by 30°.

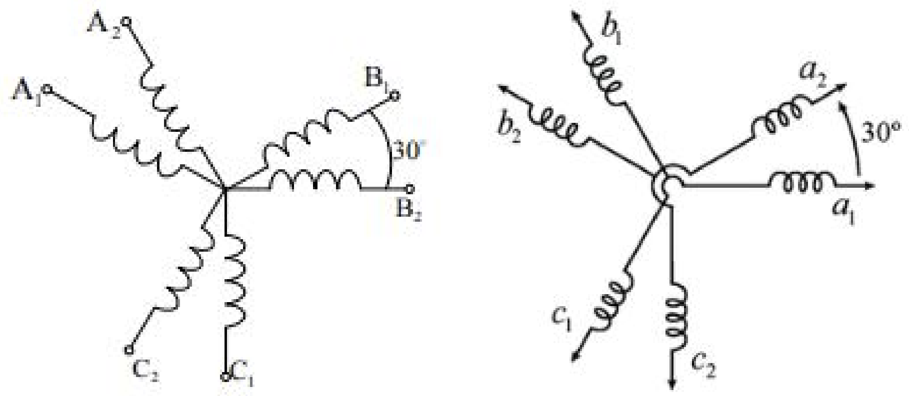

Fig. 1 Windings connection way of six-phase double Y windings shifted by 30°

III.REDUCING THE TORQUE RIPPLE OF ONE PHASE OPEN

The six-phase double Y-shift 30° windings PMSM can still output enough torque to keep the electric vehicle operating when the motor phase opens, but the torque ripple will be larger in the motor as compared to the three-phase PMSM. It is necessary to feed the three-phase symmetrical currents into the three-phase symmetrical windings of the PMSMs to guarantee that the stator synthesis MMF forms a circular rotating magnetic field. Thus, the winding space phase and the current time phase are both connected to the stator synthesis MMF. A circular revolving magnetic field is created solely by the positive sequence component that is created by the winding current. The torque ripple induced by the negative sequence synthetic component increases if the six-phase double Y-shift 30° windings PMSM works in the phase open since each phase's negative sequence cannot counteract the other's.

Considering the A1 winding space axis as the origin of the space coordinate and the moment at which the A1 phase current reaches its maximum value as the time coordinate zero point, it is assumed that the C1 phase winding open fault occurs. This assumption is based on the winding symmetry, which indicates that assuming any phase open will be reasonable and will not affect the analysis result. It is possible to think of the six-phase double Y-shift 30° windings as two sets of three-phase windings: three-phase windings {A1, B1, C1} and three-phase windings {A2, B2, C2}. The left five phases continue to operate while the C1 phase winding is open, or when $i_{C1} = 0$. Zero sequence synthetic component exists in one set of {A2, B2, C2} three-phase windings since they are still supplied symmetrical currents. However, the synthetic MMF of the two phases' windings, A1 and B1, results in non-zero negative sequence components. Therefore, the torque ripple can be minimized if there is a way to remove the synthetic negative sequence component.

The left phase windings space position cannot be altered when a single phase is open; this means that the B1 phase winding axis will always lag the A1 phase by 120°. However, the controller can determine the time angle of each phase. The A1 phase current can be described as follows if the time coordinate zero point is chosen to be the moment the current reaches its highest value.

$$i_{A1} = I_m \cos \omega t \tag{1}$$

where *Im* is current amplitude, ω is the angular frequency.

Make the adjusting phase angle of the B1 phase winding current as x, so the current of the B1 phase winding can be expressed as:

$$I_{B1} = I_m \cos(\omega t - x) \tag{2}$$

Therefore, A1, B1 two-phase windings MMFs are:

$$f_{A1} = F_{\phi 1} \cos \theta \cos \omega t \tag{3}$$

$$f_{B1} = F_{\phi 1} \cos(\theta - 2/3\pi) \cos(\omega t - x) \tag{4}$$

where $F_{\varphi 1}$ is the fundamental amplitude of the phase winding MMF, and θ is the space phase angle.

Divide the two-phase windings MMFs A1, and B1 into positive and negative sequence components, that is,

$$f_{A1} = (1/2)\, F_{\phi 1} \cos(\omega t + \theta) + (1/2)\, F_{\phi 1} \cos(\omega t - \theta) \qquad (5)$$

$$f_{B1} = (1/2)\, F_{\phi 1} \cos(\omega t + \theta - x - 2/3\pi) + (1/2)\, F_{\phi 1} \cos(\omega t + \theta - x + 2/3\pi) \qquad (6)$$

Add f_{A1} and f_{B1} to obtain the combined MMF, $f = f_{A1} + f_{B1}$

$$f = (1/2)\, F_{\phi 1} \cos(\omega t + \theta) + (1/2)\, F_{\phi 1} \cos(\omega t - \theta) +$$
$$(1/2)\, F_{\phi 1} \cos(\omega t + \theta - x - 2/3\pi) + (1/2)\, F_{\phi 1} \cos(\omega t + \theta - x + 2/3\pi) \qquad (7)$$

where the negative sequence component f^- is:

$$f^- = (1/2)\, F_{\phi 1} \cos(\omega t + \theta) + (1/2)\, F_{\phi 1} \cos(\omega t + \theta - x + 2/3\pi) \qquad (8)$$

Since the synthetic negative sequence component directly generates torque ripple, one phase must open to minimize the torque ripple. The phase angle of the B1 phase winding current needed to prevent torque ripple when a phase is unplugged can be found by reducing the negative sequence component to zero.

$$\mathrm{Cos}\,(\omega t + \theta - (x/2) - (\pi/3))\ \mathrm{Cos}\,((x/2) + (\pi/3)) = 0$$

$$\mathrm{Cos}\,((x/2) + (\pi/3)) = 0 \qquad \xRightarrow{x =} 60^0$$

The solution is x = 60°, which means that the B1 phase winding current phase angle needs to be modified to lag the A1 phase by 60° when the C1 phase is open. Similar to this, the phase angle of the C1 phase winding current should be changed to lag the B1 phase by 60° when the A1 phase winding open fault occurs. The phase angle of the C1 phase winding current needs to be changed to advance the A1 phase by 60° while the B1 phase winding is open. The A1 winding space axis should continue to be assumed as the origin of the space coordinate in all calculations. Additionally, the advanced phase angle of the two left phases in the phase open set should not be altered, and the moment the A1 phase current reaches its maximum value should be assumed as the time coordinate zero point.

IV. FINITE-ELEMENT SIMULATION

Fig. 2 and Fig. 3 are the load torque waveforms of the three-phase PMSM and six-phase PMSM respectively. The load air gap flux density of the conventional three-phase PMSM and six-phase PMSM with six-phase double Y-shift 30° windings, respectively, was simulated using finite element software, Ansoft. It is evident that in the typical three-phase PMSM, only the 1st, 11th, 13th, 17th, 19th, and 23rd order harmonics remain, whereas, in the six-phase PMSM with double Y-shift 30° windings, all other order harmonics are absent. This indicates that some of the three-phase PMSM's armature response magnetic field harmonics, including the 5th, 7th, 17th, and 19th harmonics, are eliminated by double Y-shift 30° windings.

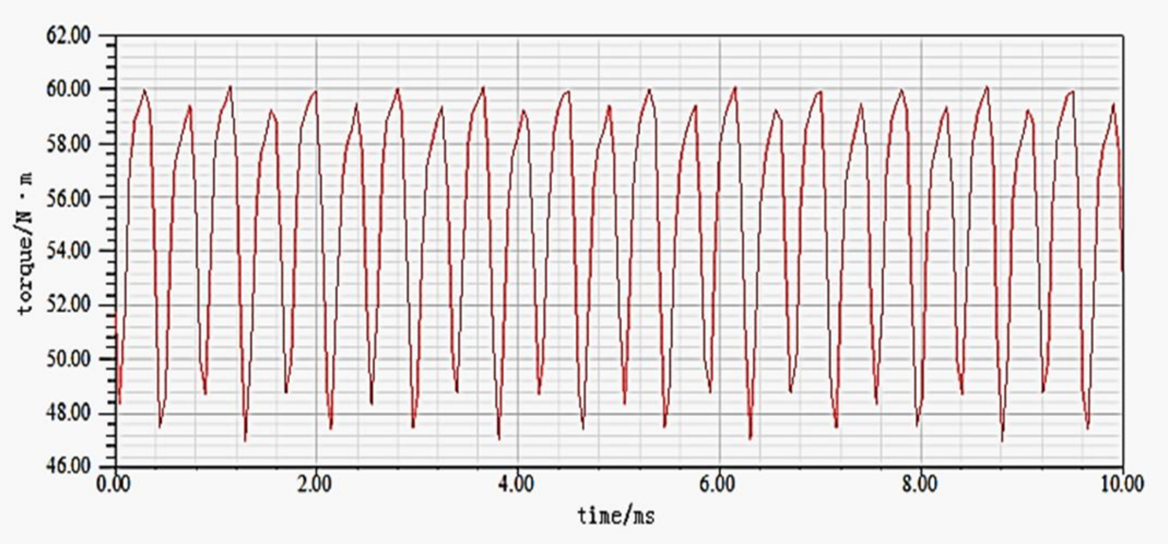

Fig. 2 The three-phase PMSM load torque

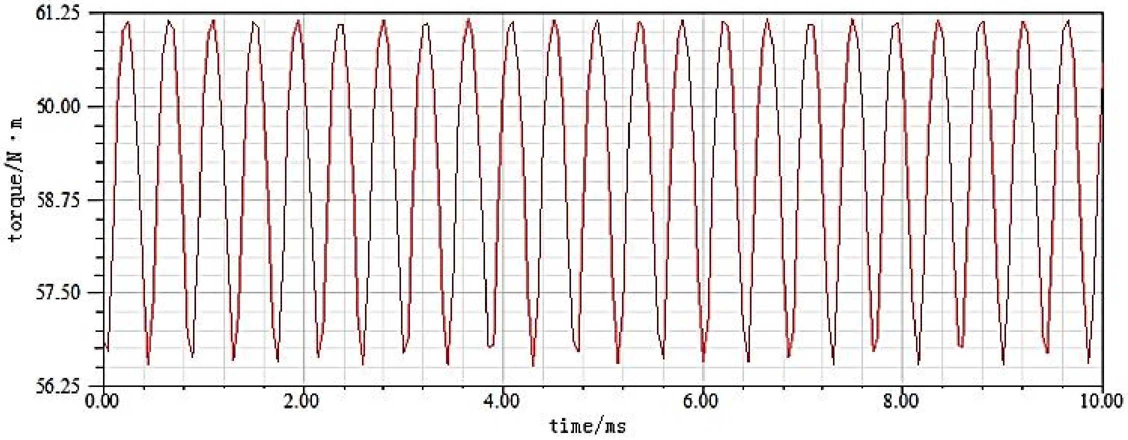

Fig. 3 The six-phase PMSM load torque

In a three-phase conventional PMSM, the left A1 and B1 two-phase windings continue to operate even when the C1 phase winding phase is open, or when the C1 phase winding current drops to zero. The torque ripple is caused by the left two phases' inability to combine to generate a regular circular rotating field. The torque waveform of a three-phase PMSM when the C1 phase is open. It is evident that the torque ripple rises abruptly to 53.5% and the output torque is reduced to about two-thirds of its typical amount. Additionally, the remaining A1, B1, A2, B2, and C2 five-phase windings continue to operate when the C1 phase winding in the six-phase PMSM with double Y windings displaced by 30° is open, or when the C1 phase winding current becomes 0.

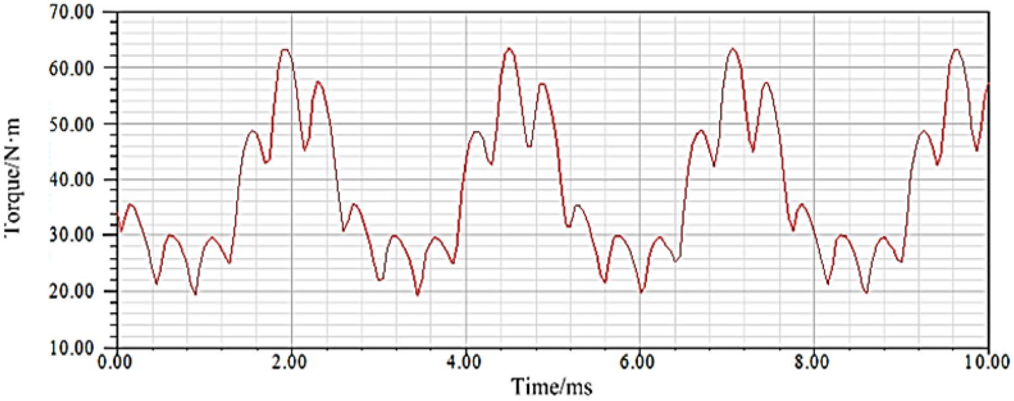

Fig. 4 The torque waveform when the C1 phase open in a three-phase PMSM

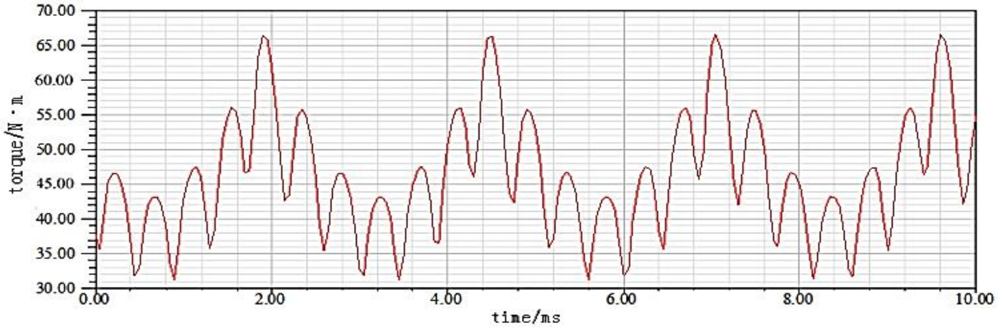

Fig.5 The torque waveform when the C1 phase open in a six-phase motor

The preceding simulation results show that the six-phase double Y-shift 30° PMSM has a torque ripple of 36.2% and that the output torque is reduced to nearly half of its usual value. Although the torque ripple is 17.3% less than that of the three-phase PMSM, it is still quite large when a fault occurs.

Assuring that the A1 phase angle is fixed and that the phase angle of the B1 phase winding current lags by various A1 phase angles—30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, and 270°—will aid in confirming the accuracy of the results. The results have been tabulated in Table I.

TABLE I

Torque table of various phase angle

Degree (^{0})	Output Torque (Nm)	Torque Ripple (%)
30	42.9	40.9
60	46.8	26.1
90	47.4	30.2
120	45.1	35.2
150	40.7	43.6
180	35.6	54.3
210	31.2	63.3
240	30.5	62.2
270	29.7	72.6
300	31.2	71.0
330	34.9	62.1

It is evident that when the phase angle of the B1 phase winding current lags A1 by 60°, the torque ripple of the six-phase double Y shift 30° PMSM is at its minimum. Before modifying the phase angle, the motor's torque ripple could reach 35.2%; after changing, the torque ripple was reduced by 11.2%. This result indicates that the torque ripple in a six-phase PMSM can be minimized by varying the phase angle of the left phase winding's current when phase open occurs.

V. CONCLUSION

The paper presents the design of a six-phase winding PMSM intended for use in electric vehicles. When a single phase fault arises, the minimum torque ripple can be obtained by removing the negative sequence component of the MMF and modifying the left windings' phase angle. It is inferred that without altering the phase angle of the A1 phase, the phase angle of the B1 phase winding current should lag by 60° when the C1 phase is open. Likewise, the following outcomes are attained. The phase angle of the C1 phase winding current should be set to lag the B1 phase by 60° when the A1 phase winding is open. The phase angle of the C1 phase winding current needs to be changed to advance the A1 phase by 60° while the B1 phase winding is open. The same logic applies if a phase within another phase is open. According to the simulation results, the torque ripple can be reduced by 11.2% by modifying the left phase angle approach.

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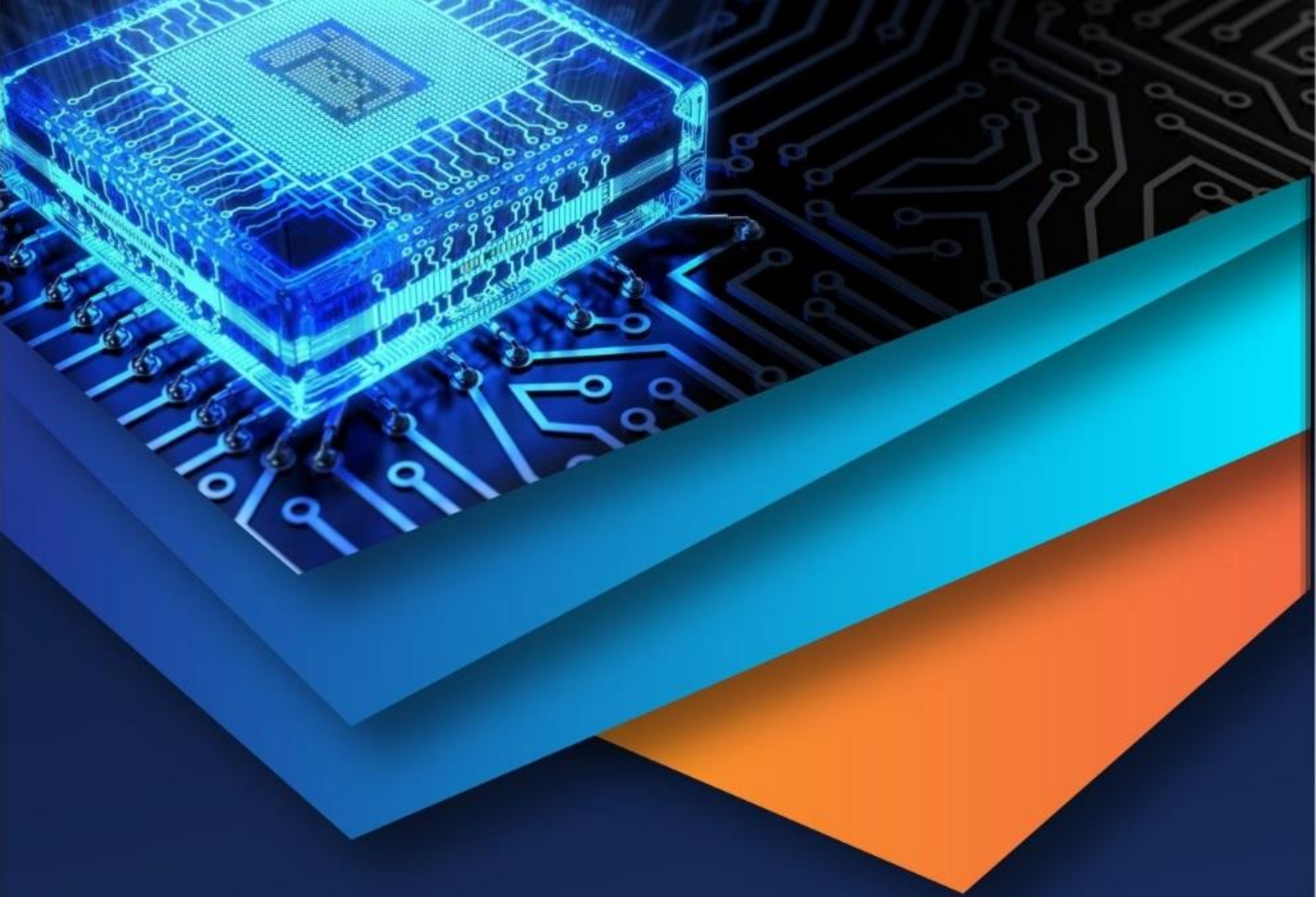

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