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Comparison Analysis of Torque Ripple and Demagnetization by FC in PM BLDC Motor

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Abstract: In this paper, we analyzed and compared changes of demagnetization under fault conditions and commutation torque ripples in a PM BLDC motor. Changes of freewheeling current are analyzed at different speeds. Commutation torque ripple is analyzed in the freewheeling current section.

Also, the change of demagnetization phenomenon is compared and analyzed through a change of flux density according to the change of freewheeling current. Consequentially, we studied reliability and stability through changes of demagnetization and commutation torque ripple.

Keywords: Brushless DC motor, demagnetization, freewheeling current, inter-turn fault, commutation torque ripple.

I. INTRODUCTION

In permanent magnet (PM) brushless dc (BLDC) motor, high-reliability researches about fault diagnosis and high-efficiency researches about torque ripple reduction are actively studied [1], [2]. Among studies of fault diagnosis and torque ripple, many studies on demagnetization of PM and commutation torque ripple are especially conducted [3], [4]. Demagnetization of PM and commutation torque ripple are affected by freewheeling current (FC) occurred when the inverter switch turns on or off. In recent times, even if many studies on commutation torque ripple considering the FC are actively conducted for high efficiency, the studies on the demagnetization considering the freewheeling current are not actively conducted. Therefore, we conducted a demagnetization analysis depending on the variation of FC for improving the reliability of the PM BLDC motor.

Furthermore, if a fault of the BLDC motor is occurred such as inter-turn fault (ITF) owing to broken coil insulation, the input current increases. And an increment of the input current is destroyed by the electrical and magnetic imbalance. For this reason, the ITF generates irreversible demagnetization.

If the demagnetization phenomenon has occurred, magnetic flux is reduced by the decrease of back electromotive force (BEMF), and then electric loading is beyond magnetic loading by the increase of input-current. When PM demagnetization continuously occurs during an ITF, irreversible demagnetization (ID) can occur [5]. ID not only decreases the control performance of a BLDC motor but also quickly deteriorates it. Thus, we need to analyze the demagnetization phenomenon to study fault diagnosis for high reliability.

Torque ripple generates unacceptable speed ripple, vibration, and acoustic noise. So, torque ripple has been one major factor to achieve high performance in the PM BLDC motor. Torque ripple can be divided into three types. First is cogging torque ripple which causes motor design.

The second is a high-frequency torque ripple which causes pulse width modulation. The last is the commutation torque ripple which causes the turning inverter switch on or off. The commutation torque ripple is usually.

Because it can be reached 50% of the average torque. Ideally, the PM BLDC motor doesn't produce commutation torque ripple. But, in practice, when the BLDC motor is commutated, commutation torque ripple occurs. Thus, we are necessary to do studies about commutation torque ripple for high performance.

Thus, in this paper, we analyzed the causes of the change of FC. Furthermore, commutation torque ripple and demagnetization phenomenon are analyzed depending on the FC

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II. THE FREEWHEELING CURRENT

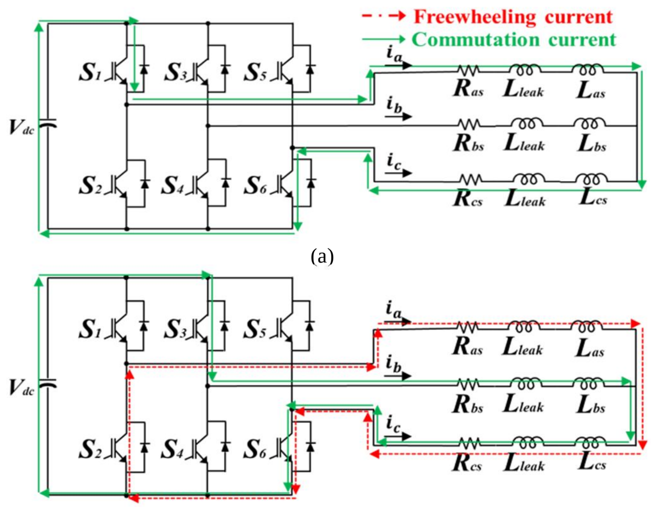

Fig. 1. Commutation state from S1S6 to S3S6 in PM BLDC motor. (a) Switch S1S6 ON commutation current. (b) Switch S3S6 ON commutation current and the FC.

S1 to S6 are switches of inverter. Ras, Rbs, and Rcs are the winding resistances. A leak is the leakage inductance. Las, Lbs, and Lcs are the phase inductances of the PM BLDC motor.

The FC is, when the BLDC motor is commutated through inverter switch turning on or off, called phenomenon that currently remains although commutation turns off by time constant. Fig. 1 shows the commutation state to operate the PM BLDC motor. As shown in Fig. 1, the dotted line is the FC.

Thus, in case that the resister and inductance are constant in the motor, change of the FC doesn't occur. But, FC may be changed when the BLDC motor changes its speed in the constant torque region or when it is loaded. In Fig. 1 (a), after switches of S1 and S6 are commutated; the PM BLDC motor is operated by turning off S1 and on S3. In an ideal case, the FC is not occurred because of nonexistent inductances of motor and linkage. But in practice, inductances of motor and linkage recharge energy. And the energy flow to the dotted line in Fig. 1 (a).

We conducted the finite-element method (FEM) analysis to confirm the change of the FC when the BLDC motor's speed is changed in the constant torque region. Frequency is different according to speed. Thus, the period is changed. Provided that period is changed, charged, and discharged energy of the inductance is changed according to current. When increased speed shortens the period, the energy-charged in the inductance is reduced. Therefore the slope of FC is increased. Fig. 2 is a half period of phase-A current according to PM BLDC motor's speed through FEM analysis. As shown in Fig. 2, the period is changed by the PM BLDC motor's speed. Also, we can check the same size's starting point of the FC according to the speed. Consequentially, the slope of the FC is changed by the PM BLDC motor's speed.

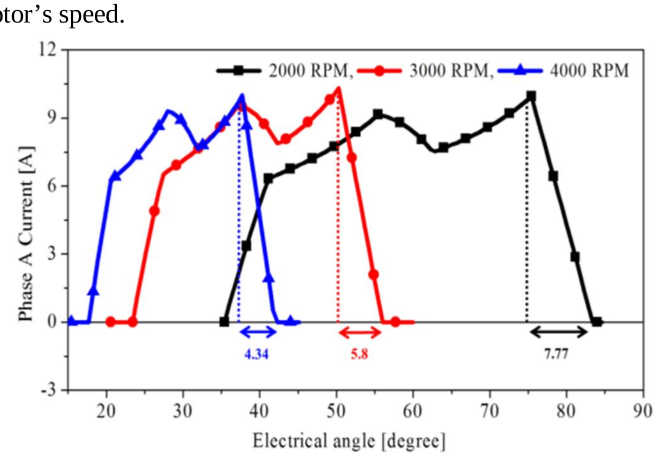

Fig. 2. Phase-A current according to PM BLDC motor's speed through FEM analysis

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III. THE COMMUTATION TORQUE RIPPLE

The commutation torque ripple is generated by a change of the commutation current when the switch turns on or off. Ideally, the commutation torque ripple is not generated because of any variation of the FC. While in practice, the commutation torque ripple is occurred by the variation of FC like Fig. 3(a), (b). As shown in Fig. 3, cases of the freewheeling current section are third. In Fig. 3(a), the decrease rate of phase-A current differs from the increase rate of phase-B current. This phenomenon generates a ripple of phase-C current. In the section of generating the FC, the commutation torque ripple is yielding when the rate of decreasing FC and the rate of increasing commutation current are different. Fig. 4 represents phase current and torque on the velocity 3000 rpm. In the section of FC in Fig. 4, the commutation current ripple is generating according to the difference between the starting point of decreasing FC and the ending point of increasing commutation current. Also, this current ripple yields commutation torque ripple. In other words, commutation torque ripple is generated in the FC section and it leads to produce commutation torque ripple. In Fig. 4, it wouldn't matter because the torque ripple is lower than the torque peak value. However, if the ITF is caused, the commutation torque ripple is even higher than the torque peak value.

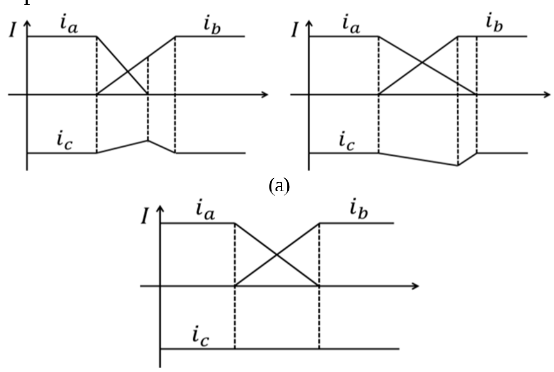

Fig. 3. Phase current in accordance with a variation of the freewheeling current.
(a) Causes of commutation torque ripple. (b) Non-commutation torque ripple.

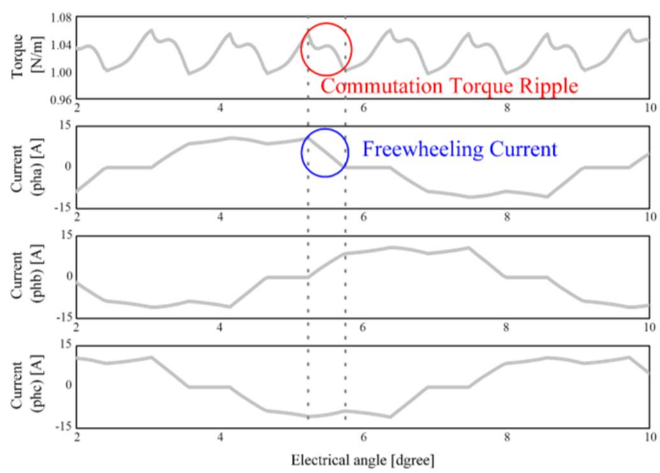

Fig. 4. Phase current and torque of the PM BLDC motor at 3000 rpm speed.

IV. MAGNETIC FIELD DISTRIBUTION AND DEMAGNETIZATION

Fig. 5 analyzed by FEM is flux path and flux density according to the change of FC. The FC divides into three kinds. Model-1 shows a state, as shown in Fig. 3(b). On the basis of the FC gradient of model-1, model-2 and 3 have respectively delayed times of 0.5 ms and 1 ms. Namely, when the FC is changed, magnetic field distribution is analyzed how to change. In Fig. 5, the flux path of phase-B is different in the FC. This flux line can disregard in a normal state. However, it can be severely affected by the demagnetization phenomenon when an ITF is generated. If an ITF has occurred, the phase current of the fault coil is increased. Increased phase current produce more flux. For this reason, the flux path of phase-B flows in the opposite direction to the flux path of the PM. It means that its flux path demagnetized the flux path of PM when the flux path is increased by ITF. As a result, the flux of phase-B can make serious demagnetization of the PM.

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ITF influence electromagnetic characteristic by circulating current of short-circuits. In particular, the reverse magnetic field which is caused by circulating current generates demagnetization. If the reverse magnetic field continuously influences PM, the PM will lose its original characteristic by increasing the demagnetization phenomenon. The demagnetization phenomenon is mainly intensified once flow overcurrent. Fig. 6 shows the demagnetization phenomenon through the change of the FC in normal and ITF states. As a result, the more the change of FC is big; the demagnetization phenomenon of the overcurrent state grows bigger. As the demagnetization of PM is gradually increased, the PM can be irreversible demagnetization.

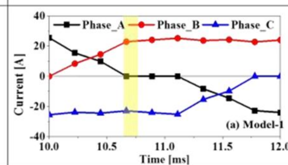
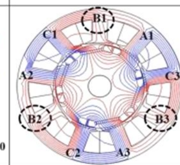
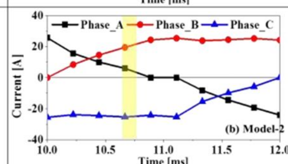
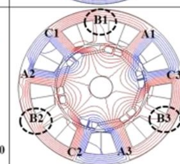
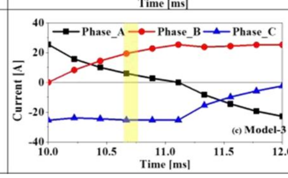
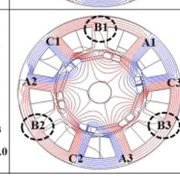
Model	Current [A]	Flux Line	Teeth Flux Density
Model-1			0.3178 [T]
Model-2			0.2066 [T]
Model-3			0.2034 [T]

Fig. 5. Magnetic field characteristic according to the FC

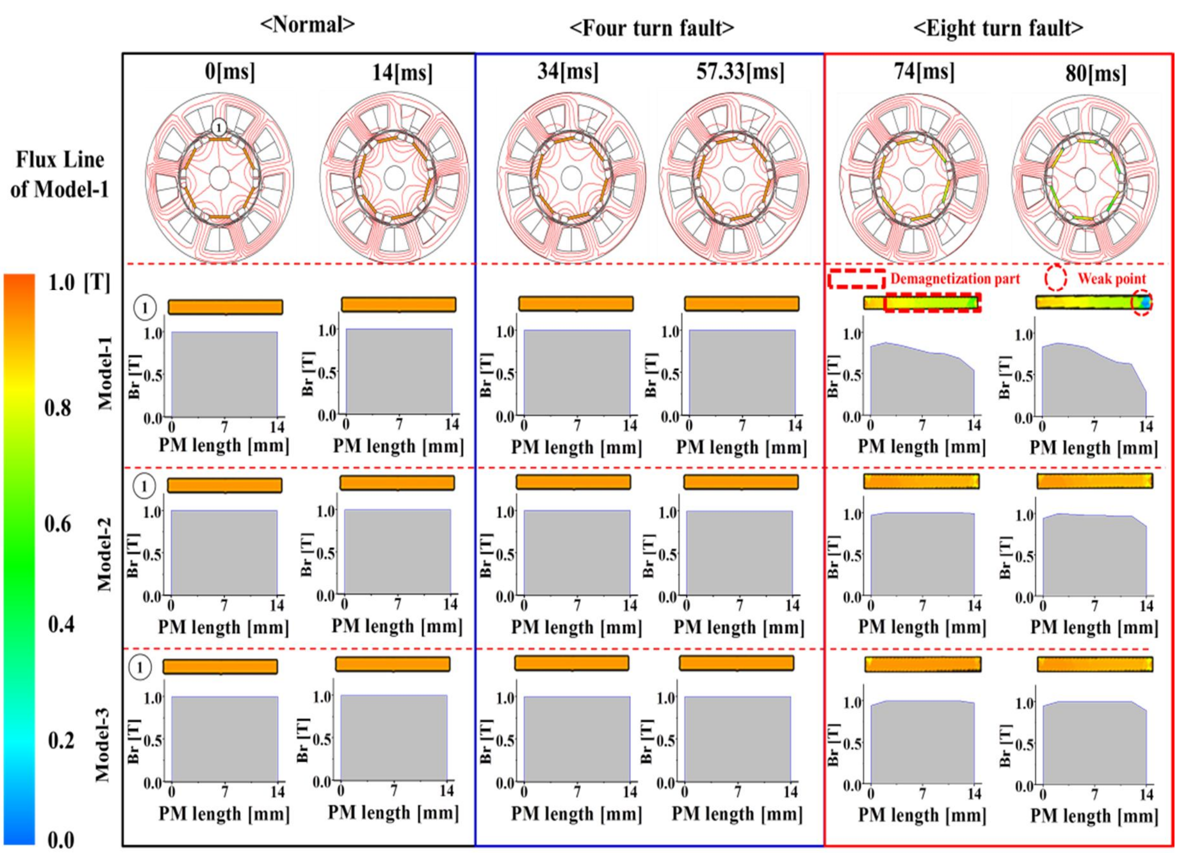


Fig. 6. Characteristics of magnetic field and demagnetization.

V. COMPARISON ANALYSIS OF DEMAGNETIZATION AND COMMUTATION TORQUE RIPPLE IN ACCORDANCE WITH FC

Freewheeling current is changed when the rotating speed of the PM BLDC motor varies. In addition, it affects the commutation torque ripple and demagnetization. Thus, we analyzed and confirmed the effect on freewheeling current using FEM simulation.

Fig. 7 is the result of phase-A current according to PM BLDC motor's speed in light of from normal state to fault state. In the normal state, the phase current is constant, but the phase current is increased in the fault state. Because the lower speed the ITF has occurred in the small size of BEMF, the lower BEMF becomes [7]. Therefore, the more the PM BLDC motor's speed decreases, the more the current is increased in the ITF. As Fig. 4 is confirmed, the commutation torque ripple can be ignored in the normal state. However, commutation torque ripple has largely occurred when ITF generates as Fig. 8 is shown. When Fig. 8 is shown in fault state in accordance with speed, the biggest torque ripple can be periodically checked. This is commutation torque ripple. This commutation torque ripple has most largely occurred in the speed 2000 rpm which has the largest current.

Fig. 9 shows that demagnetization is changed according to speed. Demagnetization has not occurred in normal state and 4turn fault state. However, demagnetization occurred at 2000 rpm and 3000 rpm in the case of an 8-turn fault. In addition, we can verify that the largest demagnetization has occurred at 2000 rpm. In conclusion, demagnetization of PM is occurred by the inverse magnetic field of fault current more than the magnetic field of PM when ITF has occurred.

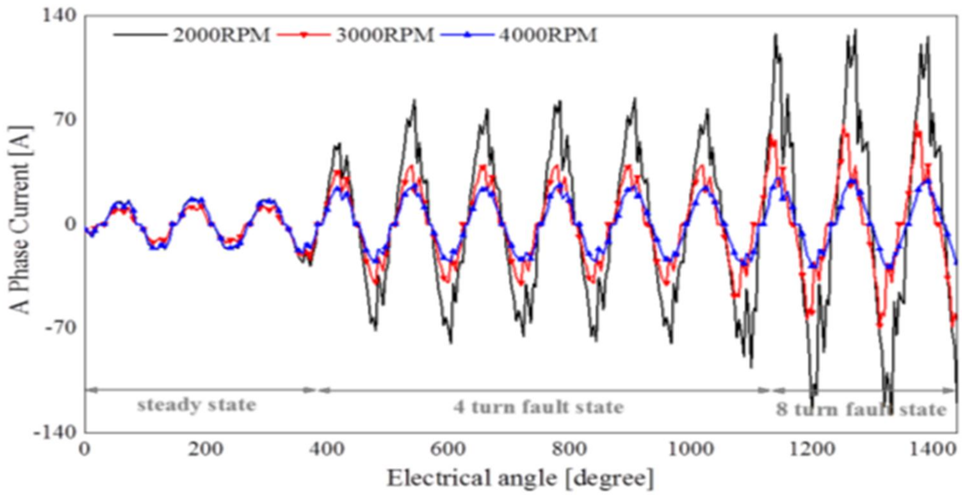


Fig. 7. Comparison of A phase currents with consideration for states of normal, 4 turn fault, and 8 turn fault according to PM BLDC motor’s speed.

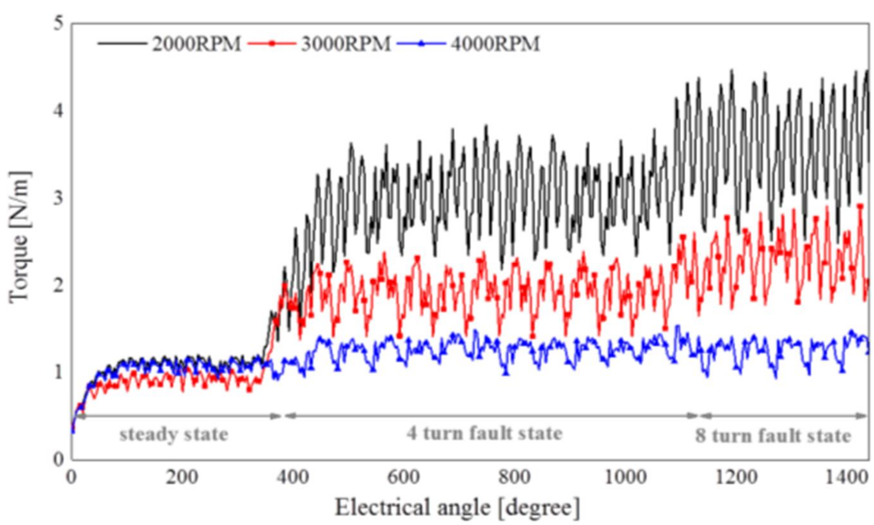


Fig. 8. Comparison of torque with consideration for states of normal, 4 turn fault, and 8 turn fault according to PM BLDC motor’s speed.

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VI. CONCLUSION

In this study, we analyzed the change of the FC in accordance with the PM BLDC motor's speed. Furthermore, commutation torque ripple and demagnetization are analyzed how to be influenced by FC. First, we analyzed torque ripple and magnetic field characteristics according to the FC gradient. On the basis of these analyses, we analyzed demagnetization according to the PM BLDC motor's speed. As a result, the more its speed is decreased, the more demagnetization and torque ripple are well happened. The size of the current is largely increased when the PM BLDC motor's speed is decreased in the ITF state. The variation breadth of largely increased current is relatively small in the FC section. Smaller FC section and higher commutation current generate a great deal more demagnetization. In addition, the more intervals of FC and commutation current are big, the more commutation torque ripple is deepened.

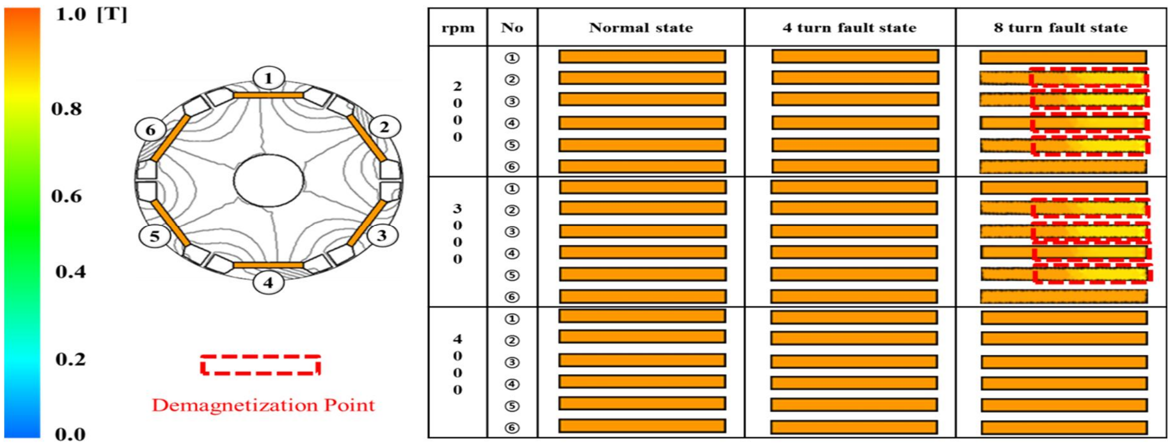

Fig. 9. Br and PM in accordance with PM BLDC motor’s speed about states of normal, 4 turn fault, and 8 turn fault.

In this project, for a transmission system of spur gear pair made of steel (en-24) and for a composite laminate spur gear pair (al-sic) / steel (20mn cr5) and peek450g combinations, stress analysis is to be made under static load conditions using Ansys and the results should be compared.

In this project, the gear is divided into 5 layers each of the same thickness. The thickness of each layer is 64mm. Different material combinations are used in each layer.

VII. ACKNOWLEDGMENT

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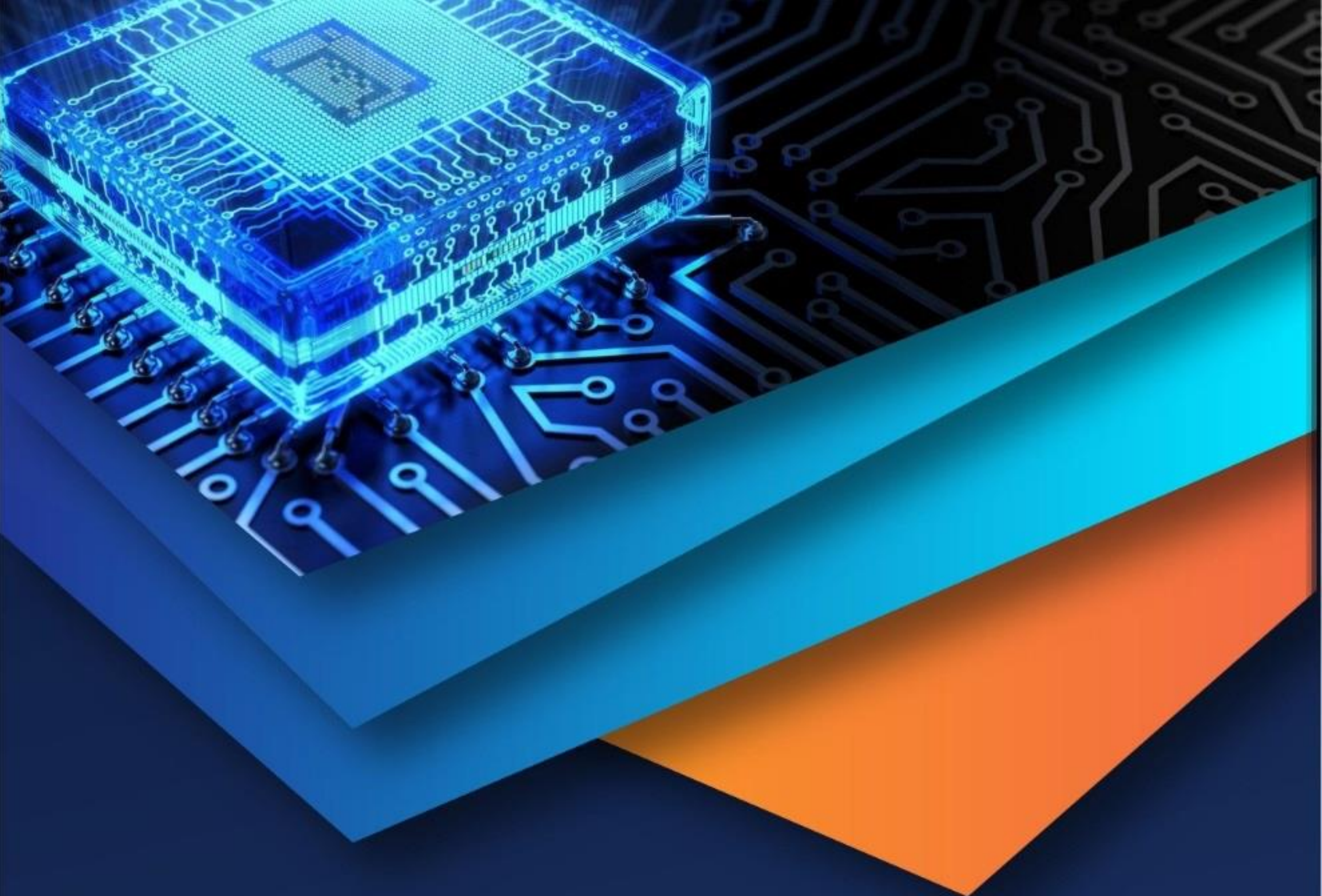

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