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High-Performance Interior Permanent Magnet Synchronous Motor for Electric Vehicles over Wide Speed Range

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Abstract: Battery electric vehicle (EVs) has become very popular with the interest of environmentally friendly electric vehicles rather than the conventional-Internal Combustion Engine (ICE) vehicles. To run with power, it needs the continuous wide working speed range of motors for the stable power region, strong power in high speed and a great start rallying torque in the low speed. This paper presents a simulation model of an Interior Permanent Magnet Synchronous Motor IPMSM for electric vehicle (EV) traction purpose in MATLAB/Simulink. This consists of Field Oriented Control (FOC), and runs Flux Weakening (FW) controller. 25 The EV market grows rapidly, hence the IPMSM is the best motor for such application due to that the motor has high torque-to -current ratio, high power mathematical eqns. We were able to identify behavior of the motor using FOC control also below base speed, when using FW control at rated speeds; the model indicated response was robust [1]. In addition, we will demonstrate greater high-speed torque using a feedforward flux weakening controller method, with constant power. The responses of speed, below and above rated speed will be stated regarding the results of the simulation. This model approach can suggest a rough level of advice on how to select an appropriate IPMSM configuration regarding distinct vehicle applications and drive conditions.

Index Terms: pure electric vehicle, flux weakening (FW), modelling interior permanent magnet synchronous motor (IPMSM), Field Oriented Control (FOC), FTP75 Drive Cycle.

I. INTRODUCTION

The shift toward cleaner and more sustainable transportation systems is accelerating taking place around the world. The need to address climate change, reduce urban air pollution, and lessen the reliance on dwindling fossil fuel resources all contribute to this development. Within this frame, electric vehicles (EVs) have risen to prominence as a game-changing solution due to their positive environmental effects, energy efficiency, and greater economic sustainability. In contrast to the conventional Internal Combustion Engine (ICE) vehicles which burn hydrocarbon fuels and emit devastatingly carbon-intensive gases EVs support a greener paradigm of sustainable mobility as they rely on electricity stored in onboard batteries. The traction motor, the central component of the propulsion system that transforms electrical energy into mechanical drive force, is a vital enabler of EV performance. The selection of a suitable electric motor significantly influences the overall system efficiency, dynamic responsiveness, and driving comfort. Out of the wide range of motor technologies, the interior permanent magnet synchronous motor (IPMSM) has become very popular in the EV industry. These motors offer high power density, high torque-to-current ratio, large speed range, and high thermal and structural durability [2]. The permanent magnets embedded in the rotor yields more saliency and both magnetic and reluctance torque components thus making IPMSM highly suitable for EV drive cycles especially when stressed under urban and highway duties. To build, model, and perform the evaluation of an IPMSM based drive system adapted for the electric vehicle application is the aim of the research. A primary focus on developing advanced control systems, particularly FoC and FW, which are paramount to utilizing IPMSMs [3]. FOC allows for separate management of torque and flux, providing exceptional accuracy and responsive performance, especially at reduced speeds. Conversely, FW broadens the motor's operational speed range past its fundamental limits by reducing the rotor flux, enabling the system to sustain efficient performance at greater vehicle speeds without surpassing voltage or current limitations [4]. To verify the practicality and efficacy of the suggested control framework, simulations are performed using the Federal Test Procedure (FTP-75) driving cycle, a standardized benchmark that replicates actual urban driving with regular stops and varying accelerations. Through the modelling of motor dynamics and the incorporation of control algorithms within a realistic simulation setting, this research not only showcases theoretical efficacy but also confirms practical relevance in real-world scenarios [5].

Ultimately, this research contributes a comprehensive framework for deploying high-performance IPMSM drives in modern EVs. The findings emphasize the pivotal role of precision control in achieving energy-efficient, high-torque, and reliable operation. As the transportation sector moves toward electrification, IPMSMs when paired with intelligent control schemes are poised to become a foundational technology in the pursuit of efficient, eco-friendly, and intelligent mobility solutions.

II. MATHEMATICAL MODELLING OF IPMSM

An accurate mathematical model is vital for the design, analysis, and simulation of high-performance drive systems, such as electric vehicles (EVs), which demand high efficiency and dynamic performance. The Interior Permanent Magnet Synchrounous Motor (IPMSM) is an ideal candidate for traction as well as for other motor technologies since it can produce magnetic torque as well as reluctance torque. To fully exploit the potential of IPMSM, a complete dynamic model is needed, which covers the electrical and mechanical behavior, at various operating points.

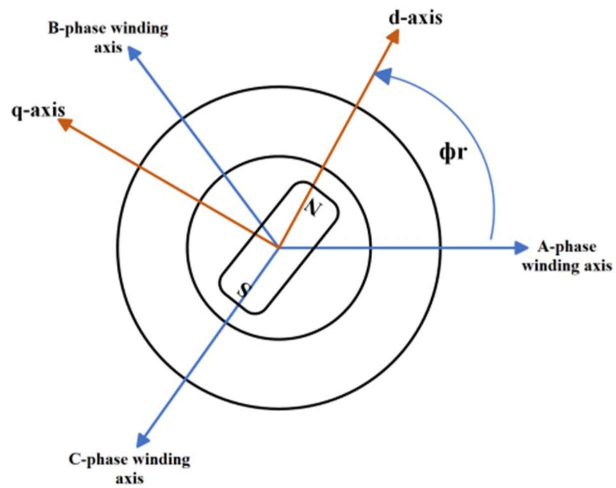

Fig 1: d-q axis reference frame representation

The Fig [1] represents the modeling methodology that converts the original three-phase representation into a two-axis rotating reference frame using the well-known Clarke and Park transformations [6]. This transformation enables the separation of the three phase sinusoidal currents and voltages of the stator into two orthogonal components, known as the direct axis (d-axis) and the quadrature axis (q-axis), which are aligned with the magnetic axis of the rotor. The q-axis is perpendicular to the rotor and generates torque directly while the d-axis is aligned with the rotor permanent magnet flux. By separating the regulation of torque and flux the d–q reference coordinate system reduces regulator complexity and affords the use of modern control mechanisms such as Field Oriented Control (FOC). The eqns [1] & [2] for stator voltage for the IPMSM can be represented as a function of the electrical speed of the motor, time varying flux couples, and resistance of windings in relation to the d–q reference frame. The general forms are:

$$V_d = R_s i_d + \frac{d\lambda_d}{dt} - \omega_e \lambda_q \quad (1)$$

$$V_q = R_s i_q + \frac{d\lambda_q}{dt} + \omega_e \lambda_d \quad (2)$$

where id and iq in eqn [1] & [2] are the stator currents, λd and λq are the flux linkages in the d- and q-axes, Rs is the stator windings resistance, ωe is the rotor electrical angular speed, and Vd and Vq are the stator voltages in the d- and q-axes. The flux linkages can be calculated based on the stator inductances and magnetic flux generated by the rotor as given in the eqn [3]:

$$\lambda_d = L_d i_d + \lambda_m \quad (3)$$

In this case, λm is the magnetic flux created by the rotor's permanent magnets, and Ld and Lq mentioned in eqn [4] are inductances in the d-axis and q-axis, respectively. The eccsqn [4] states that the motor also has electromagnet torque, which is the interaction between the stator current and the flux from the permanent magnets, in addition to the reluctance torque induced by the rotor saliency. This torque in eqn [4] can be expressed as follows:

$$T_e = \frac{3}{2} p \left[\lambda_m i_q + (L_d - L_q) i_d i_q\right] \quad (4)$$

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The term p in eqn [4] is the number of pairs of poles in the motor and Te is the torque produced by the electro-magnetism. The eqn [5] demonstrates the inherent advantage of the IPMSM over surface mounted PMSM, in that the additional component of reluctance torque can be used to improve performance. The rotor's mechanical behavior is represented through rotational dynamics [7]. The net torque applied to the rotor in eqn [5] causes angular acceleration, countered by mechanical inertia and frictional forces. The relationship is described by:

$$J\frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \qquad (5)$$

where TL is the load torque B is the viscous damping coefficient ωm the mechanical angular velocity and J is the rotor inertia as shown in eqn [5]. Idealized assumptions are made when constructing operational simulation models that include the aforementioned modes of operation. The main assumptions are that the stator winding is sinusoidally distributed resulting in a balanced magnetic field and that saturation and slotted effects are neglected with constant inductances and linear magnetic behaviour. These simplifications facilitate real-time simulation and control design while preserving essential system dynamics.

The complete IPMSM model, encompassing both electrical and mechanical eqns, can be implemented in a modular form within platforms such as MATLAB/Simulink. This allows for the separation of electrical subsystems governing current, voltage, and flux behavior from the mechanical subsystem, which models rotor dynamics and torque output. This simulation may be used to incorporate control techniques to assess how the motor responds to different driving cycles and load scenarios.

III. FLUX WEAKENING CONTROL STRATEGY FOR HIGH-SPEED IPMSM OPERATION

A. Importance of Voltage and Current Limitations

The IPMSM (interior permanent magnet synchronous motor) utilized in the high-performance EV drive needs to be run properly over as wide of a speed range as possible, extending from zero speed and far beyond its base speed. At the higher speeds, however, the back-emf induced by the rotor's magnetic field rises linearly with rpm. When this back-EMF is close to or exceeds the inverter's DC-link voltage, it is both physically impossible and impractical to control the voltage across the stator winding to your target using standard Field-Oriented Control (FOC) [8]. The suspension will harden to any continued increases in acceleration.

The eqn [6] and [7] states that to prevent the motor drive from violating the voltage and current limits set by the inverter and hardware ratings, it is essential to enforce specific operating boundaries:

$$\sqrt{I_d^2 + I_q^2} \leq I_{max} \qquad (6)$$

$$\sqrt{V_d^2 + V_q^2} \leq V_{max} \qquad (7)$$

Where Vd and Vq are the voltages, Id and Iq are the stator current d-axis and q-axis components. The inverter maximum line-to-line voltage (@ sine wave voltage) of a Space Vector PWM (SVPWM) system Vmax={Vdc/$\sqrt{3}$};

Adhering to these constraints ensures that both the thermal limits of the inverter and the insulation limits of the motor are respected under all operating conditions.

B. Overview of Flux Weakening Control

As the motor transitions into the high-speed region beyond its base speed the flux weakening technique becomes essential for continued speed increase. The essence of flux weakening lies in actively reducing the motor’s internal magnetic field to bring down the back-EMF, thus maintaining the required voltage headroom for current regulation. Negative d-axis current is injected into the stator coils, where Id is acting against the PM flux as opposed to normal operation where the q-axis current is providing torque [9].

The injected negative Id limits the total air-gap flux linkage so the back-EMF is only limited to a maximum voltage. Some torque capability is reduced because effective flux linking the stator field has been reduced but this is needed to also extend the operating limits of the IPMSM into the constant power region where torque continues to decrease with speed and power is nearly constant.

The eqn [8] is the precise calculation of Id under flux weakening is guided by the following eqn derived from voltage constraint conditions:

$$\boldsymbol{I_d} = \frac{\left(-\Psi_m L_d + \sqrt{(\Psi_m L_d)^2 - (L_d^2 - L_q^2)\left[\Psi_m^2 + L_q^2 I_a^2 - \left(\frac{V_{max}}{\omega}\right)^2\right]}\right)}{}\left(L_d^2 - L_q^2\right) \qquad (8)$$

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Where:

- Ψm = flux linkage for permanent magnets
- Ld and Lq = The inductances of the d- and q-axes
- Ia = total stator current magnitude
- ω = electrical angular velocity

Once the Id value is computed by using eqn [8], the remaining allowable current budget is used to compute the torque-producing Iq, ensuring the current magnitude stays within inverter limits.

C. Integration with the Vehicle Control System

In the proposed simulation model, the flux weakening mechanism was incorporated into the control architecture alongside the FOC loop. A supervisory logic block monitors the motor speed and automatically triggers the transition to flux weakening mode once the base speed threshold is exceeded [10]. In this region, the system dynamically adjusts the Id reference to a negative value according to the calculated requirement, while simultaneously modifying Iq to balance torque output and current constraints.

This dynamic current vector management enables the system to:

- Sustain operation beyond base speed,
- Prevent voltage saturation at the inverter,
- Maintain drive efficiency and stability across the full range of vehicle speeds.

Additionally, simulation results confirm the smooth transition between base speed and extended-speed zones, validating the correct functioning of the flux weakening loop and its positive impact on vehicle performance.

IV. IMPLEMENTATION OF CONTROL SCHEME

An IPMSM forms the basis for the high-performance vector control strategy used for an electric vehicle (EV) drive train. The intention is to provide accurate torque production, efficient energy consumption, and robust dynamic performance across a wide range of operating conditions. The Fig [2] represents a cascade type SMC strategy consisting of a Field-Oriented Control (FOC) for low-speed performance and a Flux Weakening (FW) for high-speed performance was implemented to ensure the performance is achieved [11].

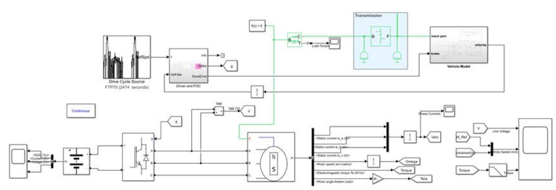

Fig 2: complete electric vehicle (EV) simulation model

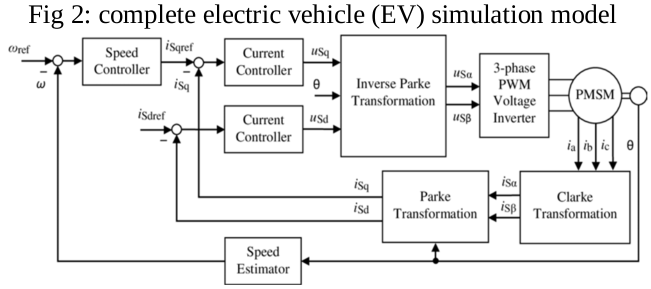

Fig 3: block diagram of Field-Oriented Control method

The Fig [3] represents the field-oriented control and it is the backbone of this control structure, utilizing Clarke and Park transforms to separate stator current into d - axis (Id) and q - axis (Iq) components. The first, torque reference is determined by the outer speed control loop relative to the driver-demand speed input and the vehicle speed. From the speed deviation, a q-axis current reference (Iq_ref), which has a direct correlation with the electromagnetic torque of the Interior Permanent Magnet Synchronous Motor (IPMSM), is derived through a proportional-integral (PI) control mechanism.

The direct-axis current reference (Id_ref) serves to augment the flux linkage; nevertheless, Id_ref is conventionally sustained at zero within the constant torque operating region to optimize the efficiency of energy utilization. The current control loop, executed within the inner power stage, incorporates a specialized PI control algorithm designed to produce voltage commands in a rotating reference frame, namely Vd and Vq, while concurrently monitoring the current parameters id and Iq. The equivalent d-q axis currents are converted back into stationary frame, post-processed and used to formulate PWM gate signals for the voltage source inverter, allowing for control of stator current as recording from respective frames of reference. In addition, this ensures the cgs control systems are able to smoothly transition the motor to different operating conditions.

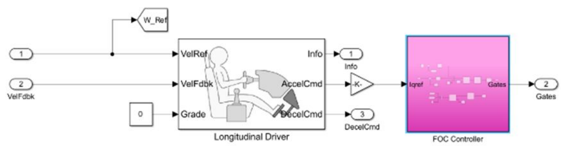

Fig 4: Driver Control and FOC Interface for IPMSM Drive

When the electric motor is driven in the region of, or above its base speed, the motor is controlled by Flux Weakening. At high speeds, back-EMF will be close to the DC link voltage of the inverter, resulting in a lack of torque capability [12]. Thus, a counter d-axis current is injected to provide additional magentizing flux. This allows a lowering of back-EMF and permits operation above base speed without going over the inverter's voltage limits [13]. The control logic developed is completely modeled and validated in MATLAB/Simulink, with distinct subsystems like the driver interface, IPMSM dynamics, inverter logic, FOC controller, and flux weakening algorithm structured for modularity and real-time interaction. By adapting to the FTP-75 urban driving cycle's fluctuating torque and speed needs, the control system produces a realistic simulation environment as shown in Fig [4].

VI. SIMULATION RESULTS

The proposed EV propulsion system simulation was completed in MATLAB/Simulink after the FTP-75 urban drive cycle in order to validate the dynamic and steady-state performance of the proposed system consisting of the IPMSM and FOC, FW. The results shown in Fig [5] were able to confirm that the controller was able to reliably track speed and regulate torque across all loads and speeds. The monitored velocity under the FTP-75 parameters facilitated the corroboration of the legitimacy of the external speed feedback loop and the internal current regulation provided by the Field-Oriented Control (FOC) algorithm. The real speed of the vehicle was very similar to the FTP-75 reference. Torque output changed rapidly in reaction to acceleration and deceleration events, emphasizing the system's swift adjustment to temporary road conditions. The electromagnetic torque exhibited a steady waveform with peaks during high-load situations, guaranteeing efficient drivability and responsiveness. Throughout the 135-second simulation, the inverter's output voltage remained constant, indicating a dependable power supply for the motor with minimal fluctuations—a crucial component for maintaining control precision and energy efficiency.

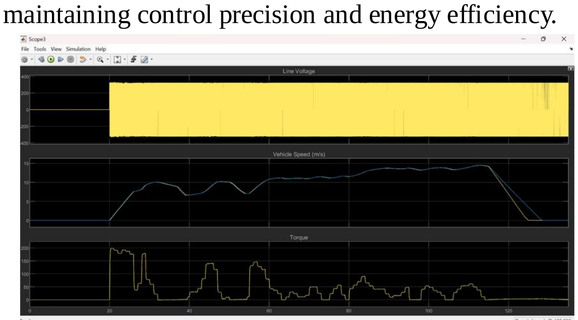

Fig 5: Voltage, Speed and Torque output waveforms

Additional insights were gained by analyzing the battery performance throughout the driving cycle. The State of Charge (SOC) decreased steadily from an initial level of around 50% to 49.6%, confirming genuine energy usage during vehicle operation as shown in Fig [6] of plot [1]. The battery current waveform in Fig [6] of plot [2] displayed both positive and negative peaks; the positive peaks corresponded to high-demand intervals such as acceleration, while negative regions reflected regenerative braking, effectively feeding energy back into the battery.

The battery voltage represented in Fig [6] of plot [3] was largely stable in the 320–330 V range, with brief voltage dips during heavy current draw and minor rises during regenerative events, confirming reliable battery behaviour under dynamic loading.

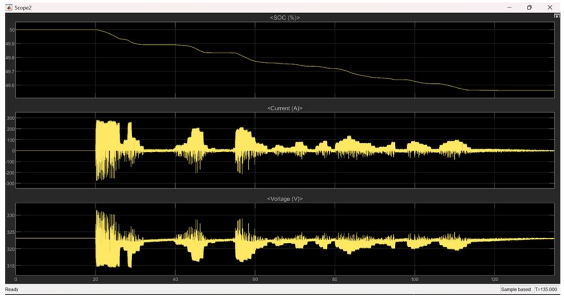

Fig 6: SOC, Current and Voltage Waveforms

The Fig [7] shows the mechanical load torque on the motor, extracted during the drive cycle, exhibited frequent oscillations in line with speed variations. These variations accurately replicated real-world vehicular forces such as rolling resistance, road slope, and inertia-induced torque, thereby validating the simulation model's realism and mechanical coupling accuracy.

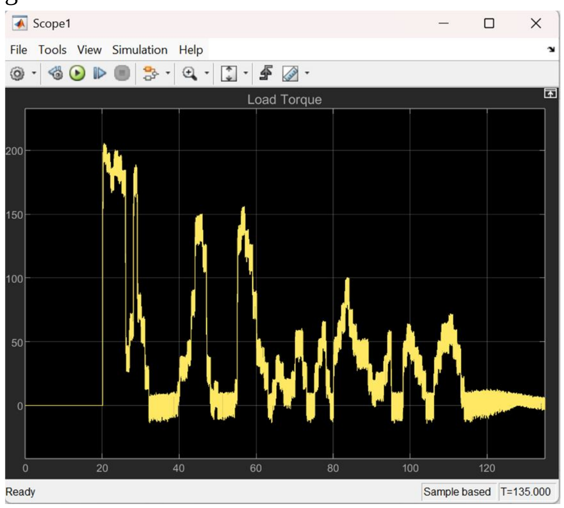

Fig 7: Load Torque waveform

The three-phase stator currents of the IPMSM in Fig [8] revealed a symmetrical sinusoidal profile modulated by high-frequency PWM switching from the inverter. Initial current magnitudes were higher during vehicle start-up, gradually stabilizing during steady-state operation. This reflects the FOC system's capability to manage varying current demands while maintaining waveform balance and motor protection.

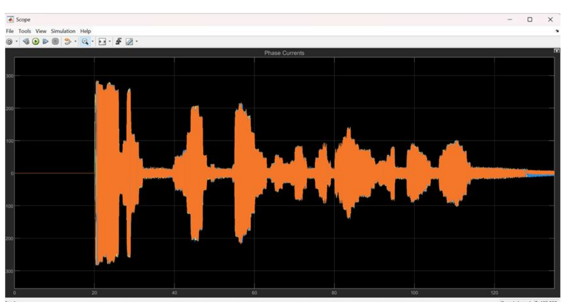

Fig 8: 3-phase current waveform

Additionally, a series of architectural simulations demonstrate the robustness of the complete EV control structure. The integrated driver model responded effectively to the FTP-75 cycle by continuously adjusting the acceleration and braking signals based on the speed error. These signals were converted into current references, which were tracked precisely by the FOC controller using Clarke and Park transformations.

The inverter was activated by the gate signals that resulted, providing the motor with the proper three-phase voltages. Dynamic torque and flux management, which are essential for effective propulsion, were preserved by this close control loop. The complete EV model also included four-wheel dynamics and environmental interactions, providing feedback to the control system for accurate vehicle behavior.

The overall system displayed stable operation throughout the simulation window, confirming that the coordinated implementation of FOC and FW with real-world drive cycles results in a well-balanced, energy-efficient, and high-performance electric vehicle propulsion system by the Figs [5], [6], [7] & [8].

VI. CONCLUSION

The efficiency of combining feedforward Flux Weakening (FW) and Field-Oriented Control (FOC) techniques over a broad operating speed range was shown by the simulation study and control implementation of the IPMSM-based electric vehicle propulsion system. The model, developed and executed in MATLAB/Simulink, was subjected to the standardized FTP-75 urban driving cycle, which closely mirrors real-world stop-and-go traffic conditions. The results affirm that the proposed control scheme ensures precise torque regulation at low speeds and extends motor capability beyond base speed without compromising system stability or energy efficiency. The vehicle exhibited responsive speed tracking, consistent torque output, and smooth transitions during acceleration and deceleration phases. The inverter voltage and three-phase current waveforms remained within safe and operational limits, demonstrating robust electrical performance. Battery behaviour, in terms of current, voltage, and SOC, confirmed efficient energy usage and successful implementation of regenerative braking during deceleration periods. The validity of the system was also demonstrated by realistic handling of the load torque fluctuations, which are demanded by the driving profile. Together, these results demonstrate the practicability and appropriateness of applying the novel IPMSM and advanced control strategies for EVs. The approach developed in this research work, beyond enhancing the drivability and the energy efficiency of the vehicle, offers to the EV system a rate of scalability capable to meet the efficiency and the performance requirements of the modern electric mobility solutions.

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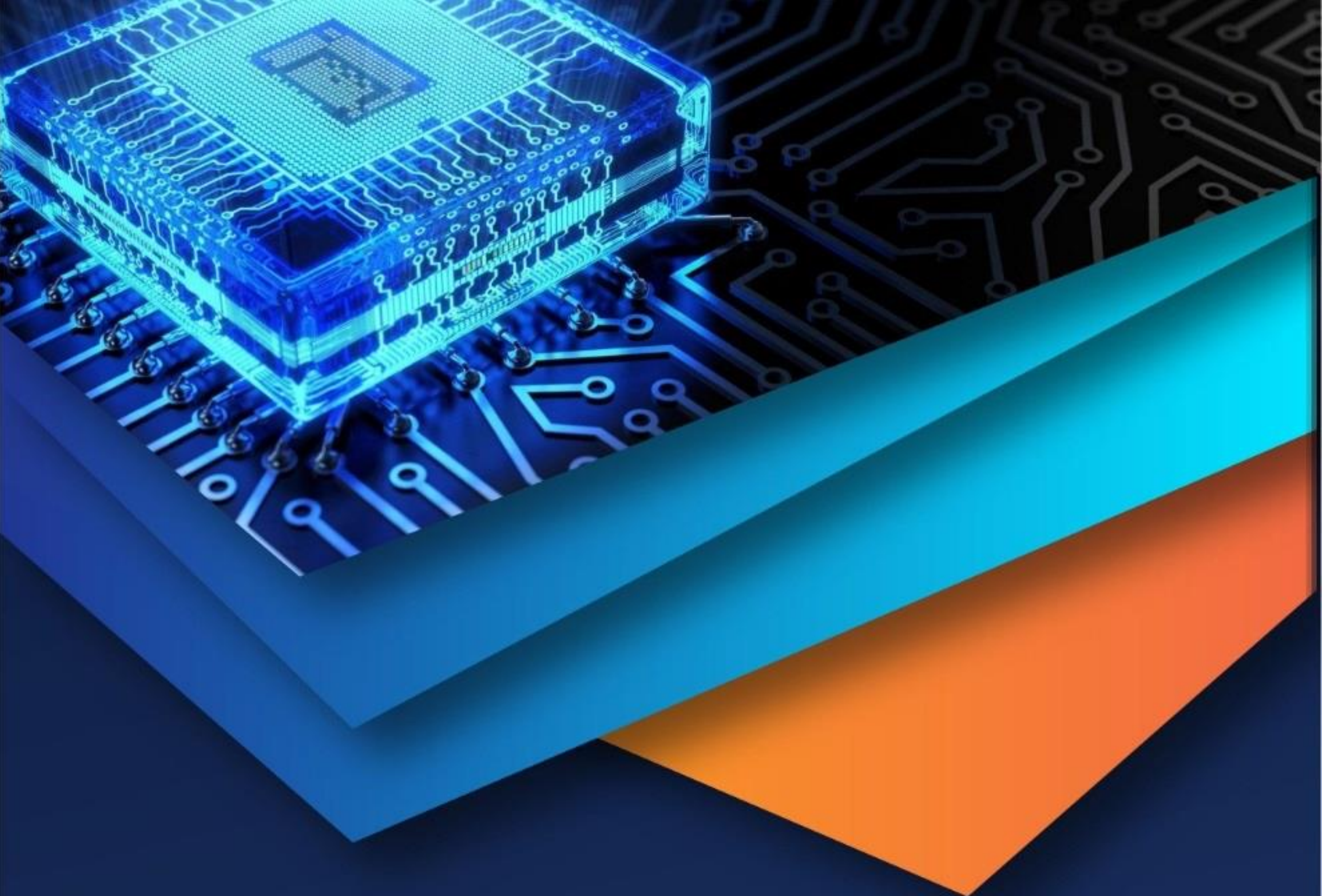

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