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Wheel Speed Control Algorithm for Four-Wheel Hub Motor Drive

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Abstract: This research paper mainly solves the problem of the independent driving and coordinated control between the four-wheel hub motors in electric vehicle. In order to drive four motors independently it is required to set the correct speeds when the vehicle takes a turn. This research paper gives and control algorithm and a motor controller model to set the ratio of wheel speeds of inner and outer wheels to make a smooth turn while maintaining the desired speed of linear motion.
Keywords: Simulink software, Motor controller, Hub motor, mechanical differential, four-wheel drive and Pulse width modulation.

I. INTRODUCTION

Electric vehicles are the latest trend in automobile industry. As per the decay of fossil fuel resources in the world, the automobile manufacturers attempted on manufacturing electric vehicles (EV). These are powered by internal battery and the propulsion system is electric motor. Due to the increment of electronic components in vehicles, several electronic control systems are being installed in these vehicles.

A differential is a mechanical device which splits the engine torque in to two ways, allowing each output to spin at a different speed. When the vehicle takes a turn, the inner wheels rotate at a lower speed than the outer wheels. The differential is found in all vehicles including rear-wheel, front wheel and all-wheel-drive vehicles. This component individually controls the outer and inner wheels of the vehicle and let the vehicle take a turn properly. Conventional differential is a mechanical component and this is used in vehicles for decades. Electronic differential is an innovative concept in electric vehicle technology research areas. In here, wheels are powered by individual motors and the electronic controlling performs the functionality of the differential. There are many advantages by using an electronic controlled differential in a vehicle.

The objective of this research is to develop a control algorithm for an electronic differential. This paper will illustrate the concept of electronic differential, discuss the advantages compared to conventional differential and motor controller logic to implement electronic differential. A mathematical model is developed to validate the input-output relationship of the algorithm. This mathematical model is integrated with hub motor controllers to properly control the speed of inner and outer wheels.

II. THEORY

A. Advantages of electronic control system over mechanical control systems

Upon the emergence of large-scale electrical vehicle manufacturing, the controlling units of vehicles are converted to electronic means. Mechanical control systems used for engine controlling, applying brakes and transmission are now being replaced by electronic control systems. Due to that, precise and smooth controlling can be achieved and could reduce the use of bulky mechanical components. As an example, Internal Combustion Engine, transmission system, differential system of a traditional vehicle could be replaced with four independent motors connected directly to all the wheels with a precise control mechanism. As presented in the advantages of electronic control systems over conventional methods are listed below.

1) Avoided heavy, bulky mechanical arrangements. Energy efficiency of the vehicle is increased due to this.
2) Maximum turning angle of a normal vehicle is around 40 degrees. New model can support higher turning angles which gives more mobility options for the vehicle.
3) Due to the possibility of individual controlling of each wheel, it can provide better torque considering the traction surface for each wheel.

B. The Drive System of an EV

An Electric Vehicle's drive system performs the same functions as that of a vehicle powered by an internal combustion engine. The drive system is the part of the electric vehicle which transmits mechanical energy to the traction wheels causing the electric vehicle to move. Electric vehicles utilize an electric motor to rotate the wheels of the vehicles. There are several different drive systems designs in use today. These include vehicles with a single large electric motor coupled to the rear wheels through a differential housing, two smaller motors to power-up each wheel separately through independent drive shafts and also using four hub motors at each wheel to independently provide torque at each wheel. Though the electronic differential system can be directly applied for electric vehicles, it is not widely found in available electric vehicles in the market.

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III.DESIGN

A. Development of Mathematical Model for wheel Speed ratio Calculation

The relationship between steering angle, vehicle speed and speeds of rear wheels must be derived by a mathematical model. The Ackerman Steering Principle defines the geometry that is applied to all vehicles to enable the correct turning angle of the steering wheels to be generated when negotiating a corner or a curve. The intention of Ackermann geometry is to avoid the need for tyres to slip sideways when following the path around a curve. In order to ensure an ideal rolling of the wheels during cornering all wheels need to have their axles arranged as radii of a circle with a common centre point.

As the rear wheels are fixed, this centre point must be on a line extended from the rear axle. In order to intersect this rear wheel axis with the axes of the front wheels it requires the inside front wheel is turned, when steering, at a greater angle than the outside wheel. This is depicted in Fig.1. Note that the angle of inner front wheel (β) is greater than the angle of outer front wheel (α).

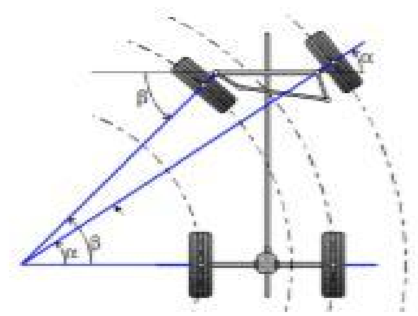

Fig.1 Geometrical arrangement of wheels in a turn (Vehicle is taking a left turn)

B. Relationship between inner and outer wheel speeds

Mathematical model will address the relationship of speeds of inner and outer wheels of the vehicle considering the turning angle of the vehicle. Fig.2 depicts the parameters that is to be considered for constructing of the model. The detailed geometry of a vehicle for slide slip control is used here.

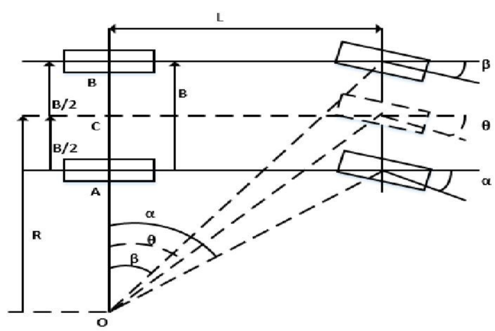

Fig.2 Geometrical representation of wheels in a turn with parameters

R – Cornering radius B – Track width of the rear axel
L – Wheel base 0 – Centre of cornering
α – Angle displacement of front right wheel
β – Angle displacement of front left wheel
θ - Angle of displacement of imaginary middle wheel also the steering angle of vehicle

The diagram shown in Fig.2 illustrates a vehicle having four wheels. When the vehicle is steered by angle θ, the inner and outer wheels should be turned by α, β angles respectively. This is accommodated by the steering rack of the vehicle. It should be noted that the steering angle is changed by the driver and inner-outer wheel angles depend on that steering angle. Therefore, θ is an independent variable and α, β are dependent variables. When the vehicle is moving forward

A = β = 0o

When taking a turn, it is

$\beta < \theta < \alpha$ for right turns or $\alpha < \theta < \beta$ for left turns.

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C. Derivation of Equations for wheel Speeds

1) *Step1:* Referring to the diagram shown in Fig.2, the radius of the curve can be expressed by the angles of the front wheels.

$$R = OC = \left(OA + \frac{B}{2}\right) = \left(OB - \frac{B}{2}\right)$$

$$OA = L\ COT\ \alpha\ ,\quad OB = L\ COT\ \beta$$

$$\therefore R = L\ COT\alpha + \frac{B}{2} = L\ COT\beta - \frac{B}{2} = L\ COT\ \theta$$

It is clear that both inner and outer wheel angles have a relationship to steering angle. The steering angle can be represented by a single imaginary middle wheel angle. The control algorithm for rear wheel motor driven vehicles is developed based on this imaginary middle wheel concept. This method can replace the initial four-wheel model; hence reduce the complexity of calculations. This replacement model is illustrated in Fig.3.

2) *Step 2:* It is possible to calculate the relationship between θ,α,β

$$\frac{B}{2} = R - L\ COT\alpha$$

$$R = L\ COT\beta - \frac{B}{2}$$

$$\text{Substitute R and } \frac{B}{2}$$

$$L\ COT\ \theta = L\ COT\beta - L\ COT\ \theta + L\ COT\alpha$$

$$COT\ \theta = \frac{(L\ COT\beta + L\ COT\alpha)}{2}$$

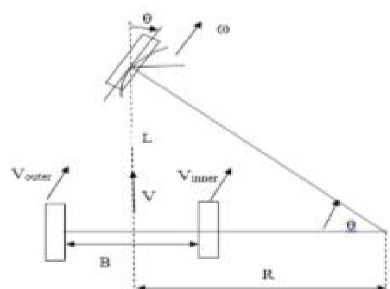

Fig.3 Simplified geometric model with parameters

V – Vehicle linear speed, ω – Vehicle angular speed

Vinner – Linear speed of inner wheel Vouter – Linear speed of outer wheel

3) *Step 3:* The distance between center of rotation and vehicle's center line is given by

$$R = \frac{L}{\tan\theta}$$

4) *Step 4:* The linear velocity equations of the left and right wheels can be derived based on the following equations. From the top view, the centers of both driven wheels of the vehicle are spinning with equal angular velocity about the point 0. Both wheels have the same angular velocity about the point 0, but different distances from the center of rotation. These different distances are creating the angles as discussed before. Therefore, when θ ≠ 0,

$$V_{inner} = \omega\left(R - \frac{B}{2}\right)$$

$$V_{outer} = \omega\left(R + \frac{B}{2}\right)$$

By substituting ω from (2) and R from (1)

$$V_{inner} = \frac{V}{R}\left(R - \frac{B}{2}\right)\ ,\quad V_{inner} = V\left[1 - \left(\frac{B\tan\theta}{2L}\right)\right]$$

$$V_{outer} = \frac{V}{R}\left(R + \frac{B}{2}\right)\ ,\quad V_{outer} = V\left[1 + \left(\frac{B\tan\theta}{2L}\right)\right]$$

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If the wheel radius is Rd, the speed of each wheel in revolutions per minute (RPM) can be calculated as

$$\text{RPM inner} = V_{inner}\left|\frac{60}{(2\pi\, R_d)}\right|$$

$$\text{RPM outer} = V_{outer}\left|\frac{60}{(2\pi\, R_d)}\right|$$

D. Motor Controller Block Diagram

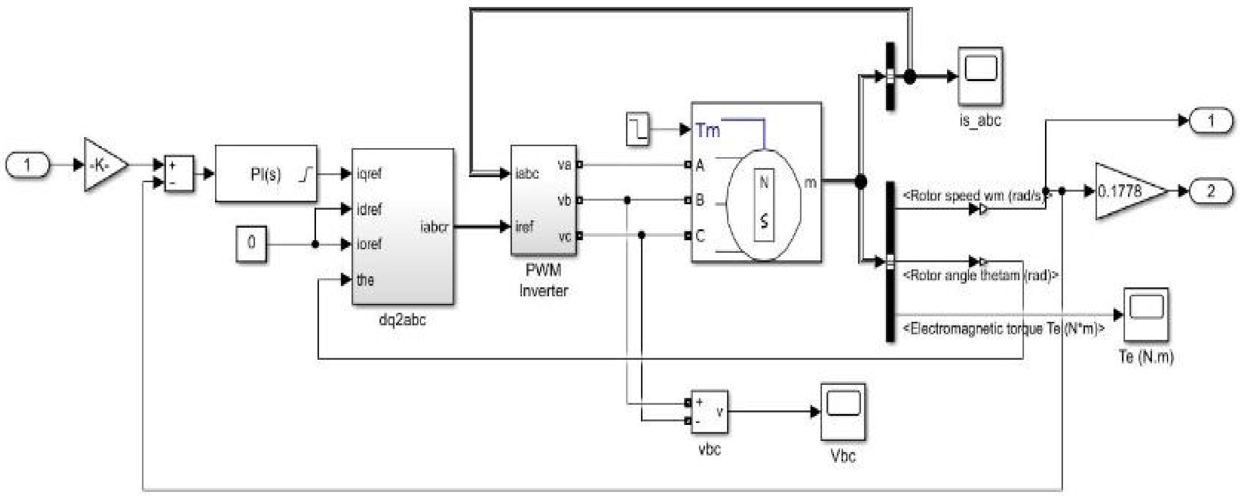

Fig.4 Block diagram of single motor and its controller

The figure 4 shows a design a motor controller used to control a single hub motor. Four of such controllers are interconnected to main controller to properly control the speed of inner and outer wheels during turning. Each individual motor controller controls the speed of the wheels according to the value given by the main controller.

E. Mathematical Model of main Controller Logic

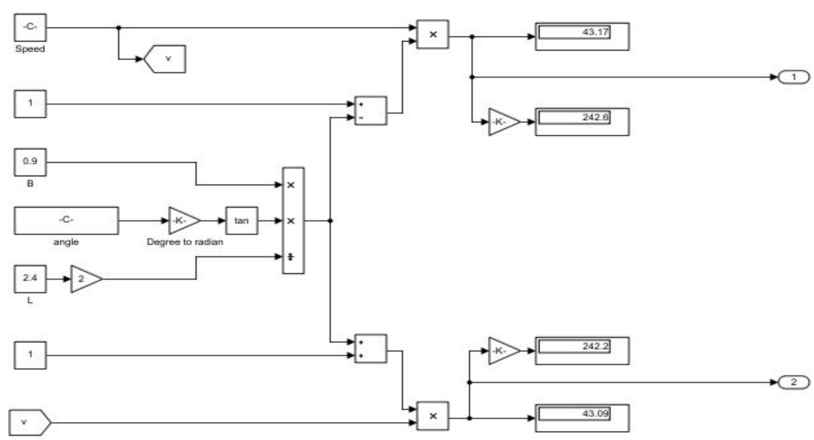

Fig.5 Block diagram of control algorithm

The control algorithm explained in section 3.C is converted into mathematical model. This controller takes some input parameters such as linear speed of the vehicle, steering angle and few constants. This control logic is interfaced with all four individual motor controllers. This logic controls the speed of individual motors.

F. Block diagram of complete model

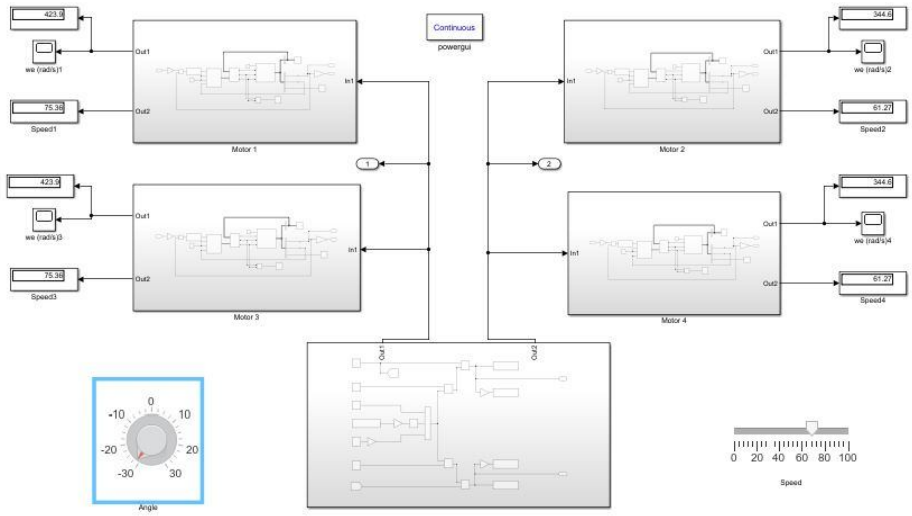

Fig.6 Block diagram of complete model

The figure 6 shows the final interface of the developed model. In this simulation model a knob labelled as angle is used to vary the steering angle during the simulation and a slider block labelled as speed is used to vary the speed during the simulation. By varying the speed and steering angle during the simulation the output speed of individual wheel is obtained and the values are verified.

IV. RESULTS AND DISCUSSION

The proposed simulation model is developed, and the results are verified by giving different input conditions. The results obtained by the simulation model and the theoretical values obtained from the calculations are appeared to be similar.

A. Simulation Results

Below is the figure indicating wheel numbers at different wheel position. The graph of the different wheels is labelled with corresponding number. The output waveform or graph showing speed in rpm at the wheel for different steering angle and linear speed of the vehicle is obtained.

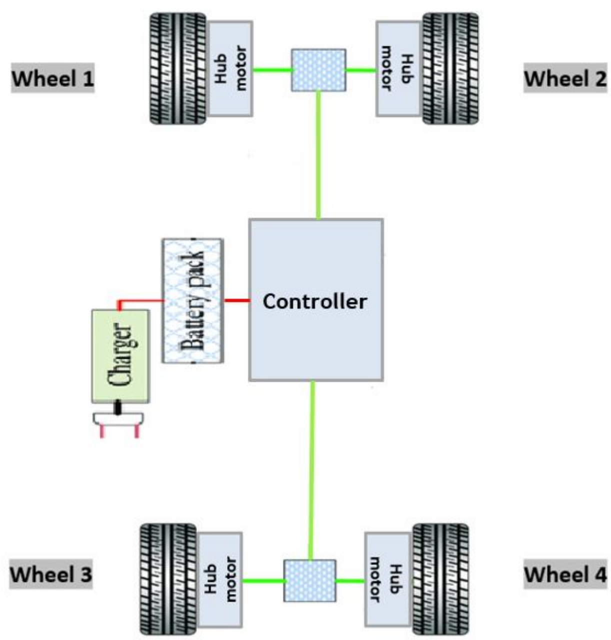

Fig.7 Wheelbase indicating the wheel numbers

B. Waveform of the wheel speed response

Figure 8 shows the output speed at individual wheels. The speed and steering angle are varied and the speed at individual wheels are obtained at the output. The linear speed of the vehicle is kept constant for some time. The steering angle is varied in both the directions and the output waveform is obtained.

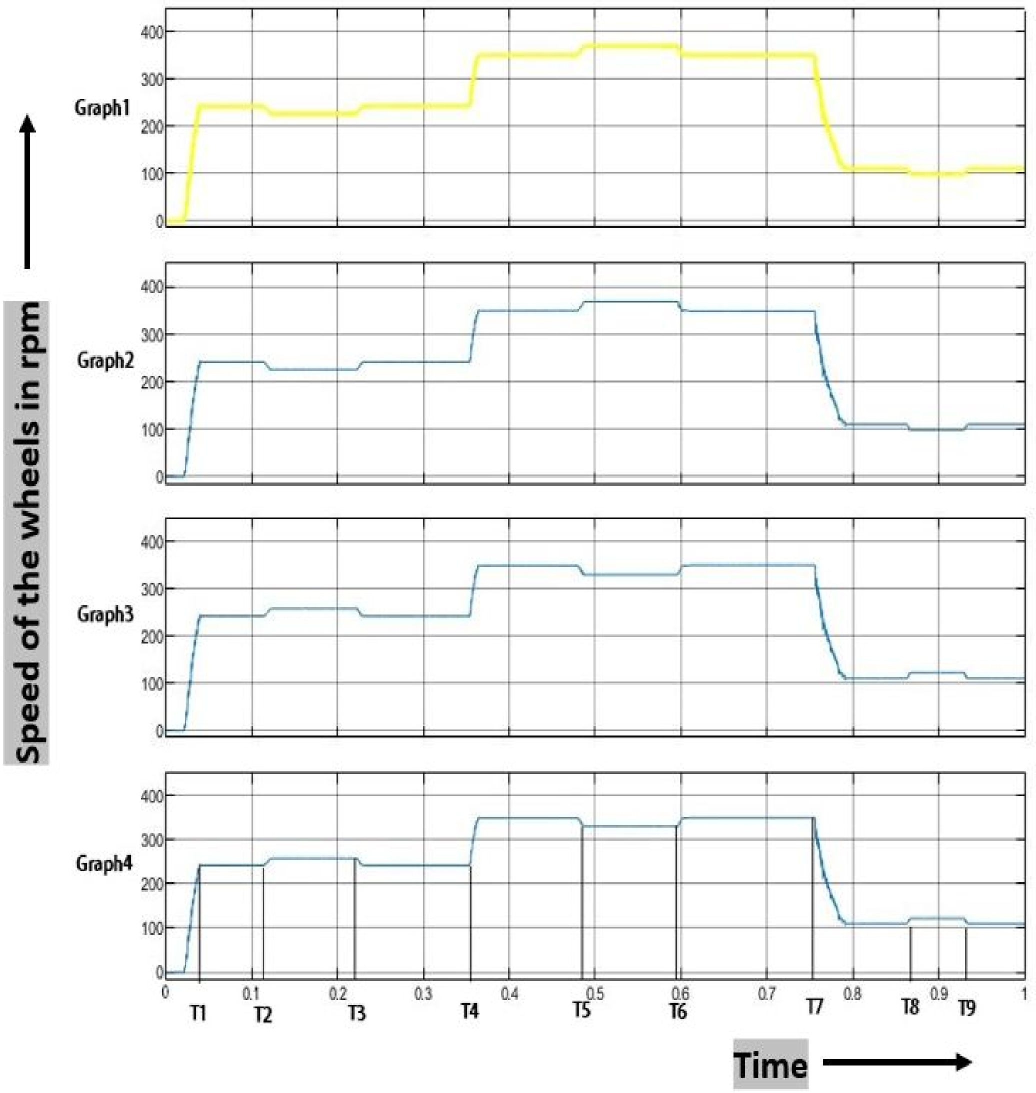

Fig.8 Output speed at individual wheels

Here graph 1 shows the variation of speed in front left wheel. Graph 2 shows the speed of back left wheel. Graph 3 shows the variation of speed in front right wheel. Graph 4 shows the speed of back right wheel.

By varying the knob in the simulation, the steering angle input is varied in the system. And by varying the linear actuator the linear speed of the vehicle is varied. Thus, the steering angle and the linear speed of the system can be varied dynamically. Thus it provide a simulation design which is interactive enough to give dynamic response.

At T1 the speed of the vehicle is increased to 40km/h with steering angle 00, the corresponding rpm of all the wheels can be seen in the waveform. At T2 the steering is turned left by an angle of 150, as seen in the output there is decrease in rpm at the inner(left) wheels and increase in rpm at the outer(right) wheels. At T3 the steering angle is bought back to 00. At T4 the speed of the vehicle is increased to 60km/h the corresponding rpm can be seen in the graph. At T5 the steering is turned right by an angle of 200, as seen in the output there is decrease in rpm at the inner(right) wheels and increase in rpm at the outer(left) wheels. Hence the speed at individual wheels are varying according to the mathematical calculation.

V. CONCLUSION AND FUTURE SCOPE

All four motors which are connected to individual wheels must be almost identical in its physical parameters. Otherwise it is not possible to have same measurements as Rise time, Settling time for the motors. The mathematical model is proven for giving correct inner and outer wheel speed ratio when steering a vehicle. By using this model, the conventional differential can be replaced with electronic counterpart hence achieve more benefits for the automobile industry. The PID controller can be integrated to the main controller model explained in this project to increase the stability and accuracy of the control method used. The four-wheel hub motor drive system is currently the cutting-edge technology in the automotive field and hence the design of controller for this drive system place an important role in the development of electric vehicles.

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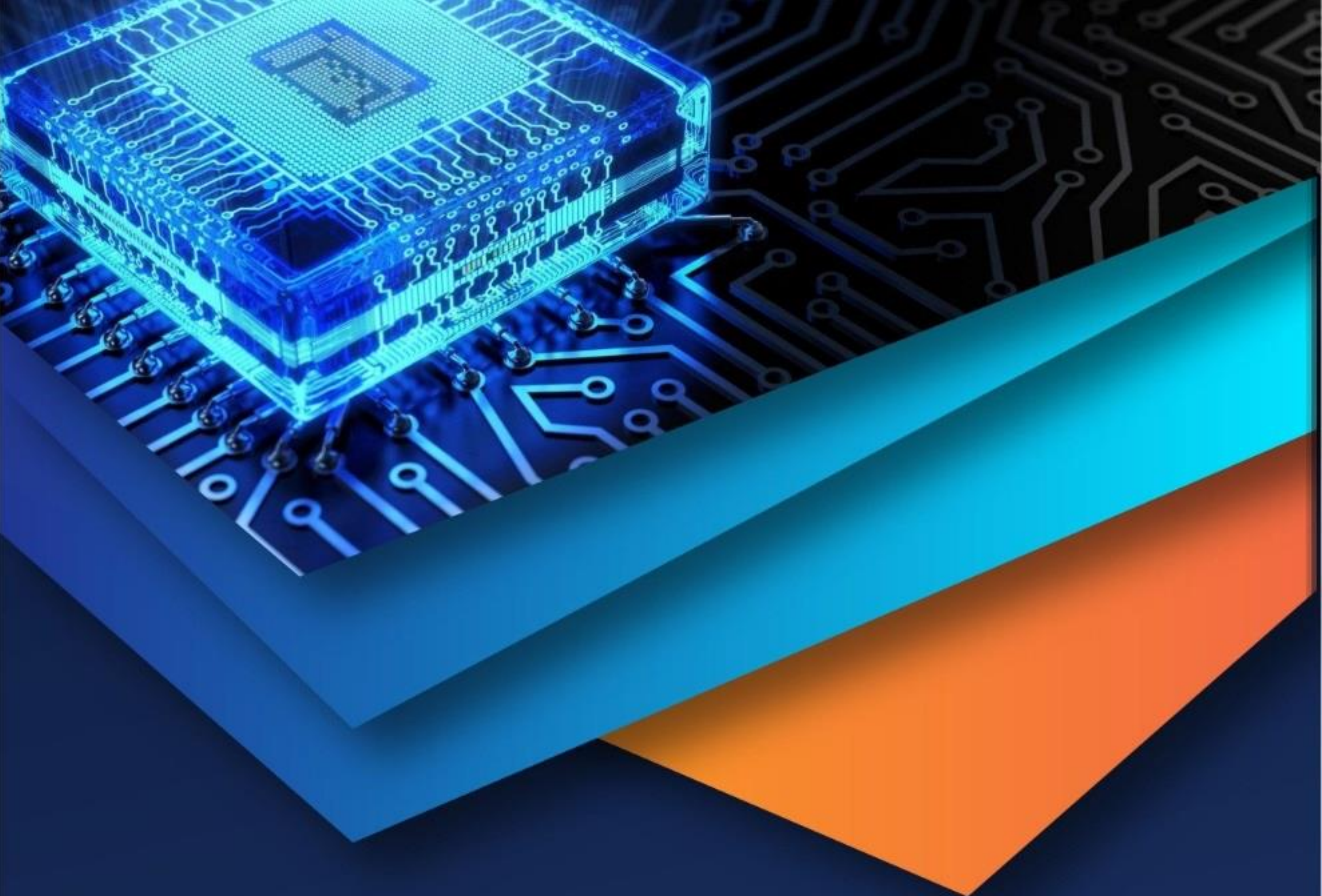

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