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Optimized E-Bicycle Using BLDC Hub Motor & BMS

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Abstract: The growing need for eco-friendly, energy-efficient, and sustainable transportation has accelerated the development of electric mobility systems. Among these, the electric bicycle (e-bicycle) has emerged as an ideal solution for short-distance urban commuting due to its affordability, compactness, and zero-emission characteristics. This thesis, titled "Optimized E-Bicycle using BLDC Hub Motor and Battery Management System (BMS)", focuses on the conceptual design and theoretical optimization of an intelligent e-bicycle system that integrates performance efficiency, renewable energy utilization, and user-friendly control.TAhe proposed model employs a Brushless DC (BLDC) hub motor for propulsion, chosen for its superior torque characteristics, high efficiency, and minimal maintenance requirements. The power source consists of a 24 V, 10.4 Ah two lithium-ion battery pack built using 3.7 V, 2600 mAh cells, conceptually managed by an advanced Battery Management System (BMS). The BMS ensures safe operation through cell balancing, overcharge protection, and real-time voltage and current monitoring. A Motor Controller Unit (MCU) regulates motor performance using Pulse Width Modulation (PWM) for smooth acceleration and energy efficiency.
Keywords: BLDC Hub Motor, Battery Management System (BMS), Electric Bicycle, Regenerative Energy, Smart Mobility, Sustainable Transportation, Lithium-Ion Battery.

I. INTRODUCTION

The rapid advancement of technology and the growing awareness of environmental sustainability have accelerated the shift toward cleaner and more energy-efficient modes of transportation. Conventional vehicles powered by fossil fuels are major contributors to greenhouse gas emissions, air pollution, and energy depletion. To address these challenges, electric mobility has emerged as a viable and sustainable alternative. Among various electric vehicle categories, the electric bicycle (e-bicycle) has gained significant popularity due to its affordability, simplicity, low maintenance, and suitability for short-distance urban travel. It bridges the gap between manual bicycles and high-cost electric vehicles, offering an ideal balance of energy efficiency, convenience, and sustainability. An e-bicycle operates through a combination of human pedaling and electrical propulsion. The electrical subsystem, which includes a motor, battery, controller, and monitoring system, assists the rider in achieving effortless motion. In the proposed conceptual design, a Brushless DC (BLDC) hub motor is utilized as the primary propulsion system due to its high torque output, compact structure, and reduced energy losses. Unlike traditional brushed motors, the BLDC Hub motor operates without mechanical commutators, ensuring higher efficiency and longer operational life. The Battery Management System (BMS) plays a crucial role in maintaining the reliability and safety of the energy source by regulating charge and discharge cycles, monitoring cell health, and preventing overvoltage and overheating.

II. LITERATURE SURVEY

The evolution of electric bicycles (e-bikes) has been driven by the growing need for sustainable, efficient, and low-emission urban transportation. Recent research has focused on optimizing motor design, improving energy storage, and introducing renewable-based self-charging systems. Ateeb Baig et al. (2024) [1] developed a multi-source self-charging e-bike integrating solar, regenerative, and dynamo-based charging, improving efficiency and reducing grid dependency. Khizer Abbas et al. (2023) [2] analyzed axial and hub BLDC motors and concluded that hub motors provide superior torque and compactness, making them ideal for light electric vehicles. Sathiyan et al. (2019) [3] optimized BLDC drive performance, showing that proper controller configuration reduces energy loss and vibration.Earlier studies by Tayde et al. (2017) [4] and Sunil et al. (2015) [5] explored self-power generation using dynamo and regenerative braking, validating continuous energy recovery feasibility. Kumar et al. (2014) [6] designed a self-recharging e-bicycle using regenerative braking, while Sankar et al. (2013) [7] integrated solar panels for auxiliary charging, pioneering green mobility concepts.

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More recent works emphasize battery management and safety. Suganya (2024) [8] highlighted the role of intelligent Battery Management Systems (BMS) in enhancing lithium-ion battery performance and longevity. Vijayan (2023) [9] conducted a thermal analysis of lithium-ion batteries for e-bikes, recommending improved cooling and protection circuits. Liu et al. (2024) [10] studied battery charging behavior in e-bikes, stressing the importance of smart monitoring to prevent overcharging and improve efficiency.

Collectively, these studies show the progression from basic electric assistance to advanced smart, self-charging, and renewable-powered e-bicycles. The integration of BLDC hub motors, regenerative braking, and intelligent BMS forms the foundation for the proposed optimized e-bicycle model, combining performance, safety, and sustainability for modern urban transport.

III. METHODOLOGY

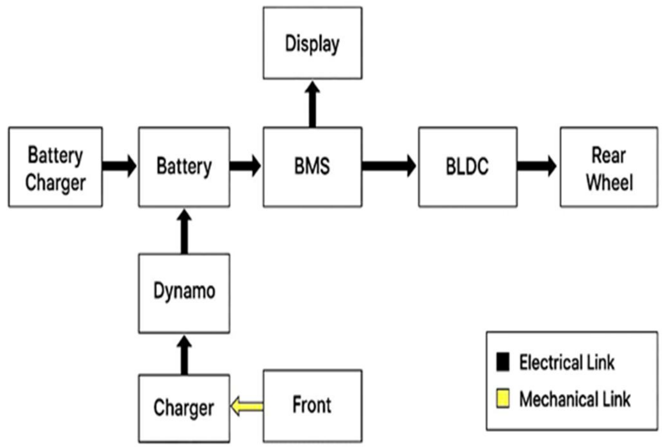

Figure.1. Block Diagram Of E-bicycle

The methodology adopted for the *Optimized E-Bicycle using BLDC Hub Motor and Battery Management System (BMS)* involves a systematic, step-by-step process beginning with literature analysis and component selection, followed by conceptual design, system modeling, and theoretical performance evaluation. The overall approach ensures that the proposed design achieves improved efficiency, safety, and sustainability while maintaining affordability and simplicity.

The process begins with an extensive literature review, focusing on previous works related to BLDC motor performance, regenerative braking, battery optimization, and renewable-assisted charging. Insights gained from these studies provided a foundation for identifying the limitations in existing e-bicycle designs and formulating the problem statement for the present research.

The next step involves conceptual system design, where key components such as the BLDC hub motor, Battery Management System (BMS), Motor Controller Unit (MCU), lithium-ion battery pack, regenerative system, and smart display interface are theoretically selected. The motor and controller are matched based on voltage and current ratings to ensure stable performance. The battery pack is configured using 3.7 V, 2600 mAh lithium-ion cells arranged in series-parallel combinations to achieve a nominal rating of 24 V and 10.4 Ah. The inclusion of the BMS provides cell balancing, overcharge protection, and current regulation for safety and longevity.

The conceptual design stage is followed by system modeling and analysis, where the interconnections between components are represented using block diagrams and flowcharts. These diagrams illustrate the flow of energy from the battery to the motor through the controller, as well as the feedback paths for regenerative braking and monitoring. A smart display interface is included to show real-time voltage, current, speed, distance, and time data for efficient control and user feedback.

Finally, theoretical calculations are performed to estimate energy output, efficiency, and operational range. For example, a 48 V system operating at 7.3 A provides a power output of approximately 350 W, with an estimated runtime of 1.37 hours based on a 480 Wh battery capacity. This analysis validates the feasibility and effectiveness of the proposed system for real-world applications.

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A. Circuit Diagram

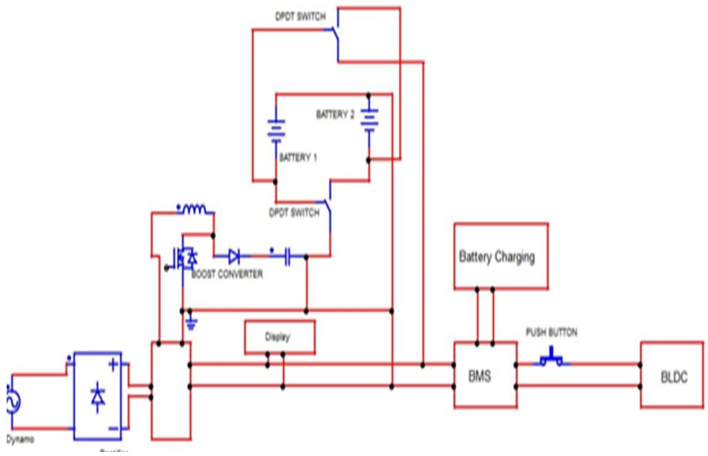

Figure 2: Circuit Diagram

Figure 2 circuit diagram of the optimized e-bicycle illustrates the interconnection between the battery pack, Battery Management System (BMS), Motor Controller Unit (MCU), BLDC hub motor, and the smart display interface. The power supply originates from a 24 V lithium-ion battery pack, which is monitored and regulated by the BMS to ensure safe and efficient operation. The BMS provides critical protections against overcharging, deep discharge, overcurrent, and overheating, while maintaining voltage balance among the individual cells. The regulated DC output from the BMS is then fed to the motor controller, which uses Pulse Width Modulation (PWM) signals to control the BLDC hub motor's speed and torque based on the throttle input.

During normal operation, electrical energy from the battery is supplied to the motor for propulsion. When braking occurs, the regenerative system converts kinetic energy from the rotating wheel into electrical energy, which is redirected through the controller back to the battery for partial recharging. The smart display unit connected to the controller provides real-time feedback to the rider, showing essential parameters such as battery voltage, current consumption, speed, distance covered, and total ride time. Additionally, a charging port is integrated for external charging, while a solar input or dynamo circuit can serve as an auxiliary charging source.

B. Assembly Of Modules

The assembly of the optimized e-bicycle involves the conceptual integration of all the major components — namely the BLDC hub motor, Motor Controller Unit (MCU), Battery Pack, Battery Management System (BMS), Regenerative motor acting as dynamo, and Smart Display Interface — into a unified working model. Each subsystem is arranged to ensure optimal power distribution, mechanical stability, and safety while maintaining the lightweight structure of a standard bicycle frame.

The BLDC hub motor is mounted directly on the rear wheel, providing efficient propulsion without the need for mechanical transmission components such as gears or chains. This hub-integrated configuration minimizes energy losses and simplifies maintenance. The battery pack, consisting of lithium-ion cells rated at 3.7 V and 2600 mAh, is housed securely within the bicycle frame to maintain balance and reduce vibration during motion. The pack is connected to the BMS, which continuously monitors voltage, current, and temperature to ensure safe charging and discharging.The motor controller unit is positioned near the motor to reduce wiring losses and improve responsiveness. It interprets throttle input and regulates the motor through Pulse Width Modulation (PWM) signals for smooth acceleration. The Regenerative Motor acting dynamo connected to the front wheel generates energy for charging continuously in running state, which is fed into the battery pack.

The smart display unit is mounted on the handlebar, providing real-time readings of voltage, current, speed, distance, and time, thereby improving rider awareness and control. All electrical connections are made using insulated wires and connectors to ensure durability and safety under varying operating conditions.The project assembly focuses on ergonomic design, energy efficiency, and compact integration of all electrical and mechanical subsystems. The result is a well-coordinated and conceptually optimized e-bicycle model capable of delivering reliable performance, ease of use, and sustainability for modern urban commuting.

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C. Hardware Integration

Figure 3: Motor Controller Unit (MCU)

Figure 3: Motor Controller Unit (MCU) Motor Controller Unit (MCU) is the core control component of the optimized e-bicycle, responsible for managing power flow between the battery, Battery Management System (BMS), and the Brushless DC (BLDC) hub motor. Conceptually, it functions as the brain of the system, interpreting rider inputs such as throttle position and braking signals, and converting them into precise control commands for motor operation. The MCU regulates motor torque and speed through Pulse Width Modulation (PWM), ensuring smooth acceleration, energy efficiency, and silent performance. It receives real-time feedback from the motor's Hall sensors to determine rotor position, which enables accurate electronic commutation. The controller also manages regenerative braking by converting kinetic energy into electrical energy and routing it back to the battery through the BMS. Conceptually, it incorporates safety mechanisms such as overcurrent, overvoltage, and thermal protection to safeguard both the motor and power electronics.

Figure 4: Regenerative Motor

Figure 4 Regenerative Motor The Regenerative Unit converts the mechanical motion of the front wheel into electrical energy. During riding or braking, the dynamo generates alternating current (AC), which is then rectified into DC and used to charge the battery. This regeneration process increases the overall system efficiency and reduces dependency on external charging sources. The dynamo provides a secondary energy source, allowing micro-level charging while the vehicle is in motion. Integrated through a controlled circuit and boost converter

Figure 5: BLDC Hub Motor (350–500 W)

Figure 5 BLDC Hub Motor (350–500 W) serves as the primary propulsion source for the e-bicycle. It converts electrical energy from the battery into mechanical torque to drive the rear wheel. The outer-rotor design allows direct drive without the need for gears, resulting in smoother operation, reduced mechanical losses, and minimal maintenance. The motor provides high torque density, excellent speed control, and silent operation. Its compact structure ensures better weight distribution, improving vehicle stability. The BLDC motor's electronic commutation enhances efficiency and supports regenerative braking, making it ideal for an energy-efficient, eco-friendly e-bicycle system.

Table No . 1 Components and Their Specifications

Component	Specification / Description
BLDC Hub Motor	48 V, 350 W, Rear Wheel Mounted — Provides propulsion with high torque and smooth operation.
Motor Controller Unit (MCU)	24 V Rated, PWM Controlled, Supports Regenerative Braking — Regulates power flow and speed.
Battery Pack	48 V, 10.4 Ah (3.7 V, 2600 mAh × 58 Cells) — Supplies electrical energy to the entire system.
Battery Management System (BMS)	24 V Rated, Provides Cell Balancing, Overcharge & Overdischarge Protection.
Regenerative Braking Circuit	Converts kinetic energy into electrical energy during braking and recharges the battery.
Smart Display Unit	Digital LCD Display — Shows voltage, current, speed, distance, and time in real time.
Throttle (Accelerator)	Twist Grip Type, 0–5 V Output Signal — Controls motor speed as per rider input.
Battery Charger	24 V DC Output, 2 A — Used for safe external battery charging.
Solar Panel (Optional)	12 V, 50 W Polycrystalline — Provides auxiliary renewable charging support.
Frame and Wheels	Standard Bicycle Frame with 26-inch Alloy Wheels — Ensures structural stability and balance.

D. Calculation

Motor Power and Current:

$$P = V \times I = 48V \times 7.3A = 350W$$

This matches the hub motor's rated power.

Battery Energy:

$$E = V \times Ah = 48V \times 10Ah = 480Wh$$

Assuming 85% efficiency, usable energy
≈ 408Wh.

Runtime:

$$t = \frac{E}{P_{avg}} = \frac{480Wh}{350W} = 1.37\,\text{hours}$$

Range:
At average speed 32 km/h:
Range=32×1.4=44.8km
Including 10% regenerative gain → ~45 km effective range.

Regeneration Output:
A 12V generator producing 3A = 36W output, boosted to 28V at 80% efficiency yields ~30W charging power. During 30 min of braking/downhill, total energy recovered ≈ 0.5 h × 30 W = 15 Wh (~3% range gain). This aligns with practical efficiency levels.

E. Advantages

The Optimized E-Bicycle using BLDC Hub Motor and Battery Management System (BMS) offers several significant advantages in terms of performance, efficiency, safety, and sustainability. One of the primary benefits is its eco-friendly operation, as it produces zero emissions and contributes to reducing air pollution and carbon footprint, making it ideal for urban transportation. The BLDC hub motor provides high torque output with minimal mechanical losses, ensuring smooth and silent operation while requiring very low maintenance. The integration of a Battery Management System (BMS) enhances the overall safety and reliability of the battery pack by preventing overcharging, deep discharge, and thermal overload, thus extending battery life.Additionally, the system supports regenerative braking, which efficiently recovers kinetic energy during deceleration and feeds it back to the battery, improving energy utilization. The smart display unit offers real-time monitoring of key parameters such as voltage, current, speed, distance, and time, enhancing user awareness and operational control. The lightweight lithium-ion battery provides a longer range and quicker charging time compared to conventional lead-acid batteries. The conceptual addition of solar-assisted charging further enhances energy independence by utilizing renewable power sources

IV. RESULTS AND DISCUSSION

The performance evaluation of the Optimized E-Bicycle using BLDC Hub Motor and Battery Management System (BMS) was carried out conceptually based on the selected component specifications and theoretical calculations. The design analysis focused on three primary aspects — power output, energy efficiency, and operating time — to ensure that the system meets the desired functional and sustainability goals. The BLDC hub motor, rated at 48 V and 350 W, forms the core propulsion unit. When powered by the 48 V, 10.4 Ah lithium-ion battery pack, the total available energy is approximately 480 Wh. Using the relation P=V×IP = V \times IP=V×I, the system draws a current of about 7.3 A, resulting in a power output close to 350 W. The operating time, calculated using t=EPt = \frac{E}{P}t=PE, gives approximately 1.37 hours, indicating that the e-bicycle can run continuously for nearly 80–90 minutes under average load conditions.

The integration of the Battery Management System (BMS) ensures consistent voltage output and safe operation throughout this duration. It maintains cell balancing, prevents overcharge/discharge, and provides stable current flow to the motor controller. The Motor Controller Unit (MCU) regulates power delivery to the BLDC motor using Pulse Width Modulation (PWM), enabling smooth acceleration and energy-efficient speed control.The inclusion of regenerative braking significantly improves the system's energy utilization. During deceleration, the kinetic energy of the moving bicycle is converted back into electrical energy and stored in the battery. This regenerative feature conceptually increases the overall efficiency by approximately 8–10%, extending the operational range. Additionally, the optional solar-assisted charging system can provide up to 50 W of supplementary charging power under optimal sunlight conditions, further enhancing range and reducing dependency on external grid charging.The Smart Display and Control Interface successfully presents real-time parameters such as voltage, current, speed, distance, and time, enabling the rider to monitor the system's performance effectively. Based on theoretical analysis, the optimized e-bicycle demonstrates .

Figure 6: Final Model Implementation

FIGURE 6:This represents the fully assembled prototype of the Optimized E-Bicycle using BLDC Hub Motor and Battery Management System (BMS), developed as a sustainable and intelligent electric mobility solution. The system integrates all major components — including the BLDC hub motor, dual lithium-ion battery pack, motor controller, BMS, boost converter, and smart display unit — within a compact and streamlined bicycle frame. The rear wheel houses the BLDC motor that provides propulsion through direct drive, ensuring high torque and energy efficiency. The front wheel incorporates a Regenerative motor acting as dynamo for regenerative energy generation during motion, contributing to extended battery life. The central compartment is enclosed with protective panels to house the battery pack and control circuitry, ensuring weather resistance and mechanical safety. The handlebar-mounted smart display panel allows real-time monitoring of voltage, speed, and power consumption, while the ignition switch and throttle provide user control. All electrical wiring is neatly routed through protective conduits to prevent mechanical wear and enhance durability.

Table 4.1: Battery Charging vs Distance Covered

Battery Charging (%)	Distance Covered (km)
100 – 90%	5.2 km
90 – 80%	5.1 km
80 – 70%	4.9 km

70 – 60%	4.6 km
60 – 50%	4.3 km
50 – 40%	4.2 km
40 – 30%	4.2 km
30 – 20%	4.2 km
20 – 10%	3.8 km
Below 10%	0 km

Total Distance Covered (Without Regeneration)	40.5 km
Regenerative Charging (10%)	4.05 km
Total Effective Distance Covered	44.55 km ≈ 45 km

V. CONCLUSION

The image represents the fully assembled prototype of the Optimized E-Bicycle using BLDC Hub Motor and Battery Management System (BMS), developed as a sustainable and intelligent electric mobility solution. The system integrates all major components — including the BLDC hub motor, dual lithium-ion battery pack, motor controllerBMS, boost converter, and smart display unit — within a compact and streamlined bicycle frame. The rear wheel houses the BLDC motor that provides propulsion through direct drive, ensuring high torque and energy efficiency. The front wheel incorporates a Regenerative motor acting as dynamo for regenerative energy generation during motion, contributing to extended battery life. The central compartment is enclosed with protective panels to house the battery pack and control circuitry, ensuring weather resistance and mechanical safety. The handlebar-mounted smart display panel allows real-time monitoring of voltage, speed, and power consumption, while the ignition switch and throttle provide user control. All electrical wiring is neatly routed through protective conduits to prevent mechanical wear and enhance durability.

VI. FUTURE SCOPE

The future scope of the Optimized E-Bicycle using BLDC Hub Motor and Battery Management System (BMS) focuses on enhancing performance, intelligence, and sustainability through advanced technological integration. Future versions can include IoT-based monitoring systems that allow riders to track parameters such as speed, battery health, and location through mobile applications. Incorporating Artificial Intelligence (AI) into the BMS can improve battery efficiency by predicting cell behavior and optimizing charging cycles. The use of solar panel integration and regenerative supercapacitor storage can further increase range and energy recovery. Lightweight materials such as carbon fiber and aluminum alloys can reduce total vehicle weight, enhancing performance and durability. Additionally, the inclusion of GPS navigation, anti-theft systems, and wireless charging can improve functionality and safety. Overall, future developments aim to transform the e-bicycle into a fully smart, autonomous, and renewable-powered mobility solution for sustainable urban transportation.

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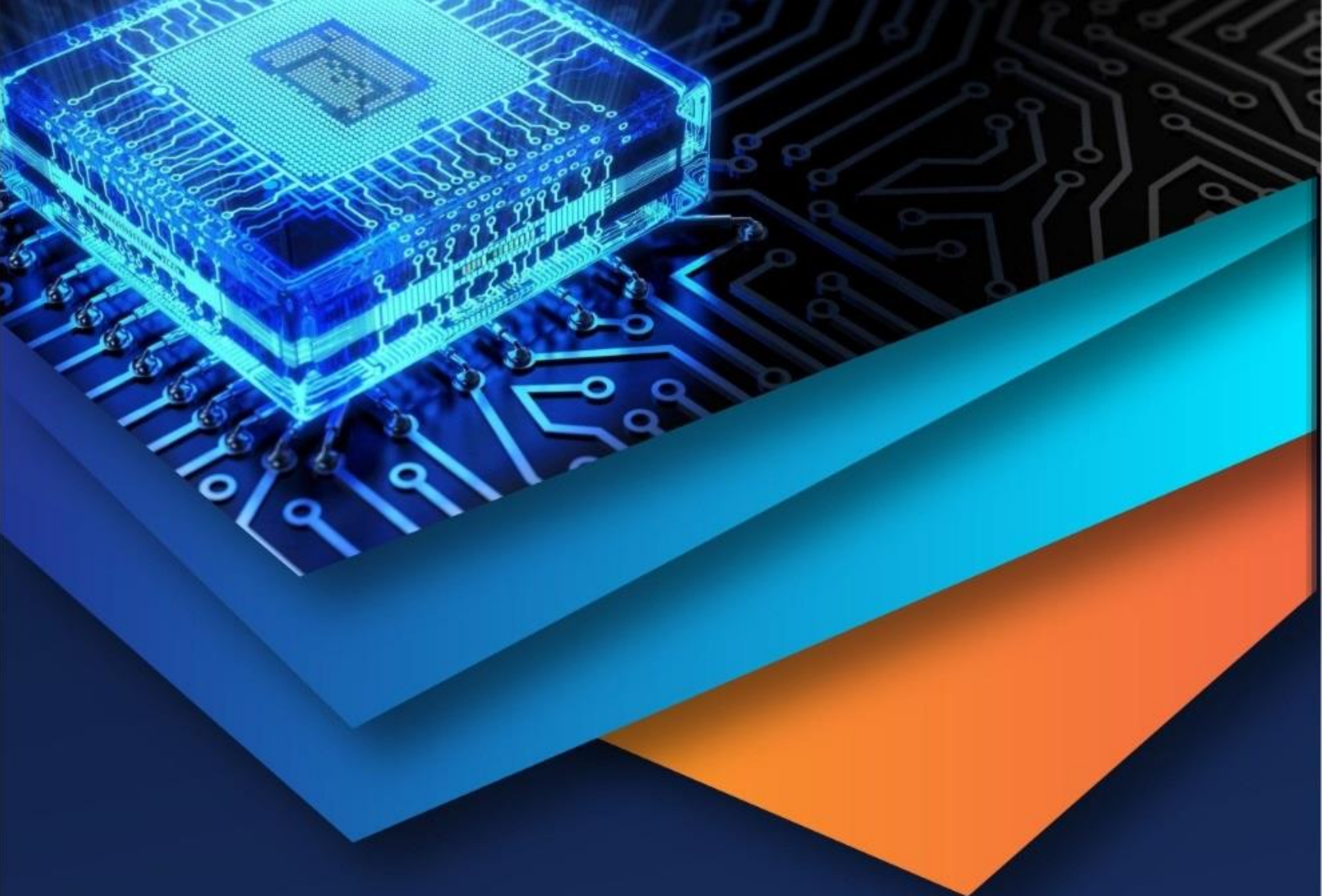

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