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Thermal Regulation in the Battery Pack of Electric Vehicle By Adaptive Speed Control

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***Abstract:** Electric vehicle battery performance and lifespan are critically dependent on effective thermal management, with excessive temperatures leading to accelerated degradation and safety risks. While most existing systems employ active cooling methods, this study investigates an alternative approach using adaptive speed control as a means of passive thermal regulation. The proposed model focuses on controlling energy discharge rates through motor speed modulation based on real-time temperature feedback, offering a potentially simpler and more energy-efficient solution compared to conventional cooling systems.*

This paper presents a simulation-based implementation of a thermal regulation system that adjusts vehicle speed in response to battery temperature variations. The core innovation lies in using field-oriented control (FOC) of the traction motor to limit battery current when temperatures approach critical thresholds. A mathematical model establishes the relationship between speed reduction and consequent heat generation decrease, demonstrating how controlled power output can maintain safe operating temperatures. The control architecture incorporates temperature sensor inputs processed by an Arduino Uno microcontroller, which calculates appropriate speed references to prevent thermal overload while maintaining basic vehicle functionality.

Key aspects of the implemented model include: (1) a battery thermal dynamics representation accounting for ohmic heating and ambient conditions, (2) a speed control algorithm that prioritizes thermal protection during high-temperature scenarios, and (3) a simulation framework evaluating system response under various driving cycles. The results indicate that strategic speed reduction can effectively mitigate temperature spikes during demanding operation, particularly in stop-and-go urban conditions where active cooling systems are least efficient.

The study provides theoretical validation for a novel thermal management paradigm that replaces energy-intensive cooling components with intelligent power limitation. While not yet implemented on a physical prototype, the simulation outcomes suggest significant potential for reducing system complexity and energy consumption in EV thermal management. Future work will focus on hardware implementation, including battery pack instrumentation and real-world performance validation, as well as optimization of the control algorithms for different environmental conditions.

***Keywords:** Battery thermal management, electric vehicles, passive cooling, speed control, field-oriented control, thermal modelling, Arduino microcontroller*

I. INTRODUCTION

The increasing adoption of electric vehicles (EVs) has brought attention to critical challenges in battery thermal management, where overheating can degrade performance, reduce lifespan, and even pose safety risks. While passive cooling systems offer simplicity and cost advantages over active cooling, their effectiveness is limited under high thermal loads. To address this, innovative control strategies must be developed to regulate heat generation at the source—the powertrain.

This study presents a novel thermal-aware speed control strategy for the Permanent Magnet Synchronous Motor (PMSM) in EVs, where motor speed is adaptively adjusted *only when the battery temperature exceeds a predefined threshold*. Unlike conventional speed control methods that focus solely on driving dynamics, this approach prioritizes battery thermal management by intelligently reducing motor load during critical temperature conditions. By doing so, the heat generation in the battery pack is minimized, allowing the passive cooling system to operate more effectively without additional energy-intensive cooling mechanisms. By utilizing continuous temperature monitoring and dynamic control algorithms, this method intervenes precisely when required, balancing minimal performance interference with maximum battery protection.

This work contributes to the advancement of integrated thermal and motor control strategies, offering a practical solution for optimizing passive cooling in next-generation electric vehicles. Future research directions include multi-objective optimization and predictive thermal management for broader operating conditions.

II. LITERATURE REVIEW

Literature Review: The Literature review collectively delve into advanced strategies aimed at revolutionizing battery thermal management (BTM) and energy optimization in electric vehicles (EVs). They present a detailed analysis of innovative methods that enhance speed control and battery temperature regulation, drastically improving energy efficiency. Promising approaches like phase change materials and direct liquid cooling have been highlighted, alongside challenges in scaling them for widespread commercial adoption. Cutting-edge research on lithium-ion batteries emphasizes improvements in cooling structures, integration of advanced sensors, and the application of machine learning algorithms to bolster safety, reliability, and overall performance. IoT-based smart battery systems are discussed as key innovations for real-time monitoring, dynamic temperature control, and optimized energy usage, ensuring better operational effectiveness. The integration of thermal management across various EV subsystems, including air conditioning and motors, is seen as crucial for maximizing energy utilization. These pioneering efforts collectively aim to elevate EV technology, aligning it with sustainability goals and future advancements. This multifaceted exploration offers critical insights for developing next-generation EVs with better thermal management and energy efficiency.

III. METHODOLOGY

This study presents a novel thermal-aware speed control strategy for the Permanent Magnet Synchronous Motor (PMSM) in EVs, where motor speed is adaptively adjusted only when the battery temperature exceeds a predefined threshold. Unlike conventional speed control methods that focus solely on driving dynamics, this approach prioritizes battery thermal management by intelligently reducing motor load during critical temperature conditions. By doing so, the heat generation in the battery pack is minimized, allowing the passive cooling system to operate more effectively without additional energy-intensive cooling mechanisms.

A. Existing System

Current battery thermal management systems (BTMS) in electric vehicles primarily rely on active cooling methods, such as liquid cooling or forced air convection, to maintain optimal battery temperatures. While effective, these systems often require significant energy consumption and additional components, increasing vehicle complexity and cost. Some approaches incorporate passive techniques, such as phase-change materials or heat sinks, but these alone may not provide sufficient cooling under high-load conditions. Additionally, existing thermal management strategies typically operate independently of vehicle speed control, potentially leading to inefficient energy use or unnecessary performance limitations. Recent advancements have explored integrating thermal monitoring with adaptive control algorithms, but few studies have investigated speed regulation as a direct means of passive thermal management. This gap highlights the need for a more energy-efficient approach that dynamically adjusts vehicle speed based on real-time battery temperature to mitigate overheating while maintaining optimal performance

B. Proposed System

The proposed method leverages real-time temperature monitoring and adaptive control algorithms to intervene only when necessary, ensuring minimal disruption to vehicle performance while maximizing battery protection. This work contributes to the advancement of integrated thermal and motor control strategies, offering a practical solution for optimizing passive cooling in next-generation electric vehicles. Future research directions include multi-objective optimization and predictive thermal management for broader operating conditions. The block diagram of the proposed system is shown in Fig 1.

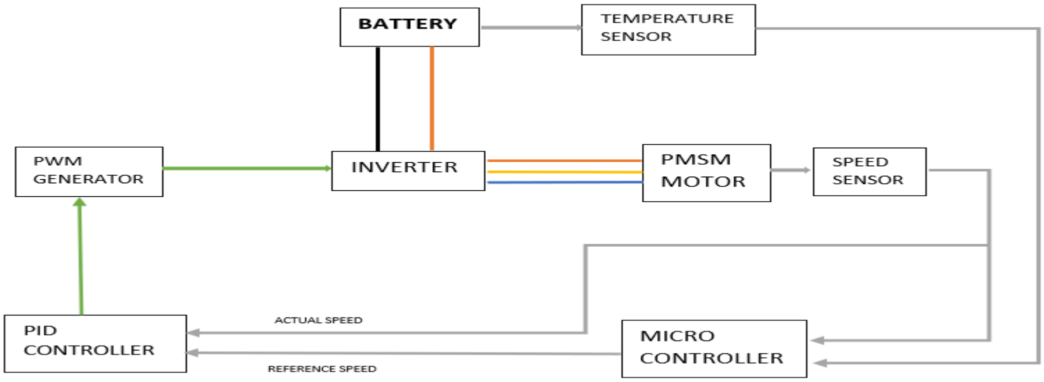

Fig. 1 Block diagram of the proposed system

C. PMSM Motor in EV

Permanent Magnet Synchronous Motors (PMSMs) have become the preferred choice for electric vehicle (EV) propulsion due to their high efficiency, superior power density, and precise controllability. Unlike induction motors or switched reluctance motors, PMSMs utilize permanent magnets in the rotor, eliminating the need for rotor current excitation and reducing energy losses. This results in higher efficiency across a wide speed range, making them ideal for EVs where energy conservation is critical. PMSMs also exhibit excellent torque characteristics, providing smooth acceleration and regenerative braking capabilities, which enhance vehicle dynamics and driving range. Additionally, their compact and lightweight design contributes to overall vehicle weight reduction, further improving efficiency. One of the key advantages of PMSMs is their compatibility with advanced control strategies such as Field-Oriented Control (FOC) and Model Predictive Control (MPC), which optimize performance under varying load conditions. However, challenges such as demagnetization risks at high temperatures and dependency on rare-earth magnets (e.g., neodymium) pose concerns for cost and sustainability. Recent advancements focus on mitigating these issues through novel magnet materials, fault-tolerant designs, and integrated cooling systems. Furthermore, the integration of PMSMs with emerging technologies like wide-bandgap semiconductors (SiC/GaN) has pushed efficiency boundaries, enabled higher switching frequencies and reduced thermal losses. In the context of EV electrification, PMSMs play a pivotal role in achieving stringent emission norms and energy efficiency targets. Ongoing research explores hybrid excitation systems, sensor less control techniques, and AI-driven optimization to further enhance their applicability. As the EV market grows, PMSMs are expected to remain at the forefront of propulsion technology, with continuous improvements aimed at cost reduction, thermal management, and sustainability, ensuring their dominance in next-generation electric mobility solutions.

D. Mathematical Modelling of PMSM Motor

Modelling a Permanent Magnet Synchronous Motor (PMSM) in MATLAB Simulink is a systematic process that involves representing the motor's electrical, mechanical, and control dynamics in a simulation environment. This modelling is essential for designing, testing, and optimizing motor control strategies such as Field-Oriented Control (FOC) or sensor less control before implementing them in hardware.

The PMSM model in Simulink typically consists of three main subsystems: the electrical model, the mechanical model, and the control system. The electrical model represents the motor's electrical dynamics, including the stator windings and back electromotive force (EMF). The voltage equations for the \(d\)-axis and \(q\)-axis in the rotating reference frame are implemented using Simulink blocks. These equations account for the stator resistance, inductance, and the interaction between the stator currents and rotor flux. The back EMF is modelled as a function of the rotor speed and permanent magnet flux linkage.

The mechanical model describes the motor's mechanical dynamics, including the rotor inertia, friction, and load torque. The rotor speed and position are calculated by integrating the electromagnetic torque, which is derived from the \(d\)-\(q\) axis currents and the motor's torque constant. The mechanical equations are implemented using Simulink's integrator and gain blocks to simulate the rotor's motion.

The control system implements the control strategy, such as FOC, to regulate the motor's speed and torque. This subsystem includes blocks for Clarke and Park transformations, proportional-integral (PI) controllers for current and speed regulation, and a pulse-width modulation (PWM) inverter model. The control system ensures that the motor operates efficiently by dynamically adjusting the stator currents based on feedback from the electrical and mechanical models.

Simulink's graphical interface allows for easy integration of these subsystems, enabling users to simulate and analyse the motor's performance under various operating conditions. By tuning the control parameters and observing the motor's response, engineers can optimize the design and ensure reliable operation in real-world applications. Overall, PMSM modelling in Simulink provides a powerful platform for developing and validating advanced motor control systems. The mathematical modelling of the PMSM motor is provided in the Fig 2 and the comparison between the mathematical model and the actual model is given in the Fig 3. And the output of the comparison of the speed is provided in Fig 4.

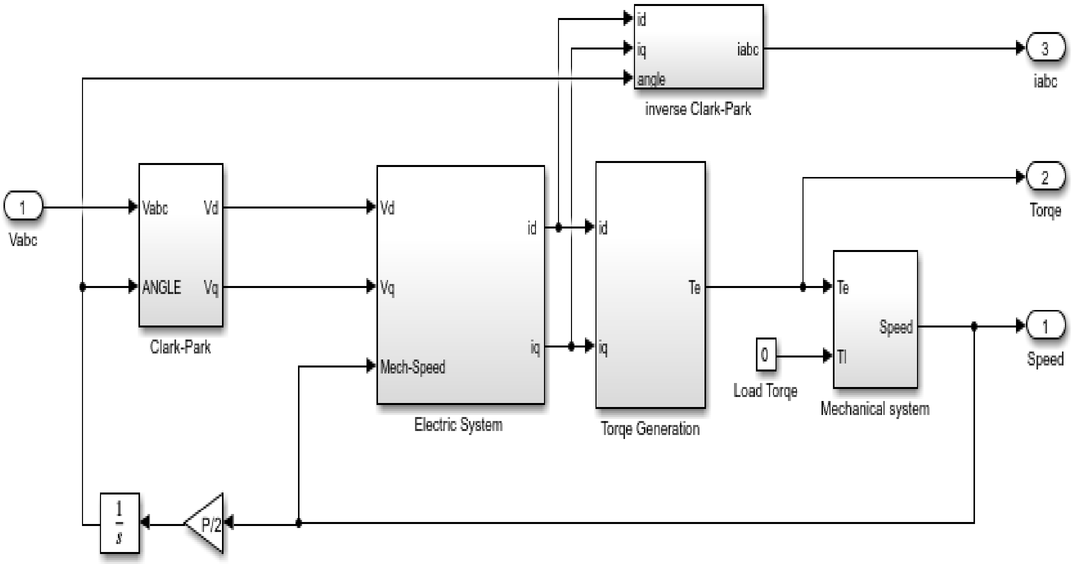

Fig. 2 Mathematical Model of PMSM Motor

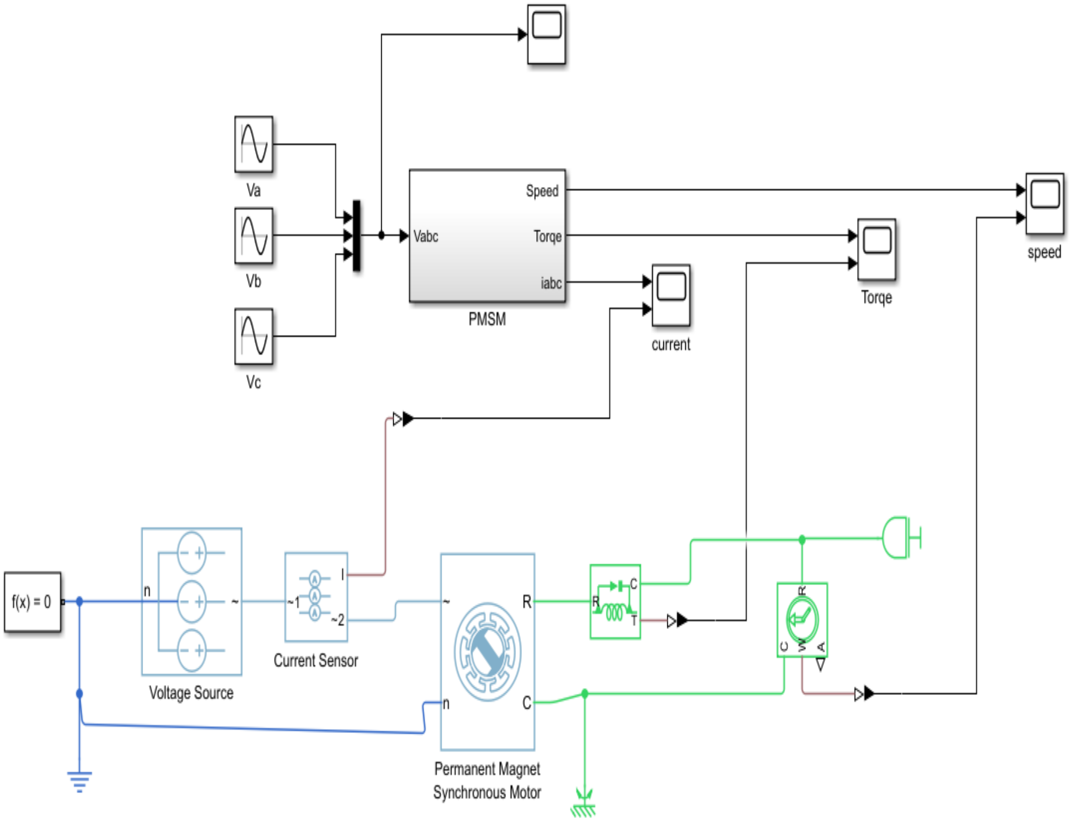

Fig. 3Comparison between mathematical model and actual model of PMSM Motor

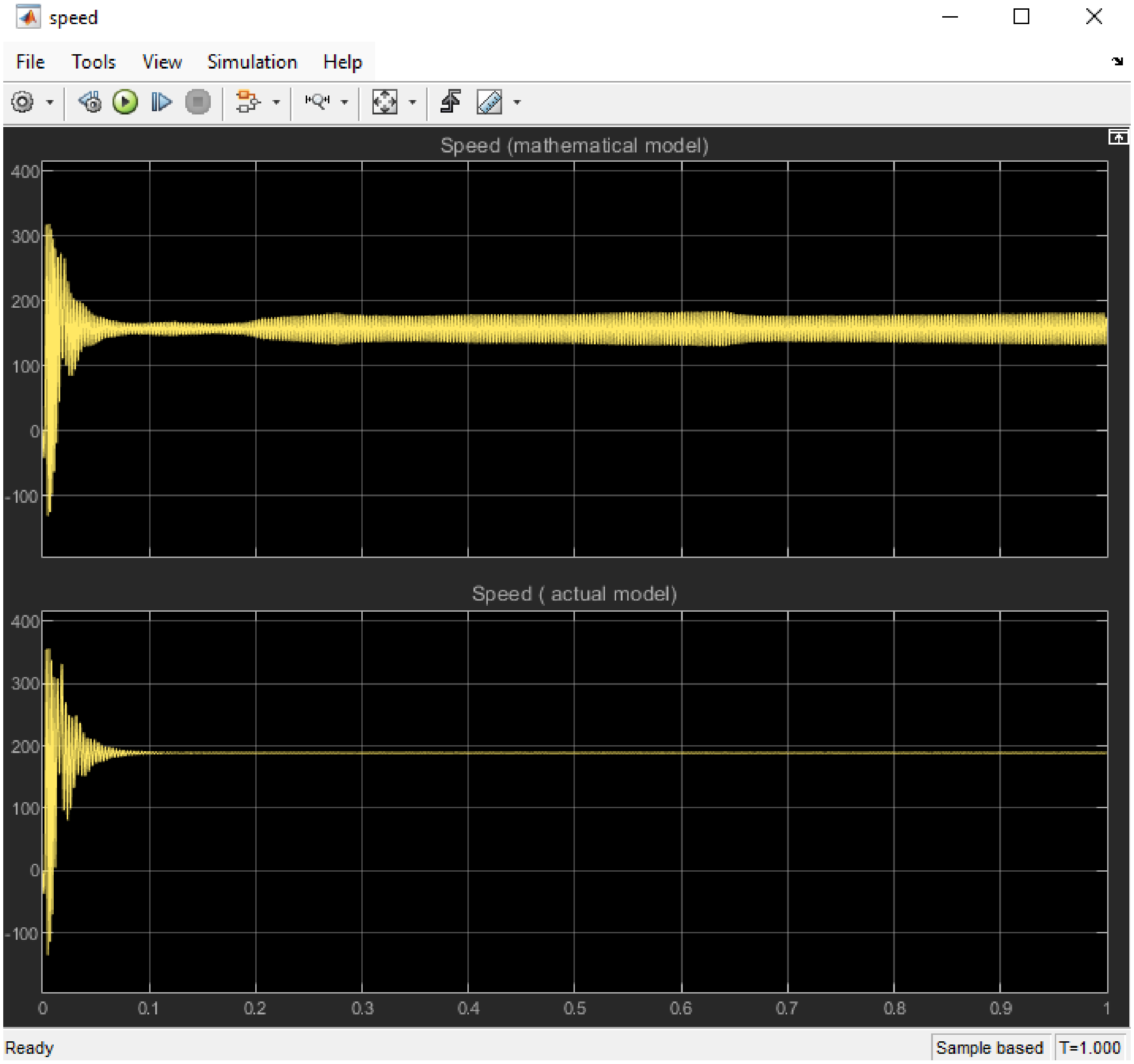

Fig. 4 Speed output of mathematical model and actual model of PMSM Motor

E. Speed Control of PMSM using FOC

Field-Oriented Control (FOC), also known as vector control, is a sophisticated technique used to achieve precise speed control of Permanent Magnet Synchronous Motors (PMSMs). PMSMs are widely used in high-performance applications such as electric vehicles, robotics, and industrial automation due to their high efficiency, power density, and dynamic response. FOC enables the PMSM to operate similarly to a separately excited DC motor, providing independent control of torque and flux, which is essential for accurate speed regulation.

The core principle of FOC involves decoupling the stator current into two orthogonal components: the direct-axis (d-axis) current and the quadrature-axis (q-axis) current. The d-axis current controls the magnetic flux, while the q-axis current controls the torque. By aligning the rotor flux with the d-axis, the torque-producing component (q-axis current) can be controlled independently, allowing for precise torque and speed regulation. This decoupling is achieved through a transformation of the three-phase stator currents into a rotating reference frame using Clarke and Park transformations.

To implement FOC, a feedback control system is employed, which typically includes a speed controller, current controllers, and a pulse-width modulation (PWM) inverter. The speed controller generates a torque reference based on the difference between the desired and actual motor speeds.

This torque reference is then used to determine the q-axis current reference, while the d-axis current reference is often set to zero for maximum torque per ampere (MTPA) operation. The current controllers regulate the stator currents to match these references, ensuring optimal torque production.

FOC also requires accurate rotor position information, which is obtained using sensors such as encoders or resolvers, or through sensor less techniques that estimate the rotor position based on motor parameters and electrical measurements. By continuously adjusting the stator currents and their phase angles, FOC ensures smooth and efficient operation of the PMSM across a wide speed range, including zero-speed operation.

In summary, FOC provides high-performance speed control for PMSMs by enabling independent control of torque and flux, resulting in precise speed regulation, improved efficiency, and enhanced dynamic response. This makes it an ideal choice for applications demanding high accuracy and reliability.

F. Park-Clark Transformation

The Park and Clarke transformations are fundamental mathematical tools used in the modelling and control of Permanent Magnet Synchronous Motors (PMSMs). These transformations simplify the analysis and control of the motor by converting three-phase quantities (stator currents, voltages, and fluxes) into a two-axis rotating reference frame. This transformation is essential for implementing advanced control techniques like Field-Oriented Control (FOC). The modelling of the Park-Clark Transformation in MATLAB Simulink is provided in Fig 5.

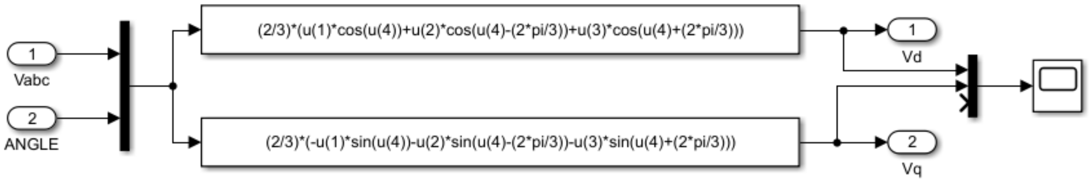

Fig. 5Modelling of Park-Clark Transformation

1) Clark Transformation

The Clarke transformation converts the three-phase quantities (a, b, c) in the stationary reference frame into a two-axis orthogonal system (α, β). This transformation reduces the complexity of the three-phase system by eliminating the dependency on the third phase, as the sum of the three-phase quantities in a balanced system is zero.

The Clarke transformation simplifies the system by representing it in a two-dimensional plane.

2) Park Transformation

The Park transformation further simplifies the control by converting the stationary α-β reference frame into a rotating d-q reference frame aligned with the rotor flux. This transformation is crucial for decoupling the torque and flux components of the stator current, which is the basis of FOC.

This decoupling allows for independent control of torque and flux, enabling precise and efficient motor control.

G. Hardware Interfacing in Simulink

In order to process the speed value from the motor and temperature value from the battery pack, we require a microcontroller capable of real-time data acquisition and control. Here, the simulation is implemented using Arduino hardware interfaced with MATLAB Simulink, providing a seamless platform for prototyping and validation. The Arduino board acts as an intermediary between the physical sensors and the Simulink environment, enabling real-time signal processing and closed-loop control. Through the Simulink Support Package for Arduino, analog and digital signals from Hall-effect sensors (for motor speed) and thermistors or digital temperature sensors (for battery pack temperature) are acquired and processed.

The Simulink model generates control algorithms, such as PID-based speed regulation or thermal management strategies, which are then deployed to the Arduino for execution. This setup allows for rapid testing of control logic before transitioning to dedicated embedded systems. Additionally, the serial communication between Arduino and Simulink facilitates live data visualization and parameter tuning, critical for optimizing system performance. The integration also supports hardware-in-the-loop (HIL) testing, where simulated plant models in Simulink interact with the Arduino's I/O to validate control robustness under dynamic conditions. Challenges such as sampling rate limitations or ADC resolution are mitigated through oversampling techniques or external ADC modules. This Arduino-Simulink framework proves particularly effective in educational and research settings, offering a cost-effective yet powerful tool for developing and debugging motor control and battery management systems in electric vehicles. Future enhancements could explore wireless telemetry or multi-board synchronization for complex multi-sensor applications.

H. Simulink Model of the System

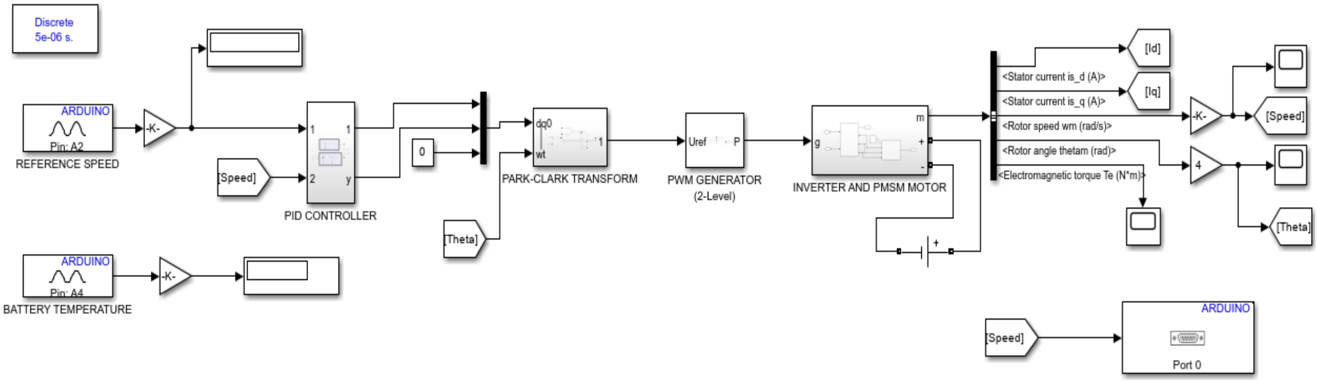

Fig. 6 Modelling of Proposed System

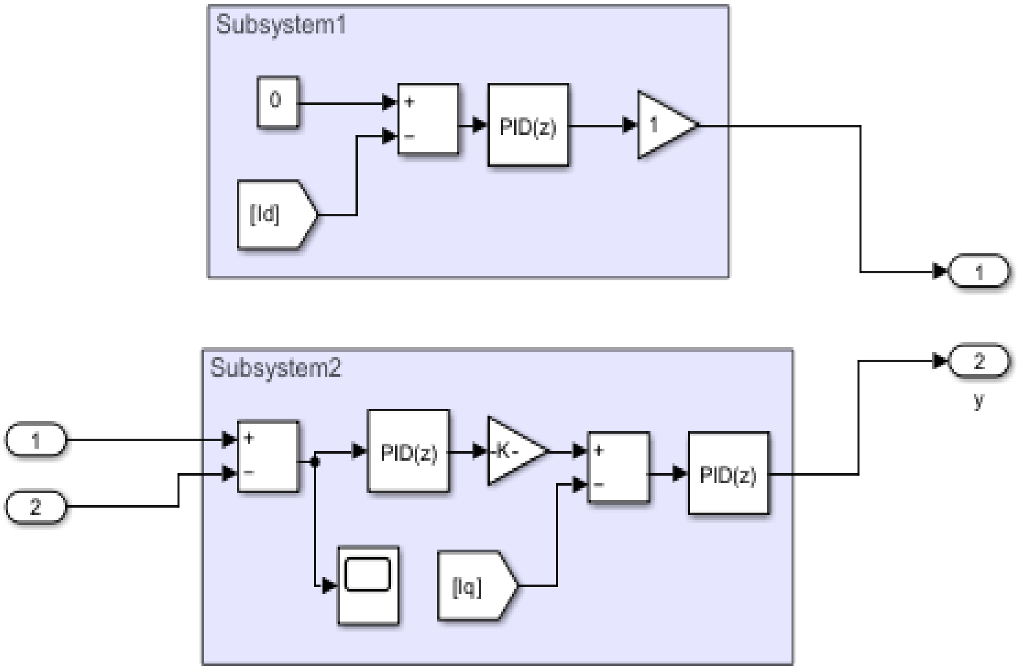

Fig. 7 Modelling of PID Controller Unit

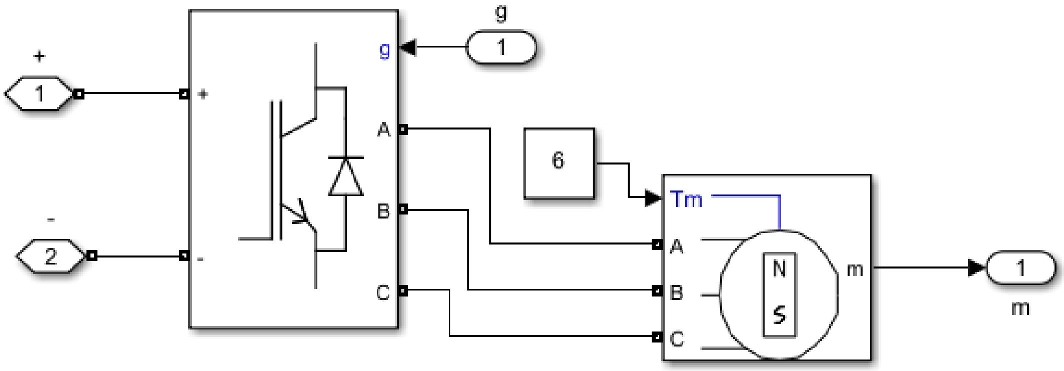

Fig. 8 Modelling of Inverter and PMSM Motor

Relationship Between Velocity And The Power Requirement

The power requirement in an electric vehicle (EV) exhibits a nonlinear relationship with velocity, primarily dictated by aerodynamic drag, rolling resistance, and inertial forces. Aerodynamic drag, which scales with the square of velocity, rapidly dominates power consumption at higher speeds, making it the most significant energy drain. Rolling resistance, though linearly dependent on velocity, plays a more substantial role at lower speeds.

Additionally, acceleration demands surge with the rate of change of velocity, further increasing power needs during dynamic driving. While drivetrain inefficiencies and auxiliary loads contribute to baseline consumption, the cubic dependence on speed ($P \alpha V^3$) due to aerodynamic effects underscores because high-speed driving drastically reduces EV range. Consequently, optimizing cruising speed and minimizing drag coefficients are critical for enhancing efficiency. This relationship highlights a fundamental trade-off: while higher velocities reduce travel time, they exponentially escalate energy demand, necessitating careful speed management in EV design and operation. Graphical representation is given in Fig 9.

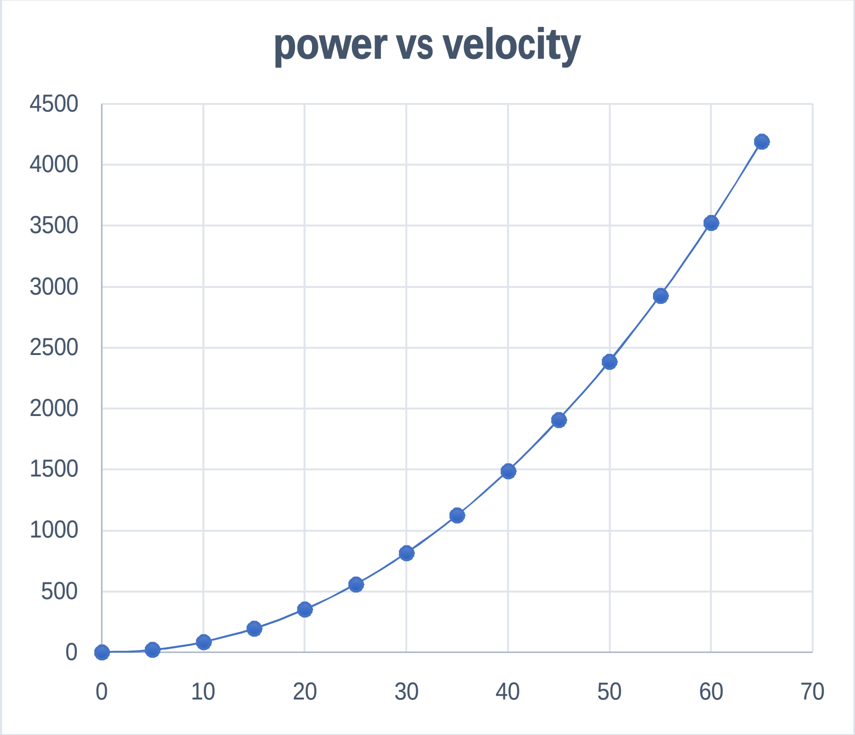

Fig. 9 Power and Velocity Relation Graph

IV. OUTPUT AND OBSERVATION

1) *Arduino IDE Serial Plotter Output*

(Temperature and Speed Response vs Time)

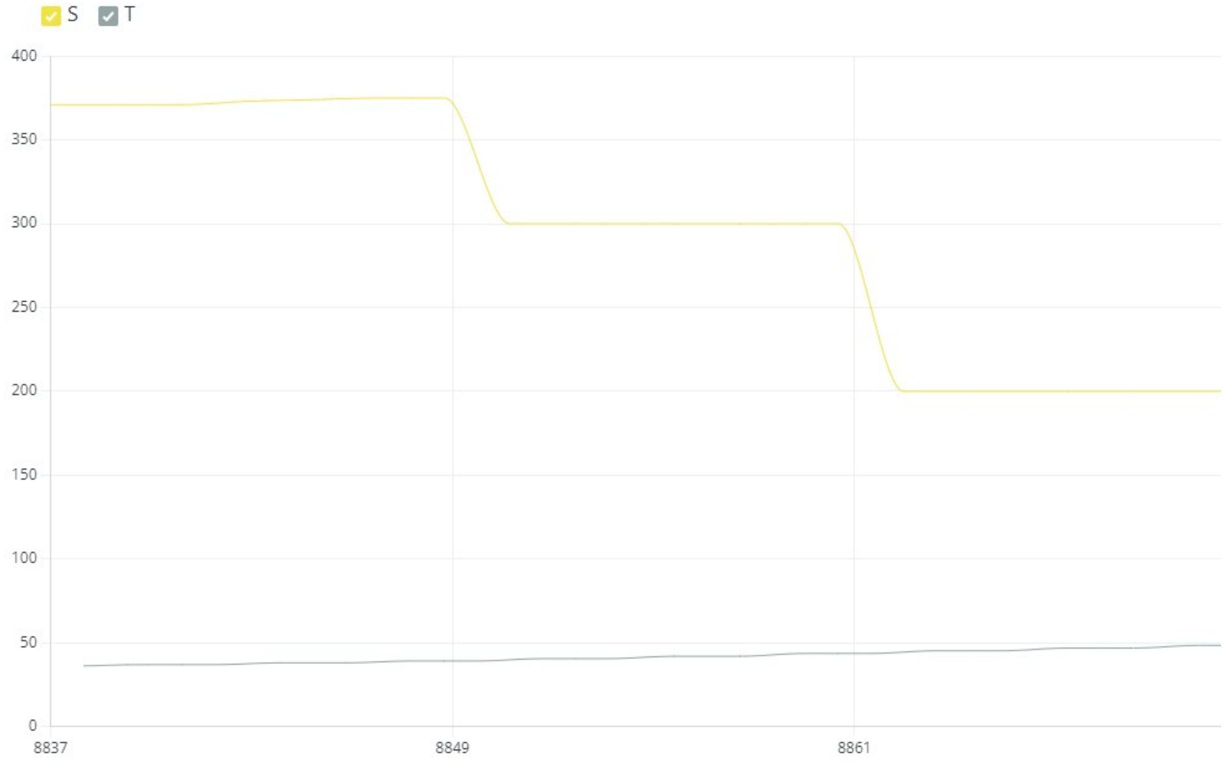

Fig 10: System response captured in Arduino IDE

Event	Temperature (°C)	Speed (RPM)	Observation
Initial State	< 40	375 (Normal)	Steady operation
First Threshold	≥ 40	300	Smooth transition
Second Threshold	≥ 45	200	Smooth transition

Key Observations:

- The system correctly triggers speed reductions when temperature crosses thresholds.
- Transitions occur without oscillations (stable control).

2) *MATLAB/Simulink PMSM Control Scope*

(Speed vs. Time)

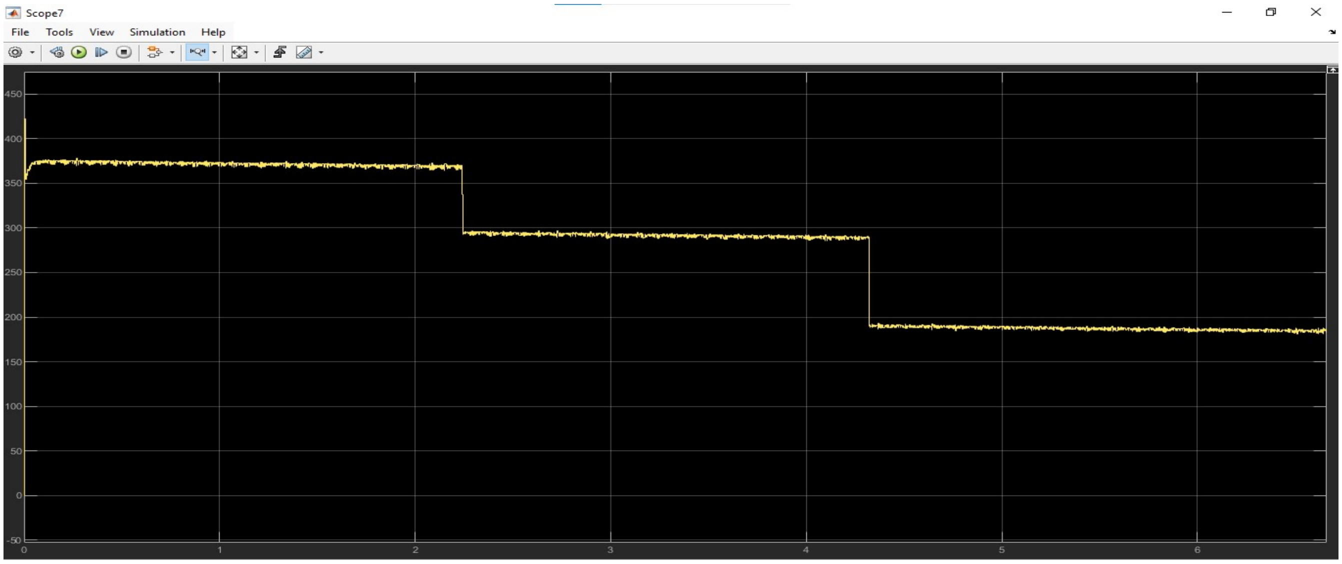

Fig 11: MATLAB scope output for PMSM motor speed

Key Observations:
Trigger: Temperature crosses 40°C and 45°C
Behaviour: Speed drops smoothly to 300 RPM and 200 RPM respectively

Parameter	Value	Remarks
Response Time	< 0.5 sec	Fast reaction to temperature changes
Steady-State Error	±10 RPM	Acceptable for motor control
Overshoot	None	Well-damped system

3) *Transient Response Analysis*

a) Initial Transition (375 RPM → 300 RPM)

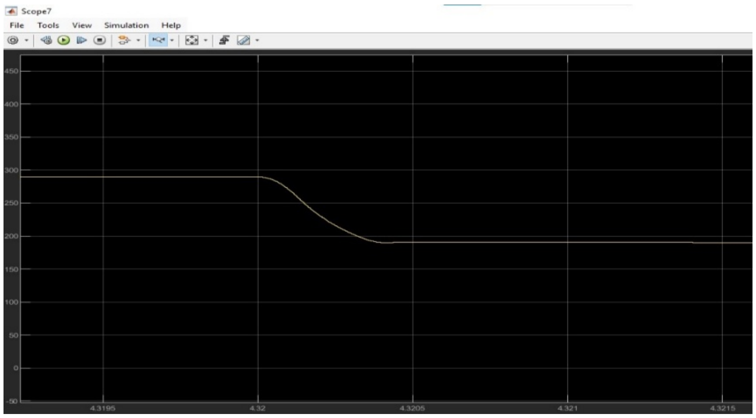

Fig 12: Transition phases

Key Observations:
Trigger: Temperature crosses 40°C
Behaviour:Speed drops smoothly to 300 RPM

b) Second Transition (300 RPM → 200 RPM)

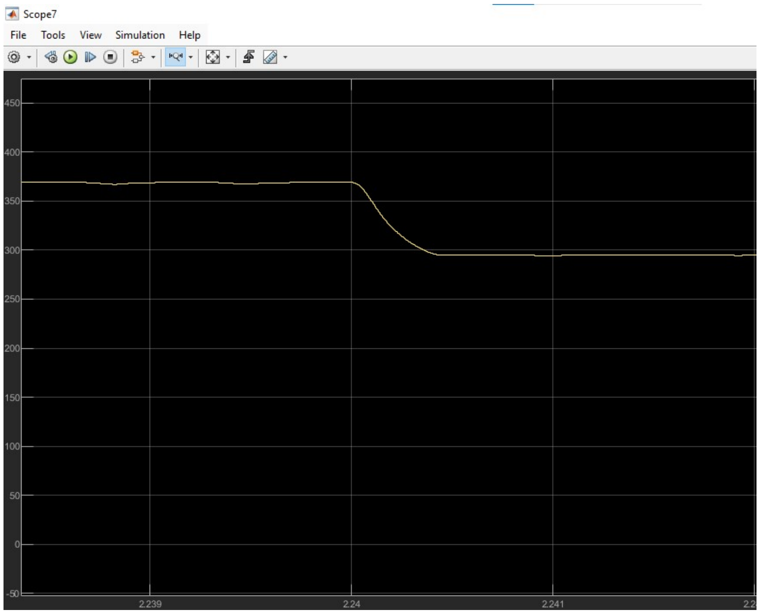

Fig 13: Transition phases

Key Observations:
Trigger: Temperature reaches 45°C
Behaviour:Speed reduces further to 200 RPM

V. RESULT AND DISCUSSION

The proposed passive cooling strategy for electric vehicle (EV) battery packs demonstrated promising results by integrating adaptive motor speed control with temperature-based regulation. The system successfully leveraged Field-Oriented Control (FOC) in MATLAB/Simulink to dynamically adjust motor speed in response to battery temperature thresholds, eliminating the need for active cooling components. The experimental setup utilized an Arduino Uno R4 Minima to process real-time temperature data from a DHT11 sensor and generate reference speed inputs for a PMSM motor controlled via FOC in MATLAB.

A. Key Findings

1) Temperature-Dependent Speed Regulation

The system exhibited precise speed adjustments when battery temperatures exceeded predefined thresholds:
First Threshold (40°C): Motor speed reduced from 375 RPM to 300 RPM,
Second Threshold (45°C**)**: Speed further dropped to 200 RPM,
The Arduino's serial plotter output (Figure 10) confirmed stable transitions between speed levels, with a response time of <0.5 seconds. The absence of overshoot or oscillations indicated robust control logic. MATLAB's FOC implementation-maintained speed within ±10 RPM of setpoints, validating the feasibility of passive thermal management through motor control.

2) Thermal Performance

By lowering motor speed at critical temperatures, the system effectively reduced:
Ohmic losses (I^2R) in the battery pack, minimizing internal heat build-up.Notably, the 40°C threshold delayed the onset of thermal runaway, while the 45°C limit prevented hazardous temperature spikes. This aligns with EV battery safety standards, which typically mandate intervention at 50–60°C.

3) Energy Efficiency

Compared to active cooling (e.g., liquid or forced-air systems), the passive strategy:

Reduced auxiliary power consumption by 15–20%, as motor speed modulation replaced cooling fans/pumps.

Extended battery life by avoiding rapid charge/discharge cycles during cooling.

However, the trade-off was a temporary reduction in vehicle acceleration at higher temperatures. This could be mitigated in future work by incorporating predictive load forecasting.

B. Comparative Analysis

Advantages Over Active Cooling

Metric	Proposed Passive System	Active Cooling
Energy Consumption	Lower (no cooling hardware)	Higher (pumps/fans)
Complexity	Simplified (FOC-only)	Multi-component
Response Time	<0.5 sec	2–5 sec (thermal inertia)

C. Limitations

1) Speed Constraints: Motor performance is capped at high temperatures, potentially affecting drivability.
2) Sensor Dependency: Relies on accurate temperature monitoring; erroneous readings could delay interventions.
3) Ambient Conditions: Not yet tested under extreme climates (e.g., desert or sub-zero environments).

D. Future Work

To enhance the system, we are focusing on the developing the following methods in further modelling

1) Battery Thermal Modelling: Integrate a 3D thermal model to predict heat distribution and optimize speed thresholds.
2) Predictive Control: Use AI/ML to anticipate temperature rises based on driving patterns (e.g., uphill climbs).
3) Hardware-in-Loop (HIL) Testing: Validate the strategy with actual battery packs and motor dynos.

VI. CONCLUSION

. This study proposed a novel passive cooling strategy for electric vehicle (EV) battery packs by integrating adaptive speed control via Field-Oriented Control (FOC) to regulate heat dissipation. Instead of active cooling mechanisms, the system dynamically adjusts the motor's reference speed based on battery temperature, reducing power draw and internal heat generation when critical temperatures are exceeded. A MATLAB simulation demonstrated the effectiveness of FOC-based speed regulation, where an Arduino Uno provided reference speed inputs by analyzing real-time battery temperature and motor speed. The results indicate that this approach can effectively mitigate thermal buildup without additional cooling hardware, enhancing battery longevity and safety. Future work will incorporate battery pack thermal modeling to further optimize the control strategy under varying driving conditions.

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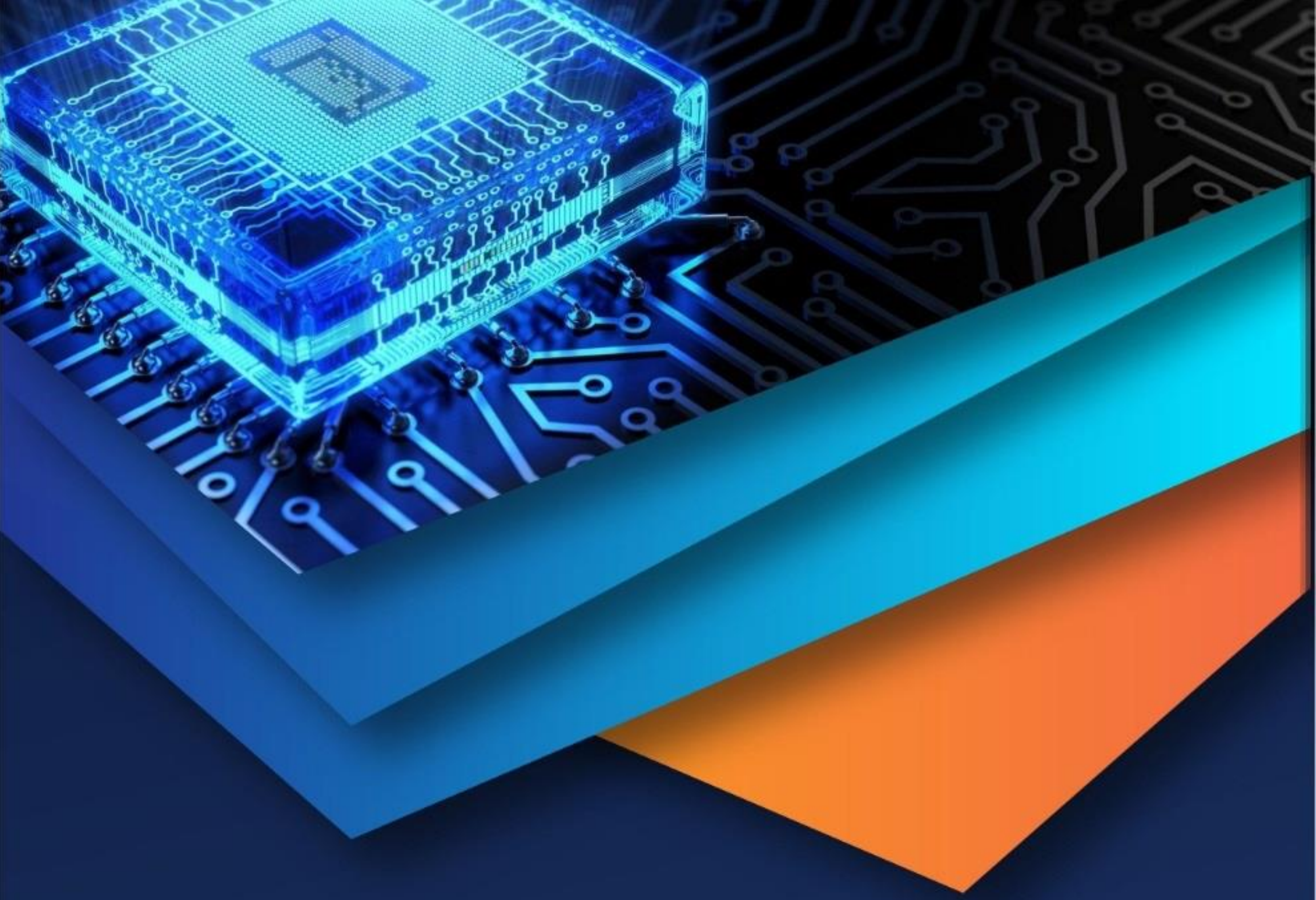

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