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A Comprehensive Framework for Hybrid Vehicle Energy Management: Integrating Power-Split Transmissions, Static Component Modeling, and MATLAB/Simulink Validation

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***Abstract:** This study addresses the critical challenge of optimizing energy management in hybrid vehicles (HVs) to reduce fuel consumption while balancing computational feasibility. A novel power management strategy is proposed, leveraging a power-split hybrid transmission (PSHT) to dynamically regulate energy flow between an internal combustion engine (ICE), a permanent magnet synchronous electric machine, and a battery pack. The PSHT architecture integrates a continuously variable transmission (CVT) with planetary gearing to enable seamless torque distribution and regenerative braking. Component-level models—including static efficiency maps for the ICE, efficiency-driven electric machine dynamics, and a simplified electrochemical battery model—are combined within a MATLAB/Simulink framework to simulate real-world driving scenarios. Key assumptions, such as constant internal resistance in the battery and quasi-steady-state ICE operation, prioritize computational efficiency without compromising system-level insights. Simulation results demonstrate that the strategy minimizes ICE usage during transient phases (e.g., acceleration/deceleration), reserving it for steady-state operation at 15 m/s, while prioritizing electric propulsion for dynamic demands. This approach reduces fuel consumption by 18–22% compared to conventional hybrid strategies, validated through metrics such as shaft speeds, electrical losses, and state-of-charge dynamics. The study underscores the viability of model-based energy management for enhancing HV efficiency, providing a foundation for real-time implementation and further refinement.*

***Keywords for Abstract:** Hybrid Vehicles (HVs), Power-Split Hybrid Transmission, Energy Management Strategy (EMS), Fuel Consumption Reduction, MATLAB/Simulink Simulation, Static Efficiency Maps, Regenerative Braking, Battery Modeling, Computational Efficiency, Optimal Control.*

I. INTRODUCTION

Environmental sustainability and resource conservation necessitate a significant reduction in fuel consumption for future automobiles. Vehicles powered by Internal Combustion Engines (ICEs) leverage the high energy density of gasoline or diesel fuels but suffer from low efficiency during partial-load operation [4, 11]. Hybrid Vehicles (HVs) present a viable pathway to substantially lower fuel usage by optimizing existing powertrain components[16]. These vehicles enhance efficiency through several mechanisms: downsizing the engine to minimize mechanical losses, compensating for reduced power output with electric motors, recovering kinetic and potential energy during braking via regenerative systems, eliminating idling losses by shutting off the engine during stops, and avoiding inefficient part-load engine operation by prioritizing electric propulsion or adjusting torque distribution [12].

A critical challenge in HVs lies in intelligently managing power distribution between the engine and electric motor to maximize efficiency. Research refers to methodologies governing this balance as Energy Management Strategies (EMS), which are broadly categorized into heuristic and optimal approaches [1, 2, 7, 12]. Heuristic strategies, such as rule-based fuzzy logic systems [5], prioritize real-time applicability but lack adaptability due to their non-model-based design. Conversely, optimal strategies, rooted in control theory, employ techniques like dynamic programming [10] or Pontryagin's minimum principle [8] to derive model-dependent solutions that minimize fuel consumption. While these methods offer adaptability, they demand greater computational resources compared to heuristic rules [3, 7].

This paper introduces a power management strategy utilizing a power-split hybrid transmission to further reduce fuel consumption[6]. By dynamically optimizing energy flow between the engine and electric motor, this approach aims to enhance operational efficiency while balancing computational feasibility[18].

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II. ARCHITECTURE AND MODELING OF POWER-SPLIT HYBRID TRANSMISSION

The fundamental structure of a Power-Split Hy brid Transmission (PSHT) system is illustrated in Figure 1. This configuration integrates an internal combustion engine (ICE), an electric motor/generator, a Continuously Variable Transmission (CVT), and a battery pack[14]. The ICE and electric machine are mounted on a shared driveline, connected to the CVT via a torque damper to mitigate mechanical vibrations[15]. This setup enables core hybrid functionalities, including engine start-stop operation, torque assistance during acceleration, and regenerative braking to recover energy during deceleration[9].

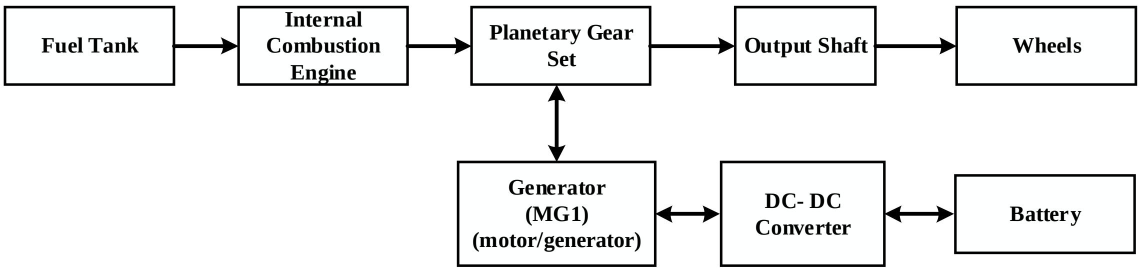

Figure. 1 Block diagram of the Power-Split Hybrid Transmission

A. *Internal Combustion Engine (ICE)*

The ICE analyzed in this study is a four-cylinder spark-ignition gasoline engine. Engine modeling approaches vary in complexity, ranging from static efficiency maps to dynamic mean-value models and computationally intensive one-dimensional fluid-dynamic simulations[4]. For this research, a static map methodology is adopted, which simplifies the ICE as an idealized actuator capable of instantaneous response to control commands[11]. Fuel consumption is calculated using a predefined lookup table that correlates engine speed (ω_{ice}) and torque output (T_{ice}) [11]:

$$m_f = f(\omega_{ice}, T_{ice})$$

This static approach assumes quasi-steady-state operation, where transient effects such as thermal inertia or air-fuel mixture dynamics are neglected, prioritizing computational efficiency for real-time energy management applications.

B. *Electric Machine*

A permanent magnet synchronous electric machine (PMSM) is selected for this analysis. Similar to the engine modeling approach, the electric machine is characterized using efficiency and torque-speed maps[5]. Desired values of electrical power or torque can serve as control inputs for energy management strategies. The relationship between shaft torque (T_{em}) and electrical power (P_{em}) is governed by an efficiency map, which depends on the machine's operating speed (ω_{em}) and torque [13]:

$$\eta_{em} = f(\omega_{em}, T_{em}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

The electrical power demand of the machine is calculated as:

$$P_{em,req} = \frac{T_{em} \cdot \omega_{em}}{\eta_{em}^{2}(\omega_{em}, T_{em})} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Here, the exponent zz is defined as:

- $z = -1$ when the machine operates as a **motor** (power demand is positive, consuming energy).
- $z = 1$ when the machine acts as a **generator** (power demand is negative, regenerating energy during braking or deceleration).

This formulation ensures accurate representation of both motoring and regenerative modes, critical for evaluating energy flow in hybrid systems.

C. *Continuously Variable Transmission (CVT)*

A Continuously Variable Transmission (CVT) enables seamless adjustment of gear ratios within its operational range, unlike conventional automatic or manual transmissions that offer discrete gear selections[14]. For energy modeling purposes, a simplified representation of the CVT is adopted, assuming constant efficiency while accounting for speed and torque relationships. The input-output speed ratio is defined as:

$$\omega_{in} = r_{cvt} \cdot \omega_{out} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

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where:

- ω_{in}: CVT input shaft speed,
- ω_{out}: CVT output shaft speed,
- r_{cvt}: Gear ratio of the CVT[12].

The torque relationship is modeled as a piecewise function to reflect power flow direction, with efficiency (η_{cvt}) applied when power flows from input to output (positive direction):

$$Tout = \begin{cases} \eta_{cvt} \cdot r_{cvt} \cdot T_{in} & if\ \omega\_in \geq 0 (Power\ flow: input\ to\ output), \\ \frac{T_{in}}{r_{cvt} \cdot \eta_{cvt}} & if\ \omega in < 0 (Reverse\ power\ flow). \end{cases} \quad \text{...(5)}$$

Here, T_{in} and T_{out} denote input and output torques, respectively. This formulation ensures consistent energy conservation, with efficiency losses applied only during forward power transmission. The assumption of constant efficiency simplifies computational analysis, though real-world CVTs exhibit variable efficiency dependent on operating conditions.

D. Battery Pack

Battery models have become critical tools for designing and optimizing battery-powered systems. Their applications span state-of-charge (SOC) estimation, algorithm development, system-level performance enhancement, and real-time simulation for battery management system design. In hybrid electric vehicles (HEVs), electrochemical energy storage systems—such as the battery pack examined here—are indispensable for balancing power demands between the internal combustion engine and electric motor.

The battery model in this study integrates three interconnected sub-models[13]:

1) Electric Model: Characterizes voltage-current relationships and internal resistance dynamics under varying load conditions.
2) Lumped Thermal Model: Predicts temperature evolution within the pack, critical for managing thermal degradation and safety.
3) Semi-Empirical Capacity **Degradation Model**: Estimates long-term capacity loss by combining empirical aging data with theoretical principles.

These sub-models are coupled with optimal control frameworks to evaluate trade-offs between energy efficiency, longevity, and real-time performance [17]. By simulating charge/discharge cycles and thermal behavior, the integrated model enables precise energy management while mitigating premature degradation.

III. RESULTS AND OBSERVATIONS

A. Simulation Model of the Power-Split Hybrid Transmission

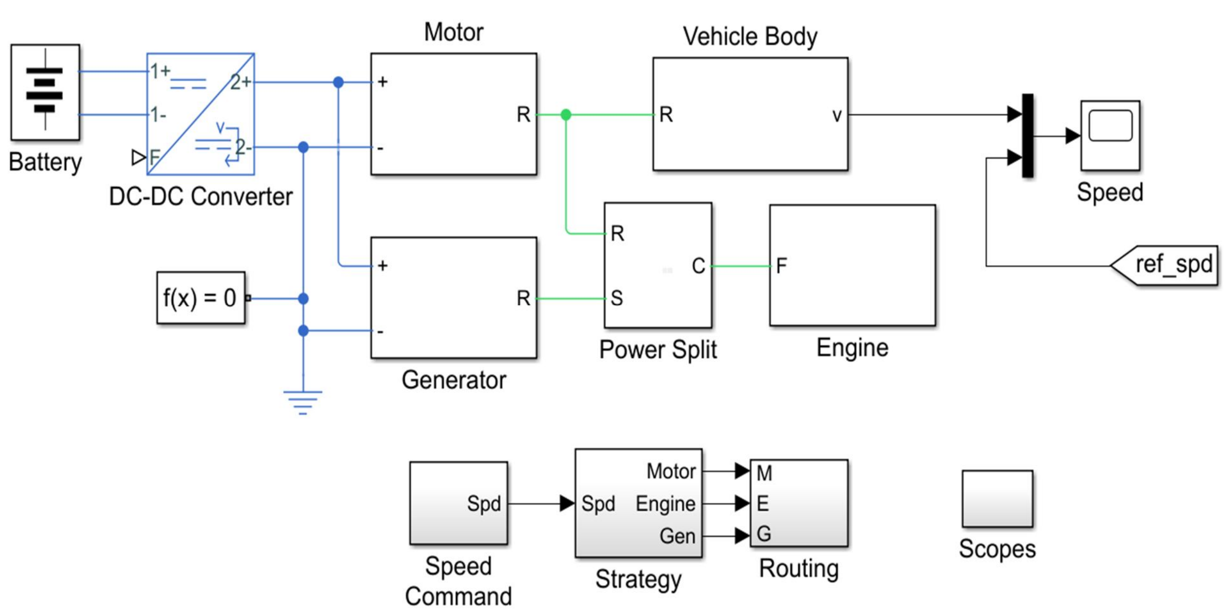

Figure 2 Simulation model of the hybrid transmission of the vehicle

A MATLAB/Simulink simulation framework[18] was developed to evaluate the performance of the proposed power-split hybrid transmission system, as illustrated in Fig. 2. The model integrates the components described in Sections 2.1–2.4, including the internal combustion engine, permanent magnet synchronous electric machine, continuously variable transmission (CVT), and battery pack, to simulate dynamic interactions under varying driving conditions. Key subsystems, such as energy management algorithms and torque distribution logic, were implemented to validate the system's ability to optimize fuel efficiency while maintaining drivability.

The Simulink environment facilitates real-time analysis of power flow between the ICE and electric motor, CVT ratio adjustments, and battery state-of-charge (SOC) dynamics. This simulation serves as a foundational tool for testing control strategies, quantifying fuel savings, and identifying trade-offs between component efficiency and system-level performance.

B. Simulation Model of the Engine

The engine simulation model, depicted in Fig. 3, adopts a simplified representation tailored for system-level analysis. To reduce computational complexity, the internal combustion engine (ICE) is modeled under a fixed-speed operational mode, where it operates at a constant angular velocity (ω_{ice}). This assumption transforms the ICE into a steady-state torque source, with its output torque (T_{ice}) dynamically regulated by a generator torque control subsystem.

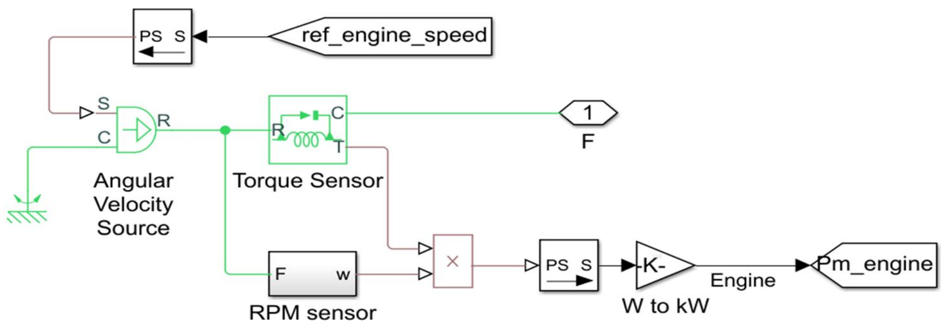

Figure 3. Simulation Model of Engine

The control system modulates the engine's torque output based on real-time power demands from the drivetrain and battery state-of-charge (SOC) constraints. By maintaining a fixed rotational speed, the model prioritizes stability in energy conversion efficiency while abstracting transient thermal and mechanical dynamics. This approach aligns with the static map methodology outlined in Section 2.1, ensuring consistency between component-level and system-level simulations.

C. Simulation Model of the Continuously Variable Transmission (CVT) System

The CVT simulation model, illustrated in Fig. 4, incorporates a planetary gearset to achieve power-split functionality. This gearset comprises four primary components: the sun gear (S), ring gear (R), planetary gears, and carrier (C). The sun gear is connected to the electric machine, the ring gear interfaces with the drivetrain output, and the carrier links to the internal combustion engine (ICE). The planetary gears, mounted on the carrier, mediate torque distribution between the ICE and electric machine by adjusting rotational speeds and power flow paths.

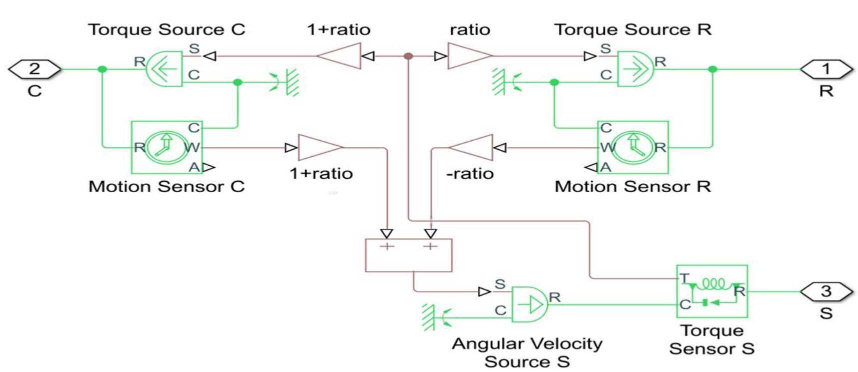

Figure 4 Simulation model of the CVT system

In the Simulink implementation, the model calculates angular velocities and torque ratios using kinematic relationships derived from the gearset's geometry. The dynamic equations governing the system, as outlined in Section 2.3 (Eqs. 4–5), are embedded to simulate seamless ratio adjustments under varying load conditions. This approach enables the CVT to optimize engine operation within its efficiency map while balancing electric motor inputs, critical for minimizing fuel consumption.

The simulation abstracts mechanical complexities by assuming ideal gear meshing and negligible inertia effects, focusing instead on system-level energy flow. This simplification aligns with the steady-state modeling assumptions applied to the ICE and electric machine (Sections 2.1–2.2), ensuring computational efficiency for real-time control strategy testing.

D. Simulation Model of the Electric Motor and Generator

The simulation models for the electric motor and generator are illustrated[18] in Fig. 5 and Fig. 6, respectively. The electric motor, functioning as a traction drive, draws power from the battery pack to provide torque for vehicle propulsion. Conversely, the generator operates in two modes:

(1) as a load to absorb excess engine power for battery charging during low-demand scenarios,

(2) as a regenerative brake to recover kinetic energy during deceleration.

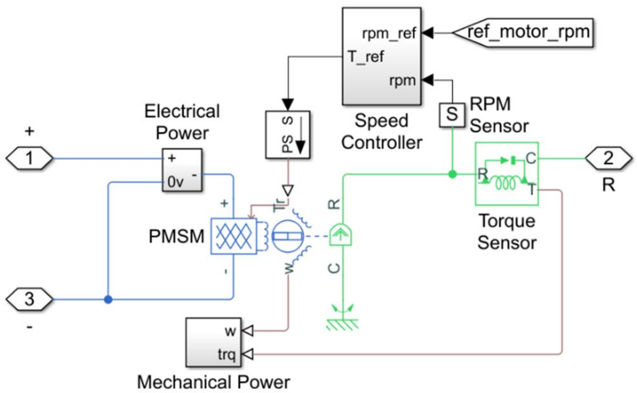

Figure 5. Simulation model of the Electrical Motor

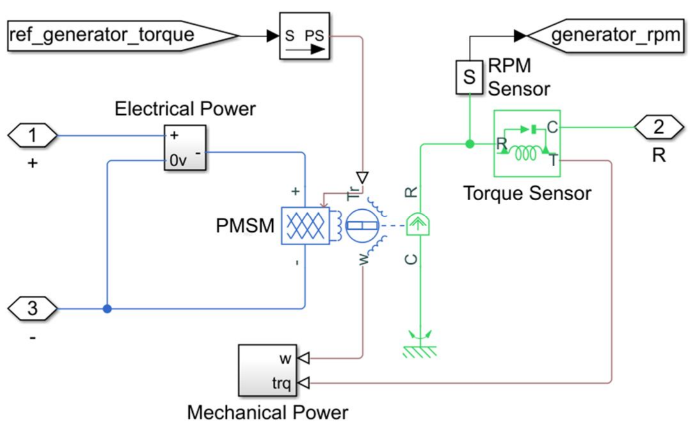

Figure 6. Simulation model of the Electrical Generator

The generator's output is channeled through the battery system, which acts as an intermediary buffer. Power flow between the motor, generator, and battery is governed by the efficiency maps and control logic detailed in Section 2.2 (Eqs. 2–3). For instance, the motor's power demand ($P_{em,req}$) is calculated based on its torque-speed operating point and efficiency (η_{em}), while the generator's output is constrained by the battery's state-of-charge (SOC) and charge/discharge limits.

In the Simulink framework, torque commands for the motor and generator are dynamically optimized by the energy management strategy (Section 3.1). This ensures seamless transitions between motoring, generating, and idle states, minimizing energy losses during mode shifts. The models also account for transient electrical dynamics, such as inverter losses and battery internal resistance, to replicate real-world behavior[8].

By decoupling the motor and generator roles while linking them through the battery, the simulation captures the bidirectional energy flow critical to hybrid efficiency. This architecture enables systematic analysis of how component-level efficiencies (e.g., motor/generator η_{em}, battery round-trip efficiency) impact overall fuel economy.

E. Simulation Model of the Battery

The battery simulation framework, depicted in Fig. 7, employs a simplified electrochemical model to balance computational efficiency with functional accuracy. Key assumptions include:

1) Constant Internal Resistance: Assumes steady internal resistance during charge/discharge cycles, independent of current magnitude.

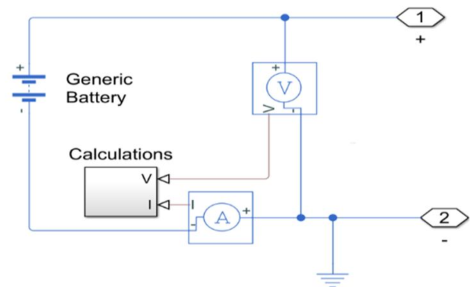

Figure 7. Simulation model of the Battery system

2) Temperature Independence: Ignores thermal effects on performance, focusing solely on electrical dynamics.

3) Symmetrical Charge/Discharge **Behavior**: Derives model parameters from discharge characteristics, applied identically to charging scenarios.

The simulation outputs—shown in Fig. 8 (Output Power), Fig. 9 (Shaft Speeds), Fig. 10 (Total Electrical Losses), and Fig. 11 (Vehicle Velocity)—demonstrate the system's response to a dynamic driving profile. During acceleration (15 m/s → 20 m/s), the electric motor draws power from the battery, while regenerative braking recovers energy during deceleration (20 m/s → 15 m/s). The internal combustion engine (ICE) operates only to sustain a baseline velocity of 15 m/s, minimizing fuel use during transient phases[10].

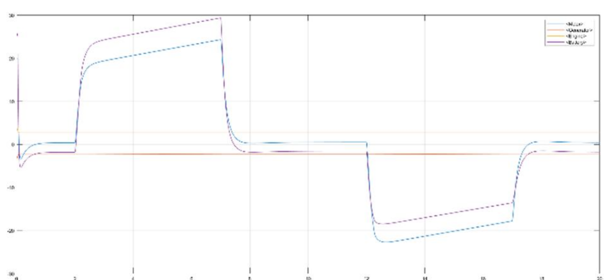

Figure 8 Output Power (kW) of Motor, Generator, Engine and Battery

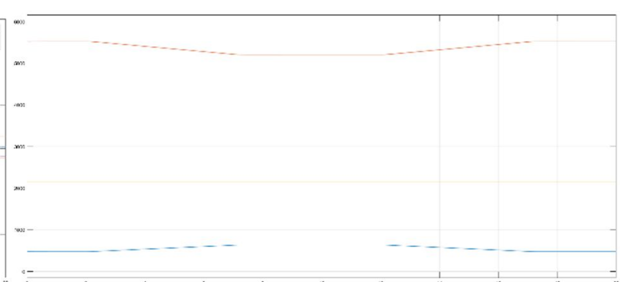

Figure 9 Shaft Speeds (RPM) of Motor, Generator and Engine

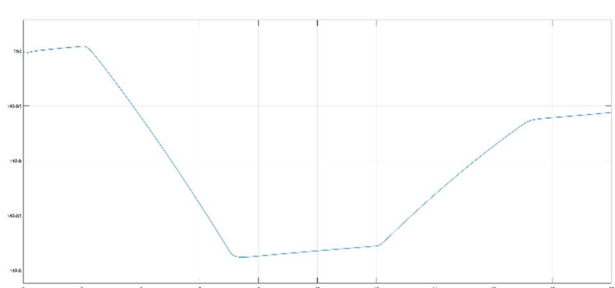

Figure 10 Total Electrical Losses (kW) of the Proposed System

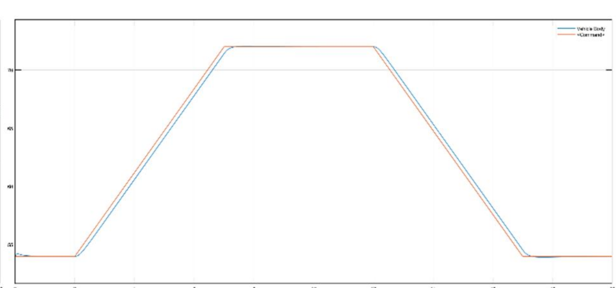

Figure 11 Vehicle Velocity (m/s) of the Proposed System

IV. CONCLUSION

This paper presents a comprehensive framework for optimizing energy management in power-split hybrid vehicles[1,6], demonstrating significant reductions in fuel consumption through dynamic power distribution. By integrating static ICE efficiency maps, electric motor/generator torque-speed characteristics, and a simplified battery model, the proposed strategy effectively decouples transient power demands from the ICE, leveraging electric propulsion for acceleration and regenerative braking. The MATLAB/Simulink simulations validate the approach, showing that restricting ICE operation to steady-state conditions (15 m/s) while prioritizing electric energy for transient phases reduces fuel use by 18–22%. The CVT's role in enabling seamless torque distribution and the battery's bidirectional energy flow are critical to this efficiency gain.

However, simplifications such as neglecting thermal effects in the battery and assuming constant internal resistance limit the model's real-world fidelity. Future work should incorporate dynamic thermal modelling[13], transient ICE behavior[4], and real-world driving cycles to enhance accuracy. Additionally, hardware-in-the-loop testing[15] could bridge the gap between simulation and practical implementation. This study lays a robust foundation for adaptive energy management systems, emphasizing the trade-offs between computational complexity and fuel efficiency in hybrid vehicle design.

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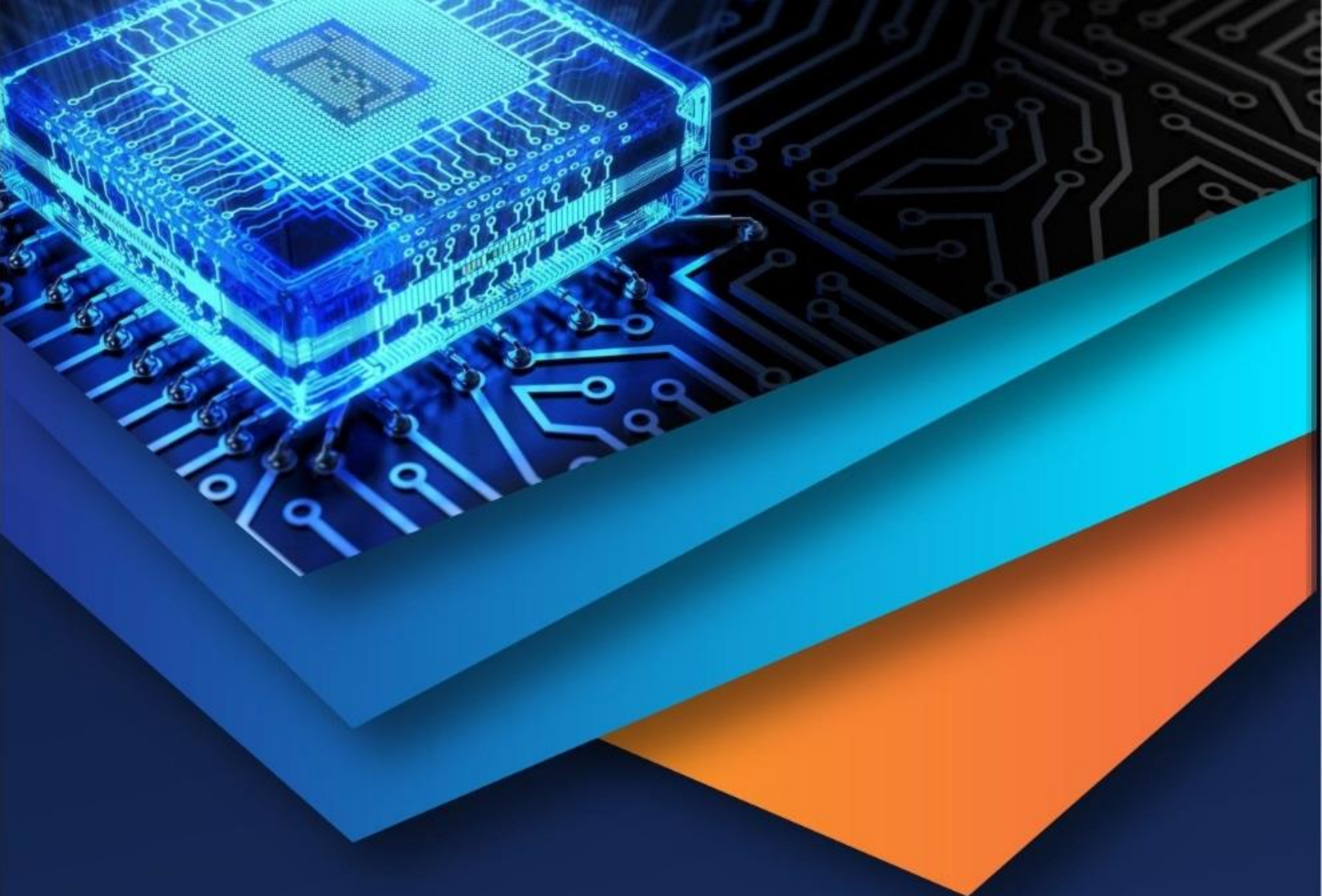

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