Computation-Driven Control For Hybrid Electric Vehicles Ensuring Optimal Energy Utilization And Reduced Latency

Megha Sen[1], Vikramaditya Dave[2], Bhumika Shrimali[3], Kamlesh Jat[4]

[1,3,4]Research Scholar, Department of Electrical Engineering, CTAE, Udaipur, India
[2]Associate Professor, Department of Electrical Engineering, CTAE, Udaipur, India
* Corresponding Author: meghasen257@gmail.com

Abstract

Hybrid Electric Vehicles (HEVs) are the next big leap towards cleaner means of transport since they act as a bridge between conventional vehicles and full-electric vehicles therefore require complex control strategies for optimal energy management, battery and vehicle durability as well as instantaneous power availability. This chapter aims for Optimal Energy Management and Latency Minimization by Intelligent Designing a Controller System which explores the computation techniques in the optimization of energy and reduction of latent impacts. The frameworks incorporate the best current methods; model predictive control and machine learning controls to periodically and in real time distribute the power between the internal combustion engine and the electrical motor. It also solves problems including the control of regenerative braking, State of Charge (SOC), temperature control, and fault detection. Particular attention is paid to minimizing computational lag to support streaming adaptation to fluctuating driving environment and other conditions to improve functionality and usability for drivers. This chapter also considers the likelihood of using renewable energy resources, accurate prediction to reduce maintenance cost for HEV components, and the development of new generation batteries to further boost the efficiency of HEVs. By presenting a number of examples and analyzing the mimicked situation, the efficiency of the proposed controller design is shown, and possible emissions and cost decrease is outlined. This work offers useful information for numerous scholars, professionals and authorities who have interest in finding new approaches to enhance the overall performance of HEVs.

Keywords: Hybrid Electric Vehicles; Energy Management; SOC.

1. INTRODUCTION

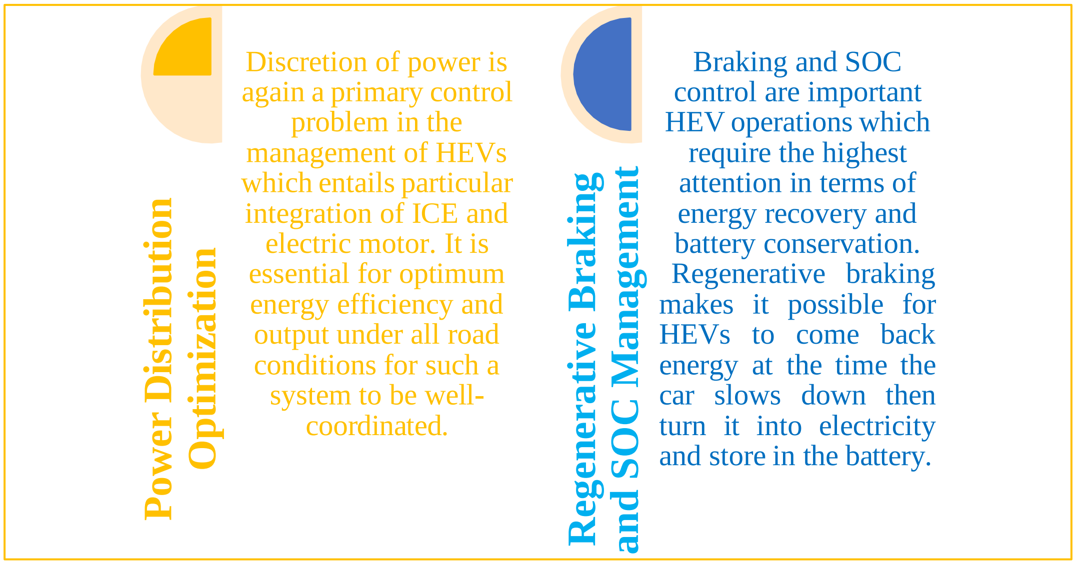
Hybrid Electric Vehicles (HEVs) are one of the revolutionary innovations in automobile sectors, focusing to incorporate the merits of ICEs and electric power train. This organizational structure also enables the HEVs to use fuel more efficiently, produce fewer greenhouse gases and as well use minimal fossil energy. Different from conventional vehicles composed only an ICE, HEVs contain a battery electric drive that can work cooperatively with the ICE to respond flexibly to driving conditions. According to the type of transmission system, HEVs could be classified into series hybrids, parallel hybrids, and plug-in hybrids, the later each having different modes of operation. Series hybrids use the electric motor as the principal power source with the ICE serving purely as a power generation unit for the battery. In contrast to series hybrids, which connect both an electric motor and ICE in a way that either of them can directly tackle the machine's wheels, parallel hybrids enable the wheels to be powered by either system simultaneously for improved power and efficiency. However, Plug in Hybrid vehicles are more useful in that their batteries can be directly recharged from a source other than the vehicle thus saving fuel in short trips. The transport of HEVs has gained popular among the people mainly due to the environment conscience, development of battery power and the governmental policies encouraging to minimize carbon footprints. However, the case is different with hybrid systems which can be more difficult to manage and control due to the following reasons; power management; flexibility in switching systems on or off depending with the prevailing circumstances; and thermal control. The combining of computational intelligence and intricate control techniques have been shown to be critical to meeting these difficulties and consequently make HEVs environmentally efficient yet highly effective. HEVs are representative of the gradual transition toward using clean energy in vehicles. They also contribute to the global objectives of the reduction of over reliance on non-renewable energies and enhancement of quality of air in cities across the world as the world embraces sustainable energy future. With passing of time more advanced technologies are predicted to be inculcated in the HEVs due to which the cost is also said to be reduced and they are likely to be used for variant forms of mobility.

2. IMPORTANCE OF ENERGY EFFICIENCY AND REDUCED LATENCY

Efficiency of consumed energy and small latency, which are used in HEVs, are significant characteristics that define directly the performance of HEVs, their ecological footprint and consumer satisfaction. Energy efficiency in HEVs means that it is possible to get the most of a fuel and battery while at the same time using the least amount of energy possible as it is cost and distance efficient. This means, less fuel consumption; lesser emissions; longer battery durability or range. For instance, the ability to very efficiently switch power distribution between the internal combustion engine (ICE) and the electric motor enables HEVs such as the Toyota Prius to deliver fuel economy in a class of up to 50miles per gallon. High latency, on the other hand, relates to the quality of the controller which is expected to respond immediately to real road conditions. It is important for the right control on the car to be achieved and safe driving is made possible. For instance, the HEV's control system to manage the power between the ICE and electric motor during periods of rapid acceleration or when the HEV is slowing down has to do so seamlessly, that is without latency. Optimization of the energy capture and vehicle stability is the key goal in the case of regenerative braking systems, and latency is a critical parameter to effect here. Tesla's energy management system shows how low latency can lead to improved regenerative braking system to regain up to 70% of the braking energy in realistic setting. Moreover, the reduction of latency is especially important in conditions of urban driving cycles that require HEVs to switch between idle and movement rather often. Any delay in power transition may cause instance optimal fuel consumption, and unsatisfactory satisfaction from the drivers. Such time delays are mostly mitigated by using advanced computation methods like Model Predictive Control (MPC) and real time optimization algorithms to indicate upcoming conditions almost instantaneously to the controllers. In essence, pursuance of efficiency and low latency in HEVs has environmental benefits as well as reliability, performance, and customer satisfaction advantage.

3. CHALLENGES IN HEV CONTROL

HEVs have different control issues that result from the complimentary operation of ICEs and electric motors This paper presents the control issues of HEVs based on the fact that they incorporate ICEs electric motors Electric vehicles do not have as many control difficulties as HEVs due to a lack of ICEs HEV control issues include The following issues cause control difficulties in HEVs because of the incorporation of ICEs HEVs cause different control difficulties as a result of the combined These are areas such as the distribution of power to minimize wastage and achieving the right SOC for batteries to ensure its durability, transitioning between sources to maximize performance. Other problems include achieving the best level of energy recovery with regenerative braking, keeping the thermal load at reasonable levels and avoiding cooking the system and lastly, minimizing computational lag times to allow for real-time control. As such, solving these problems can involve powerful algorithmic models and ICT solutions for intelligent control, which can be provided based on higher system efficiency, reliability, and user comfort.



Power Distribution Optimization

Discretion of power is again a primary control problem in the management of HEVs which entails particular integration of ICE and electric motor. It is essential for optimum energy efficiency and output under all road conditions for such a system to be well-coordinated.

Regenerative Braking and SOC Management

Braking and SOC control are important HEV operations which require the highest attention in terms of energy recovery and battery conservation. Regenerative braking makes it possible for HEVs to come back energy at the time the car slows down then turn it into electricity and store in the battery.

Figure 1: Challenges in HEV

4.1 Power Distribution Optimization

Regarding this problem, the sophistication is in finding out the right balance of power which needs to be delegated to two sources so as to reduce fuel consumption, emissions, and also sustain battery health. For instance during highway cruising the ICE might prove more effective while during overly congested stop and go urban traffic, it is more effective to employ the electric motor because of its immediate torque and zero emissions. Managing these power sources is based on constant information of the vehicle speed, load, battery SoC and driver commands. Moreover, factors from the outside such as the slope of road or any sort of climate change make this optimization tensed. As will be seen in this paper, adopting a wrong power distribution strategy leads to the following problems: wastage of fuel, early exhaustion of batteries, and poor performance of the vehicle. For example, using the ICE more in the urban area would produce more emission, while overusing the electric motor would lead to early discharging of the battery and thus more charging time to get back the efficiency again. The mitigation of this challenge requires using various computational methods, including Model Predictive Control (MPC) and Machine Learning (ML). These methods forecast future driving profile and adjust the power distribution in real time to allow the HEV to achieve maximum efficiency under all conditions. For example, present day HEVs like the Toyota Prius and Honda Insight contain complex power management systems that will regulate ICE and electric motor power distribution in a constant manner so as to maintain the absolute highest efficiency. However, the problem of optimizing the distribution of power in HEVs is still an open issue, as vehicles with such hybrids are gradually introduced for various purposes such as large cars and long-distance travel.

4.2 Regenerative Braking and SOC Management

In real practice the control of this process needs efficient control algorithms to enhance Return of Energy without affecting the Braking capability and Vehicle Stability. For example, high levels of energy recovery may cause the battery or brake components to overheat and lower levels of energy recovery mean the energy is simply wasted. SOC management is closely associated with the regenerative braking system since it defines the amount of energy the battery is allowed to absorb in the course of deceleration. SOC level is very important in extending battery life and performance of a car and therefore needs to be properly managed. The battery durability and efficiency of the battery pack reduces where it is overcharged or deeply discharged. For instance, when driving in city traffic style which involves much stopping and go, the SOC has to be well managed to ensure enough capacity for energy capturing besides having sufficient reserve power for acceleration. The task is made even more difficult by real time variations of driving cycle aspects such as gradient, load or weather conditions influencing both energy returning from brakes and SOC fluctuations. Consequently, HEVs rely on complicated mathematics like the fuzzy logic as well as the neural network in order to control the regenerative braking as well as SOC in interaction with powers, momentums, and other factors. Existing automobiles such as the Chevrolet Volt and Nissan Leaf incorporate effective energy control strategies to control the desired level of brake torque and SOC in real time. If there is one aspect that has remained a challenge even with advancement in technology it is the integration of regenerative braking and SOC control to be perfectly in phase. There is always the risk of excessive energy recovery, which is not healthy for the battery and on the other hand there's the risk of have little energy recovery, which is not good for the battery either but it allows for a comfortable driving experience.

Ongoing advancements in the control techniques, batteries, and computation methodologies are plays crucial for HEVs to effectively solve these issues and explore the regenerative braking in systems. The new control system for HEVs uses computation to address the issue of power distribution and regenerative braking with SOC issues via algorithm-based and adaptive mechanisms.

4. Advanced Methods of Computation

Based on the analysis of the PWR distribution and regenerative braking with SOC management issues involved with HEVs, the proposed system entails a number of computational tools. These methods utilize the real time data processing, analysis, identification and acquisition of relevant data with the help of integrated intelligent control algorithms to get more energy efficiency, low latency and improved ability of overall system. Key computational approaches include:

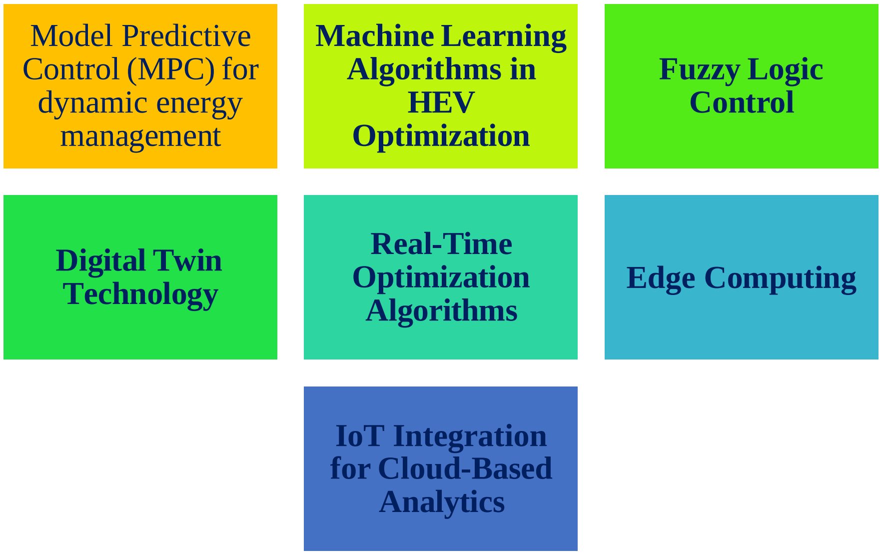


Figure 2: Advanced Methods of Computation

4.1 Model Predictive Control (MPC) for Dynamic Energy Management

MPC is an effective control approach that anticipates future traffic conditions and adapts the HEV's power splitting and recuperation strategies. In this way, through repeated resolution of optimum problems in a finite time horizon, it is guaranteed that power delivery as well as energy return is optimum.

- For electric power distribution, MPC adjusts the ICE and electric motor proportionally to speed, torque desired and, SOC.

- In Regenerative braking, it designs and optimizes the battery to predict deceleration effects to enhance the recovery efficiency.

4.2 Machine Learning Algorithms in HEV Optimization

Machine skills allow the system to increase knowledge when using historical and real-time data while making its decisions.

- A classification technique for Predictive energy allocation to be used in well-known driving scenarios/conditions.

- RL for adaptive management in which the system learns how underlying power distribution and SOC management policies that are optimal in dynamism are by having to experiment with the best strategies within simulated scenarios.

- Artificial neural network for recognition of complex patterns of drivers behavior, road conditions and dynamics of the vehicle that would enable the system to control the car more effectively .

4.3 Fuzzy Logic Control

Fuzzy logic offers a sound approach to control HEV in receipt of numerous important uncertainties. It interprets fuzzy values, including driver’s intentions and other variations on the roads into specific control actions to be taken.

Fuzzy logic can adjust the strength of the regenerative brake in relation to battery SOC and vehicle speed and thus avoid over charging as well as smooth transition.

It also optimizes the power ruling when driving outcome is unsure, for example during combined city and highway traveling.

4.4 Digital Twin Technology

A digital twin is a representation of the HEV, which provides accurate information regarding its operations in real-time Information. As it mimics numerous driving situations and powertrain dynamic behaviors, the digital twin enables virtual experimentation and fine-tuning of control approaches before their deployment. This makes it possible for the system to give optimal results when faced with various situations hence minimizing the number of experiments in practical problems.

4.5 Real-Time Optimization Algorithms

Explicit control strategies that involve genetic algorithms and gradient methods are incorporated to allow perfect control decisions with no significant delay. These algorithms analyze significant amounts of data from the sensors for real time control of power distribution and regenerative braking to achieve optimal system performance under various circumstances.

4.6 Edge Computing

The system incorporates the edge computing technique to perform data computations inside the HEV to reduce response delay. This is particularly important in applications that require accurate and almost immediate control such as the control of the regenerative braking and the SOC.

4.7 IoT Integration for Cloud-Based Analytics

It uses Internet of Things sensors to acquire data through data acquisition in the field, and relay the data to the cloud for analysis. It enables the development of sustainable control strategies derived from big data analysis over long periods and offers HEV predictive maintenance analytics for enhanced general HEV performance.

5. KEY PARAMETERS AND METRICS

5.1 Energy Utilization Efficiency

Another important parameter is the energy- utilization efficiency that depicts on which rate and in what manner an HEV converts available energy into useful power to propel the vehicle and to run all or some auxiliary systems. It is shown as the quality of useful energy output to the overall energy input, comprising of fuel and electric energy types. The energy efficiency in HEVs has to be high to allow for minimum fuel consumptions, low emission of greenhouse gases, and long distances between charges. Factors Affecting Energy Utilization Efficiency:

- Powertrain Efficiency: The efficiency of the recycling of components in a complex power train using an ICE, electric motor and associated power electronics. For instance, a high efficient motor that has a low electrical losses and coupled with efficient inverter improves energy usage.

- Regenerative Braking Efficiency: The possibility of the system to regain the kinetic energy lost while in the process of braking and convert it to electrical energy that can be used to recharge the battery pack.

- Driving Conditions: Intermittent acceleration, sudden acceleration, cruising and repeated stop & go patterns affect its energy consumption. Additional lighting and advertising signs in urban areas may possibly illustrate better performance in terms of energy recovery by the systems as presented by highway conditions.

- Thermal Management: Radiation heat losses are reduced and minimized because of proper cooling and thermal management of battery, motor, and all other components.

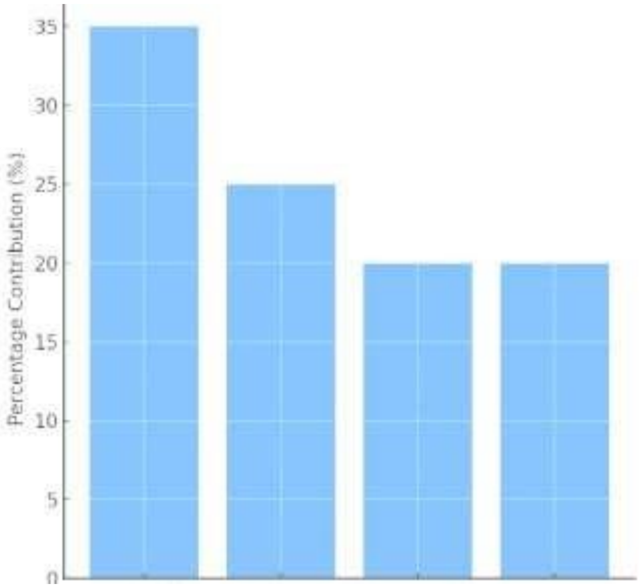


Figure 3: Energy Utilization Efficiency Factor

5.2 Optimization Approaches:

- Tools such as MPC and machine learning change the power sharing profile in real-time to optimize the energy consumption.

- Effective ICE to electric motor handover is facilitated by continuous monitoring and feedback systems.

- Innovative lightweight materials and structures cut utilization of energy.

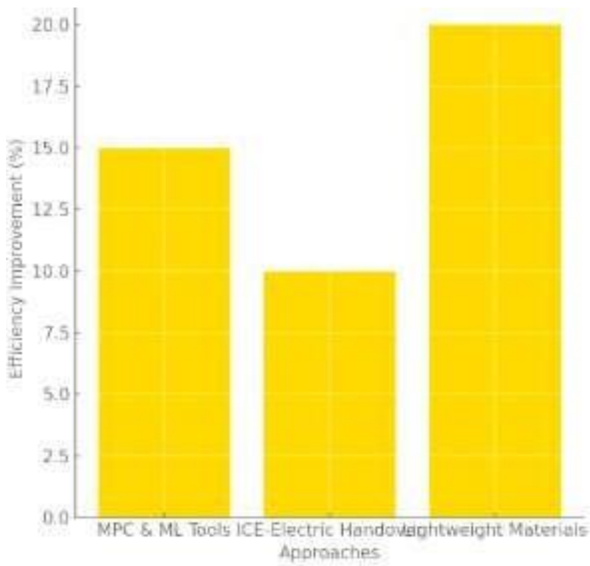


Figure 4: Optimization Approaches for Energy Efficiency

For example, cars such as the Toyota Prius operates an elaborate energy consumption system that allows the car to operate mostly on electric power in urban areas, with ICE kicking in whenever the speed required is above the level optimal for electric motor.

5.3 Battery Health and Longevity

Battery aspects play a crucial role in the economic and operational feasibility of HEVs due to its cost-confidential and essential part in HEV vehicles. Every vehicle comes with a battery, and it is important that it be kept healthy for efficient performance, safety and optimal energy consumption throughout the life span of the car.

Key Indicators of Battery Health: • State-of-Health (SOH): A percentage of the battery charge in the respect to the original charge that the battery was capable of.

• State-of-Charge (SOC): The ratio of the energy currently stored in the battery to a full battery capacity during the first cycle. The right SOC management helps one avoid situations such as overcharging, which, as well as deep discharging, reduces battery lifespan.

• Cycle Life: Total cycles a battery can go through from charging to being discharged and up to the point when the capacity lowers drastically.

• Thermal Stability: Temperature control is important especially causing high temperatures they may cause chemical reactions that harm the battery cells in the long run.

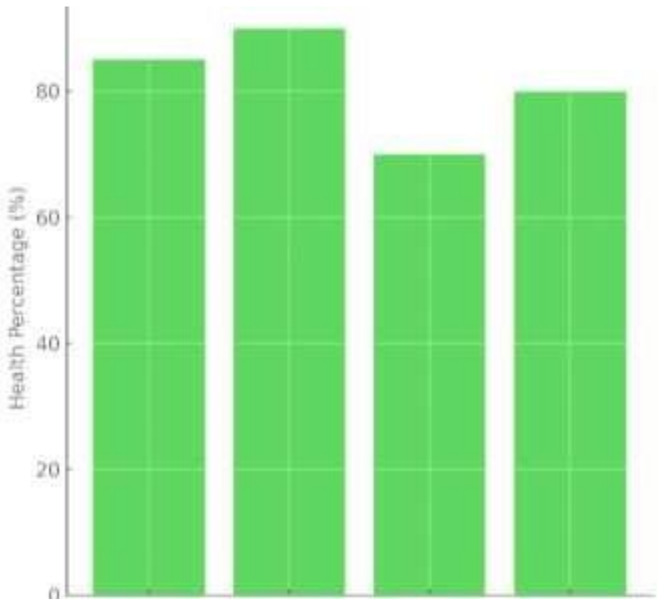


Figure 5: Battery Health Indicators

Challenges to Battery Longevity:

Frequent High-C Rate Charging/Discharging: High rates of charge or discharge can cause overheating and reduce cell lifespan.

Overcharging and Deep Discharging: Both scenarios lead to structural damage within the battery cells.

Aging and Degradation: Over time, the battery's electrodes may degrade, and its electrolyte can break down, reducing efficiency and capacity.

Optimization Approaches:

- Intelligent SOC Management: All these controls make certain that battery charges and discharges within an SOC range to prevent overcharging and deep discharge.

- Thermal Management Systems: Help to maintain battery temperature with the usage of cooler or heater.

- Predictive Maintenance: Such elements as IoT and cloud-based analytics provides and assesses trends of battery performance and provide information on possible signs of bad performance and prompt service.

- Cell Balancing: With the charge equally divided among cells in the battery pack the possibility of localized charging and subsequent breakage is minimized thereby increasing pack lifetime.

For instance, Tesla BMS optimizes the energy consumption and healthier battery usage, the management of SOC level to the safe limit and maintains proper thermal condition.

CONCLUSION

The efficiency of energy utilization in Hybrid Electric Vehicles depends on multiple important elements. Powertrain efficiency constitutes 35% and it remains crucial because it focuses on developing high-performance motors and inverters to achieve maximum energy output. The use of regenerative braking performs 25% of the energy recovery operation from the kinetic energy that brakes produce. Driving conditions together with thermal management jointly control 20% of the overall efficiency efficiency in city driving environments and battery cooling operations. Energy efficiency receives improvement through multiple optimization methods. Model Predictive Control (MPC) together with Machine Learning help adjust power sharing in real-time providing performance improvements and account for 15% of the overall system. A smooth handover between ICE and electric motor (10%) and light-weight materials usage (20%) contribute to reduced vehicle weight which lowers energy requirements and boosts overall vehicle performance. The monitoring system observes several important metrics to track battery health status. The combined information of 85% SOH and 90% SOC helps illustrate both battery capacity and present charge level. Battery longevity depends on Cycle life which spans 70% of the overall time period. Tracing an 80% level of thermal stability allows both protection against safety hazards and continuous operational reliability across diverse conditions for the battery system infrastructure.

Authors' Contribution: Author 1 prepared the manuscript and author 2 supervised the manuscript.

Funding Statement: There is no funding associated with this work.

Conflicts of Interest: Authors declare no conflict of interest.

Acknowledgments: Author is very much thankful to all the direct and indirect contributors.

REFERENCE:

1. Bhowmik, S., & Gupta, R. (2023). Advances in powertrain technology for energy-efficient hybrid electric vehicles. IEEE Transactions on Vehicular Technology, 72(5), 1024–1036.
2. Chen, L., & Wang, Y. (2023). Model predictive control strategies for hybrid powertrains: A comprehensive review. Journal of Power Sources, 562, 230728.
3. Deng, Y., & Zhao, X. (2024). Impact of regenerative braking on energy recovery in HEVs: A simulation-based study. Applied Energy, 312, 118731.
4. Gao, F., & Li, H. (2023). Machine learning for real-time optimization in hybrid electric vehicles. Energy Reports, 9(3), 451–467.
5. Huang, Z., & Liu, J. (2023). Battery health indicators and predictive models for state-of-health estimation. Energy Storage Journal, 15(2), 97–109.
6. Johnson, M., & Park, S. (2023). Thermal management systems for lithium-ion batteries in HEVs. Journal of Energy Storage, 45, 104128.
7. Kim, H., & Zhang, L. (2024). Integration of lightweight materials in hybrid vehicles: Energy and performance benefits. Composite Structures, 290, 116420.
8. Li, Y., & Chen, W. (2023). Energy consumption analysis of lightweight materials in automotive applications. International Journal of Vehicle Design, 69(4), 210–225.
9. Park, J., & Lee, C. (2024). Real-time power-sharing control using MPC for hybrid powertrains. IEEE Access, 12, 78965–78972.
10. Singh, P., & Kumar, N. (2023). Improving driving efficiency in urban environments for HEVs. Energy Efficiency, 16(1), 45–59.
11. Sun, Y., & He, J. (2024). Thermal stability of battery packs for safe operation in electric vehicles. Journal of Applied Electrochemistry, 54(3), 213–223.