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Efficient Power Management in Hybrid Electric Vehicles for Sustainable Transportation

Vijaya Gowri Govindaraju[1*], Gopalakrishnan Radhakrishnan[1*], Thamarai Selvi Govindaraju[2*]

[1]Department of Electrical and Electronics Engineering, K.S.Rangasamy College of Technology, K.S.R Kalvi Nagar, Tiruchengode, 637215 Tamil Nadu, India.
[2]Department of Electronics and Communication Engineering, Sri Sai Ram Institute of Technology, Sai Leo Nagar, West Tambaram, Chennai, 600 044 Tamil Nadu, India.

***Email**: vijayagowri@ksrct.ac.in, gopsengr@gmail.com, gvthamarai@gmail.com

Abstract

This study presents a simulation-based investigation into efficient power management strategies for hybrid electric vehicles (HEVs) featuring regenerative braking systems (RBS), with a focus on their contribution to the United Nations Sustainable Development Goals (SDGs). Regenerative braking allows for the recovery of kinetic energy during deceleration by converting mechanical energy into electrical energy, which is subsequently stored in the vehicle's battery system. This not only improves overall energy efficiency but also significantly reduces fuel consumption, carbon emissions, and brake system wear. To achieve maximum energy recovery without compromising safety, the RBS must function within minimal braking distances while ensuring smooth integration with conventional braking mechanisms. Through extensive simulations, this study evaluates a range of control strategies that coordinate regenerative and traditional power systems to enhance overall vehicle performance and energy efficiency. The results highlight the potential of intelligent energy management systems to improve the sustainability and economic viability of HEVs. These findings contribute directly to SDG7 (Affordable and Clean Energy) by promoting more efficient energy use and reducing reliance on fossil fuels. Additionally, the implementation of regenerative braking supports SDG13 (Climate Action) by lowering greenhouse gas emissions and advancing clean mobility solutions.

Keywords

Hybrid Electric Vehicle, Regenerative Braking, Fuel consumption, Carbon Emissions, Energy efficiency

Introduction

Rapid technological advancements have significantly improved transportation facilities; however, they have also contributed to increased environmental pollution, posing serious threats to

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ecosystems and human health. Conventional vehicles powered by internal combustion engines (ICEs) are major contributors to greenhouse gas emissions and environmental degradation. In response to these challenges, hybrid electric vehicles (HEVs) have emerged as a viable alternative, combining ICEs with electric propulsion systems to enhance energy efficiency and ensure uninterrupted power delivery (Amit Kumar *et al.*, 2021).

Effective energy management is a critical aspect of HEV design, with regenerative braking systems (RBS) playing a vital role in improving vehicle efficiency and extending cruising range (Qiwei Xu & Fukang Wang, 2019.Regenerative braking performance is limited at low vehicle speeds due to reduced back electromotive force (EMF), making energy recovery challenging under such conditions (Tako Nama & Praveen Tripathy, 2022).

Amid growing global energy demands and stringent environmental regulations, HEVs have gained prominence in the automotive industry owing to their high efficiency, reduced noise levels, and lower greenhouse gas emissions (Zhengwei Ma & Daxu Sun, 2020). Regenerative braking is recognized as one of the most effective energy-saving mechanisms in both HEVs and battery electric vehicles (EVs). In HEVs and EVs equipped with stepped automatic transmissions, downshifting strategies have been shown to enhance regenerative energy recovery by optimizing engine operating points (Binhao Liu & Liang Li, 2018). Furthermore, regenerative braking enables efficient reuse of the kinetic energy of decelerating electric vehicles by restoring it to the battery, thereby improving overall system efficiency (Mayank Gupta, 2020).

Fuel consumption in HEVs can be further minimized by controlling the ICE to operate within its high-efficiency region on the characteristic performance curve (Abhinav K. & Gowtham, 2022). The effectiveness of energy recovery is constrained by factors such as vehicle speed, regenerative braking current, and battery charging limits, which vary depending on battery chemistry and capacity (Warunchit Chueprasert & Danai Phaoharuhansa, 2020). Vehicle size and weight remain critical design considerations in HEVs. To address these challenges, researchers have proposed the use of dual mechanical port machines (DMPMs) to improve power density and reduce system mass (Hamed Bizhani & S.M. Muyeen, 2019). Additionally, the impact of operational profiles and emission reduction targets on hybrid vehicle design has been investigated for specific applications, incorporating force analysis and regenerative braking force calculations into vehicle network models (Xuezhou Wang & Udai Shipurkar, 2021). The performance and energy consumption of electric vehicles vary considerably under different driving conditions, with the electronic power controller playing a crucial role in ensuring stable and efficient operation (Anubhav Agrawal & Ranbir Singh, 2023).

Optimizing power management in hybrid electric vehicles with regenerative braking involves enhancing energy efficiency and extending battery life. This aims to minimize fuel consumption, reduce emissions and maximize the overall efficiency of the hybrid system ensuring a sustainable and eco-friendly driving experience. Hybrid electric vehicle contributes to the following sustainable development goals SDG-7(For affordable and clean energy) and SDG-13(Climatic Change).

Methodology

A hybrid electric vehicle (HEV) incorporating regenerative braking is designed to enhance energy efficiency and reduce fuel consumption. The HEV considered in this study is a two-wheeler configuration equipped with two electric machines: a hub motor mounted on the front wheel and a brushless DC (BLDC) motor mounted on the rear wheel, both of which participate in regenerative braking (RGB), as illustrated in Fig. 1. In HEVs, regenerative braking represents a critical energy recovery mechanism. The vehicle integrates an internal combustion (IC) engine, typically fueled by gasoline or diesel, with an electric motor, enabling coordinated operation of the two power sources for vehicle propulsion. During braking or when the accelerator is released, the electric motor transitions into generator mode. Unlike conventional braking systems that dissipate kinetic energy as heat through friction, the proposed system converts the kinetic energy of the wheels into electrical energy, which is stored in the onboard battery. The recovered energy can subsequently be utilized to assist the IC engine or to propel the vehicle during low-speed operation and acceleration. Consequently, regenerative braking significantly improves overall vehicle energy efficiency, reduces mechanical wear of conventional braking components such as brake pads, and enables effective recovery of energy that would otherwise be lost in traditional braking systems.

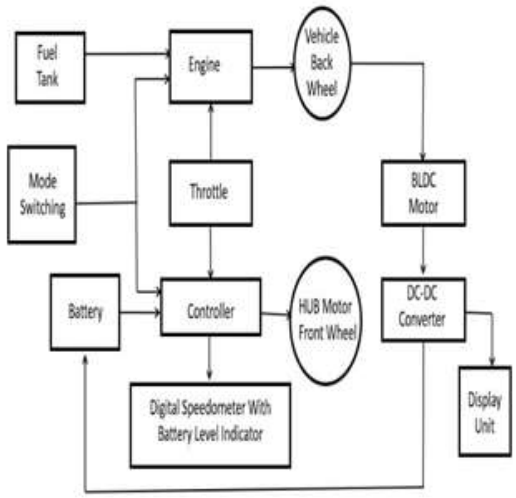

Figure 1. Block Diagram of Hybrid Electric Vehicle

The components and specifications of the proposed hybrid electric vehicle (HEV) are presented in Table 1. A hub motor is integrated into the front wheel to provide direct traction. During freewheeling conditions, the kinetic energy of the wheel is converted into electrical energy and stored in the battery, thereby improving the driving range and overall energy efficiency of the HEV. This energy recovery process constitutes regenerative braking.

The battery is interfaced with the hub motor to propel the vehicle, while the internal combustion (IC) engine drives the rear wheel. The throttle serves as the control interface between the IC engine and the motor controller. A digital speedometer and battery state-of-charge indicator are incorporated into the vehicle display. During freewheeling, the BLDC motor operates in generator mode and converts kinetic energy into electrical energy via a DC–DC converter, enhancing energy recuperation and enabling battery recharging. A dedicated display unit indicates the amount of recovered energy.

The system is modelled and simulated using MATLAB/Simulink, a block-diagram-based environment for multi-domain simulation and model-based design. Simulink supports system modelling, dynamic simulation, automatic system-level code generation, and continuous verification and validation of embedded systems. Its graphical modelling interface, configurable block libraries, and numerical solvers enable effective analysis of dynamic behaviour. Integration with MATLAB facilitates the incorporation of computational algorithms and post-processing of simulation results for further performance evaluation.

Table 1. Components and Specifications

S.No.	Components used	Type	Range
1	Electric Motor	16 inch HUB Motor	48V/1000W
2	Battery	Lead Acid	48V/7A
3	Intelligent Controller	Motor Controller	48V/1000W/30A
4	Converter	DC to DC Buck Converter	12V/5Amp
5	Three Speed Throttle with Forward Switch	Electronic Components	Works on 48V
6	Digital Display Unit	Speedometer and Battery Level Indicator	48V/60V
7	Electric Motor for Regenerative Braking	BLDC Motor	24V/500W
8	Converter	DC to DC Boost Converter	12V/5Amp
9	Digital Display Unit	Regenerative Voltage Level Indicator	Works on 48V

The simulink diagram of the proposed system and the controller diagram are shown in Figure 2. Each controller enables their performance parameter in enhancing the output. The engine block has throttle control to control the two modes, the hybrid electric vehicle battery mode and IC engine mode. Motor and generator output parameter like stator current, rotor speed and electromagnetic torque are measured and the output can be seen in the scope in MATLAB.

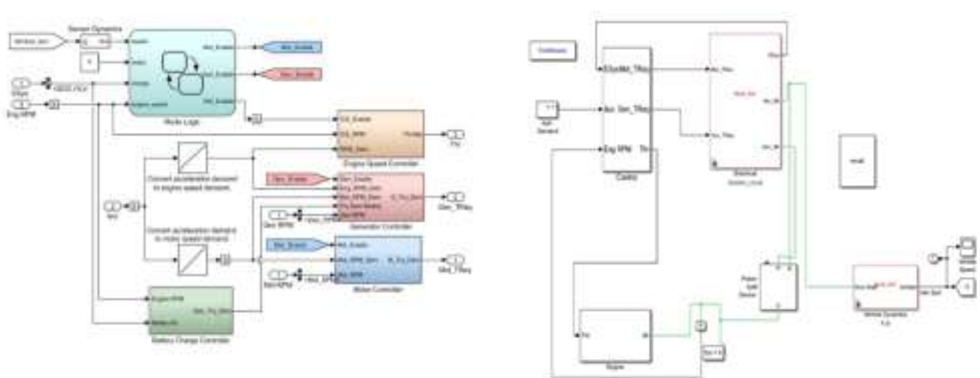

Figure 2. Simulation Block Diagram

Results and Discussion

The proposed design focuses on achieving seamless energy enhancement in hybrid electric vehicles through an integrated regenerative braking system. In this approach, the kinetic energy recovered during braking is converted into electrical energy by a generator and utilized to recharge the battery.

Figure 3 illustrates the battery output voltage. The voltage of the lead-acid battery is stepped up using a boost converter to meet the DC bus requirements. The battery constitutes a critical component of the hybrid electric vehicle, serving as the primary energy storage unit. It can be charged initially from the utility supply and subsequently recharged during vehicle operation through regenerative braking, wherein the generator converts kinetic energy into electrical energy.

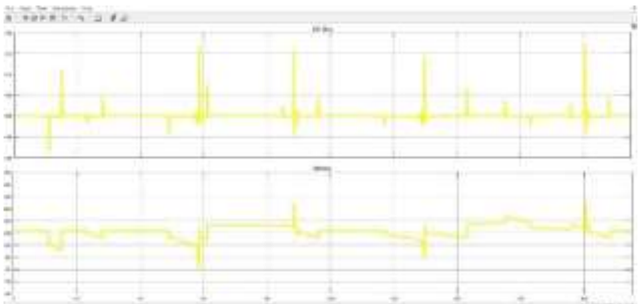

Figure 3. Output of Battery

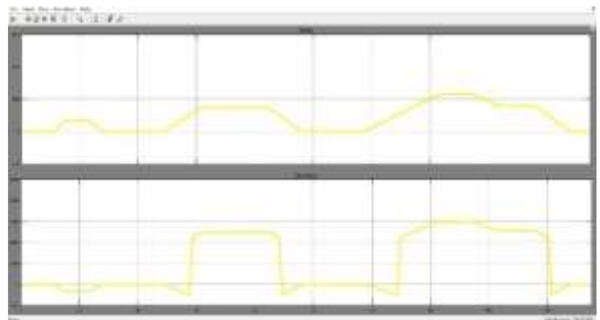

Figure 4. Output of Motor and Generator

Figure 4 presents the output characteristics of the BLDC motor. The BLDC motor operates bidirectionally, functioning as a generator when reverse voltage is applied. During this mode, the kinetic energy from the vehicle wheels is converted into electrical energy, which is subsequently utilized to recharge the battery.

Optimized power management in hybrid electric vehicles incorporating regenerative braking is essential for improving energy efficiency and prolonging battery lifespan. The primary objectives include reducing fuel consumption and emissions while maximizing the overall efficiency of the hybrid powertrain, thereby promoting sustainable and environmentally friendly transportation. The future scope of this system lies in the development of advanced control algorithms and improved energy storage technologies. Enhanced coordination among the internal combustion engine, electric motor, and regenerative braking system can further improve energy utilization and overall vehicle performance.

Conclusion

The suggested approach has the advantages of being straightforward and very efficient when compared to other comparable types of regenerative braking methods. When using ESS in conjunction with regenerative braking, regeneration efficiency is increased by around 20%. Additionally, it is demonstrated that the EV's driving range is enhanced by around five cycles. It may be inferred that the suggested plan guarantees the EV's safe deceleration and is capable of efficiently capturing braking energy. Research on novel energy storage solutions, such as advanced batteries or super capacitors, could further improve the storage and release of energy in HEVs.

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References

Abhinav. K. & Gowtham. (2022). Hybrid sources powered electric vehicle configuration and integrated optimal power management strategy. *IEEE Access*, vol.10, 121684. https://doi.org/10.1109/ACCESS.2022.3217771

Amit kumer, Oishikha Chakraborty, & Sayemul Islam (2021). Control strategies of different hybrid energy storage systems for electric vehicles applications—A review. *IEEE Access*, vol. 9, 51865–51866.https://doi.org/10.1109/ACCESS.2021.3069593

Anubhav Agrawal, & Ranbir Singh. (2023). Mathematical modeling of driving forces of an electric vehicle for sustainable operation. *IEEE Access*, vol. 11. https://doi.org/10.1109/ACCESS.2023.3309728

Binhao Liu, & Liang Li. (2018). Hybrid electric vehicle downshifting strategy based on stochastic dynamic programming during regenerative braking process. *IEEE Transaction on Vehicular Technology*, 6(67), 4716. https://doi.org/10.1109/TVT.2018.2815518

Hamed Bizhani, & S.M. Muyeen. (2019). Dual mechanical port machine based hybrid electric vehicle using reduced switch converters. *IEEE Access*, vol.7, 33665. https://doi.org/10.1109/ACCESS.2019.2903765

Mayank Gupta. (2020). Evaluation of regenerative braking and its functionality in electric vehicle. In IEEE Explore (International Conference for Emerging Technology, Belgaum, India). https://doi.org/10.1109/INCET49848.2020.9154047

Qiao Zhang, & Yexin Zhang.(2022). Modeling of regenerative braking energy for electric multiple units passing long downhill section. *IEEE Transaction on Transportation electrification*, 8(3), 3742-3743. https://doi.org/10.1109/TTE.2022.3169901

Qiwei Xu, & Fukang wanng. (2019). Research on the efficiency optimization control of the regenerative braking system of hybrid electrical vehicle based on electrical variable transmission. *IEEE Access*., vol. 7, 116823.https://doi.org/10.1109/ACCESS.2019.2936370

Tako Nama, & Praveen Thipathy. (2022). Design modeling and hardware implementation of regenerative braking for electric two wheelers for hilly roads. *IEEE Access*., vol. 10, no. 6, pp. 130602.https://doi.org/10.1109/ACCESS.2022.3229597

Warunchit Chueprasert, & Danai Phaoharuhansa. (2020). Study of regenerative braking system and brake force using pulse width module. *In MATEC Web of Conference proceedings*. https://doi.org/10.1051/matecconf/202030601004

Xuezhou Wang, & Udai Shipurkar. (2021). Sizing and control of a hybrid ship propulsion system using multi-objective double-layer optimization. *IEEE Access*, vol.9. https://doi.org/10.1109/ACCESS.2021.3080195

Zhengwei Ma, & Daxu Sun. (2020). Energy recovery strategy based on ideal braking force distribution for regenerative braking system of a four wheel drive electric vehicle. *IEEE Access*, vol.8 pp. 136234.https://doi.org/10.1109/ACCESS.2020.3011563