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Energy Management Schemes for Hybrid Electric Vehicles

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Abstract *– An internal combustion engine (ICE) and one or more electric motors are combined in hybrid electric vehicles (HEVs) to improve fuel economy and lower greenhouse gas emissions. This paper explores the various HEVs, such as series hybrids, parallel hybrids, series-parallel hybrids, and plug-in hybrid electric vehicles (PHEVs). Each types are described in terms of its components and operational modes, highlighting the advantages and challenges associated with each type. Key technological components of HEVs, such as the ICE, permanent magnet synchronous motors (PMSM), battery systems, and power electronics, are discussed in detail, emphasizing their roles in optimizing vehicle performance. Furthermore, advanced energy management systems (EMS) using reinforcement learning (RL) and operational charts are examined, demonstrating their capacity to raise overall vehicle performance, lower emissions, and increase fuel efficiency. This paper concludes by underscoring the significant contributions of HEVs towards sustainable transportation and the importance of ongoing innovations in battery technology, control systems, and powertrain architectures for the future of eco-friendly automotive solutions.*

Keywords – Hybrid Electric Vehicles, Battery Model, DC-DC Converter, Reinforcement Learning

1. INTRODUCTION

To supplement the world's depleting petroleum supply, a variety of alternative energy sources have been investigated for hybrid vehicles. There is growing concern about vehicle usage because fossil fuels have negative consequences on the environment. For use in vehicles, sources like batteries, fuel cells, supercapacitors, photovoltaic cells, or solar energy, are being investigated. The future generation of transportation is known as HEVs. These HEVs are energized by combinations of various renewable energy sources [1]. HEV provide possible options for reducing pollution and preserving fossil fuels for a safe environment and eco-friendly transportation. Optimizing parts, systems, and controls is necessary to design these energy-efficient powertrains. Controls include fuel economy, driving performance, pollutants, management strategy, and battery management [2]. ICEs and electrical machines are combined to create HEVs. Energy storage systems, motors, bidirectional converters, and maximum power point trackers are the essential parts of HEVs [3]. Hybrid energy storage systems for EVs provide advantages over traditional energy storage systems in driving range, operating temperature, power, and energy density [4]. HEVs are not required to charge the battery from the external side because it consists of two sources such as ICE and electric motor [5]. HEVs face various problems related to torque fluctuation and inadequate range [6]. The EV battery releases stored energy feedback into the grid through V2G technology [7]. The ICE-based vehicles are completely dependent on the fossil fuel. This dependency on fossil fuels is reduced by using fuel cell-based vehicles, that provide high efficiency in compression to EVs [8]. The use of efficient modeling and energy management systems requires optimizing the economy and performance of HEVs [9]. The power management system reduces problems related to developed hybrid renewable energy-based powered EVs [10]. The lithium-ion batteries are used in EVs due to excellent electrochemical performance [11]. HEVs have drawn significant research interest from academia and industry as a mid-term technology from conventional ICE vehicles to EVs, and they are making up a growing portion of the market [12]. Future technical developments indicate that fuel cell-driven EVs will develop quickly and turn into a great replacement for traditional automobiles. One important component of these FCHEVs is the DC-DC power converter unit [13]. Designing an effective EMS utilizing vehicle-to-infrastructure/vehicle-to-vehicle information for HEV is still a problem and a serious issue due to the ongoing development of intelligent connected vehicle technologies [14]. Energy management is essential for HEVs to operate more efficiently and produce less greenhouse gases [15]. Powertrain malfunctions are significant in terms of safety considerations [16]. Energy management in HEV is possible with the help of machine learning [17], [18]. Long charging periods and limited drive range problems caused by the nature and immaturity of battery technology lead automakers to search for alternate power sources, such as supercapacitors and fuel cell technologies, to power EVs [19], [20].

2. HEV ARCHITECTURE AND TYPES

HEVs combine an ICE with one or more EMs to increase fuel efficiency and reduce greenhouse gas

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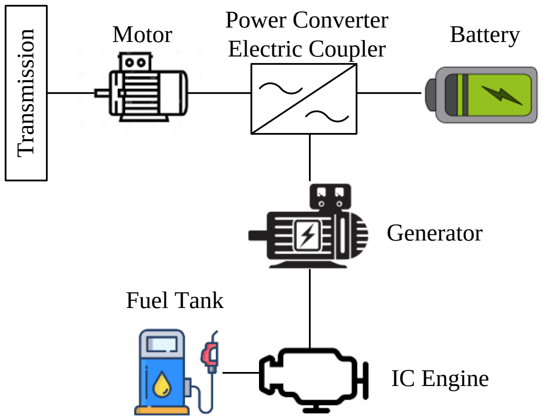
emissions. The architecture of HEVs is based on how the ICE and electric motors are integrated and used. There are various types of HEV architectures, including:

2.1 Series Hybrid

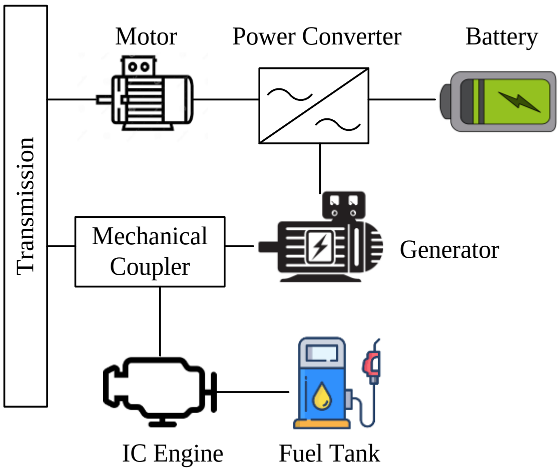
The series hybrid vehicles combine an ICE with an electric motor, but unlike parallel hybrids, the ICE doesn't directly drive the wheels, as shown in Fig. 1(a). Instead, it serves as a generator to produce electricity, which is then used to charge the battery or run the electric motor. This configuration allows an EV to operate in electric-only mode, providing higher efficiency and lower emissions during city driving or stop-and-go traffic. When the battery depletes, the ICE kicks in to extend the vehicle's range. This setup optimizes engine operation within its most efficient range, reducing emissions and fuel consumption. The electric motor offers smooth and instantaneous torque, enhancing the driving experience. Additionally, series hybrids can often integrate regenerative braking systems, capturing energy typically lost during braking to recharge the battery. This configuration offers significant flexibility in energy management, allowing for smaller engines and better fuel efficiency. However, the dual-system nature of series hybrids can lead to increased complexity and higher costs. Overall, series hybrids represent a transitional technology bridging the gap between traditional combustion engines and fully electric vehicles, combining the benefits of both to achieve improved fuel efficiency and reduced environmental impact.



a) Series hybrid

2.2 Parallel Hybrid

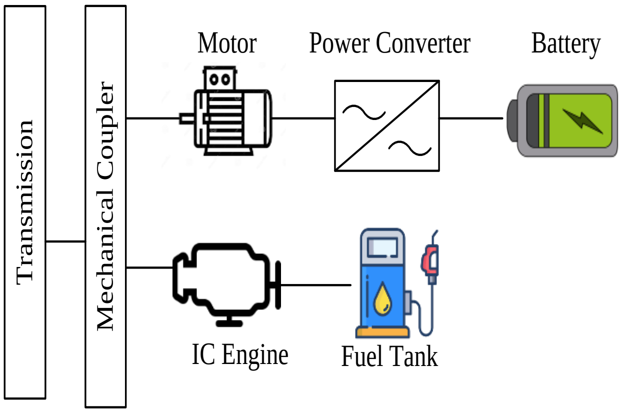
Parallel HEVs (PHEVs) integrate an ICE with the electric motor, allowing both to provide propulsion independently or together for optimized performance and efficiency. The ICE, electric motor, battery pack, gearbox (transmission), and power electronics are among the essential parts, enabling the EV to operate in electric-only mode for short trips and low speeds, ICE-only mode for high speeds and long distances, and hybrid mode where both systems combine for better acceleration, as illustrated in Fig.1 (b). In PHEVs, the transmission system controls the electric motor and ICE power distribution. It guarantees seamless switching between various driving modes and the best possible performance from both power sources. Regenerative braking is also utilized, enabling the battery to be recharged by the electric motor while braking [2]. To transform kinetic energy into electrical energy, the electric motor functions as a generator during braking. The battery pack is subsequently recharged by storing this energy. PHEVs offer benefits including increased performance, lower emissions, and better fuel economy, though they face challenges like higher complexity, increased costs, and concerns over battery lifespan. Notable examples include the Toyota Prius, Honda Accord Hybrid, and Chevrolet Volt. Future trends point towards increased battery capacity for longer electric ranges, advancements in power electronics for improved efficiency, and integration with renewable energy for more sustainable charging. Overall, PHEVs represent a versatile and efficient step towards environmentally friendly transportation.



(b) Parallel Hybrid

2.3 Series-Parallel Hybrid

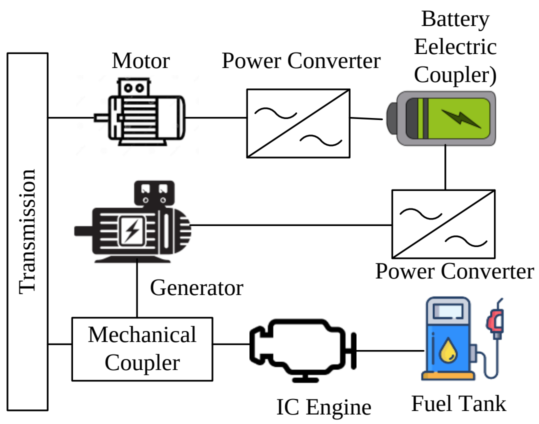
By combining the advantages of parallel and series hybrid systems, series-parallel HEVs (SPHEVs) enable flexible power distribution between the electric motor and ICE. In this configuration, an EV operates in series mode, where the ICE generates electricity for the motor, or in parallel mode, where the wheels are directly driven by both the electric motor and the ICE. The ICE, electric motor, generator, battery pack, transmission, and power electronics are among the essential parts, as shown in Fig.1 (c). With this dual-mode flexibility, SPHEVs use the electric motor for low-speed driving and maximize performance and fuel economy according to the driving condition, short-distance travel, and the ICE for higher speeds and longer distances. Additionally, regenerative braking captures energy to charge the battery while braking. SPHEVs' advantages include improved performance flexibility, lower emissions, and fuel efficiency. Challenges involve increased complexity, higher costs, and managing the balance between ICE and electric motor usage.



c) Series-parallel hybrid

2.4 Plug-in Hybrid Electric Vehicles

In addition to having a bigger battery pack that is recharged by connecting to an external power source, PHEVs also include an electric motor. This enables PHEVs to run exclusively on electricity for a certain distance, usually enough for everyday commutes, before switching to hybrid mode where the ICE kicks in for extended driving. The key components include the ICE, electric motor, battery pack, charging port, transmission, and power electronics, as illustrated in Fig.1(d). The electric-only mode offers significant fuel savings and reduced emissions, while the hybrid mode provides flexibility and extended range. By transforming kinetic energy during braking into electrical energy, regenerative braking also aids in battery recovery. PHEVs combine the environmental benefits of EVs with the long-range capabilities of conventional vehicles, making them versatile and efficient. Challenges include higher upfront costs, the need for charging infrastructure, and battery degradation over time. Notable examples of PHEVs are the Chevrolet Volt, Mitsubishi Outlander PHEV, and Toyota Prius Prime. Future trends indicate improvements in battery technology, increased electric range, and better integration with renewable energy sources, further enhancing the appeal and sustainability of PHEVs.



(d) Complex hybrid

Fig. 1. HEV architecture and types, (a) series hybrid, (b) parallel hybrid, (c) series-parallel, (d) complex hybrid.

3. TECHNOLOGICAL COMPONENTS

HEVs incorporate various advanced technologies to optimize performance and efficiency.

3.1 Internal Combustion Engine (ICE)

An ICE is a kind of heat engine in which fuel is burned in a combustion chamber that is a component of the working fluid flow circuit together with an oxidant, typically air. When high-temperature and high-pressure gases are created during combustion in an internal combustion engine, they expand and exert direct stress on engine components. Pistons, turbine blades, rotors, or nozzles are frequently subjected to this force. Through the utilization of force, chemical energy is converted into mechanical energy that can move the component across a distance.

3.2 Permanent Magnet Synchronous Motors (PMSM)

An electric motor known as PMSM produces a steady magnetic field that synchronizes with the stator's revolving magnetic field through the application of permanent magnets inside the rotor. The stator generates an alternating magnetic field by having windings that resemble those of an induction motor. Three-phase AC electricity is normally supplied to the stator utilizing an inverter. PMSMs are renowned for their exceptional torque and speed control, great power density, and high efficiency. They function at synchronous speed, which means that there is no slip and the rotor speed is the same as the stator's spinning magnetic field speed. The lack of brushes means that PMSMs require less maintenance, are very dependable, and function well at both low and high speeds. They also have good power-to-weight and torque-to-current ratios, making them appropriate for applications needing strong yet small motors. They are a popular option in many demanding and energy-sensitive applications because of their great efficiency and dependability. The vehicle speed vs ECE-47 drive cycle of PMSM is illustrated in Fig. 2.

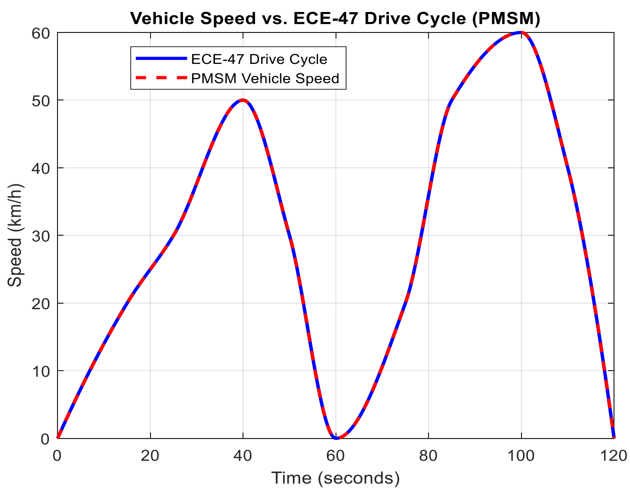
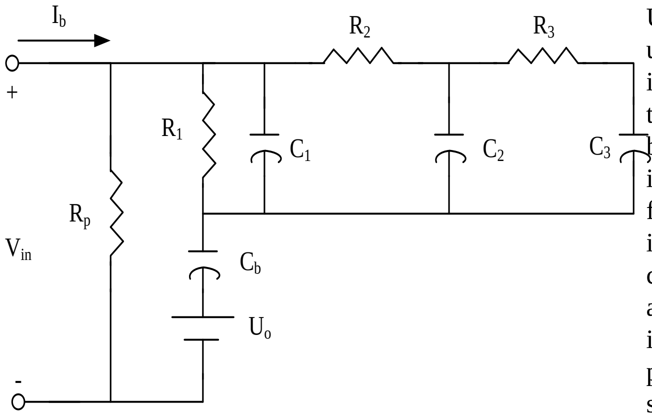


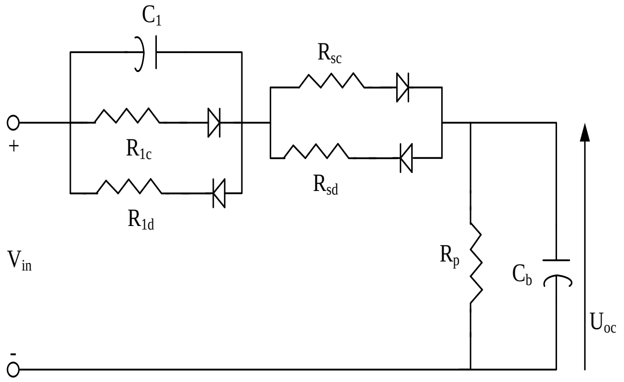
Fig. 2. Vehicle speed vs ECE-47 drive cycle of PMSM.

3.3 Battery Systems

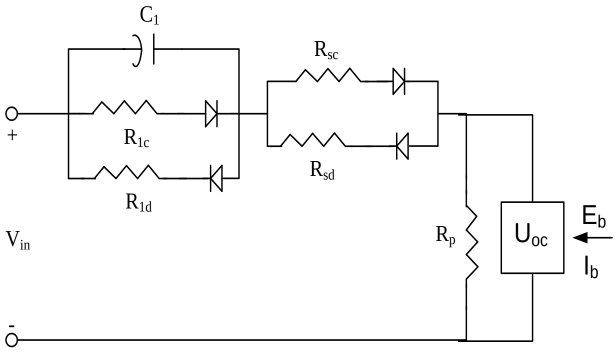
The battery's state of charge (SOC), capacity, temperature, and age are all significantly influenced by its performance. The constant resistance coupled with the optimal voltage source forms the basis of a basic battery concept. The internal resistance and the battery's state of charge are not taken into consideration by this basic model. In Fig. 3(a), a variable resistance can be used in place of R_b to increase the simplicity of the model and the self-discharge, Rp. The linear component for self-discharge, Rp. This model does not take temperature dependency into account, despite having increased accuracy. Fig. 3(b) displays a different model that Salameh created. A dynamic model that is more realistic has been achieved by adding two more element blocks to the circuit, as shown in Fig. 3(c). In this new dynamic battery model, the battery temperature T, V_{oc} is influenced by both the actual discharge current (I_b) and the energy taken from the battery (E_{cd}) [2].



(a) Enhanced battery model.



(b) Enhanced battery model developed by Salameh.



(c) Adaptive battery model.

Fig. 3. The battery systems, (a) enhanced battery model, (b) enhanced battery model developed by Salameh, (c) adaptive battery model.

3.4 Power Electronics

A power converter regulates the voltage of many power sources using the rated voltage of the DC machine. Under different power situations, the DC/DC converter used with different motor driving methods, such as inverters, to control the flow of power. Figure 5 shows the common power converter topologies seen in HEVs: buck, boost, and cuk. A buck converter is used to increase the current while stepping down the voltage from a higher level to a lower level. This buck converter is made with a switch (transistor), diode, inductor, and capacitor. Switch is a MOSFET or IGBT, used to chop an input voltage. The diode provides a channel for the inductor current while the switch is off. The main purpose of an inductor is to store energy when the switch is on and release it when the switch is off, smoothing the current. The schematic model of the converters is displayed in Fig.5. A boost converter reduces current while increasing voltage from a low level to a higher level. The voltage can be increased or decreased by the cuk converter, causing the output voltage to fall short of an input voltage. A compression output voltage of a boost and buck converters, the cuk DC-DC converter is more intricate as shown in Fig. 4.

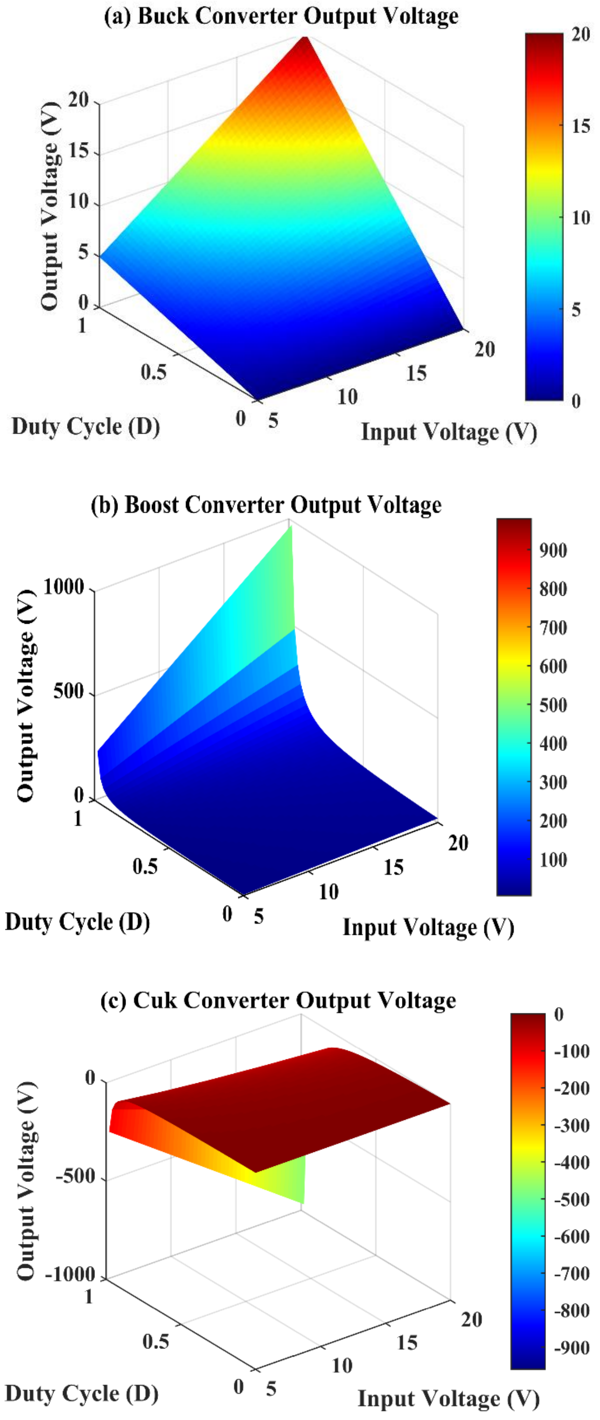
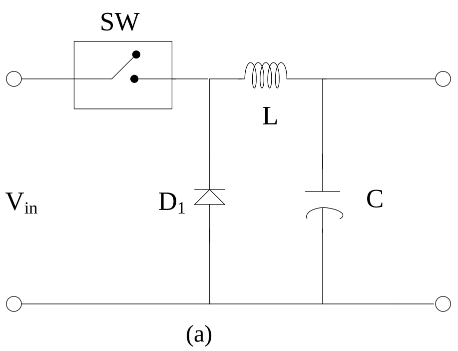


Fig. 4. Input, Output, and duty cycle for converter (a) buck converter output voltage (b) boost converter output voltage (c) cuk converter output voltage.



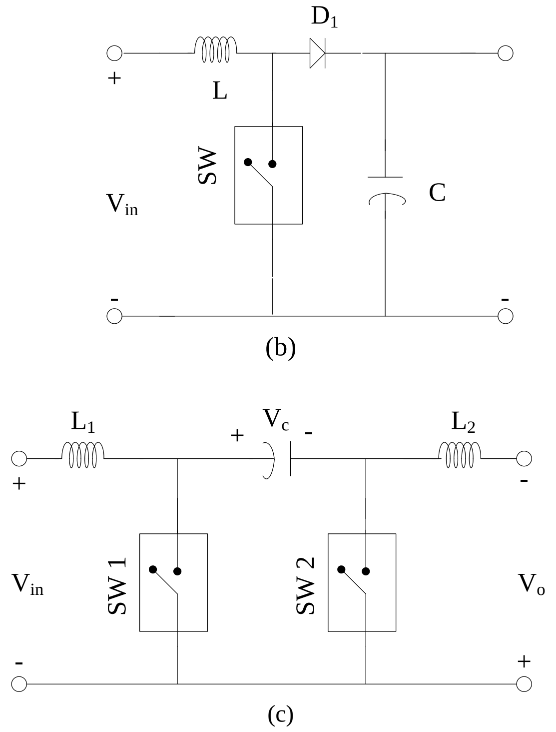


Fig. 5. PSPICE schematic model, (a) buck converter, (b) boost converter, (c) cuk converter.

4. ENERGY MANAGEMENT SYSTEM (EMS) OF HEV

HEVs utilize sophisticated control systems to manage the ICE and electric motor interaction.

4.1 EMS with Reinforcement Learning

Energy management strategies for HEVs using reinforcement learning targets to optimize power transmission between an ICE and an electric motor to maximize fuel economy, minimize emissions, and improve overall vehicle performance. Important elements of RL-based energy management for HEVs include the environment, that is the drivetrain, electric motor, battery, and ICE; the agent, which is the RL algorithm deciding how to distribute power in real-time; the state, which represents the current status of the HEV, including battery SOC, vehicle speed, engine status, and road conditions; actions, such as splitting power between the ICE and motor; the reward, which is feedback based on metrics like fuel consumption, emissions, battery wear, and driving comfort; and the policy, which is the agent's plan for choosing actions as exposed in Fig. 6.

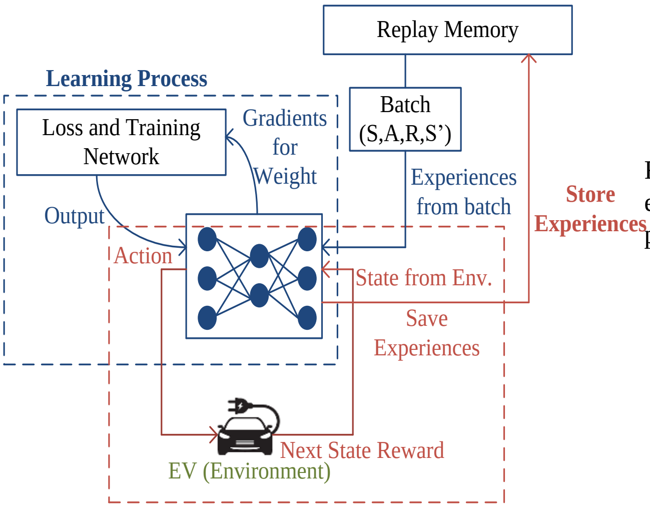


Fig. 6. The reinforcement learning for HEV.

State space (S) indicates the various states of the HEV. These states include battery SOC, vehicle speed, engine speed, and road gradient calculated by equation (1).

$$S=\{s_1,s_2,....,s_n\} \quad (1)$$

Action space (A) represents the possible actions of the agent. Actions include ratios of power distribution between motors and internal combustion engines and charging or discharging the battery as given by equation (2).

$$A=\{a_1,a_2,....,a_n\} \quad (2)$$

After acting (a), the transition probability (P) of changing states by equation (3).

$$P(s_{t+1}|s_t,a_t) \quad (3)$$

The immediate reward received by reward function (R) after taking an action in a given state by equation (4).

$$R(s_t,a_t) \quad (4)$$

The policy (π) is the strategy used by the agent to determine actions based on states by given below equation (5).

$$\pi(a|s) \quad (5)$$

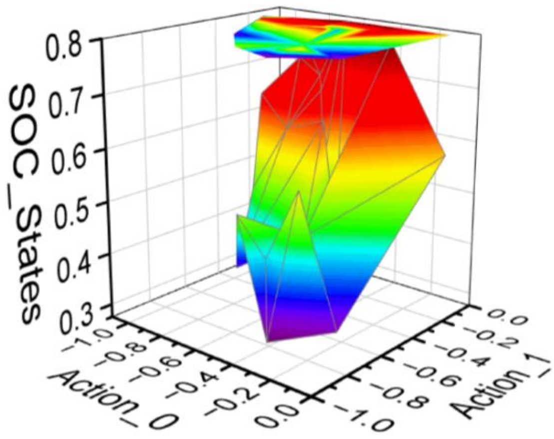
The expected cumulative benefit for being in states and abiding by π is represented by the value function (V) and given by equation (6).

$$V^{\pi}(s)=E_{\pi}\left[\sum_{t=0}^{\infty}\gamma^t R(s_t,a_t)|s_0=s\right] \quad (6)$$

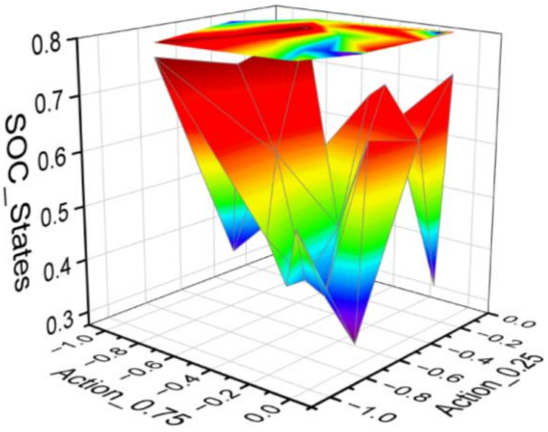
The anticipated total benefit of acting a in state s and abiding by π is known as Q-function (Q) and is calculated by equation (7).

$$Q^{\pi}(s,a)=E_{\pi}\left[\sum_{t=0}^{\infty}\gamma^t R(s_t,a_t)|s_0=s\right] \quad (7)$$

HEVs effectively manage energy by implementing RL-based techniques, which will enhance fuel efficiency, reduce emissions, and improve overall performance.



a)



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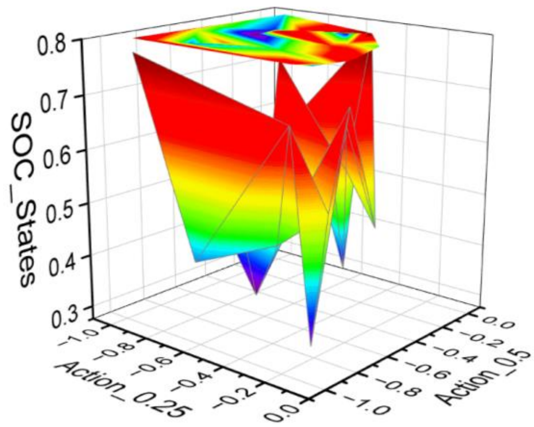
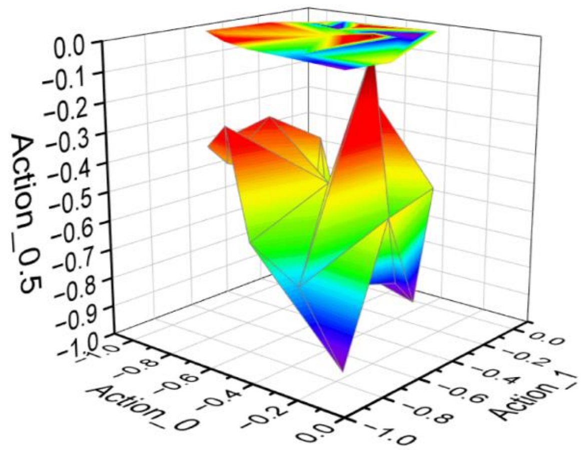


c)



d)

Fig. 7. Applicable across all actions, a) SOC with action '0' and '1', b) SOC with '0.25' and '0.75' c) SOC with '0.25' and '0.5', d) intermediate action.

The EMS for a HEV using RL, action represents the decision made by the RL agent regarding how to split the power demand between the internal combustion engine and the electric motor shown in Fig.7. Action space is a predefined set of possible decisions or "actions" that the RL agent take. In this figure, the action space is represented by `[0, 0.25, 0.5, 0.75, 1]`. These numbers indicate the proportion of power allocated to the engine.

`0` → All power is supplied by an electric motor.

`1` → All power is supplied by an internal combustion engine.

Intermediate values represent a split of the power demand between the engine and motor.

4.2 EMS with Operation Chart of PHEV

EMS for a PHEV maximizes EV efficiency by dynamically switching operating modes depending on the SOC and power demand. The SOC is divided into three levels: high (60%–65%), medium (42%–60%), and low (below 40%), as shown in Fig.8. The EV uses the electric motor to increase efficiency and lower emissions when the SOC is large and the power demand is minimal. The EMS switches to hybrid mode, where the ICE and the electric motor are employed to balance the performance and fuel cost, as power demand rises or SOC falls to the medium range. In charge-sustaining mode, the car mostly depends on the ICE to keep the battery charged and prevent it from running out of power when the SOC drops below 40% or the power demand is high. This dynamic adjustment improves fuel economy reduces emissions, and preserves battery health, extending the vehicle's range and lifespan. The operation chart guides these transitions, ensuring the PHEV operates in the most economical mode given the current SOC and power demand.

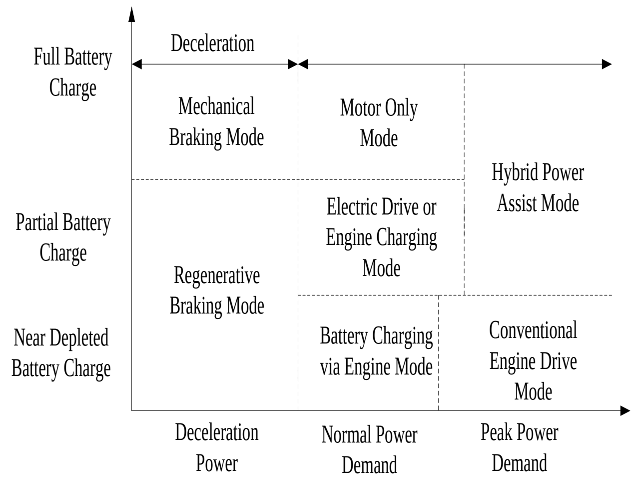


Fig. 8. EMS featuring an operational chart for PHEV.

5. CONCLUSION

This paper concludes that Hybrid Electric Vehicles represent a significant advancement towards sustainable transportation. Continued innovation in battery technology, control systems, and powertrain architecture will enhance their efficiency and affordability. HEVs are poised will significantly contribute to lessening the transportation sector's negative environmental effects while opening the door for the wider use of fully EVs. PHEVs and HEVs are major technological advances in the automobile industry that are intended to lower greenhouse gas emissions and fuel consumption. Series, parallel, series-parallel, and plug-in hybrid HEV designs all present different benefits and difficulties. With their electric-only functioning, series hybrids are excellent for driving in cities, whereas parallel hybrids provide more adaptable performance by combining power sources. Plug-in hybrids increase the driving range of electric-only vehicles with bigger batteries, while series-parallel hybrids provide variable power distribution. EMS based on RL is being used more and more to optimize power distribution between ICEs and EMs, which will further improve fuel economy and lower emissions.

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