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A Review of Hybrid Electric Vehicle Configurations: Advances and Challenges

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Abstract

Hybrid electric vehicles (HEVs) are essential to achieving sustainable mobility objectives. The configurations used in HEVs are reviewed in this paper, along with their advancements and remaining challenges. The paper explores the fundamental parts of HEVs, such as motor controllers, energy storage systems, and powertrains. Different motor types and control techniques are analyzed, along with advancements in battery technology for improved energy density and lifespan. The role of maximum power point trackers in optimizing solar panel output for plug-in hybrids is explored. The article emphasizes the critical function of DC-DC converters in regulating voltage levels and the importance of efficient energy management systems in optimizing HEV performance. A comparative analysis of parallel, series, and power-split hybrid powertrains highlights their unique advantages and limitations. Finally, the discussion section explores overall trends, advancements in HEV configurations, and challenges such as cost reduction, range limitations, and battery recycling. The conclusion emphasizes the potential of HEVs for sustainable transportation and briefly mentions future research directions for HEV configurations. Most controllers have the same reaction with less distortion for the backstepping control. The main reason is that Backstepping control's effectiveness depends on accurate controller tuning. Torque distortion can be considerably reduced with carefully selected parameters. This article summarizes multiple comprehensive reviews that studied different literature on hybrid electric vehicle configurations, advances and challenges. This work aims to guide researchers and practitioners in relating their work to existing research and gaining insights into what their work can contribute to the field.

Keywords: Hybrid energy storage system, Backstepping Control, Slide mode control, Enhanced field-oriented control, Maximum Power Point Tracking.

1. Introduction

Rising oil costs and rates of carbon dioxide (CO_2) and carbon monoxide (CO) emissions all of a sudden caused dangerously high levels that are detrimental to the environment, cause global warming, cause health problems, etc.[1]. Researchers, scientists, and decision-makers were forced to focus on green technology since it can potentially lessen and even eliminate harmful environmental effects. This century's primary emphasis will be the automobile sector, the Century of Technology Evolution. HEV technology is poised to revolutionize the automotive industry[2]. This review paper explores HEVs, explicitly highlighting the many setups that support their functionality. It will explore the various parts of a HEV, looking at how developments in each field affect efficiency and performance. Every component is essential, from the electric motors that drive the vehicle to the advanced energy management systems that maximize power flow[3].

This review will show various combinations, including exploring the different motor types in HEVs and how technological improvements have increased their power and efficiency[4]. The latest battery and supercapacitor (SC) technology developments will be emphasized to increase longevity and range[5]. Review how technique improvements result in smoother and more effective functioning and the control strategies utilized to manage the electric motor's performance[6].

Review of a comprehensive comparison of different maximum power point tracking (MPPT) techniques for photovoltaic systems [7]. The crucial role that DC-DC converters play in varying the voltage applied to various HEV components will be emphasized[8].

The three primary HEV powertrain configurations, parallel, series, and power-split, will be compared to emphasize their distinct benefits and drawbacks[9]. This review attempts to thoroughly understand the current state of HEV technology and its promise for sustainable transportation by looking at these developments and difficulties.

Figure 1 shows the expected sales of new hybrid electric vehicles in the United States through 2030[10]. As seen below, anticipated HEV sales are almost at 1,154,210 for this year (2023), so it has depended on this forecasting for the next few years. According to the forecast, HEVs' features will significantly increase demand for HEVs during this time, and the sales of HEVs will reach 4,719,375 by 2030.

Hybrid electric vehicles can be divided into three primary categories based on recent developments: internal combustion engine hybrid electric vehicles (ICHEVs), fuel cell hybrid electric vehicles (FCHEVs), and all-electric vehicles (EVs). Table 1 compares the various attributes of each drivetrain[11].

The road map of this paper can be summarized as follows: section 2 presents the research methodology. In contrast, section 3 clarifies the popular MPPT algorithms for HEVs, and section 4 shows DC-DC converters for boosting power in HEVs. Also, results and discussion are presented in section 5, and finally, the conclusion and remarks have been drawn successfully.

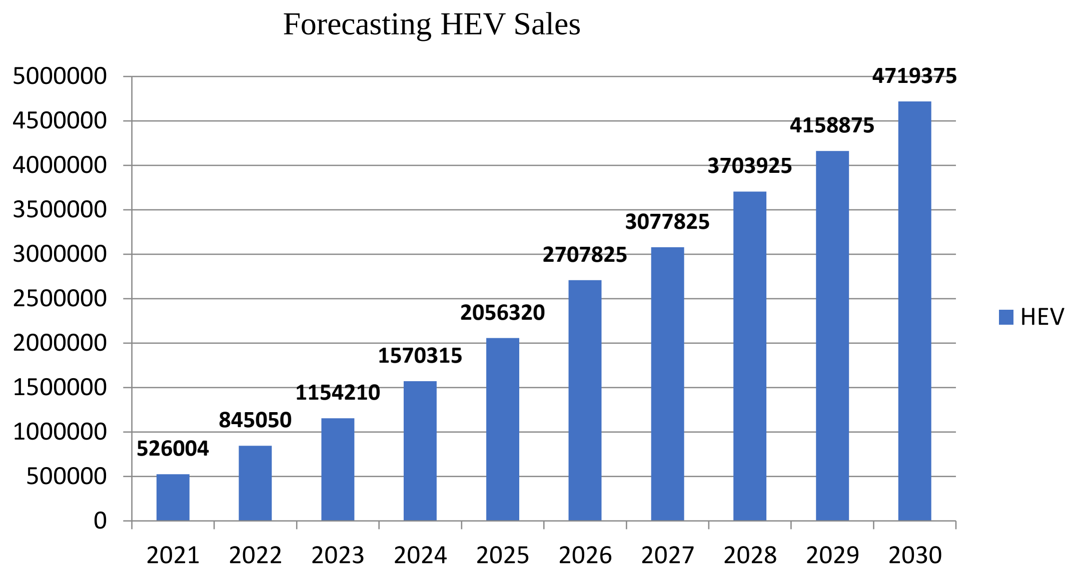


Figure 1: Hybrid electric vehicle sales forecast to 2030[10].

Table 1: Technical features of Electric Vehicles, Hybrid Electric Vehicles, and Fuelcell Hybrid Electric Vehicles [12].

Characteristics	Electric Vehicles	Hybrid Electric Vehicles	Fuelcell Hybrid Electric Vehicles
Propulsion System	Electric motor based.	Electric motor & internal combustion engine (ICE).	Electric motor based.
Energy Storage	Battery Ultra-capacitor Flywheel	Fuel tank Battery Ultra-capacitor Flywheel	Fuel cell Battery Ultra-capacitor
Energy Source Infrastructure	Electric charging facility.	Electric power Refueling station.	Hydrogen cylinder, Hydrogen refiner & refueling station.
Advantages	Zero emission Quite Smooth operation Energy efficient Independency from petroleum product Commercialized.	Low emission Higher fuel economy Long driving range Reliable Commercialized Durability.	Ultra-low emission, competent driving range, highly efficient Independence from petroleum products, reliable durability, and high cost.
Drawbacks	the limited range for driving, Weak dynamic reactions, and the long time needed to recharge.	Complex system Costly Bulky Increased component.	Slow dynamic response Not commercialized Sophisticated electronic controller.
Major Issues	Size & weight of battery pack Infrastructure for the charging station.	Size & weight of battery pack & ICE Integration of components.	Cost of fuel cell Infrastructure for hydrogen conditioning, storage, and refilling system.

2. Research Methodology

a) Electric Motors

Any HEV's electric motors are its core component, and they transform energy storage system (ESS)-powered electrical energy into the mechanical rotation that drives the vehicle. While many electric motors can be used with HEVs, each has unique benefits and drawbacks.

Here's a breakdown of four common types:

2.1 Permanent Magnet Synchronous Motor

The Permanent Magnet Synchronous Motor (PMSM) is a leading contender for HEVs in the electric motor arena[13]. It is an attractive option for powering these green vehicles because of its efficiency, power density, and controllability[14]. Figure 2 shows the construction of PMSM with stator and rotor.

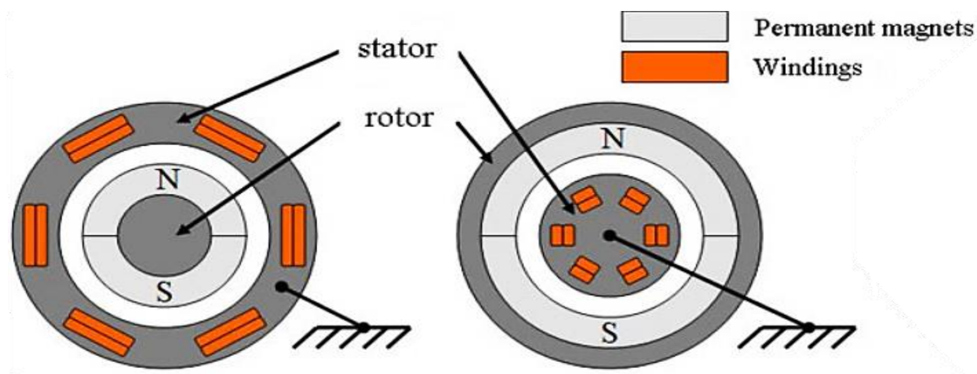


Figure 2: The PMSM construction[15].

Below is the PMSM motor's mathematical model[16][17]:

This type of equation system gives the dynamics of the PMSM in the (d - q) frame of reference:

Electric Equation is given in (1&2):

$$\frac{di_d}{dt} = -\frac{R_a}{L_a} i_d + p\, i_q \omega_m - \frac{1}{L_a} u_d \quad (1)$$

$$\frac{di_q}{dt} = -\frac{R_a}{L_a} i_d + p \frac{\psi_{PM}}{L_a} \omega_m - p\omega_m i_d - \frac{1}{L_a} u_q \quad (2)$$

The mechanical equation is as follows in (3):

$$\frac{d\omega_m}{dt} = -1.5 \frac{p}{J} \psi_{PM}\, i_q - \frac{f}{J} \omega_m - \frac{1}{J} T_L \quad (3)$$

where is the armature resistor and inductance are R_a and L_a, respectively. The drive train is a single equivalent mass model based on Newton's second law. Hence, the one-mass or lumped-mass model is utilized for tiny signal analysis of PMSM.

i_d, i_q are the stator currents for the d-q representation. p is the number of poles.

ψ_{PM} is the permanent flux linkage.

u_d, u_q the d-axes and q-axes stator voltage.

J and f_v are the flowing viscous friction and moment of inertia for the motor.

ω_m and T_L represents the motor speed and the load's torque, respectively.

2.2 Brushless DC Motor

The Brushless DC Motor (BLDC) is an impressive rival for HEVs in electric motors[18]. A popular option for HEVs, the BLDC offers an appealing combination of price, simplicity, and good performance, even though it doesn't quite achieve the peak efficiency of its permanent magnet , the PMSM[19].

Figure 3 depicts the BLDC motor's equivalent circuit. The mathematical model of the phase BLDC motor in (4).

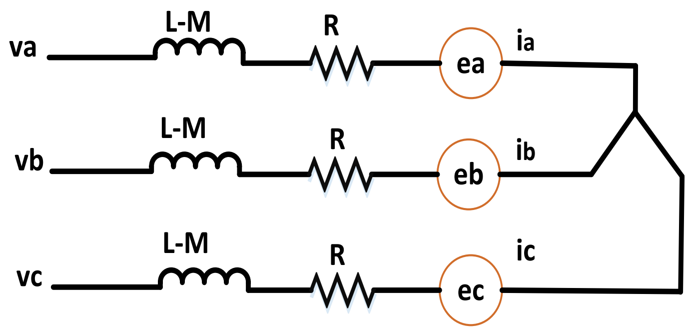


Figure 3: Equivalent circuit of the BLDC motor [20].

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & L_{ab} & L_{ca} \\ L_{ba} & L_b & L_{bc} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{4}$$

where e_a, e_b, e_c is the back EMF for a three-phase. i_a, i_b, i_c is the three-phase current. v_a, v_b, v_c is the rated voltage of the motor. The stator winding inductance is L_a, the mutual inductance is M., and R_a is the stator winding resistance.

The torque ripple can be computed by (5):

$$T_{ripple} = T_{max} - T_{min} / T_{avg} \tag{5}$$

2.3 Induction Motor

HEVs have seen the emergence of Induction Motors (IMs), also called asynchronous motors. Despite being less attractive than their permanent magnet counterparts, IMs provide a strong, dependable, and affordable choice for HEVs[21].

2.4 Switched Reluctance Motor:

One currently famous electric motor used in HEV is the switched reluctance motor (SRM). The SRM has different benefits and challenges than its electronically commutated or permanent magnet but uses a more straightforward construction[22].

Benefits of SRM motor in HEVs:

- High torque-to-weight ratio
- Robust construction tolerates harsh conditions
- Lower manufacturing cost compared to PMSM
- Regenerative braking capability
- Potential for higher efficiency at certain operating points

Table 2 compares the few notable and widely applied EM.

Table 2: Five commonly used EMs for EV/HEV applications [23].

Category	Brushless DC	PMSM	Switched Reluctance	Induction Motor
Type	AC	AC	DC	AC
Family	Synchronous excited PM	Separately excited	Synchronous unexcited	Squirrel cage
Power to rotor	PM	PM	Induced	Induced
Power to stator	Pulsed dc	AC	Pulsed dc	AC
Overall cost	High	High	Medium	Medium
Weight	Low	Medium	Medium	Medium
Commutation method	Internal electronic	External electronic	External electronic	External elections
Controller cost	Very high	High	High	High
Maintenance Requirement	Negligible	Negligible	Negligible	Negligible
Speed control method	Frequency-dependent	Pulse width modulation (PWM)	Frequency-dependent	Frequency-dependent
Starting torque	>175% of the rated	>200%of rated	Up to 200% of the rated	High
Speed range	Excellent	Controllable	Controllable	Controllable
Efficiency	High	High	Less than PMDC	High
Application	HEV & EV	HEV & EV	Normal vehicle	HEV & EV
%Efficiency with motor &electronic	78	90	85	84

b) Energy Storage Systems

HEVs are propelled by an electric motor and an internal combustion engine (ICE). The ESS is a crucial part of this system and essential to optimizing performance, efficiency, and driving pleasure[24]. The two main competitors in the HEV ESS market, batteries and supercapacitors, are the subject of this review.

1) Rechargeable Batteries

Chemical processes in batteries allow them to store electrical energy. When the battery is being charged, electricity enters it and causes chemical reactions that store energy. The chemical energy that has been saved is transformed back into electricity when the electric motor requires it[25].
The equivalent circuit for the battery is shown in Figure 4.

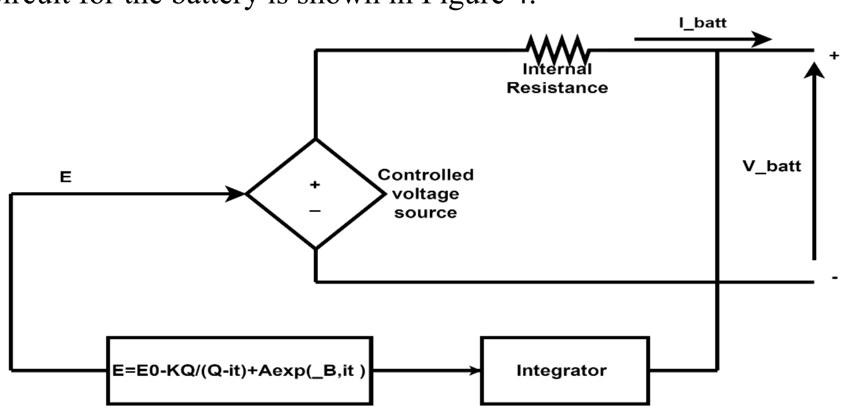


Figure 4: Battery's equivalent circuit[26]**.**

The battery's charge & discharge model equation is in (6&7).

- Discharge Model ($i^* > 0$)

$$E_{batt} = E_o - Ri - k\frac{Q}{Q-it}i^* - k\left(\frac{Q}{Q-it}\right)it + Aexp(-B.it) \tag{6}$$

- Charge Model ($i^* < 0$)

$$E_{\mathrm{batt}}=\mathrm{E}_0 - Ri - k\frac{Q}{it+0.1Q}i^* - k(\frac{Q}{Q-it})i_t + A\,exp(-B.it) \tag{7}$$

where is:
E_0: steady voltage expressed in volts (V), E: voltage when there is no load (V
K: Polarization resistance is measured in Ohms, or polarization constant is measured in V/Ah, I*: dynamics of low-frequency current, in A, i: battery current, expressed in A, i_t : extracted amount, expressed in Ah.
Q: The maximum capacity of the battery is expressed in Ah, A: voltage exponential, given in (V), B: Ah−1, or exponential capacity.

2) Supercapacitors

Supercapacitors (SC) use electrostatic storage to store electrical energy. Unlike batteries, they don't require chemical interactions[27]. When charged, electrodes divided by an electrolyte store energy in an electric field. When needed, this energy is quickly released. Figure 5 below shows the SC electrical model[28].

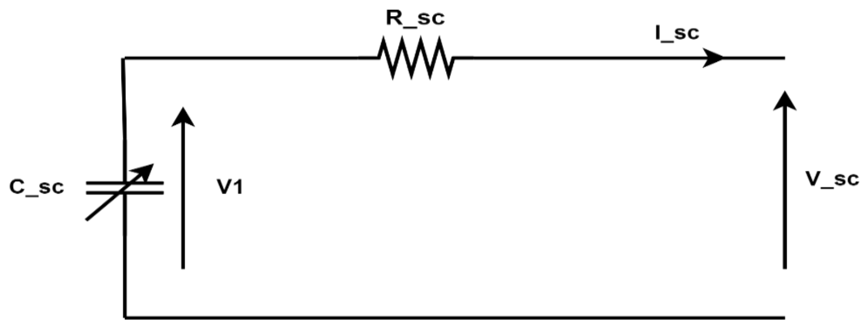


Figure 5: Supercapacitor equivalent circuit [29]**.**

The mathematical model of SC is given below in (8):

$$V_{SC} = V_I - R_{SC} * I_{SC} = \frac{Q_{SC}}{C_{SC}} - R_{SC} * I_{SC} \quad (8)$$

Where V_{SC}: supercapacitor voltage (V) , R_{SC}: SC resistance,I_{SC}: SC current(A) ,Q_{SC}: the amount of energy that is stored within a cell, C_{SC}: SC stack capacitor, P_{SC}: SC power (W).

c) Speed Control Techniques for Electric Motors in HEVs

Accurate speed control is necessary for the electric motors in HEVs to operate at peak efficiency, performance, and comfort during driving. Several advanced control strategies have been created to achieve this control. Here, we explore three prominent methods: Backstepping Control, Slide Mode Control (SMC), and Enhanced Field Oriented Control (EFOC)[30].

1) Backstepping Control

Backstepping control is one nonlinear control method that uses a systematic design approach. It divides the complex motor dynamics into smaller subsystems. Each subsystem is built with its control law to guarantee that the entire system—the electric motor—follows the intended speed trajectory[31].

2) Slide Mode Control (SMC)

SMC is a robust control technique that utilizes a switching control law. It forces the system state (motor speed and current) to slide along a predefined switching surface that separates the desired operating region from the undesired region. This approach ensures the motor speed remains within the desired range despite external disturbances[32] [33].

3) Enhanced Field Oriented Control (EFOC)

EFOC is an advanced version of Field Oriented Control (FOC), a well-established technique for AC motor control. It transforms the complex dynamics of the motor into a more straightforward DC motor-like equivalent. This allows for independent control of the motor's torque and flux, enabling precise speed regulation[34].

d) Maximum PowerPoint Tracking for Solar Panels in HEVs

Plug-in hybrid electric vehicles (PHEVs) offer a compelling solution for sustainable transportation. However, optimizing the energy collected from these vehicles' solar panels is necessary to increase efficiency. This is where MPPT comes into play. It will show various well-known algorithms used in PHEVs and go into the area of MPPTs [35].

3. Popular MPPT Algorithms for HEVs

1) Perturb and Observe (P&O)

This is a simple method that is commonly used. It functions by gradually varying the solar panel's operating voltage and tracking any changes in power. If the power increases, the P&O method keeps the voltage perturbed in the same direction. In contrast, the direction of perturbation is reversed if the power drops. This repetitive procedure helps the algorithm's convergence towards the MPP[36].

2) Incremental Conductance (INC)

This algorithm compares the change in voltage (ΔV) to the change in current (ΔI) of the solar panel. The panel's negative voltage equals the ratio of $\Delta V/\Delta I$ at the MPP. Based on this principle, the InC algorithm adjusts the operating voltage, guiding the system towards the MPP[37].

3) Particle Swarm Optimization (PSO)

PSO is an advanced method motivated by birds' swarming behaviour. A virtual particle disruption is created, each particle standing in for a possible solar panel working point. These particles communicate as they travel across the voltage-current gap [38]. With time, the swarm moves closer to the MPP according to the theory of "survival of the fittest."

4) Artificial Neural Network (ANN)

This approach utilizes machine learning. An ANN is trained on a large solar panel voltage, current, and power data dataset. Once trained, the ANN can predict the MPP based on the current operating conditions of the solar panel, offering a potentially more accurate and efficient tracking solution[39].

4. DC-DC Converters for Boosting Power in HEVs

HEVs rely on a combination of electric motors and ICE. The DC-DC converter is one essential part of this system. This adaptable device is necessary for controlling the electrical power flow inside the HEV; specific models, such as boost converters and super-lift Luo converters, are designed to meet voltage level requirements[40]. Begin to investigate these two well-known HEV choices and learn more about the world of DC-DC converters. An input DC voltage is transformed into an output DC voltage using a DC-DC converter. This allows for efficient power management in HEVs, where various components operate at varying voltage levels. For example, the battery might provide a lower voltage, while the electric motor might require a higher voltage for optimal operation.

1) Boost Converters

DC-DC converters called "boost" converters are made expressly to raise, or "boost," the input voltage to a greater output voltage. They achieve this by using an inductor to store energy during the "on" state of a switch and a diode and capacitor to release that energy during the "off" state of the switch. The output voltage can be much higher than the input voltage by carefully adjusting the switch timing [41]. In HEVs, boost converters are essential for increasing the battery pack's voltage to a level that can power the electric motor. This ensures the engine runs smoothly and provides the required power for propulsion[42]. Figure 6 shows the boost converter equivalent circuit.

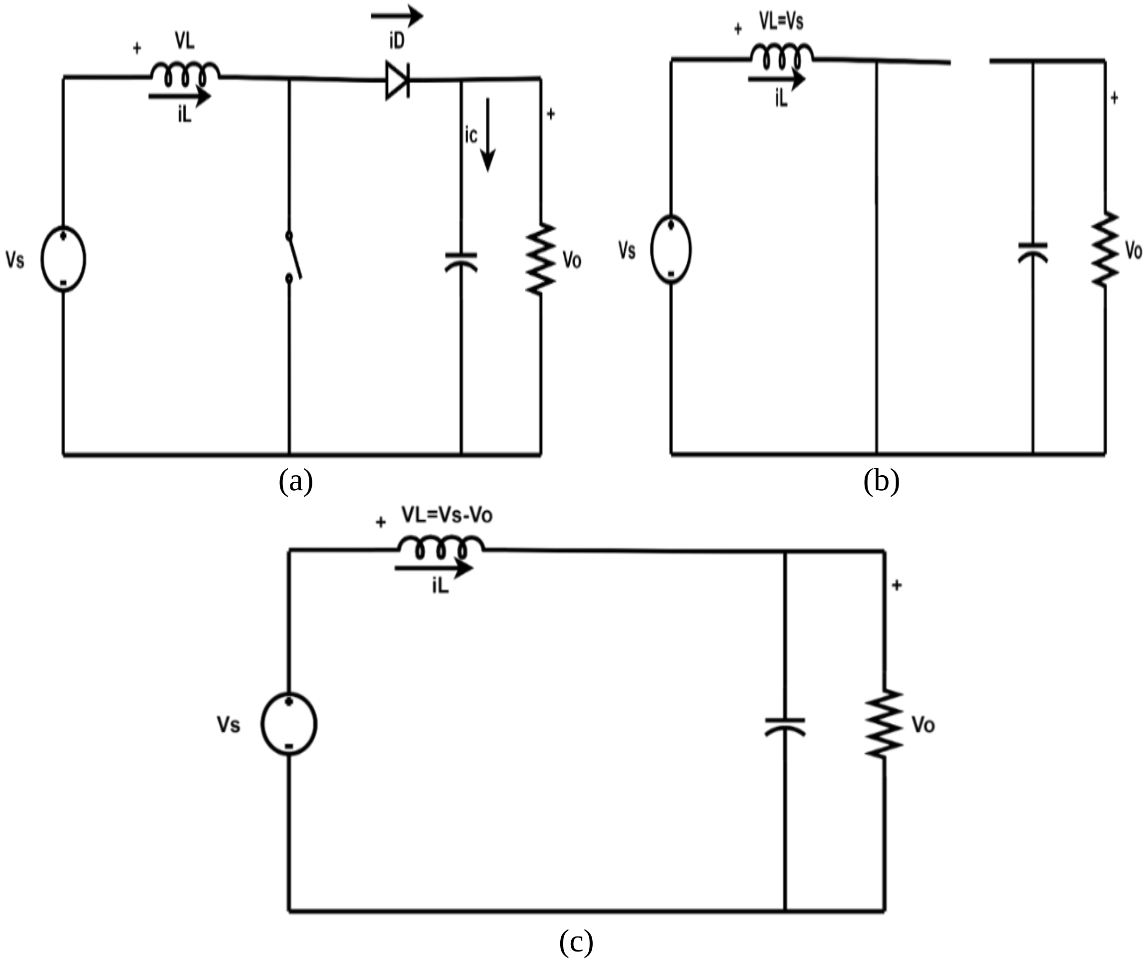


Figure 6: Boost converter :(a) circuit; (b) circuit equivalent for the closed switch (c) circuit equivalent for the open switch [43]**.**

2) Super-Lift Luo Converter

An alternative to the conventional boost converter is the super-lift Luo converter. Its output voltage can sometimes be more than twice that of an input voltage, making it even more potent than a typical boost converter. Like the boost converter, it utilizes an inductor and a switch to store and release energy. However, the super-lift Luo converter incorporates an additional capacitor and diode in its circuit, allowing for a higher voltage boost ratio. Super-Lift Luo converters can benefit HEVs where a significant voltage increase is needed. For example, they might be used in high-performance HEVs where the electric motor requires a substantially higher voltage than the battery pack can provide[44] [45]. Figure 7 shows the super_lift luo converter equivalent circuit.

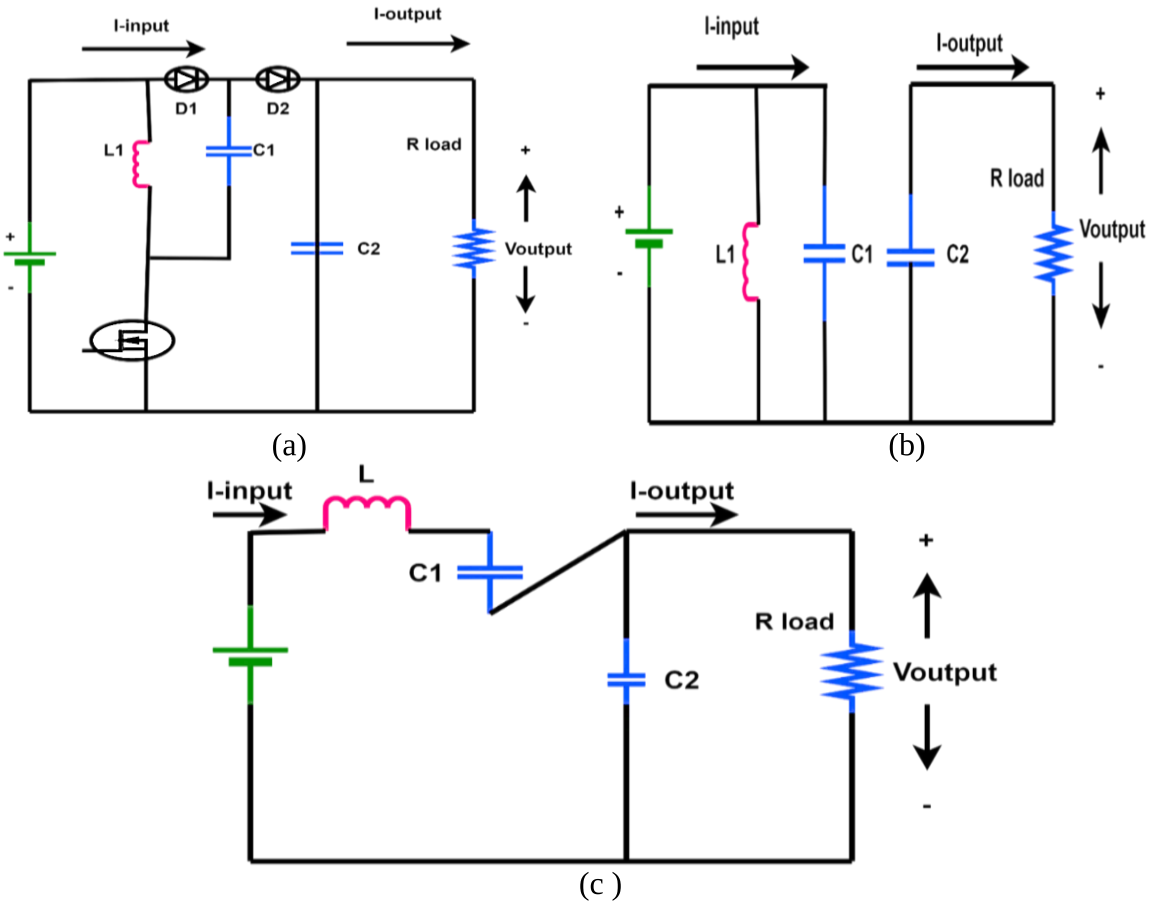


Figure 7: Equivalent circuit super-lift luo converter during (b) turn on (c) turn off [46].

f) Powertrains in HEVs

HEVs combine the power of ICEs and electric motors to produce exceptional fuel efficiency and lower pollutants. The powertrain arrangement of the HEV is a vital component of this power symphony. Let's delve into three main types of HEV powertrains: series, parallel, and the versatile series-parallel hybrid.

1) Series Hybrid

In a series hybrid, the ICE acts solely as a generator. It doesn't directly power the wheels. Instead, it produces electricity to charge the battery pack, which powers the electric motor that drives the wheels[47].

2) Parallel Hybrid:

In a parallel hybrid, the ICE and the electric motor can independently power the wheels. The driver can choose between electric, gasoline-only, or a combination of both scenarios[48].

3) Series-Parallel Hybrid: The Best of Both Worlds

Series-parallel hybrids, also known as split power hybrids, combine series and parallel configuration elements. They offer the most flexibility in terms of power delivery[49]. Figure 8 shows the connection type of HEV powertrains.

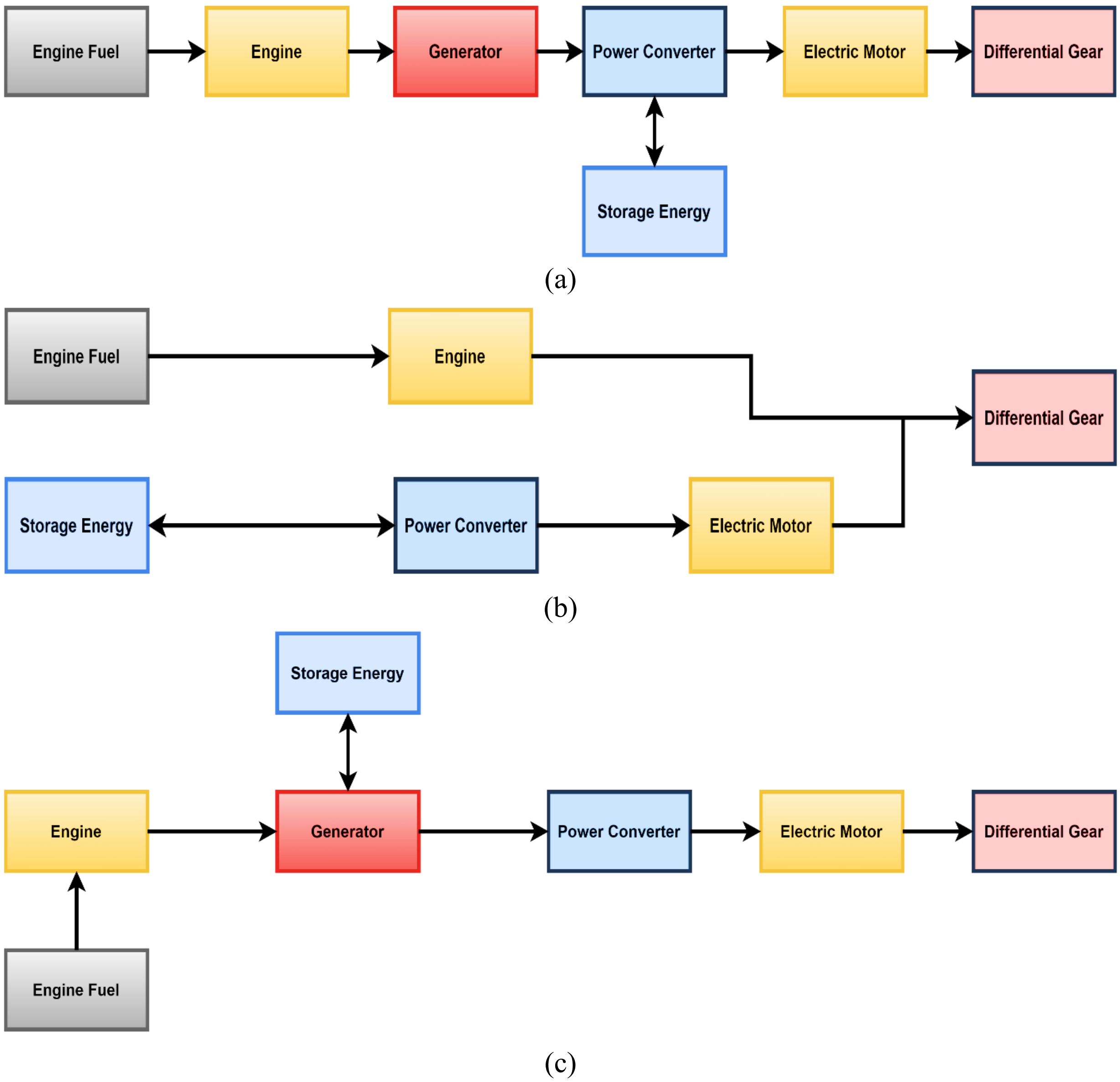


Figure 8: Powertrains types of HEV (a)series (b)parallel (c)series-parallel [50]**.**

5. Results and Discussions

This section will present some results and advantages for each component based on comparisons with other types.

5.1 PMSM and BLDC Comparisons

Two prominent rivals in the electric motor industry are PMSM and BLDC. Both works are well in various contexts, but picking one can be crucial. This review explores these motors' differences, emphasizing torque and speed ripple, starting current, HESS compatibility, precision in tracking torque and speed, and total harmonic distortion (THD). If these criteria are recognized, it will be well-equipped to select the motor that best suits its requirements. Figure 9 represents the performance of both motors in speed tracking. By observing the figure, the PMSM generally provides more stable superior variable

speed tracking capabilities and less fluctuating than BLDC. The reason is that BLDC has a trapezoidal back EMF, which results in uneven torque production throughout the rotation. It is unevenness, known as torque ripple, can cause fluctuations in speed as the motor attempts to maintain a desired setpoint.
In contrast, PMSMs boast a sinusoidal back EMF. It translates to a smoother and more consistent flow of torque, minimizing these disruptive fluctuations and enabling the motor to track speed changes more precisely. Figure 9(b) shows that the PMSM has smoother output constant torque and fewer fluctuations than BLDC. The reasons of that are the inherent sinusoidal nature of PMSMs leads to smoother torque production, minimizing fluctuations and enabling better constant torque output at variable speeds, and simpler PMSM control schemes allow for faster and more precise adjustments, ensuring the motor maintains the desired torque even during speed changes.
On the other hand, the BLDC has trapezoidal back EMF, which means the voltage induced in the motor windings as they rotate isn't constant throughout the rotation cycle. This results in fluctuations in torque production, leading to jerkiness and inconsistencies in maintaining a continuous torque output at varying speeds. These factors make PMSMs the preferred choice for applications requiring smooth and highly accurate constant torque control at variable speeds, such as industrial robots, electric vehicles, and precision control machinery. The fluctuations due to no motor are perfect. Manufacturing tolerances and imperfections in materials can lead to slight variations in magnetic field strength and back EMF. These variations can cause minor torque ripples even in PMSMs. BLDCs are generally more susceptible to these imperfections due to their reliance on discrete permanent magnets and stator windings. Figure 9(c) shows the BLDC has a higher starting current than PMSM because BLDC motors rely on a solid initial magnetic field interaction between the rotor magnets and stator windings to initiate rotation. A high current must be supplied to the windings during start-up to generate this strong field quickly. The high current translates to a surge in the starting current for the BLDC motor. PMSMs, on the other hand, benefit from the inherent alignment between the rotor magnets and the generated magnetic field in the stator. That alignment creates a more natural starting torque, requiring less initial current to overcome inertia and begin rotation. From Figure 9c, the maximum starting current can be obtained.
$Max\ I_{dc-BLDC} = 10.2\ A, Max\ I_{dc-PMSM} = 9.85\ A$

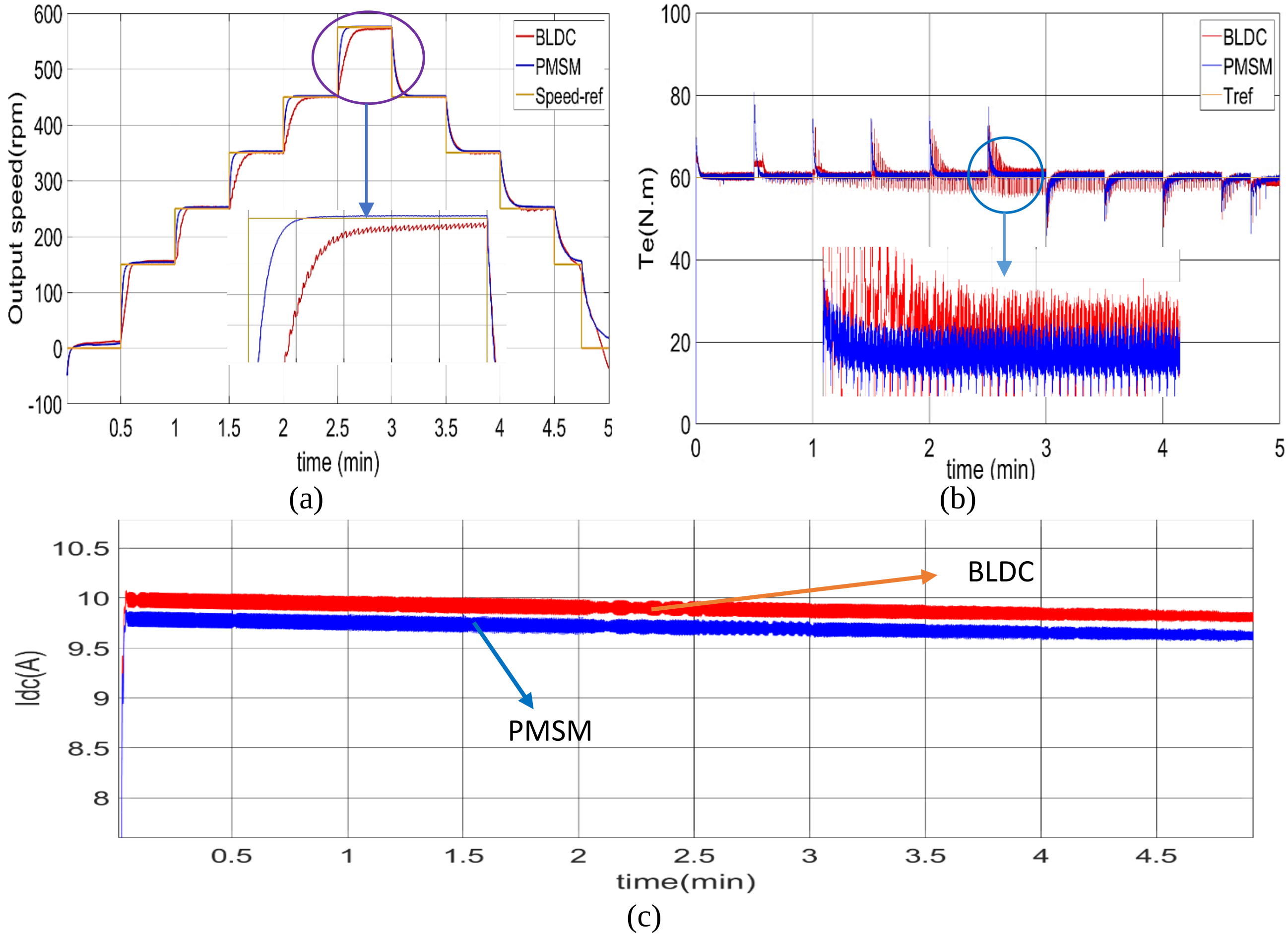


Figure 9: System response for electric motors (a)Output speed (b)Output torque (c)Starting DC-current.

Table 3 compares PMSM and BLDC depending on the HEV system results under different scenarios.

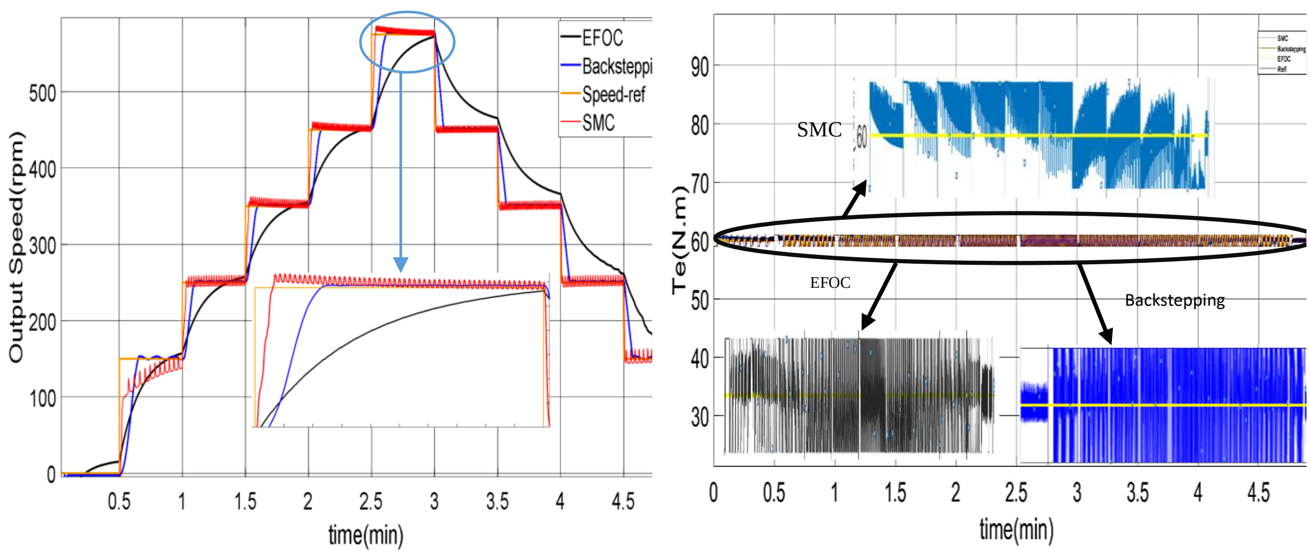
Table 3: Comparison between PMSM and BLDC under different scenarios.

Feature	PMSM	BLDC
Torque Production	Smoother, sinusoidal back EMF	Uneven, trapezoidal back EMF (torque ripple)
Control Scheme	Simpler, directly aligns with back EMF	More complex, needs to compensate for back EMF
Sensorless Control	Possible estimates based on back EMF	It is not ideal; it relies on physical sensors
Speed & Torque Tracking	More precise, faster response	Less precise, potential delays
Fluctuations	Less fluctuation due to smoother torque	More fluctuations due to torque ripple
Overshoot	Minimized due to faster response	This can occur during speed/torque changes

5.2 Speed Controllers Comparisons

The selected speed controller greatly influences a PMSM's performance. Three popular control strategies are compared in this analysis: EFOC, Backstepping Control, and SMC. It will evaluate their advantages and disadvantages, but you must understand that the best option depends on your particular application's speed and torque profile. Figure 10 compares speed controller results depending on variable speeds and constant torque. After zooming the peak output speed response in Figure 10(a), the backstepping control responds more accurately in variable speed scenarios than the other controller. It results from methodical design. Backstepping control employs a systematic process in which every action builds on the one before. The controller can better maintain the intended speed reference by adjusting its output and explicitly considering the speed variations. It allows control law to incorporate variable speed dynamics of variable speed directly. By explicitly considering the speed variations, the controller can adjust its output more effectively to maintain the desired speed reference. Figure 10(b) shows the controller's constant torque response. Most controllers have the same reaction with less distortion for the backstepping control. The main reason is that Backstepping control's efficacy depends on accurate controller tuning. Torque distortion can be considerably reduced with carefully selected parameters. Based on eq (6), the torque ripple can be calculated:

$T_{ripple-EFOC} = 4.5\%$, $T_{ripple-SMC} = 2.5\%$, $T_{ripple-Backstepping} = 3.34\%$.



(a) (b)

Figure 10: Speed controllers' response (a)output speed (b)output torque.

Table 4 summarizes a simple comparison between EFOC, backstepping, and slide mode controllers.

Table 4: Simple comparison between EFOC, backstepping, and slide mode controllers.

Feature	Backstepping Control	SMC	Enhanced FOC
Variable Speed Tracking	Best	Good	Good
Torque Ripple	Low	Low	High
Distortion	Low	Moderate	High
Complexity	High	Moderate	Low
Computational Resources	High	Low	Low

Backstepping control is a strong option for HEV applications because of its flexibility, improved tracking performance, and capacity to reduce torque ripple. The possible advantages for overall performance, drivetrain efficiency, and passenger comfort outweigh the implementation hurdles. Backstepping control is an excellent option for HEVs that stress smooth operation and accurate control.

5.3 Battery and Supercapacitor

For HEVs, batteries and SC provide complementary advantages and disadvantages. SCs manage the sudden spikes in power needed for regenerative braking and acceleration, while batteries supply the high energy density required for continuous electric driving. The future of HEVs might see a hybrid Energy Storage System (HESS) combining batteries and SC to leverage the best of both worlds:

- A high energy density that provides a longer electric range.
- High power density for enhanced braking and acceleration.
- Long lifespan and efficient operation.

This combination would provide a more efficient, robust, and sustainable driving experience for future hybrid vehicles. Table 5 shows the comparisons between ESS elements for battery and SC.

Table 5: Battery vs supercapacitor: A comparison for HEVs [51]**.**

Feature	**Battery**	**Supercapacitor**
Energy Storage Mechanism	Chemical Reaction	Electrostatic Field
Energy Density	High	Low
Power Density	Low	High
Charging Time	Slow (Minutes to Hours)	Fast (Seconds to Minutes)
Discharging Time	Moderate (Seconds to Hours)	Fast (Seconds to Minutes)
Lifespan	Thousands of Cycles	Millions of Cycles
Efficiency	High (80-90%)	Very High (Up to 98%)
Cost per kWh	Lower	Higher
Self-Discharge	Yes (Slow)	No
Applications in HEVs	Primary energy storage for long electric range	Assisting battery during acceleration/regeneration

5.4 MPPT Comparisons

Various MPPT algorithms are represented by P&O, INC, PSO, and ANN; each has advantages and disadvantages. Selecting the suitable algorithm for an HEV solar panel system requires careful consideration of application-specific needs and priorities. Improvements in MPPT algorithms and control systems will ensure even more effective solar energy harvesting for a sustainable future as HEV technology develops. Table 6 shows comparisons of different types of MPPTs.

Table 6: Comparison of popular MPPT algorithms for solar panels in HEVs [52]**.**

Feature	**Perturb and Observe (P&O)**	**Incremental Conductance (InC)**	**Particle Swarm Optimization (PSO)**	**Artificial Neural Network (ANN)**
Algorithm Complexity	Simple	Simple	Complex	Complex
Operating Principle	Iterative adjustments based on power changes	Compares change in voltage to change in current	Mimics behaviour of swarming particles	Machine learning-based prediction
Implementation Difficulty	Easy	Easy	Moderate	Difficult
Convergence Speed	Fast	Fast	Slower	Variable
Accuracy	Moderate	Moderate	High	High
Computational Resources	Low	Low	Moderate	High
Sensitivity to Noise	Moderate	Moderate	Low	High (during training)
Suitability for HEVs	Good for basic MPPT	Good for basic MPPT	Ideal for high-efficiency applications	Potential for future HEVs

5.5 Powertrains Comparison in HEV

Different needs are met by series, parallel, and series-parallel HEV powertrains. Choosing the best option for a given application requires understanding each configuration's advantages and disadvantages. As HEV technology advances, further refinements and innovations can be expected in powertrain design, offering even greater efficiency, performance, and flexibility for the future of hybrid vehicles. Table 7 shows the powertrain comparison.

Table 7: HEV Powertrain Comparison: Series vs. Parallel vs. Series-Parallel [53]**.**

Feature	Series Hybrid	Parallel Hybrid	Series-Parallel Hybrid
Concept	ICE acts as a generator, and electric motor drives the wheels	ICE and electric motors can independently power wheels	Combination of series and parallel operation
Power Delivery	Electric motor only	ICE, electric motor, or both	Electric motor only (series mode) or both ICE and electric motor (parallel mode)
Efficiency	High at all speeds	Good at low speeds, lower at high speeds	Highest potential efficiency across various speeds
Fuel Economy	Excellent in city driving, lower on highways	Good overall, maintains efficiency at high speeds	Excellent potential for overall fuel economy
Acceleration	Moderate	Strong	It can be excellent, depending on the combined power output
Complexity	Simpler	More complex	Most complex
Cost	Lower	Higher	Highest
Applications	City driving, range-extended EVs	Everyday driving	High-performance HEVs, large vehicles requiring flexibility

6. Conclusion and Remarks

This study has explored various key components and technologies contributing to the efficiency and performance of HEVs. It has been studied energy storage technologies, emphasizing how batteries and SC work together. It looked at several electric motor control strategies, emphasizing how crucial accurate speed control is to good performance. This research focused on MPPT algorithms, which are essential for optimizing the energy obtained from solar panels in HEVs. Finally, various HEV powertrain configurations have been compared, offering distinct advantages and disadvantages. Also, the speed control of the wheel and energy management control are two important factors to study when designing any system. In each of the aspects above, individual interpretations do not depend on the mentioned methods. Instead, they can be added to the systems to make them more accurate and reliable. Two prominent rivals in the electric motor industry are PMSM and BLDC. Both works are well in various contexts, but picking one can be crucial. This review explores these motors' differences, emphasizing torque and speed ripple, starting current, HESS compatibility, precision in tracking torque and speed, and total harmonic distortion.

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مراجعة تكوينات المركبات الكهربائية الهجينة: التطورات والتحديات

الخلاصة: تبحث هذه المقالة في المكونات والتقنيات الرئيسية التي تؤثر على كفاءة وأداء السيارات الهجينة . في أنظمة تخزين الطاقة، ونقارن بين البطاريات والمكثفات الفائقة لملاءمتها للاستخدام في السيارات الهجينة الكهربائية .يتم فحص الدور الحاسم لتقنيات التحكم في المحركات الكهربائية في تعظيم الأداء .بعد ذلك، نقوم بالتحقيق في خوارزميات تتبع نقطة الطاقة القصوى، مع تسليط الضوء على أهميتها في تحسين حصاد الطاقة من الألواح الشمسية المستخدمة في السيارات الهجينة الكهربائية. ستقارن الدراسة سيارات القيادة الهجينة الكهربائية التسلسلية والموازية والتسلسلية الموازية ، حيث تحلل مزاياها المميزة واعتبارات اختيار التكوين الأمثل.تؤكد المقالة أن السيارات الهجينة الكهربائية تستفيد من نقاط قوة كل من المحركات الكهربائية ومحركات الاحتراق الداخلي لتحسين كفاءة الوقود وتقليل الانبعاثات .يعتمد اختيار نظام تخزين الطاقة الأمثل على احتياجات التطبيق الخاصة بكثافة الطاقة وتوصيل الطاقة .تضمن تقنيات التحكم المتقدمة تشغيلًا دقيقًا للمحرك الكهربائي، مما يعظم الكفاءة والأداء .تلعب خوارزميات تتبع نقطة الطاقة القصوى دورًا حيويًا في تعظيم خرج الطاقة الشمسية للسيارات الهجينة الكهربائية .يتأثر اختيار تكوين مجموعة نقل الحركة للسيارات الهجينة الكهربائية بظروف القيادة وأهداف كفاءة الوقود وتوقعات الأداء.

بالنظر إلى المستقبل ، يعد مستقبل السيارات الهجينة الكهربائية بالمزيد من التطورات في جميع هذه المجالات .سيؤدي البحث في البطاريات عالية الكثافة والمكثفات الفائقة المحسنة إلى تحسين قدرات تخزين الطاقة بشكل أكبر .ستؤدي التطورات في خوارزميات التحكم في المحركات إلى تشغيل المحرك الأكثر دقة وكفاءة .سيعمل التعلم الآلي والخوارزميات التكيفية على تحسين دقة وكفاءة تقنيات تتبع نقطة الطاقة القصوى .أخيرًا ، سيصبح تصميم مجموعة نقل الحركة للسيارات الهجينة الكهربائية أكثر تعقيدًا ، حيث يحقق التوازن بين الكفاءة والأداء والمرونة لاحتياجات القيادة المختلفة .من خلال تحسين هذه المكونات والتقنيات الرئيسية ، ستستمر السيارات الهجينة الكهربائية في لعب دور حاسم في تحقيق مستقبل نقل أكثر استدامة وكفاءة.

الكلمات المفتاحية: نظام تخزين الطاقة الهجين، التحكم في الخطوة الخلفية، التحكم في وضع الشريحة، التحكم المعزز في المجال، تقنيات التحكم في السرعة، تتبع أقصى نقطة للطاقة، الاضطراب والمراقبة، التوصيل التزايدي، تحسين سرب الجسيمات، الشبكة العصبية الاصطناعية.