INVITED PAPER

State of the Art and Trends in Electric and Hybrid Electric Vehicles

This article provides insight into the current challenges and breakthroughs in the field of electric vehicles (EVs) and hybrid electric vehicles (HEVs).

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ABSTRACT | Electric and hybrid electric vehicles (EV/HEV) are promising solutions for fossil fuel conservation and pollution reduction for a safe environment and sustainable transportation. The design of these energy-efficient powertrains requires optimization of components, systems, and controls. Controls entail battery management, fuel consumption, driver performance demand emissions, and management strategy. The hardware optimization entails powertrain architecture, transmission type, power electronic converters, and energy storage systems. In this overview, all these factors are addressed and reviewed. Major challenges and future technologies for EV/HEV are also discussed. Published suggestions and recommendations are surveyed and evaluated in this review. The outcomes of detailed studies are presented in tabular form to compare the strengths and weaknesses of various methods. Furthermore, issues in the current research are discussed, and suggestions toward further advancement of the technology are offered. This article analyzes current research and suggests challenges and scope of future research in EV/HEV and can serve as a reference for those working in this field.

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I. INTRODUCTION

Hazardous emissions and greenhouse gases (GHGs) are the side products of the combustion of fossil fuels for energy needs. The emission of GHG is the major cause of rapid climate change, such as global warming and the melting of polar ice. The GHGs are mainly comprised of CO_2, NO_x, CO, and methane [1]. Fig. 1 shows the emission of GHG from various usage sectors and shows that transportation shares almost 14%. Worldwide development and expansion of numerous urban areas have substantially increased the number of vehicles on the road. Of course, this high percentage of transportation GHG is due to the vehicle's internal combustion engine (ICE). Therefore, the decarburization of transportation will eliminate the CO_2 emissions of the transportation sector. This has motivated modern efforts to replace ICE-based vehicles with alternative power plants that are sustainable and clean. Electrifying transportation is one promising approach to solve the above health and environmental problems. Thus, electric vehicles (EVs) have been viewed as a substitute for ICE vehicles. The EV offers the possibility of zero vehicle emissions, lower lifetime cost, enhanced safety, and possible renewable energy. However, the present EV technology is associated with the problems of limited range, high initial cost, and longer recharge time compared with the ICE vehicles. The limited range of EVs may not pose a problem in many metropolitan areas and developing countries. However, the present lack of necessary fast-charging stations poses a barrier to entry even in

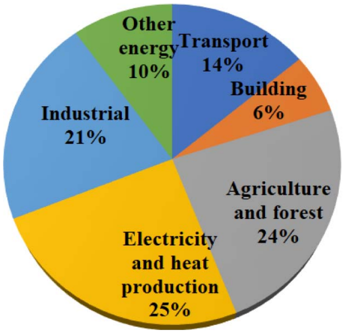

Fig. 1. *Sectors responsible for the emission of GHG [2].*

these suitable areas. One alternative for overcoming the disadvantages of EVs is hybrid EVs (HEVs). The HEV technology can be developed to overcome the aforementioned shortcomings of both ICE vehicles and EVs. The HEV combines the ICE with a battery-powered electric motor (EM), combining the advantages of both for transportation. These include low emissions, high reliability, high fuel efficiency, and long range compared with the ICE or EVs.

Furthermore, the HEV can still recover the braking vehicle kinetic energy, as in the EV. However, the HEV powertrain is more complex compared to the EV or the ICE vehicle [3]. This complexity stems from its components and controls. This article presents an overview of the important components utilized in the HEV powertrain, as well as their architectures, energy management strategies (EMSs), choice of power electronic converters, hybrid energy storage systems (HESSs), and traction motors.

Fig. 2 depicts a system-level design procedure for a high-efficiency HEV powertrain. The first level is the selection of the architecture. There are four major types of powertrain topologies: series, parallel, series–parallel, and complex. This selection plays a pivotal role in designing an efficient powertrain. Details of HEV architecture are presented in Section II. The second level determines the required advanced technology components and their ratings to be integrated into the powertrain.

This level includes the choice of the energy storage system (ESS), EM, and dc–dc/dc–ac converters. The third stage is the selection of the EMS. This is a very crucial aspect as it is responsible for maintaining the operation of each component, and the overall system, in their most energy-efficient region. For example, the EMS is responsible for splitting the power demand between the electrical and mechanical power plants, with the consideration of their efficient operating regions and their various constraints. A well-designed EMS can significantly improve the powertrain fuel economy while maintaining battery health and reducing tailpipe emissions. The EMS adopted should consider the various objectives and constraints so that the design goals can be achieved.

II. BASIC STRUCTURE AND OPERATION OF EV/HEV POWERTRAINS

A. History of EV

The first EV was developed in 1834 [4]. In the 19th century, many companies were attempting to design EVs with more advanced technologies, especially in America, Britain, and France. However, the technology limitations in batteries and rapid advancement of the ICE vehicle lead to the demise of EVs by the 1930s. By the beginning of the 21st century, intense interest in zero-emission vehicles (ZEVs) resulted in renewed interest in EVs. Several EV products have become available since that time.

B. History of HEV

In 1898, German Dr. Ferdinand Porsche fabricated the first HEV, named Lohner Electric Chaise. Porsche utilized an ICE to drive the generator that gave power to the traction EM. This HEV was capable of moving almost 40 mi on battery alone.

Krieger Company in 1903 made an HEV by using the gasoline-based engine to charge a battery pack. Based on Pieper patents, commercial vehicles were built from 1906 to 1912 by a Belgium firm [4].

In 1904, Henry Ford addressed the problems related to ICE, such as noise, vibration, and foul smell and produced inexpensive, lightweight, and hybrid vehicles. Henry Ford's production of HEV had ceased by 1920.

In 1905, H. Flute (American) filed a patent for a petroleum EV. He proposed to use an EM to assist the ICE by

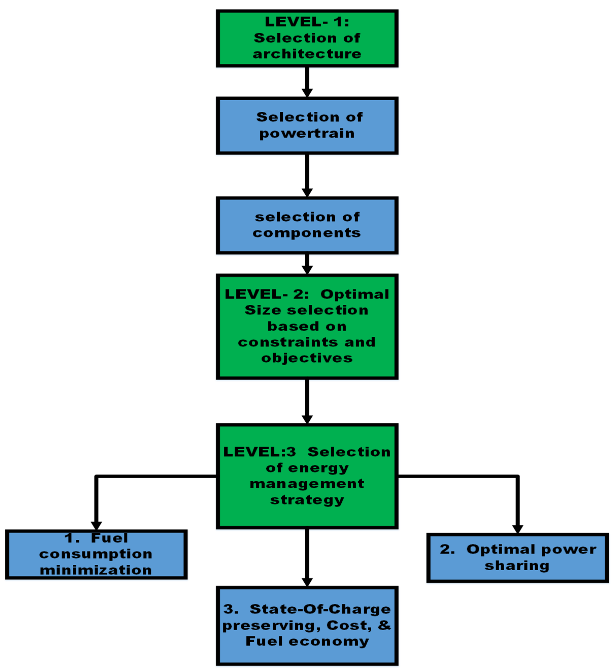

Fig. 2. *Flow chart system-level design of HEVs.*

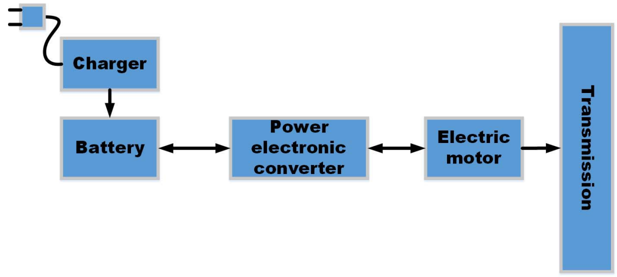

Fig. 3. *EV architecture.*

which he was able to achieve 25 mi/h. Other attempts were made in the 1970s in producing consumer HEVs.

In 1997, the first modern HEV was developed by Toyota, named Prius. This attracted new interest in this technology. Honda Insight was the next HEV introduced in the United States. Since then, almost every other auto manufacturer has introduced an HEV in their line of products [5], [6].

C. Scope of HEV

The worldwide annual sale of HEVs reached 1.6 million units by the year 2018. It was estimated that these numbers will rise to two million in the year 2019, seven million by 2020, 30 million by 2030, and 100 million by 2050 [7].

D. Architecture of EV

The EV powertrain mainly consists of an electric traction motor, its associated power electronic converters, an ESS, and the powertrain controller [8]. In EVs, the power electronic converters are of two types, i.e., the dc–dc converters and the dc–ac converters. The energy storage can be of one or a combination of electrochemical battery, fuel cell, and flywheel [9]. The control system is an essential part of the EV and controls the various energy resources at various driving conditions. The battery is usually charged from the utility grid using a battery charging unit that can be placed onboard or at the charging station. The basic architecture of the EV powertrain is shown in Fig. 3.

E. Architectures of HEV

The HEV powertrain consists of two or more power plants. The ICE is the primary source of energy, responsible for producing most of the vehicle energy and long driving range, while the EM is the auxiliary source, responsible for high-vehicle-power demands and fuel economy of the ICE. The EM charges the batteries from the excess power from ICE when not needed by the vehicle and also from the regeneration of vehicle kinetic energy. The design and control of such powertrain require advanced control algorithms and EMS, which optimizes many objectives, such as the ICE fuel economy and the state of charge (SoC) of the batteries, with the system and driving constraints. The HEV system architecture consists of a drive train, ESS, and a controller unit. The integration of these components gives rise to various HEV configurations that are summarized as follows [7].

1) Series HEVs: In the series configuration, the EM is responsible for providing the main traction force for the propulsion of the vehicle. The ICE power is used to charge the batteries by a generator. The ICE–generator pair can also directly drive the traction EM without charging/discharging the battery. There is a benefit of traction flexibility by electrically decoupling the ICE from the drive shaft in this configuration, such as in diesel–electric locomotives.

Operation modes of the series configuration may be described as follows.

1) In the starting, both, the ICE and the EM deliver power for propulsion.
2) At light load, the ICE output is higher than required for the vehicle propulsion. This excess energy is used to charge the batteries.
3) During deceleration, the EM acts as a regenerative generator to charge the batteries.
4) At standstill, the ICE may be used to charge the batteries via the generator.

The series HEV can be considered an EV with an ICE battery charger, which gives the advantage of EV with extended driving range. The series configuration has the disadvantage of having the ICE, the generator, and the EM to drive the vehicle resulting in multiple mechanical–electrical–mechanical high-power conversions, with their associated conversion inefficiencies. This configuration is suitable for long-range and heavy vehicles, such as locomotives, with possible secondary electrical loads, such as in military vehicles. Therefore, they are inherently large and expensive to address their high-power requirements. The series HEV can also give better performance in stop and go driving, such as city busses and large urban vehicles [10]. Fig. 4(a) depicts a series-HEV configuration. The series HEV can have six different operation modes.

1) ESS alone.
2) ICE alone.
3) *Combined Mode:* Both ICE–generator set and the battery provide propulsion power.
4) *Power Split Mode:* The ICE–generator provides power to drive the vehicle and charge the batteries.
5) Stationary battery charging mode.
6) Regenerative braking mode.

2) Parallel HEV: In the parallel HEV configuration, the ICE and EM can additively supply power to drive the wheels. The ICE and EM are coupled to the drive shaft employing two clutches. The traction power is provided by either ICE or EM, or both. The EM can also serve as a generator, where it can regenerate the vehicle decelerating energy or be driven from the ICE when it powers in excess of that required to drive the wheels [11]. Thus, the parallel configuration has two propulsion power sources: the ICE

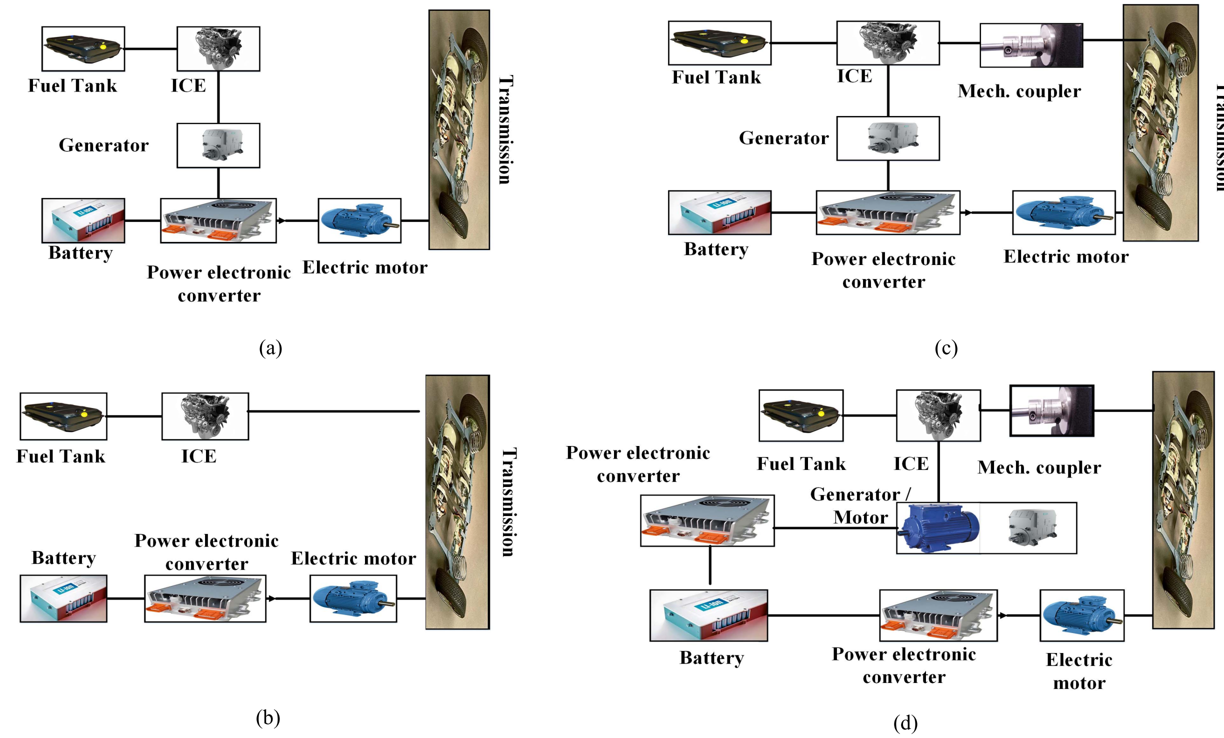

Fig. 4. ***Various architectures of an HEV. (a) Series hybrid. (b) Parallel hybrid. (c) Series–parallel hybrid. (d) Complex hybrid.***

and the EM. One advantage of this over the series configuration is smaller power ratings of these components, especially the EM, and the electromechanical power losses can be less. However, the parallel HEV can be less suitable for frequent stop-and-go urban driving conditions [12]. Fig. 4(b) depicts a parallel configuration of the HEV.

Some operation modes of the parallel HEV are as follows.

1) EM alone.
2) ICE alone.
3) Combined ICE-EM.
4) *Power Split:* The power of ICE is split to drive the vehicle and charge the battery (EM becomes generator).
5) Stationary charging.
6) Regenerative braking.

One other variation of the parallel HEV is called through-the-road (TtR) HEV where ICE drives the front wheels, while the EM drives the rear wheels.

Operation modes of the parallel configuration may be described as follows.

1) At the starting or full-throttle acceleration, both ICE and EM provide the power for vehicle propulsion. Typically, ICE and EM power sharings are 80% and 20%, respectively.
2) During normal driving, the ICE supplies the propulsion power, and EM remains at standby.
3) During deceleration, the EM behaves as a regenerative generator and charges the battery.
4) Under light-load conditions, the ICE provides propulsion power and also charging power for the batteries through the EM that works as a generator.

3) Series–Parallel HEV: The series–parallel configuration of HEV (power-split HEV) incorporates the advantages of both series and parallel HEVs. This configuration has the advantage of smaller size ESS and EM compared to the series and smaller ICE compared to the parallel configuration [13]. Furthermore, the series and parallel modes are better efficient at low and high speeds, respectively. However, it suffers from higher system complexity and the addition of a planetary gear. Fig. 4(c) depicts a series–parallel HEV configuration.

Being the hybrid system, a number of operating modes are feasible and are classified into two main categories: the ICE dominated and the EM dominated [14]. Table 1 summarizes the operating mode.

4) Complex HEV: As the name suggests, this configuration is complicated. The complex HEV is similar to the series–parallel HEV, with the critical difference of having an additional bidirectional converter. The bidirectional converter provides for bidirectional power flow in the EM. This bidirectional power flow can provide for versatile operating modes, such as the combined ICE and two EMs. This configuration suffers from complexity and its associated costliness [4]. Fig. 4(d) depicts the complex configuration of HEV.

Operation modes of the complex configuration may be described as follows.

Table 1 Summary on ICE and EM Operating Modes for Series–Parallel HEV [15]

	ICE dominating		EM dominating	
Modes of operation	Power for traction	Off condition	Power for traction	Off condition
At the starting	EM + BAT	ICE	EM + BAT	ICE
Full throttle acceleration	ICE +EM (ICE dominating)		ICE +EM (EM dominating)	
Normal driving	ICE	EM	ICE +EM	
Braking or Deceleration	EM acts as a generator to charge the batteries.		EM acts as a generator to charge the batteries	
Battery charging during driving	ICE and it also drives the generator to charge the batteries.		ICE and it also drives the generator to charge the batteries.	
Vehicle is at standstill	ICE drives the generator to charge the batteries		ICE drives the generator to charge the batteries	

1) During startup, the required traction power is delivered by the EMs, and the engine is in the OFF-mode.
2) During full-throttle acceleration, both the ICE and the EMs deliver power.
3) During normal driving, the ICE delivers power to the front wheel and to the first EM to charge the batteries.
4) During driving at light load, the first EM delivers the required traction power to the front wheel. The second EM and the ICE are in the OFF-state.
5) During braking or deceleration, both the front and rear wheel EMs act in combination as regenerative generators to charge the batteries [16].

F. Architecture of Fuel Cell Electric Vehicle (FCEV)

The FCEV uses a hydrogen FC power plant. These vehicles are environmentally friendly, as power is produced by a chemical reaction between hydrogen and oxygen to produce water as the only emission [17]. Hydrogen is used as the energy source, being economically, societally, environmentally, and climatically sustainable and readily available in the water. They have a long driving range and short refueling time. The FCEV is very fuel-efficient compared to the ICE vehicles. There have been several pilot projects launched, but FCEVs have their own set of challenges, including hydrogen safety concerns. Of course, if hydrogen is produced by fossil-fueled energy sources, most of the FCEV advantages disappear.

The architecture of FCV has two variants. The first is the basic FCEV, which has the same architecture as the EV. Another variant is the fuel cell hybrid electric, FCHEV. This variant has another ESS assisting the FC. The ESS can be batteries or UC. As in the parallel hybrid, the FC acts as the main energy source. The architectures of FCEV and FCHEV can be seen in Fig. 5.

G. Architectural Summary

The choice of architecture depends on the vehicle application and the component technologies. Table 2 shows the comparison of architectures with some of their characteristics.

III. HYBRID ENERGY STORAGE FOR HEV

The HEV HESS is a combination of two or more energy storage technologies. The main objective of HESS is to combine *the* high energy density of one storage technology with the high power density of another. The end result can be higher combined power and energy density of the storage system, better vehicle performance, better fuel economy (HEV), and longer range (EV).

A. HESS With Ultracapacitors and Batter

The energy source is the heart of EVs. Electrochemical batteries are the primary sources for EVs. However, the present-day battery technology does not adequately meet the vehicle for the high power, low cost, and high volumetric and weight energy densities [18]. Batteries also fall short in the required high charge/discharge power capabilities. Furthermore, the life span of batteries is inadequate at a high charge/discharge rate. However, the ultracapacitors (UCs), characterized by high power density (about 5–10 kW/kg [19]–[21]), can provide high peak power and currents (up to 100 A) quickly at high efficiency and reduce the acceleration time substantially [22]. However, the UCs cannot store a large amount of energy. Therefore, a promising solution may be to combine batteries with UCs forming an HESS. This can supply a high burst of power and also store enough energy to ensure an adequate driving range. Further hybridizing batteries with UCs will reduce the strain on the battery pack and potentially improve acceleration and hill-climbing performance. The UCs can also assist the battery in capturing regenerative braking energy with their fast-charging capability [23].

There can be various topologies of UC and battery combinations, as summarized in Fig. 6. Fig. 6(a) shows the passive battery and UC configuration. The UC is connected in parallel with the battery to improve the system power capability. The dc-link voltage is kept almost constant using

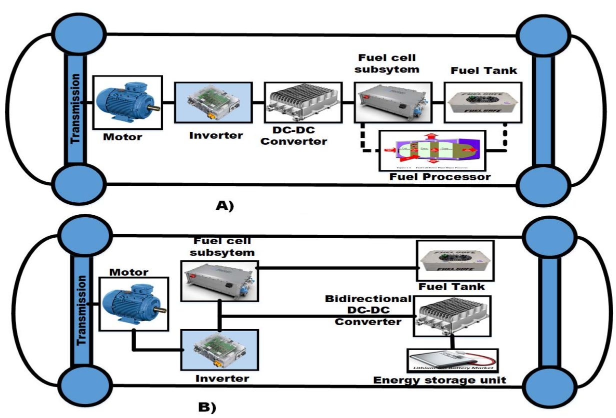

Fig. 5. *Various architectures of (a) FCEV and (b) FCHEV powertrains.*

Table 2 Comparison of Architectures

Parameters	Conventional	EV	Series Hybrid	Parallel Hybrid	Series- Parallel Hybrid	Complex
Control complexity	NA	Simple	Medium	Medium	Complex	Very complex
Weight(kg)	Very low	High	Medium	Low	Low	Medium
NOx (g/Km)	High	NA	Medium	Low	Low	Low
CO(g/Km)	High	NA	Medium	Low	Low	Low
HC	High	NA	Low	Medium	Low	Low
Fuel consumption (Km/l)	High	NA	Medium	Medium	Low	Lowest
Manufacturing energy supplied or depleted (MJ)	NA	Low	Medium	High	High	High
Loss	High	Low	High	Moderate	Low	Low
size	Bulky	Low	Bulky	Moderate	Small	Small
Efficiency	Low	High	Low	Moderate	High	High
Complexity	Low	Low	Low	Moderate	High	High
Application of hybridization	NA	NA	Full HEV and Plug-in HEV	Micro, Mild and Full HEV	Full HEV and Plug-in HEV	Full HEV and Plug-in HEV

a bidirectional dc/dc converter. Furthermore, $V_{\text{battery}} = V_{\text{UC}} \neq V_{\text{dc-link}}$. The major drawback here is that it cannot utilize the UC stored energy effectively. Fig. 6(b) represents the active battery and UC combination. This combination employs the power electronic interface. In this case, $V_{\text{UC}} < V_{\text{battery}} = V_{\text{dc-link}}$. This configuration boosts the peak power, but it suffers from frequent battery charging and discharging operations, and regenerative energy is not effectively stored by the UC. Fig. 6(c) represents the active battery and UC configuration. In this case, $V_{\text{battery}} < V_{\text{UC}} = V_{\text{dc-link}}$, enabling the use of a smaller battery bank and its associated cost since the dc-link is directly connected to the UC and its voltage fluctuations. Fig. 6(d) shows active UC-battery configurations with two converters. The UC can deliver 100% of its stored energy, $V_{\text{battery}} \neq V_{\text{UC}} \neq V_{\text{dc-link}}$. Due to the presence of the boost converter, the battery current variations are moderate, and the stress on the battery is reduced [24]. Fig. 6(e) shows a multiple-converter configuration. This configuration employs separately controlled dc–dc converters to

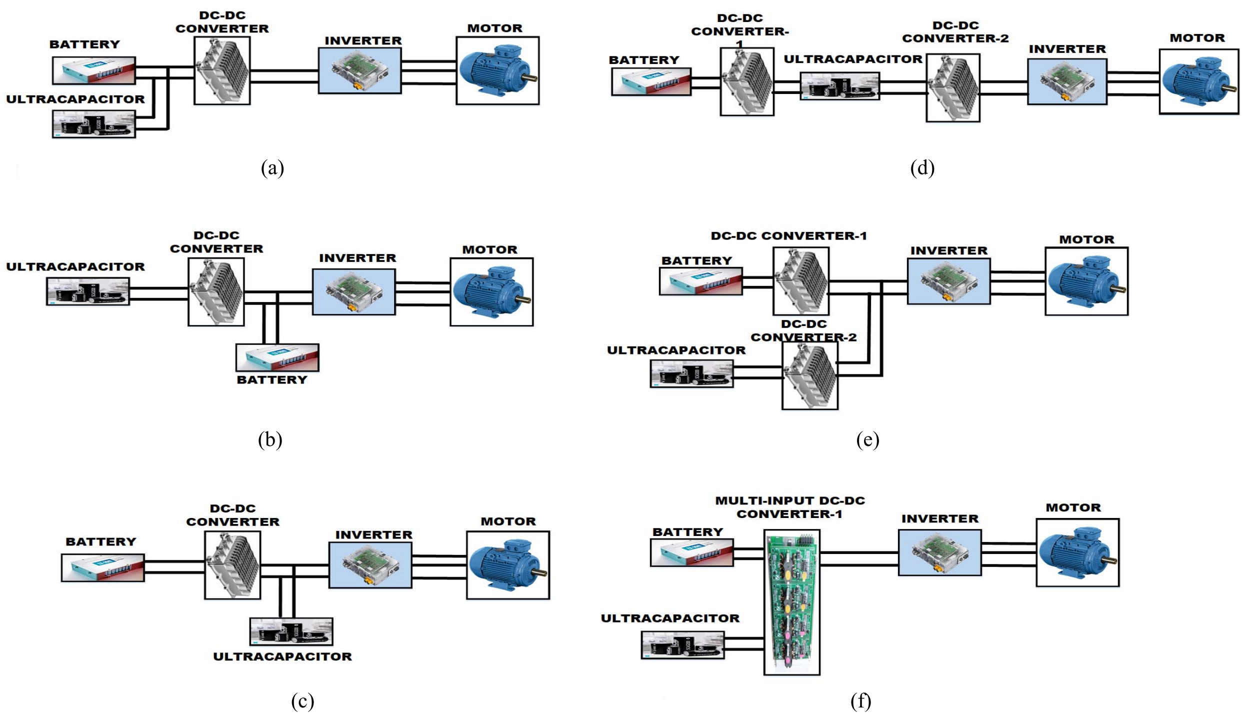

Fig. 6. *Various topologies for UC and battery combined HESS. (a) Passive cascade battery/UC configuration. (b) Active cascade UC/battery configuration. (c) Active cascade battery/UC configuration. (d) Passive cascade with two-dc–dc-converter configuration. (e) Multiple-dc–dc-converter configuration. (f) Multi-input-dc–dc-converter configuration.*

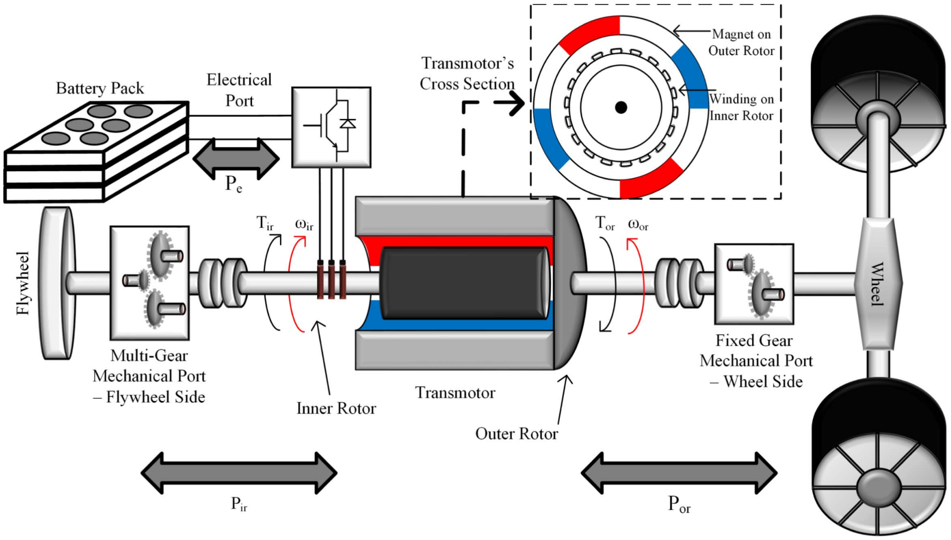

Fig. 7. ***Transmotor hybrid energy storage [15].***

connect the energy sources to the dc-link. In this case, $V_{\text{battery}} \neq V_{\text{UC}} \neq V_{\text{dc-link}}$. The main problem with this configuration is that it requires two fully rated converters. This increases the size and cost. Fig. 6(f) represents a multi-input converter configuration. This topology reduces the cost of a multiple-converter configuration. All drawbacks of the abovementioned topologies may be prevented in this configuration. In this structure, $V_{\text{battery}} \neq V_{\text{UC}} \neq V_{\text{dc-link}}$. In order to reduce the cost and weight and enhance the overall performance, this topology may be preferred for an efficient HESS [25]–[27].

B. Hybrid Battery-Flywheel Energy Storage

The transmotor-based powertrain was proposed to address some of the energy and power density limitations of the battery ESSs in EVs and HEVs. This powertrain consists of a lightweight flywheel, rotating at subcritical speeds, as a power buffer between the batteries and the drive shaft, coupled to a transmotor and the wheels. One variation of the transmotor is shown in Fig. 7. The transmotor is a specialized electric machine with two independent mechanical drive shafts (mechanical ports) and an electrical port. The mechanical torque, speed, and power of the two shafts can be quite different, with the balance of power being met by the electrical port. One main feature of the transmotor is that the mechanical power throughput, from one shaft to the other, can be much higher than the electrical ratings of the machine, its power electronics, and the associated batteries [28].

Some advantages of the transmotor-based powertrain may be summarized as follows.

A transmotor-based powertrain can recover and resupply most of the vehicle kinetic energy without electrical conversion, thus improving vehicle performance and energy efficiency.

The mechanical power rating of the transmotor far exceeds its electrical rating, thus, reducing the power ratings of the vehicle batteries and power electronics.

The transmotor can be applied to both EV and HEV drive trains to improve range, performance, efficiency, and battery size.

C. Issues and Challenges of HESS in HEV Applications

The critical issues and actions for the advancement of EV and HEV energy storage applications can be listed as follows [29]:

1) availability of the necessary raw materials and their proper disposal and recycling;
2) energy and power management of the multiple storage systems;
3) application of advanced power electronic devices and systems;
4) cost, size, and safety advantages.

D. Technological Advancement in the Field of HESS

The FC, UC, and battery can be used in an HESS system, but it may increase the cost and size of the storage system. The use of a small flywheel, in combination with a transmotor, may mitigate this problem while enhancing vehicle performance. However, at present, the UC/battery topology is the most commonly considered.

E. Suggestions and Recommendations

The HESS design is highly dependent on their constituent storage technologies. The followings are some related considerations.

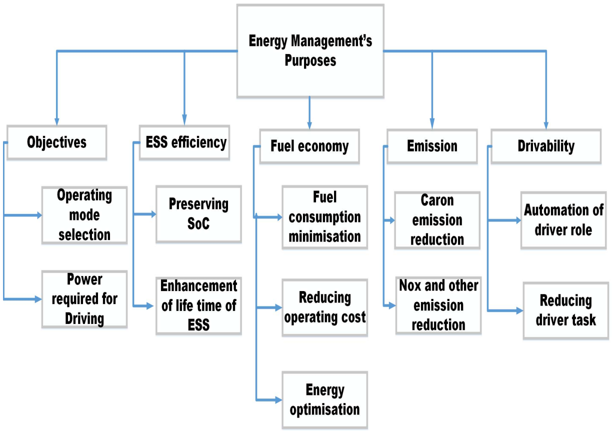

Fig. 8. ***Block diagram of EMS objectives.***

1) Hybridization must be done on the basis of complementary storage characteristics, including life cycle issues.
2) Storage hybridization is done mainly on the basis of combining the high energy density of the primary storage with the high power density of the secondary storage.
3) Specialized power electronic devices and circuits need to be used to optimize the HESS performance.
4) Fast and optimized control algorithms need to be used for energy and power management of HESS.

IV. VEHICLE CONTROL OPTIMIZATION STRATEGIES

The HEV is a nonlinear dynamic system with many objectives, such as improved fuel economy, response to road and driver demands, and reduction in emissions. The energy management system (EMS) is responsible for this task. Hence, the selection of the EMS is critical for efficiently supplying the power train, providing the required drivability, and preserving the battery SoC and state of health in the ESS, subject to various system and road constraints and limitations. Fig. 8 depicts a block diagram of various objectives of an EMS.

Many optimizations of the EMS have been proposed by researchers to control the flow of energy in HEV [30], [31]. However, a general configuration is shown in Fig. 9. Classification of EMS includes three major groups: rule-based, optimization-based, and learning-based.

A. Rule-Based EMS

The rule-based EMS (RB-EMS) can further be classified by deterministic and fuzzy-logic, as discussed in the following.

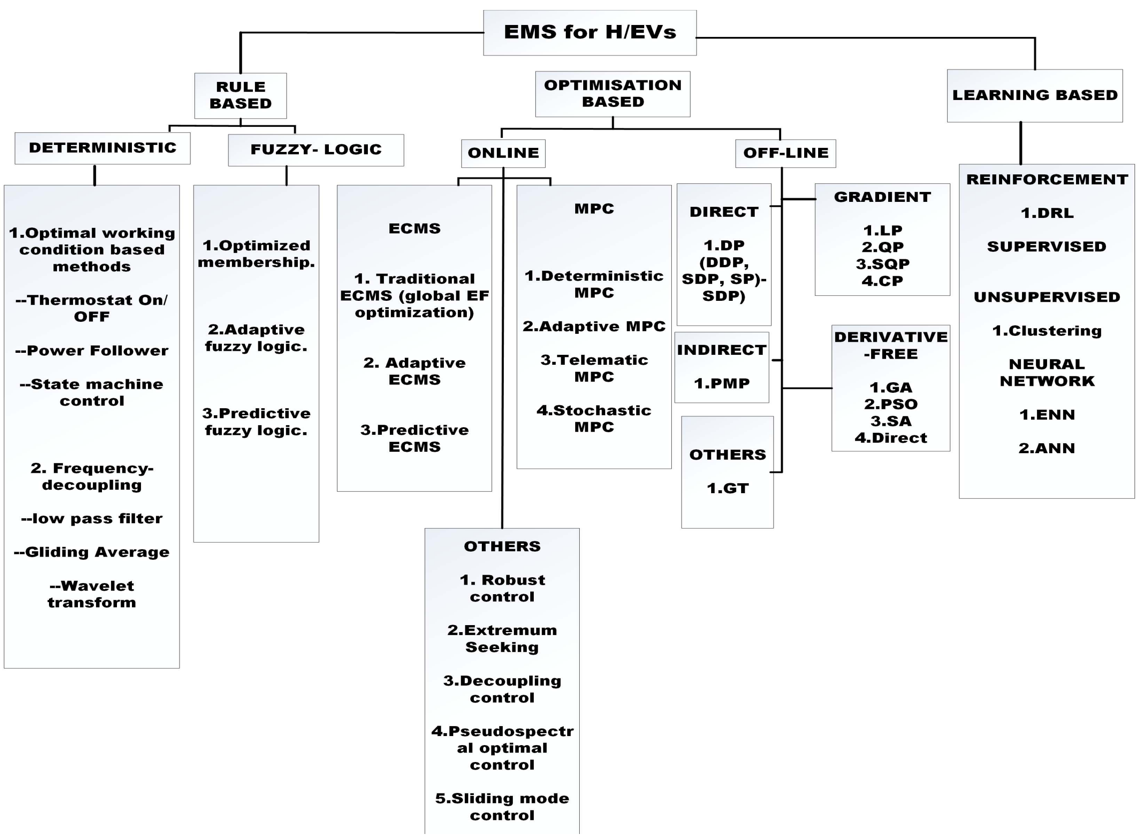

Fig. 9. ***Classification of various EMS.***

1) Deterministic Rule: The rules are designed to improve fuel economy and minimize transmission losses and emissions based on the mapping of ICE and EM efficiency regions. These rules are based on experience and the optimal operating points. The deterministic rule can further be classified as optimal working condition-based strategies and frequency-decoupling methods. These are explained as follows.

a) Optimal Working Condition-Based Strategies:

*Thermostat (*ON/OFF*) strategy:* This utilizes the generator and ICE to produce electrical energy. This method maintains battery SoC between predefined upper and lower limits at all times. However, it suffers from the drawback of not being able to supply the needed power to the vehicle in all modes. This strategy is mainly used in the series HEV and during city driving, requiring frequent start–stop cycles [32]–[35].

Power follower strategy: This strategy is also called the baseline strategy. It utilizes the generator and the ICE as the primary power sources. The controller responds to the driver's power demand. The rules of this strategy are built by heuristics and human intelligence.

In this technique, the EM only works as an auxiliary power source. The ICE and the generator work as the primary sources, and the EM only aids the ICE. This is used in series and parallels HEV [36], [37].

State machine (multimode) strategy: This strategy operates over a certain given state of the vehicle through an algorithm based on the decision tree of the stable conditions. This strategy works with various modes of operation, such as ICE only mode, where only the ICE propels the vehicle, boost mode where both the ICE and the EM provide the driving force, and the charging mode, where the ICE charges and propels the vehicle, simultaneously. This strategy is also known as the multimode strategy [38], [39].

b) Frequency-Decoupling Method: In this strategy, the frequency of the load demand is divided into low- and high-frequency components. The frequency decoupling takes place by means of a low-pass filter, high-pass filter, a gliding average strategy, and wavelet transform [40]. The high-frequency component is fed into the fast-acting power sources, and the low-frequency components are fed into the slow-acting sources [41]–[44].

2) Fuzzy Logic Strategy: This strategy is based on the if-then rule. The efficiency of this strategy is dependent on the selection of the membership function and the precise formation of fuzzy rules. The rule formation depends on the reasoning of the human. The advantage of this method is its robustness, irrespective of the mathematical model and its high adaptability [45]. The fuzzy logic can be divided into three categories, as follows.

a) Optimized-Fuzzy-Rules' Control: Fuzzy logic, when tuned by an optimization algorithm, is called optimized fuzzy. The membership function in optimal fuzzy normally gets optimized by an algorithm, such as a divided rectangle (DIRECT), particle swarm optimization (PSO), the genetic algorithm (GA) [46], and the bee algorithm [47]. This strategy is used to reduce fuel consumption, reduce emissions, maintain the battery SoC, and improve driving performance.

b) Adaptive Fuzzy Logic Control: This strategy has the capability of self-adaptation. This strategy is formed by a combination of the artificial neural network and fuzzy logic. The adaptive neural fuzzy interference system can maximize the fuel economy and maintain the SoC. This needs prior knowledge or data on the basis of which it takes actions [48]–[51].

c) Predictive Fuzzy Logic Control: This strategy predicts the state of the power train and acts in real time. This procedure uses the global positioning system (GPS) to track the vehicle and to determine the length of the trip

In this strategy, the information regarding the trip is already known [52], [53].

B. Optimization-Based EMS

The optimization-based EMS continuously searches the optimal solution based on its objective function and the constraints provided. The objective functions may get maximized or minimized based on the logic provided. However, the main objectives of the cost function are to minimize fuel consumption, reduce emissions, and preserve the battery SoC [54]. This has a dependency on prior information and data from the drive cycle. This optimization-based EMS can be categorized by off-line and online strategies.

1) Online Strategies: An online strategy neither requires prior information about the driving cycle nor assures optimized solutions for real-time adaptation. An example of an online learning strategy is the equivalent consumption minimization strategy (ECMS) and model predictive control (MPC) [55]–[57].

a) Equivalent Consumption Minimization Strategies: The ECMS is basically an off-line PMP. It can be used in the parallel HEV for operation under charge-sustaining conditions. In this algorithm, the PMP is reorganized into a local optimization by minimizing the equivalent fuel consumption. This strategy also recuperates barking energy. The ECMS can be categorized by two groups: 1) off-line estimation to determine the optimum fuel economy over a constant drive cycle and 2) online estimation, which needs full information regarding the driving cycle, as in the case of the dynamic programming (DP) [58], the GA, the shooting, and the adaptive ant colony optimization. The online equivalence factor estimation considers certain factors, such as: 1) the SoC levels; 2) the current direction of charging and discharging of the ESS; and 3) the data related to the driving conditions. The ECMS has been used as an EMS in the MPC-based strategies [59].

b) Model Predictive Control-Based Strategies: The MPC is an advancement over DP. In DP, all prior information is required, such as the road conditions, the vehicle state, and length of the trip. However, it seems quite impractical to obtain such data.

2) Off-Line Strategies: This EMS is noncasual and provides a global solution, but it needs prior information from the drive cycle. The power flow paths are different in different topologies. For example, in the series HEV configuration, the optimization can consider the energy required by the vehicle as a cost function, whereas, in the parallel HEV, the optimization may consider the fuel consumption minimization as a cost function. The constraints are usually the power demand, battery SoC, and drivability. The algorithm finds a global solution for gear shifting sequence or a power split between the ICE and the EM.

a) Direct Algorithms: A commonly used algorithm in EMS for optimization is DP. Since this DP requires prior information about the drive cycle, it is also known as deterministic DP (DDP). A suitable cost function is framed at each step. The major problems with the DDP are: 1) extensive computation time; 2) dimensionality curse; and 3) prior information of the drive cycle. Because of these shortcomings, the DDP is an unsuitable candidate for real-time implementation [60], [61].

b) Indirect Algorithms: A well-known indirect algorithm is the Pontryagin minimum principle (PMP). The PMP provides the optimal solution by satisfying the necessary conditions using the Hamilton–Jacobi–Bellman equation. The main feature of the PMP is its capability to condense a global optimization into a local Hamiltonian minimization problem [46]. The Hamiltonian is characterized by a weighting factor. The optimal value can be determined by an iterative process with various drive cycles. The PMP has the drawback of large computation time and the problem of dimensionality [62], [63].

c) Gradient Algorithms: In order to decrease the computation time and make the optimization solution more robust, gradient algorithms are used. Such procedures use the derivative of the cost function, under specific conditions, such as differentiability and Lipschitz condition, to solve the optimization problem.

The gradient-based algorithm can be categorized into linear programming (LP), quadratic programming (QP), sequential QP (SQP), and convex programming (CP). The LP algorithm is used for optimization problems when the objectives and constraints are linear. The QP is used when the objective is quadratic, the constraints are linear, and the CP is used for convex objective and concave inequality constraints. In the LP, the optimization problem is framed as convex nonlinear, and the constraints are derived through a set of linear matrix inequalities. In the QP algorithm, a quadratic cost criterion, subject to linear constraints, is formulated. In the CP technique, simplified vehicle models are considered to simplify the complex convex nature of the optimization function. Therefore, the HEV is modeled in a quadratic order of equations [64], [65].

d) Derivative-Free Algorithms: The derivative-free algorithms (DFAs) are very efficient and useful when the derivatives are not available or impractical to derive. The DFA is able to transform the solution to a global optimum, unlike the gradient algorithms that provide local solutions. The DFAs reported in the literature are the simulated annealing (SA), the GA [66], the multiobjective GA (MOGA), the PSO, and the DIRECT algorithms [67]. This strategy is basically a stochastic technique, only considering the best candidates and providing solutions based on the objective function. However, due to its stochastic nature, the SA method cannot guarantee a global optimum. Moreover, repeated annealing causes the algorithm to be computationally slow. To address these shortcomings, many engineers have used SA in ensemble with complementary algorithms, such as the RB, the PMP, and the GA.

Particle swarm optimization: This optimization method is an empirical search algorithm based on an iterative process that moves particles throughout the search space over a numerical function of the particle's position and velocity. This is a quick, inexpensive, stochastic global method of optimization. The PSO algorithm can accurately determine the direction and magnitude of the energy flow in the HEV and result in the smooth operation of the main powertrain components. The PSO has been used alone or fused with other strategies to form the EMS for HEV applications [68], [69].

Genetic algorithm: The GA begins with a set of solutions (analogous to chromosomes) called a population. The obtained solutions are chosen based on a fitness function. The most appropriate solutions are selected, and the least preferred is rejected, while the process continues. This algorithm has the ability to optimize the parameters quickly [70], [71].

e) Other algorithms: Recently, a new algorithm, called game theory (GT), has been applied to the EMS for Jaguar Land Rover HEV and FCHEV. In noncooperative GT, the drivers manually try to optimize their driving method to obtain high fuel economy and low emissions [72].

C. Learning-Based EMS

The learning-based EMS (LB-EMS) needs in-depth data analysis from real-time information to obtain the optimal solution. In the LB-EMS, precise data are not required. However, it is tedious and consumes more time to provide a solution. It is a totally data-driven method and depends on the machine learning ability as well [73].

1) Reinforcement Learning: The reinforcement learning (RL) algorithm is based on two components: a continuously interacting agent and the environment. The agent continuously interacts with the environment to fetch the information of the model at every instant. Based on the collected information, the agent takes action, which is fed as an input to the environment. The action plan of the agent is derived from the control policy adopted. Hence, the optimal policies guide the agent to perform actions to maximize the reward over time, which can be learned through an adequate amount of training. The RL-EMS

Table 3 Summary of the EMS

Algorithm	EMS	Advantages	Major challenges
Rule-based	Deterministic	-simplicity	-Low fuel economy
	FL	-Robustness, adaptive and predictive	-Different cycle needs different control parameter for controlling parameters
Offline optimization	DP	-Global optimization	-Curse of dimensionality -Prior knowledge of driving cycle -High computational cost
	PMP	-Global optimization control	-Complex mathematical modelling -Requires approximations to reduce computational burden
	Gradient	-High computational speed	-Complex model simplification -Complex mathematics -Required derivative information of the cost function
	Derivative free	-Avoid the possibility of local minima.	-Optimal solution is not the guarantee -Limited iteration
	GT	-Trade-off between conflict objective	-Computational burden -Curse of dimensionalities
Online optimization	ECMS	-Work in online mode. -Optimization based on one objective function.	-Affinity to Local optima
	MPC	-Adaptability and high predictive capability -Less computational burden -Solution close to global optimization	-requirement of prior cycle information
	Robust control	-Robust to parametric uncertainties	-Mathematics complexity
	Sliding Mode	-Robust to uncertainty and parameter fluctuations	-Complex mathematical modelling
Learning-based	Reinforcement learning	-Model-free control	-Cumbersome data collection and processing method
	NN	-Learning and adaptive capabilities	-Data need to be pre-processed before fed to NN -Uncertain contours of the training space

has been used for the series HEV, PHEV, and the parallel HEV [74], [75].

2) Supervised Learning: In supervised learning, the algorithm trains the data for the model to make correct predictions and approximation. The training continues until the desired accuracy is obtained. This EMS is basically an error-correction method with a continuous learning approach. The training data are fed into the control algorithm for calculation with the desired parameters to emulate the desired performance [76].

3) Unsupervised Learning: Unsupervised learning is based on extracting general rules from a mathematical method to decrease redundancy and organize data. The input data can have an objective function for minimization [77].

4) Neural Network Learning: Neural network learning (NNL) connects multiple neurons into sequential layers, thus forming a network. A large variety of behavior can be designed. It is basically an emulation of the human brain. The algorithm adjusts parameter weights to give the desired output. The Elman neural network (ENN) has been used to maintain the battery SoC [78]. Furthermore, a backpropagation neural network has been used for the HEV [79], [80].

5) Technological Advancement in the Field of EMS: Vigorous research is going on in new EMS controls with new results expected soon. New EMSs, such as the elephant herding optimization algorithm, the bee algorithm, and the grey wolf algorithm, are being introduced that can produce global optima and hence better fuel economy.

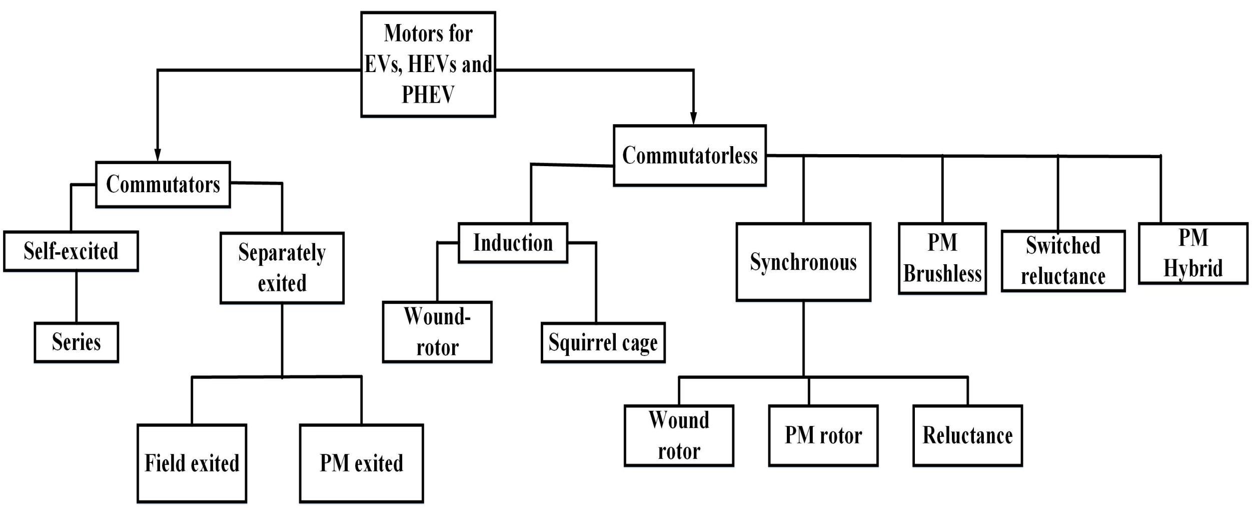

Fig. 10. ***Classification of EM for HEV applications [83].***

Table 4 Comparison of Five Most Widely Used EMs for EV/HEV Application

	Brushless DC	Series Motor	PMSM	Switched Reluctance	Induction Motors
Type	AC	DC	AC	DC	AC
Family	Synchronous excited PM	Commutator, Separately excited	Separately excited	Synchronous unexcited	Induction slip ring squirrel cage
Power to rotor	PM	DC	PM	Induced	Induced
Power to stator	Pulsed dc	DC	AC	Pulsed dc	AC
Overall cost	High	Low	High	Medium	Medium
Weight	Low	Heavy	Medium	Medium	Medium
Commutation method	Internal electronic	Mechanical Commutation	External electronic	External electronic	External electronic
Controller cost	Very high	Low	High	High	High
Pros	Good torque and Speed, fast responses, Tremendous power, Long life	Inexpensive can use field weakening, maintains constant speed, higher starting torque	No torque ripple, Higher torque, better performance, more reliable and less noisy	Low inertia, can be Tailored for specific Applications, runs cool	High efficiency
Cons	expensive	Requires Maintenance, Bulky, Limited Rotation Speed, Requires large windings in field	Complex control system, costly	Requires position Sensing	Complex controller
Maintenance requirement	Negligible	Brushes wear	Negligible	Negligible	Negligible
Speed control method	Frequency-dependent	PWM or Field weakening	PWM	Frequency-dependent	Frequency Dependent
Starting torque	>175% of rated	>175% of rated	>200% of rated	Up to 200%of rated	High
Speed range	Excellent	Limited by brushes, easy control	Controllable	Controllable	Controllable
Efficiency	High	Low	High	Less than PMDC	High
Application	HEV, EV & vehicle	HEV, EV & vehicle	HEV, EV & vehicle	Vehicle	HEV, EV & vehicle
%Efficiency with motor only	80	80	97	94	90
%Efficiency with electronic only	98	85	93	90	93
%Efficiency with motor &electronic	78	78	90	85	84
Examples	Peugeot-citrigen/berlingo (psa) (France)	Indian railways	Nissan/tino,honda/insight (Japan), Toyota Prius (Japan)	Holden/ecommodore (Australia)	Renault/kangoo (France),chevrolet/silverrado (USA)

These algorithms have not yet been validated for the HEV application but work proceeding in this direction.

6) Summary of EMS: The various EMS controls are summarized in Table 3. The algorithms that can result in driver comfort, high fuel economy, and smooth performance of the vehicle seem to be the online optimization and the learning-based algorithms.

V. TRACTION MOTORS

The sizing of the electric traction motor, EM, is a crucial factor in the design of the HEV powertrain for reducing fuel consumption and meeting the performance requirements. The ratio of maximum EM power to the ICE power may be characterized by the hybridization factor (HF) and defined as

$$\mathrm{HF} = \frac{P_{\mathrm{EM}}}{P_{\mathrm{ICE}} + P_{\mathrm{EM}}} = \frac{P_{\mathrm{EM}}}{P_{\mathrm{HEV}}}. \tag{1}$$

The performance of the EM is mainly governed by the drive cycle or the vehicle trip, cooling, and the temperature tolerance of the device. A classification of traction EM technologies is shown in Fig. 10.

The few important and widely used EM have been discussed in the following [81], [82].

A. Switched Reluctance Motors (SRMs)

The SRM has received interest in HEV applications. It offers various advantages for traction applications. These include simple and rugged construction, high-speed capability, zero short-circuit current, and the longest constant power speed range of any motor, which is highly suitable for vehicle traction. The SRM requires special power electronic drive converters. Although the SRM has lower efficiency and torque density than some of the other motors, its extended constant power speed range makes up for this deficiency in traction applications. The SRM with added magnets, MSRM, still has a simplified structure and characteristics that are favorable for traction application. Furthermore, SRM with advanced control algorithms to

Table 5 Summary of the DC–DC Converter [117]

Type of converter	Advantages	Disadvantages	Cost	Isolation	Applications
Boost converter (BC)	• Electromagnetic interference (EMI) can be reduced easily. • The circuit layout is simple. • low cost. • Controlling is easy.	• large capacitor. • high ripple rate. • voltage gain <4:1.	low	no	EV, PHEV, HEV power amplifier applications, Adaptive control applications, Battery power systems, Consumer Electronics, Communication, Battery Charging circuits, In heaters and welders, DC motor drives, Power factor correction circuits, Distributed power architecture systems.
Interleaved Boost converter (IBC)	• reduces current ripples • voltage gain is quite high • the size of the passive components is smaller • simple control	• high switching losses. • affected by duty cycle change. • high components count.	moderate	no	Smart grid, PV application and wind , EV, BEV and PHEV
Boost converter with resonant circuit (BCRC)	• the heat sink is small in size • compact size • soft switching • low EMI	• low voltage gain. • suitable for low-power conversion.	low	no	Power conversion circuitry is used in portable devices such as laptops and smart phones, as well as in computation and telecommunication
Full bridge boost DC-DC converter (FBC)	• high voltage step-up possible. • high efficiency (around 91.5%). • reduce voltage stress on the switching circuit. • galvanic isolation.	• an auxiliary clamping circuit is required. • high current stresses on the switching circuit. • a large capacitor is required.	moderate	no	More electric aircraft, HEV ,BEV and PHEV
Isolated -zero voltage switching converters (ZVSC)	• clamping circuit is not required. • fewer switching losses. • low EMI factor. • high power density	• high current rating of gates. • low fault tolerance capability. • a large capacitor is required.	moderate	yes	Fuel cell applications, BEV , HEV and PHEV
Sinusoidal amplitude high voltage DC bus converter (SAHVC)	• mode symmetry high spectral purity • noise-free • minimized output impedance	• complex control. • complex gate switching pattern. • low-power conversion.	high	yes	AC systems of power transmission, BEV, HEV and PHEV
Multiport isolated converter (MPC)	• minimize output voltage ripples. • high voltage gain. • common ground level for all gates. • galvanic isolation from all input sources. • bidirectional power flow.	• more component counts. • synchronization is difficult. • sensitive to the duty cycle. • complicated analysis, transient and steady state.	high	yes	PV, Battery storage technology, DC grid, and micro-grid BEV, HEV and PHEV
Multi-device interleaved bidirectional converter (MDIBC)	• high efficiency (97%) • low current stress on switches • capabilities of delivering the high-power. • passive component size is smaller. • the heat sink is smaller in size. • simple control. • bidirectional power flow.	• sensitive to the duty cycle. • high component count. • complicated transient/steady-state analysis.	moderate	no	BEV, HEV , PHEV , FCEV, smart grid etc.

reduce its torque ripple and increase its performance has been applied to HEV traction [84]–[87].

B. Brushless DC Motors (BLDCs)

These motors have high efficiency and high power density. Their simplicity of structure, power electronics, and controls have made them among the first motor technologies to be used in EV applications.

These can produce high torque over a wide speed range. These motors can provide smooth running and holding torques. The BLDC motors can run at extremely high speeds due to the absence of the brushes in them [88]–[90].

C. DC Series Motor

The dc series motors are equipped with a high starting torque capability that makes them a suitable option for traction applications. This motor performs well even in abrupt load change situations and offers easy speed control. However, it has brushes and commutators with their associated increase in maintenance [91], [92].

Table 6 Summary of Bidirectional DC/AC Converter

Type of inverter	Specification	Advantages	Disadvantages
CSI	• Controlled current source. • current is controlled by a series Inductance. • Not suitable for light load. • Application in AC motor drives.	• simple circuit • reverse blocking capability • withstand high voltage spikes. • converter-inverter combined. • thyristor used for commutation are simple	• limited operating frequency. • cannot provide uninterruptible power supply systems. • sluggish performance and stability problems. • Extra converter stage is required
VSI	• Controlled voltage source. • Feedback diodes are necessary. • It can be classified into series, parallel and bridge. • Used in UPS and AC drives	• low power consumption & high energy efficiency up to 90%. • capable to handle high power rating. • high tolerance against temperature • variation and no degradation in linearity. • smooth implement and controlling. • compatible with most of the recent controller as well.	• distortion of the fundamental waveform. • sudden enhancement in switching frequencies. • harmonic issues • high stress on switches
ZSI	• buck & boost in a single-stage conversion. • A special Z-network composed of 2 capacitors & inductors connected to a 3-ϕ inverter bridge allows working in buck/ boost mode using the shoot□through state.	• provides desired AC voltage output regardless of the input voltage. • yields high voltage utility factor. • overcomes voltage sags without any additional circuits. • decreases the motor ratings to deliver the required power [118]. • improves the power factor. • reduces harmonic current & common-mode voltage of the line.	• the lower average switching device • power in low boost ratio range (1/2). • in case of low voltage boost ratio much higher than 2. • right-hand plane zero in ZSI cannot be eliminated by adjusting the Z-source parameters.

D. Permanent Magnet Synchronous Motor (PMSM)

These motors have been considered as an alternative to traction induction motors (IMs). High power density and high efficiency are some of the advantages of these motors. However, they can suffer from demagnetization due to armature reaction in the windings [93]–[96].

This motor is similar to the BLDC motor as they have a PM on the rotor. These motors do have high power density and high efficiency. The difference between the BLDC and the PMSM is that the PMSM has sinusoidal back EMF, whereas the BLDC has trapezoidal back EMF. The PMSM can offer higher power ratings. Notwithstanding its high cost, the PMSM is a strong alternative to the traction IMs due to their higher efficiency. The PMSM is generally preferred for EV/HEV traction.

E. Induction Motors

The IM is very suitable for traction applications. In addition to their rugged construction, they can have sufficient constant power extended speed range, by field orientation, to make them both efficient and compact for EV/HEV applications. They are safer for vehicle applications due to their natural zero short-circuit current. They also use power electronic converters for power transfer.

The IM does not have the high starting toque of the dc series motors under fixed voltage and fixed-frequency operation. However, this can be alleviated by using some control approaches, such as the field-oriented control or constant volts/hertz methods. By using these control methods, the maximum torque is available at the start of traction application. IMs can be designed up to an efficiency of 95%. The disadvantage of the IM is in its complex inverter control [97]–[100].

F. Traction Motor Drive Summary

Table 4 shows a summary of characteristics of the various traction motor drive technologies.

G. Technological Advancements in Traction Motor

Research on developing better traction motor drives is in progress. This includes the introduction of the transmotor for traction. Sensorless control of traction motor drives has added reliability and high-speed torque control of IM and PMSM for HEV applications. Furthermore, traction motors are being developed with lower iron and copper losses for better efficiency.

VI. POWER ELECTRONIC CONVERTERS

The power electronic converters for HEVs can be categorized into two groups, i.e., unidirectional and bidirectional converters. These can also be dc–dc and dc–ac types. A brief description of each of them is given in the following.

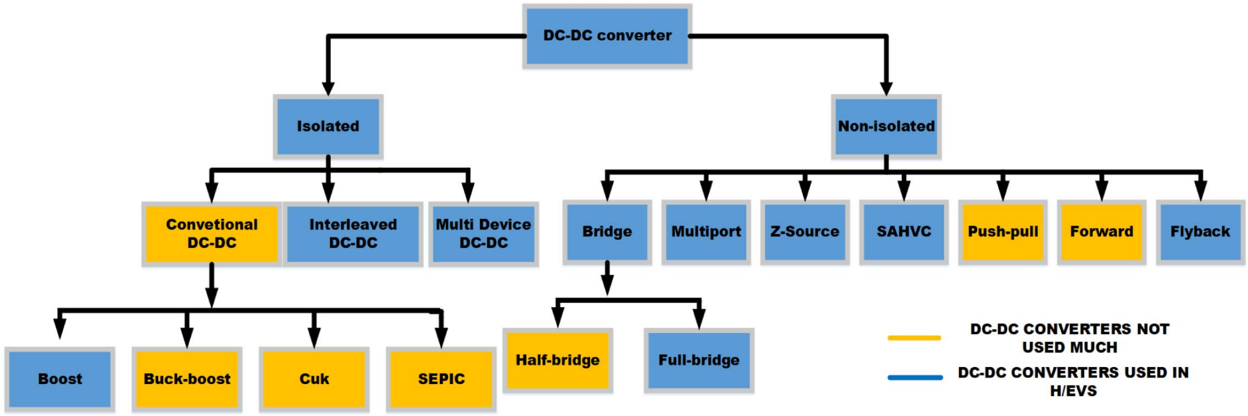

Fig. 11. *Classification of dc–dc converters for H/EVs.*

A. DC–DC Converters

Fig. 11 shows the various dc–dc converters used in HEV applications. The unidirectional dc–dc converters are used to supply the auxiliary load, such as sensors, safety, utility, entertainment, and control equipment, and they can be applied in dc drives for electric traction applications. The bidirectional converters are used during regenerative braking, backup power, and battery charging. The power flow in bidirectional converters takes place from the low-voltage end to the high-voltage end, which is referred to as the boost operation. In the regenerative braking process, the power flows from the high-voltage end to the low-voltage end (battery recharging), which is referred to as the buck operation. These bidirectional converters are also used to supply the backup power to the motor if there is malfunctioning or failures of ICE or electric drives.

A summary of the various kinds of dc–dc converters used in HEV applications is shown in tabular form in Table 5 [101]–[103]. This table will be helpful to identify the type of converter on the basis of its application and cost [104].

B. DC–AC Converter

Bidirectional dc–ac converters are responsible for increasing the controllability, performance, and efficiency of HEVs. The bidirectional converter conveys the power in both the direction, i.e., from the battery to wheels and from wheels to the battery by regenerative braking.

The traction inverters for HEV can be categorized into the voltage-source inverter (VSI) [105], the current-source inverter (CSI) [106]–[113], the impedance-source converter (ZSI) [114]–[116], and soft-switching inverters. A brief summary of these inverters is given in Table 6. From this table, it can be concluded that the ZSI topology, especially the quasi-ZSI, is very beneficial in HEV for high efficiency and fuel economy. Researchers are working to develop new methods and control algorithms for zero voltage switching (ZVS). Research is also going on to develop new topologies of ZVS, such as q-ZVS, by modifying the basic topology to make it more efficient.

VII. CONCLUSION

This review offered an overview of powertrains for EVs, HEVs, PHEVs, and FCEVs.

The fuel economy, drivability, and emissions are the main motivations for going to modern EV and HEV technologies. The HEV powertrain is more complex, in its architecture and control than the conventional and EV powertrains. This is mainly due to their two or more power sources, requiring optimal dynamic power split among them to achieve the best fuel economy. Power electronics, traction motors, and energy storage and recovery systems are the core technologies of EV and HEV powertrains. Hybridization of the ESSs divides the requirements of high energy density and high power density among two or more storage technologies, resulting in higher vehicle performance, longer range, and better fuel economies. Vigorous research and development, in the above areas, are being conducted in academic and industrial labs, internationally. The ultimate objective is to produce vehicle products that are preferable to conventional ICE vehicles in the marketplace. This will result in a natural transition to better automobiles and a healthier environment.

This article presents the review of the different technologies of EVs consisting of BEVs, HEVs, PHEVs, and FCHEVs. The various architecture XEVs with their advantages and disadvantages have been elaborated so that one can choose the correct structure to work with and bring the best out of it. Various energy storage devices have also been discussed with their combination topologies. Numerous optimization strategies to control the flow of energy in the HEV powertrain have also been detailed. Several kinds of EMs for traction have also been discussed and compared. It is observed that the PMSM and IM are considered among the best options for traction applications. Power electronics of hybrid vehicles have also been presented with their merits and demerits.

This study will help the scholars understand a broad picture of this field of study and will serve as a ready reference to anyone who wishes to update themselves on the present scenario of EVs, HEVs, PHEVs, and FCEVs. ■

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