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A comprehensive review on hybrid electric vehicles: architectures and components

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Abstract The rapid consumption of fossil fuel and increased environmental damage caused by it have given a strong impetus to the growth and development of fuel-efficient vehicles. Hybrid electric vehicles (HEVs) have evolved from their inchoate state and are proving to be a promising solution to the serious existential problem posed to the planet earth. Not only do HEVs provide better fuel economy and lower emissions satisfying environmental legislations, but also they dampen the effect of rising fuel prices on consumers. HEVs combine the drive powers of an internal combustion engine and an electrical machine. The main components of HEVs are energy storage system, motor, bidirectional converter and maximum power point trackers (MPPT, in case of solar-powered HEVs). The performance of HEVs greatly depends on these components and its architecture. This paper presents an extensive review on essential components used in HEVs such as their architectures with advantages and disadvantages, choice of bidirectional converter to obtain high efficiency, combining ultracapacitor with battery to extend the battery life, traction motors' role and their suitability for a particular application. Inclusion of photovoltaic cell in HEVs is a fairly new concept and has been discussed in detail. Various MPPT techniques used for solar-driven HEVs are also discussed in this paper with their suitability.

Abbreviations and symbols

ABS	Antilock braking system
AC	Alternating current
ADTR	Antidirectional-twin-rotary
ADVISOR	Advanced vehicle simulator
ANN	Artificial neural network
ASCI	Auto-sequential commutated mode single-phase inverter
BEV	Battery electric vehicle
BLDC	Brushless DC motor
CD	Charge depletion
CDFIM	Cascaded DFIM
CF-qZSI	Current-fed quasi-ZSI
CMPPT	Centralized MPPT
CS	Charge sustaining
CSI	Current source inverter
CS-PMSM	Compound-structure PMSM
CVT	Continuous variable transmission
DC	Direct current
DFIM	Doubly fed induction motor
DMPPT	Distributed MPPT
DRM	Double-rotor machines
DTC	Direct torque control
e-CVT	Electronic continuous variable transmission
EM	Electric motor
EMS	Energy management system
EREV	Extended range electric vehicle
ESS	Energy storage system
EV	Electric vehicle
FC	Fuel cell

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FCEV	Fuel cell electric vehicle	V_{oc}	Open-circuit voltage
FEM	Finite element method	V2G	Vehicle to grid
FL	Fuzzy logic	VSI	Voltage source inverter
FOC	Field-oriented control	ZSI	Impedance (Z) source inverter
FLC	Fuzzy logic controller	XHEVs	Full HEVs and PHEVs
GA	Genetic algorithm		
HESS	Hybrid energy storage system		
HEV	Hybrid electric vehicle		
IC	Incremental conductance		
ICE	Internal combustion engine		
ICV	Internal combustion vehicle		
IGBT	Insulated gate bipolar transistor		
IM	Induction motors		
IMCCR	Induction motor with compound cage rotor		
IPMSM	Interior permanent magnet synchronous motor		
I_{sc}	Incremental short-circuit current		
KKT	Karush–Kuhn–Tucker		
LC	Inductor capacitor		
MFM-BDRM	Magnetic field-modulated brushless double-rotor machine		
MOSFET	Metal-oxide-semiconductor field-effect transistor		
MPC	Model predictive controller		
MPP	Maximum power point		
MPPT	Maximum power point tracker		
MRAC	Model reference adaptive controller		
M-SRM	Modular-switched reluctance motor		
NPC	Neutral point clamped		
P&O	Perturb and observe		
PAM	Pulse amplitude modulation		
PHEV	Plug-in HEV		
PI	Proportional integral		
PM	Permanent magnet		
PMBLDC	Permanent magnet BLDC		
PMSM	Permanent magnet synchronous motor		
PSO	Particle swarm optimization		
PV	Photovoltaic		
PVHEV	Solar-driven HEV		
PWM	Pulse width modulation		
RC	Resistance capacitor		
SA	Simulated annealing		
SBP	Synergetic battery pack		
SFO	Stator flux oriented		
SOC	State of charge		
SRM	Switched reluctance motor		
STA	Supertwisting algorithm		
TTR	Through-the-road		
TCO	Total costs of ownership		
UC	Ultracapacitor		
VF-ZSI	Variable frequency impedance source inverter		

1 Introduction

A well-knit and coordinated transportation provides mobility to people and goods. The transportation sector mainly consists of road, railway, ships and aviation, where road transportation consumes 75% of the total energy spent on transportation. The automobile industry plays a significant role in economic growth of the world and hence affects the entire population. Since vehicles mostly run on internal combustion engine (ICE), the transportation industry is accountable for 25%–30% of the total greenhouse gases emission [1]. ICE works in the process of fuel combustion resulting in the production of various gases like CO_2, NO_2, NO and CO [2] which cause environmental degradation in the form of greenhouse effect and are responsible for their adverse effect on human health. To overcome this, the transportation industry is trying hard to manufacture vehicles that can run on alternate power sources. Electric vehicles (EVs) were tried as a solution in 1881 where battery alone propelled the vehicle and therefore required a bulky battery pack. Absence of an ICE handicapped these vehicles with a short driving range [3]. Hybrid electric vehicles (HEVs) were conceptualized to bridge the power of ICE and the emission-free nature of EVs. HEVs offer better fuel efficiency over ICE-based vehicles and generally work in charge-sustaining (CS) mode where the state of charge (SOC) of battery is maintained throughout the trip. The issue with CS mode is that its charging efficiency relies mainly on regenerative braking and gasoline, so plug-in HEVs (PHEVs) were conceptualized as a possible solution. Unlike HEVs, PHEVs have the additional facility to be charged externally through power outlets. Most of the power in a PHEV is derived from an electric motor (EM) which acts as a primary source, while ICE acts as a backup. As the battery SOC reaches a particular threshold, the PHEV behaves like a regular HEV, and the ICE kicks in and acts as a primary power source. The PHEVs mainly work in charge depletion (CD) mode where SOC is depleted up to a threshold level. PHEVs extend the all-electric range, improve local air quality and also may have grid connection capability.

Another possible approach for extending the electric range of an HEV is to allow continuous charging of the battery while running. The emergence of solar-driven

HEVs (PVHEVs) leads to continuous charging of batteries by means of solar energy, which minimizes the usage of gasoline and hence reduces environmental pollution.

Robust and affordable batteries are a primary challenge for hybrid vehicles. Various HEV battery compositions have been tried in the past with the best results from lithium-ion derivatives. Three levels of integration of battery packs are possible in vehicles: (1) singular battery cells, (2) modules, comprised of individual battery cell, and (3) battery packs, comprised of modules. Battery should be able to supply high power over short periods and must be capable of enduring millions of transient shallow cycles over vehicle life. To extend the range and life of a battery, it can be interfaced with an ultracapacitor (UC) which permits longer life cycle, higher rate of charge/discharge and lower internal resistance which result in lesser heat loss and better reliability. UC improves the efficiency cycle to around 90% from 80% [4]. The combination of battery and UC forming a hybrid energy storage system (HESS) is more efficient as compared to their individual performances.

The fundamental requirement for traction motors used in HEVs is to generate propulsion torque over a wide speed range. Two most commonly used motors in HEV propulsion are permanent magnet motor (PM) and induction motor (IM). There are various hybrid cars now available and manufactured by Audi, BMW, Chevrolet, Ford, Honda, Mercedes, McLaren, Nissan, Mitsubishi, Hyundai, Porsche, Tesla, Toyota, etc. The fuel consumption saving by a few models is shown in Table 1 [5].

Various possible architectures of an HEV are presented in Sect. 2, and bidirectional converters reported in the literature are discussed in Sect. 3. The HESS is given in Sect. 4, and Sect. 5 details the various motors used in HEVs and their controlling strategies. Section 6 deals with various MPPT algorithms used in PVHEVs, Sect. 7 points out the flipside of hybrid vehicles, and Sect. 8 presents the conclusion and recommendation. The methodology adopted for constructing this review paper is shown in the form of a flowchart in Fig. 1.

2 Architecture of HEV

The key components in an HEV consist of an electric motor (EM), battery, convertor, ICE, fuel tank and control board. These components can be categorized into three groups:

1. Drivetrains—physically integrate the ICE power source and electric drive.
2. Battery/energy storage system (ESS)—emphasizes large or modest energy storage and power capabilities.
3. Control system—instructs electric systems/ICE and manages the HESS.

These components can be integrated in different ways and sizes which results in variation in vehicle design. Based on the component integration, drivetrains mainly include series, parallel and power split designs. In [6] the HEV's architecture has been classified into six different categories, which are mild/microparallel, parallel, series, power split, combined and through-the-road (TTR) hybrids.

In series HEV, the power sources provide electrical energy at DC bus, which is then converted to traction power [7]. In parallel HEVs, traction power can be supplied by ICE or EM alone, or together by both the sources. The EM is used to charge the HESS by means of regenerative braking [8]. The parallel mild HEV is an ideal option as they provide a prime trade-off between the cost of vehicle and its performance [9]. Complex HEVs incorporate features of both parallel as well as series architecture. They are almost like the series–parallel hybrid except for the variance in power flow of the motor, which is bidirectional in complex hybrid and unidirectional in series–parallel HEVs. The disadvantage of complex hybrid is its complexity in design. A pictorial representation of these architectures is given in Fig. 2.

Architecturally, PHEV is similar to HEVs except for a large-size onboard battery, having high energy density and efficiency. The combination of CS and CD modes requires a more complex control strategy than in an HEV. PHEVs begin operation in CD mode; and as soon as the battery reaches a threshold value of SOC, the battery shifts to CS mode until the vehicle is parked and recharged. The architecture of a solar-driven HEV (PVHEV) is similar to the PHEV except for an additional photovoltaic (PV) panel, which charges the battery during a sunny day. To extract the maximum power from PV panels, the maximum power point tracker (MPPT) algorithms are applied. The block diagram of PVHEV is shown in Fig. 3.

Patterns of power flow:

The power flows in HEVs to encounter the load demand are given in Fig. 4. There are many possible patterns as given below [10]:

1. powertrain 1 alone delivers power to load;
2. powertrain 2 alone delivers power to the load;
3. both powertrains 1 and 2 deliver power to load at the same time;
4. powertrain 2 obtains power from load (regenerative braking);
5. powertrain 2 obtains power from powertrain 1;
6. powertrain 2 obtains power from powertrain 1 and load at the same time;
7. powertrain 1 delivers power to load and to powertrain 2 at the same time;
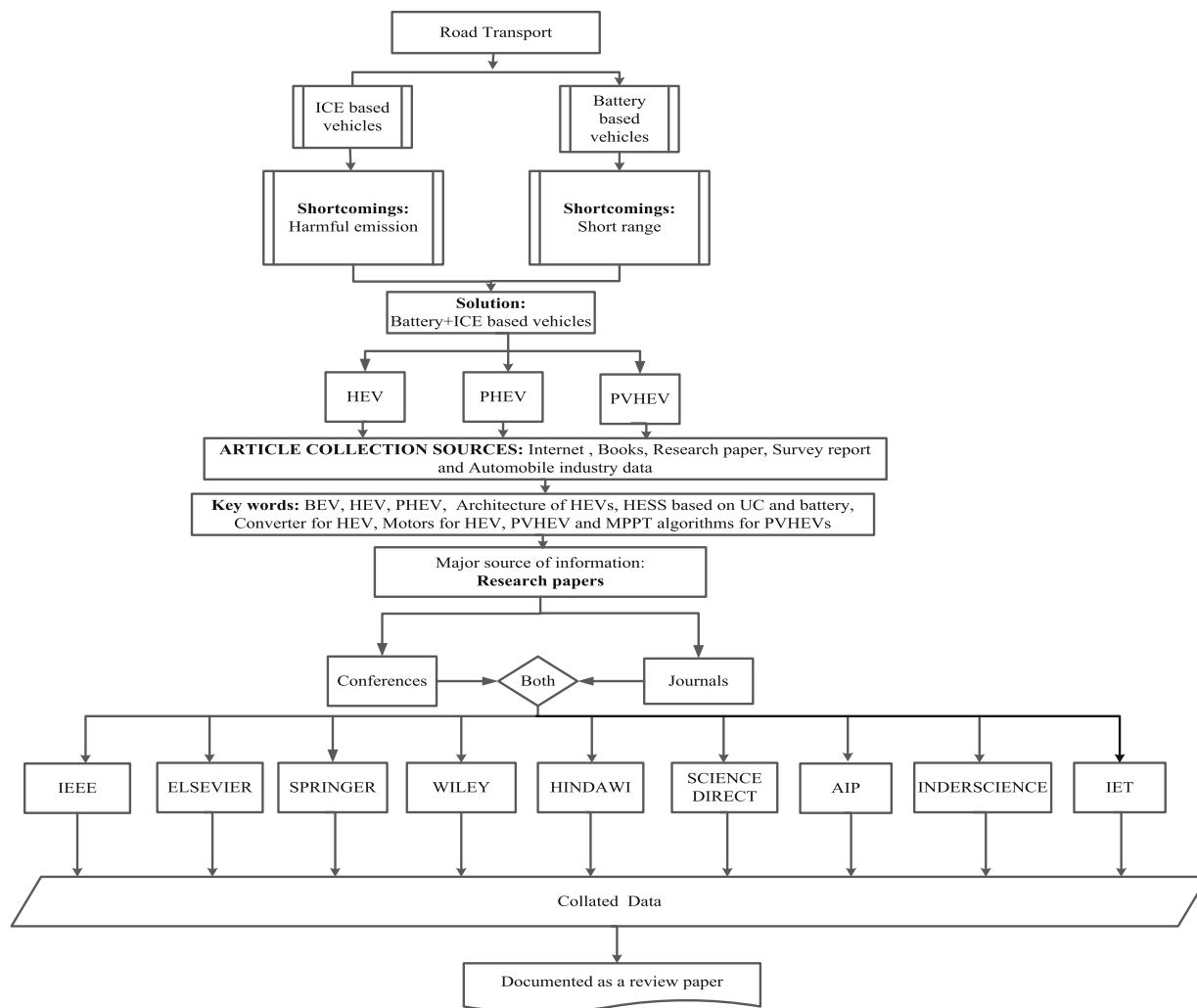
Fig. 1 Methodology adopted for constructing this review paper

8. powertrain 1 delivers power to powertrain 2, and powertrain 2 delivers power to load;

9. powertrain 1 delivers power to load, and load delivers power to powertrain 2.

Various papers have been published by researchers on the architecture of hybrid vehicles, and some of them are discussed here. In [11] a small ICE/generator was added to the battery-powered EV to develop a series hybrid drivetrain. The series hybrid drivetrain has some prominent benefits: (1) the ICE and the driven wheels are not coupled mechanically, which compels ICE to operate at its narrow optimal region; (2) single-torque source operation simplifies the speed control; (3) the torque–speed characteristic of EM obviates multigear transmission; and (4) easy drivetrain control, simple structure and easy packaging. However, it suffers from some drawbacks, as follows: (1) the conversion of energy takes place in two steps, i.e., mechanical to electrical through generator and vice versa

through motor, and hence results in more energy losses; (2) two electric machines are required, i.e., generator and motor separately; and (3) a big size traction motor is required. The series hybrid drivetrain is mostly used in heavy vehicles such as buses, trucks and military vehicles. This configuration was also considered for the analysis of hybrid lithium high-energy battery [12]. In [13], the PHEV is simulated for series and parallel architectures and it is concluded that during powering mode, the operating points of the motor for parallel PHEV are more concentrated in the extended high-speed, high-efficient region. In case of parallel PHEV, regenerative braking takes place in a high efficiency region which is not the case in the series counterpart. While analyzing the effect of different functions on energy management strategies apropos of both architectures, the parallel configuration was found to be superior [14].

In [15, 16], power split was considered for the analysis of the through-the-road (TTR) architecture, a subcategory of parallel architecture. In [17], the split—parallel architecture for TTR and its control challenges are detailed. Miller [18] employed power split architecture as it provides better liberty of power control. He also showed that electronic continuous variable transmission (e-CVT) was more efficient than the mechanical continuous variable transmission (CVT). In [7], it is discussed that hybrid cars use parallel and power split architecture, but heavy hybrid vehicles use the series architecture, so small ICE is required. Series, parallel and power split architectures have been presented in [19]. In [20], the power split architecture and its modeling in a systematic way are detailed. In [21], an energy management system (EMS) for power split/parallel architecture of HEV was employed to improve the battery life and powertrain energy efficiency. The results showed that the proposed two propulsion machines improved the powertrain efficiency by 5% as compared to one propulsion machine. In [22], a parallel active topology was used with a fuzzy logic controller (FLC) which has been implemented for online energy management of an EV. In [23], a similar kind of strategy fused with particle swarm optimization (PSO) and simulated annealing (SA) is proposed to minimize the fuel consumption and emissions for a parallel HEV. In [24], the parallel architecture is used in a bilayer distribution system. It is made up of an alternating current layer which provides aids to the system loads and an embedded direct current layer that interfaces the PV arrays with PHEVs. In [25–27],
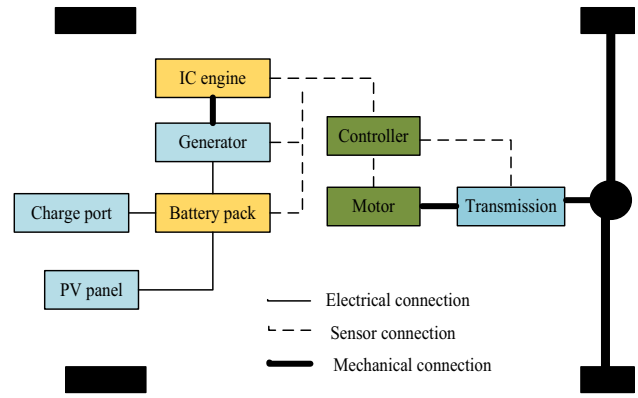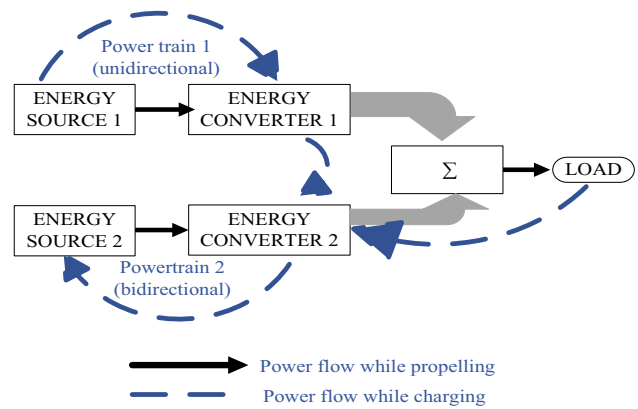
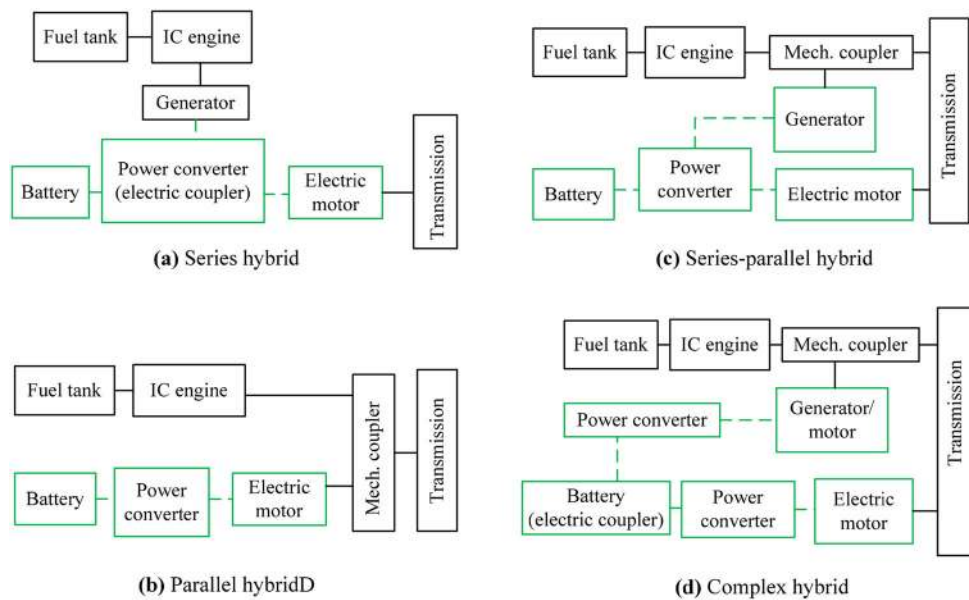**Fig. 3** Block diagram of PVHEV

Fig. 4 Patterns of power flow

Fig. 2 Various architectures of an HEV

(a) Passive battery/UC configuration

(b) Passive cascaded battery/UC configuration

(c) Active cascaded UC/battery configuration

(d) Active cascaded battery/UC configuration

(e) Active cascaded configuration with two DC/DC converters

(f) Multiple DC/DC converter configuration

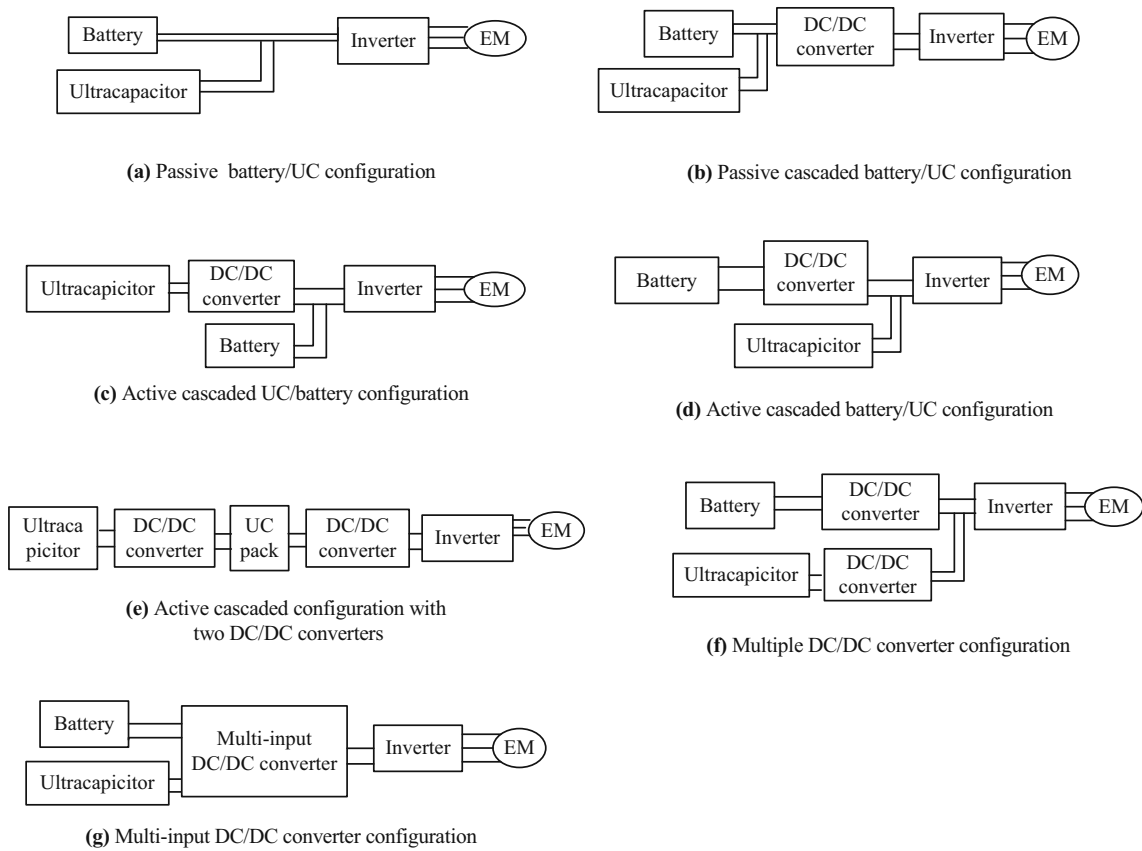**(g)** Multi-input DC/DC converter configuration

Fig. 5 Various possible configuration of UC and battery [146]

the parallel architecture is employed for PHEV and its energy management is presented.

In [28], a model of the power split PHEV powertrain and a TTR hybrid electric powertrain was simulated and their prototypes were investigated based on various parameters. A quasi-static model was used to investigate and evaluate vehicle performance, fuel economy, emissions and supervisory control of the passenger car. A low-frequency vehicle powertrain dynamics model was used to evaluate the vehicle dynamics, acceleration and braking performance of a racecar.

Based on the literature, a summary giving various architectures and their application is given in Table 2. Table 3 gives the comparison of emissions for EV and HEVs for FTP-75 urban, federal highway and commuter driving cycles. Table 4 provides a brief summary of these architectures.

There are various architectures available for HEVs, but since the complex hybrid involves bidirectional power flow, it is more suitable and beneficial compared to the rest.
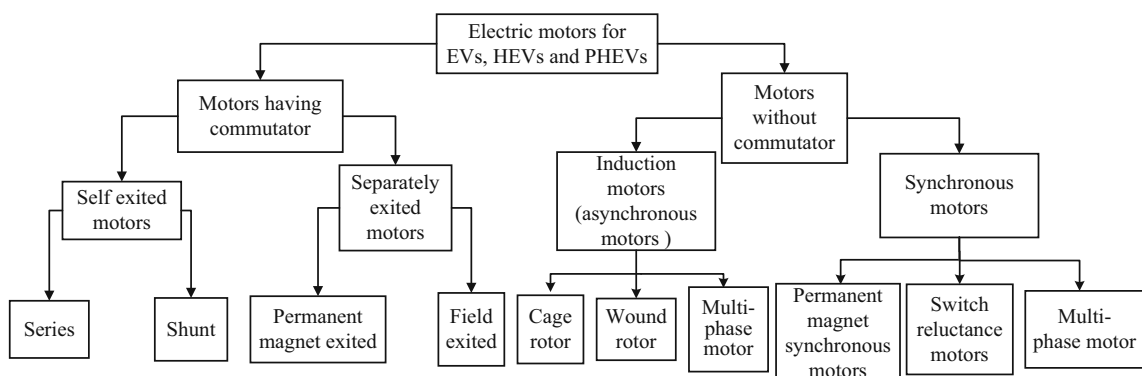

Fig. 6 Motor hierarchy

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3 Bidirectional DC/AC converter

Power converters are proliferated in all kind of applications to increase controllability and efficiency in automotive applications [30]. The bidirectional converter is essential in hybrid vehicles to convert DC from the battery/UC/fuel cell (FC) or their combination into AC that is given to the motor drive. An extensive research has been carried out on DC/AC converters including single-stage single-phase [31], single-stage three-phase [32] or zero voltage switching inverters [33]. The various motor drives used in EV and HEV have been proposed in [34–45].

There are various topologies of traction inverters such as voltage source inverter (VSI), current source inverter (CSI), impedance source converter (ZSI) and soft switching [46]. These are described below.

3.1 Current source inverter

The CSI can be used for the speed control of AC motors, especially induction motors with varying load torque. The following are the types of CSI:

1. single-phase CSI,
2. auto-sequential commutated mode single-phase inverter (ASCI) and
3. three-phase CSI.

   Advantages:

1. The circuit for CSI is simple. It uses only converter-grade thyristor having reverse-blocking capability and is able to withstand high-voltage spikes during commutation.
2. An output short-circuit or simultaneous conduction in an inverter arm is controlled by the 'controlled current source' used here, i.e., a current-limited voltage source in series with a large inductance.
3. The converter/inverter combined configuration has an inherent four-quadrant operation capability without any extra power component.

   Disadvantages:

1. It suffers from the drawback of having limited operating frequency and hence cannot be used for uninterruptible power supply systems.
2. At light loads and high frequency, these inverters have sluggish performance and stability problems.

These inverters can be divided into two categories: one is to reduce switch count, and another is to reduce capacitance for HEVs. The reduced switch scheme faces the challenge of cost and efficiency, whereas reduced capacitance reduces the cost and improves the power density of

the traction inverter. Wu et al. [47] proposed a CSI with interior permanent magnet machine, as it increases the constant-power operation regions due to voltage-boosting function. The CSI for medium- and high-power induction machines was studied in [48–54]. A novel space vector pulse width amplitude modulation (SVPWAM) method for a buck–boost CSI was proposed in [55]. Due to this technique, the switching loss had reduced by 60%. Furthermore, the power density increased by a factor of 2–3. A new type of control strategy known as the nouveau for CSI in battery-driven electric vehicle (BEV) has been proposed in [56] for better harmonic performance of the electrical machine. In [57], a method to switch off an interior permanent magnet synchronous motor (IPMSM) by using a CSI inverter in the event of a malfunction in a BEV has been presented.

3.2 Voltage source inverter

The VSI can be used practically in both single- and three-phase applications. VSIs have good speed range, multiple motor controls from a single unit and a simple regulator design. In addition, there are some disadvantages of the VSI; e.g., the power factor decreases as the speed decreases, and it induces harmonics, cogging and jerky start and stop motions. The types, advantages and disadvantages of VSI are as below:

   Types of VSI:

1. single-phase half-bridge inverter,
2. single-phase full-bridge inverter and
3. three-phase VSI.

   Advantages:

1. low-power consumption and high-energy efficiency up to 90%,
2. high-power handling capability,
3. no temperature variation- and aging-caused drifting or degradation in linearity,
4. easy to implement and control and
5. compatible with today's digital controller.

   Disadvantages:

1. attenuation of the fundamental component of the waveform;
2. drastically increases switching frequencies and hence creates stresses on switching devices;
3. generation of harmonic components.

Liu et al. [58] selected an advanced film capacitor to replace the conventional electrolytic bulk capacitors for EV applications. In [59], an adaptive flux observer to adjust itself by online estimation of DC-link voltage and rotor resistance has been proposed for VSI-based induction

Table 1 Saving in fuel consumption in some top models

Technology	Nonhybrid/nonelectric base model (BEE* fuel efficiency star rating)	Hybrid/electric model (BEE fuel efficiency star rating)	Gasoline equivalent fuel consumption reduction over base model
Diesel-based mild hybrid	Maruti Ciaz VDI (5 star)	Maruti Ciaz VDI-shvs (5 star)	7%
Diesel-based mild hybrid	Maruti Ertiga VDI (4 star)	Maruti Ertiga VDI-shvs (5 star)	15%
Gasoline based strong hybrid	Toyota Camry at 2.5 l (2 star)	Toyota Camry hybrid (5 star)	32%
Battery-operated electric	Mahindra Verito d2 (4 star)	Mahindra E-verito d2 (5 star)	68%
Battery-operated electric	–	Mahindra e2o (5 star)	–

*Bureau of Energy Efficiency

Table 2 Summary of architectures and their application

Architecture	Complexity	Efficiency	Hybridization	Computation time/mathematical complexity
Series	1	1	Full HEV and plug-in HEV	1
Parallel	2	2	Micro-, mild and full HEV	2
Series–parallel	3	3	Full HEV and plug-in HEV	3

1—low, 2—medium, 3—high

Table 3 Comparison of emission for different driving cycles [29]

Parameters	Conventional	EV	Series hybrid	Parallel hybrid
Control complexity	NA	Simple	Medium	Complex
Weight (kg)	Very low	High	Medium	Low
NOx (g/km)	High	NA	Medium	Low
CO (g/km)	High	NA	Medium	Low
HC	High	NA	Low	Medium
Fuel consumption (km/L)	High	NA	Medium	Low
Amount of energy supplied or depleted (MJ)	NA	Low	Medium	High

NA not applied

motor (IM) in HEVs. The proposed observer is capable of obtaining simultaneous flux and DC-link voltage observation with online tuning of rotor resistance. Feng et al. [60] proposed a current injection-based online parameter and VSI nonlinearity estimation method for permanent magnet synchronous motor (PMSM) drives in EVs. The nonlinearity of VSI in HEV is discussed in [61]. A new inverter design based on the silicon carbide-based semiconductor devices was proposed to fulfill the power and temperature requirements of EVs in [62]. The impact of various modulation schemes on DC-link capacitor of VSI for HEV has been discussed in [63].

3.3 Impedance source inverter

Impendence source inverter (also called Z-source inverter, ZSI for short) has been considered an efficient candidate in vehicle applications such as drive system reliability, which

Table 4 Summary on architectures

Architecture	Loss	Efficiency	Complexity	Sizing of component
Series	4	1	1	4
Parallel	3	2	2	3
Series–parallel	2	3	3	2
Complex	1	4	4	2

4—very high, 3—high, 2—moderate and 1—minimum

leads to an increase in the range of inverter output. The ZSI is one of the most promising power electronics converter topologies suitable for motor drive applications. It has the properties of buck and boost in single-stage conversion. A special Z network composed of two capacitors and two inductors connected to the well-known three-phase inverter bridge and allows working in buck or boost mode using the

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shoot-through state. The ZSI improves the stability and safety of a brushless DC (BLDC) motor drive system under complex conditions. The following are the advantages of ZSI:

1. Provides desired AC voltage output regardless of the input voltage.
2. Yields high-voltage utility factor.
3. Overcomes voltage sags without any additional circuits.
4. Minimizes the motor ratings to deliver required power.
5. Improves the power factor and reduces harmonic current and common mode voltage of the line.

There are three topologies of ZSIs, namely basic, bidirectional and high-performance ZSI [64]. Replacement of the input diode by a bidirectional switch in the basic version results in bidirectional ZSI topology. The bidirectional ZSI is able to exchange energy between AC and DC energy storage. Being a basic topology, the variable frequency (VF) ZSI cannot work in regenerative mode and hence cannot charge the battery due to which the output voltage is low [65]. However, the continuous input current by VF-ZSI is suitable for photovoltaic (PV) applications. To perform rectangular wave modulation for motor drive control, an improved circuit topology of ZSI depending on the drive condition of the H/EV has been discussed in [66]. Dong et al. [67] have developed current-fed quasi-ZSI (CF-qZSI) with high efficiency by using reverse-blocking IGBT for HEV application. CF-qZSI is able to achieve bidirectional power flow and voltage buck operation as it has a diode and an LC network in its design.

The improvements in the heat transfer capabilities of power module technologies are still inadequate, and a paradigm shift is needed in order to achieve the cost reduction and meet the power density challenges of the H/EV inverters [68]. The sustainability of inverters at very high temperature (105 °C) while operating at high efficiency is another issue to be addressed [69]. The 900V SiC MOSFET technology in the inverter reduces the energy losses and is beneficial in the mild city-style drive cycles [70]. Its application in multiphase motor drive system not only reduces power loss in the inverter but also permits the use of a smaller DC-link capacitor [71]. A high-capacity compact power module (J1 series) has been developed with compact size, high performance, lightweight and low self-inductance [72].

Another bidirectional DC/AC converter has been proposed for HEV applications, which can be used as a single input single/multiple output. The reduction in current ripple by carrier modulation method proposed in [73] leads to the reduction of DC capacitance and voltage ripple. The ripple reduction was achieved in HEV applications by using DC-link capacitor and carrier modulation technique [74, 75]. The synergetic battery pack (SBP) inverter was also introduced for H/EV applications. It has the advantage of using voltage semiconductor devices and hence improves the stability. In the SBP inverter, only one-stage conversion takes place and hence results in lesser losses and reduces the cost [76]. A pulse amplitude modulation (PAM) inverter was introduced in HEV to obtain high performance [77–82]. A fault-tolerant 4-leg topology was proposed in [83]. The quasi-ZSI (q-ZSI) [84] can buck and boost the voltage and provide the bidirectional power flow. In [85, 86], the modified space vector pulse width modulation with different pulse width modulation (PWM) sequences was applied, which led to different current ripples, switching loss, total harmonic distortion and voltage spike on the switching devices. Therefore, switching sequence and choice of PWM are important [87–89]. The strategy proposed in [90–92] allows the PMSM to work as inductors of the boost converter. This technique reduces the current ripple, thermal stress under heavy load and boosts the output.

An important criterion for deciding the size of a 3-phase PWM converter is cooling. A novel method is to have a power module concept with double-sided chip cooling

Table 5 Comparison of various topologies of the HESS [146]

Topologies	Advantages	Disadvantages
Isolated topology in Fig. 5b Isolated topology in Fig. 5c Isolated topology in Fig. 5d	Higher galvanic isolation, higher-voltage conversion ratios	Bulky, heavy, costly magnetic core, higher EMI, higher-voltage stress across switches
Nonisolated topology in Fig. 5e	Lower transfer capacitor voltage rating	Two large inductors, discontinuous output current, a larger output capacitor and a higher switch/diode voltage rating
Nonisolated topology in Fig. 5f	Reduced input/output current ripples	Having two large inductor higher transfer capacitor voltage ratings
Nonisolated topology in Fig. 5g	One small inductor no transfer capacitor voltage, lower switch/diode voltage ratings, lower switching/conduction losses	Discontinuous output current

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Table 6 Comparison of various motors used in HEV [151]

	Brushless DC	PM	Switched reluctance	Polyphase induction
Type	AC	DC	AC	AC
Family	Synchronous excited PM	Separately excited	Synchronous unexcited	Induction slip ring squirrel cage
Power to rotor	PM	DC	Induced	Induced
Power to stator	Pulsed DC	PM	Pulsed DC	AC
Overall cost	High	Medium	Medium	Medium
Weight	Low	Medium	Medium	Medium
Commutation method	Internal electronic	Mechanical commutation	External electronic	External electronic
Controller cost	Very high	Medium	High	High
Pros	Outstanding torque and speed, fast responses, tremendous power and long life	High starting torque	Low inertia can be tailored for specific applications and runs cool	High efficiency
Cons	Very expensive, limited economy to small-sized motors	Susceptible to damage if dropped, requires maintenance, bulky and limited rotation speed	Not very power full, ripple in torque and requires position sensing	Expensive controller
Maintenance requirement	Low	Brushes wear	Low	Low
Speed control method	Frequency dependent	PWM	Frequency dependent	Frequency dependent
Starting torque	> 175% of rated torque	> 200% of rated torque	Up to 200% of rated torque	High
Speed range	Excellent	Limited by brushes, easy control	Controllable	Controllable
Efficiency	High	High	Less than PMDC	High
Application	HEVs, EVs and ICVs	HEVs, EVs and ICVs	ICVs	HEVs, EVs and ICVs
Efficiency with motor only (%)	80	97	94	90
Efficiency with power electronic devices only (%)	98	93	90	93
Efficiency with motor and power electronic devices (%)	78	90	85	84
Examples	Peugeot Citroen/Berlingo (psa) (France)	Nissan/Tino, Honda/Insight (Japan), Toyota Prius (Japan), etc.	Holden/ECOmmodore (Australia)	Renault/Kangoo (France), Chevrolet/ Silverado (USA), etc.

Table 7 Comparison of MPPT algorithms used in HEVs

MPPT technique	Convergence speed	Implementation complexity	Periodic tuning	Sensed parameters
P&O	Varies	Low	No	Voltage
IC	Varies	Medium	No	Voltage and current
Fractional V_{oc}	Medium	Low	Yes	Voltage
Fractional I_{sc}	Medium	Medium	Yes	Current
FLC	Fast	High	Yes	Varies
Neural network	Fast	High	Yes	Varies

which allows very high-power densities. In addition, lower stray inductance and package resistance improvements will enable high inverter efficiencies [93]. The dual-sided cooling discussed in [94] provides better cooling options in inverters.

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Table 8 Cost breakdown for different powertrain options (in EUR) [300]

Costs type (in EUR, year 2020)	ICV	HEV	PHEV 15	PHEV 30	EREV	BEV	FCEV
Purchase price (excluding CO_2 penalties)	27,946	29,963	30,805	31,941	37,093	36,390	46,456
Resale value	− 9503	− 11,916	− 12,252	− 12,704	− 14,756	− 10,335	− 15,809
Net depreciation	18,443	18,047	18,554	19,237	22,337	26,054	30,647
Energy cost	4016	2142	1739	1564	1637	1235	2587
Maintenance and repair cost	2892	2720	2704	2692	2124	2348	2548
Other operation cost (e.g., motor tax and inspection)	330	160	160	160	160	53	53
Total cost of ownership	25,680	23,069	23,157	23,653	26,257	29,690	35,835

EREV extended range electric vehicle, also known as plug-in series HEV; *PHEV 15* and *PHEV 30*: plug-in HEVs with two different battery sizes

Table 9 Comparison of various existing hybrid vehicles

Vehicle	Driving range	Efficiency	Fuel type	Overall cost	Structure	Advantage	Disadvantage	ESS	Driving mode
ICV	High	Low	Gasoline	High	Simple	1. Matured technology 2. Better performance 3. Simple and reliable 4. Commercialized	1. Harmful emission 2. Poor fuel economy	Fuel tank	City and high way
BEV	Low	High	Electric	Low	Simple	1. Pollution free 2. Efficient	1. Poor dynamic response 2. Recharge time is high	Battery and ultracapacitor	City
HEV	Medium	Low	Gasoline + electric	Medium	Medium	1. Low emission 2. High fuel economy 3. Reliable and durable	1. Bulky 2. More number of components	Fuel tank, battery and ultracapacitor	Highway
PHEV	High	High	Gasoline + electric	Medium	Complex	1. Highly fuel efficient 2. Low emission 3. V2G or G2V capability 4. Quiet and smooth operation	1. High initial cost 2. Impact on grid	Fuel tank, battery and ultracapacitor can be charged from outlet	City and high way
PVHEV	High	High	Gasoline + electric	Low	Complex	1. Highly efficient. 2. Low emission and large size 3. Quiet and smooth operation 4. Reliable	1. Very high initial cost. 2. Extra components	Fuel tank, PV panel, battery and ultracapacitor can be charged from outlet	City and high way

4 Hybrid energy storage system

The choice of ESS depends on various parameters, including charging speed, energy density, life expectancy, cost, weight and size [95, 96]. The current trend indicates that batteries and UC remain as the main choices for ESS [97]. Batteries have low cost per watt hour, high energy density but short cycle life and low specific power, while UCs preserve high peak power, long cycle life, high cost per watt hour and low energy density [98–103]. The UCs are robust, have a quasi-infinite cycle life and can sustain highly dynamic power profiles [104, 105]. The UCs are also responsible to reduce the sulfation in lead acid batteries for EVs [106]. Furthermore, the UCs provide high-frequency and high-magnitude power, whereas the batteries fulfill low-frequency requirements. It is not possible for an individual energy storage device to fulfill all the requirements [107]. However, a combination of the two

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can help to overcome their drawbacks [108–113]. UCs tolerate the surges during the battery operation and maintain the DC-bus voltage, whereas the batteries maintain the SOC of the UCs. Therefore, the combination of these two will lead to high stability of the entire system [114, 115].

To protect EV batteries and extend their life, an UC is combined with them [116–119]. The sudden load variations are absorbed by the UC, and hence efficient use of the batteries can be achieved [120, 121]. The batteries can be modeled with 1 resistance capacitor (RC) and multiple RC branches, and an UC is added to make it a HESS. The optimal power split between the battery and an UC is an important task and influences their sizing. Quite a few papers have discussed this power split, and they are briefly presented below.

The UC and battery parameters can be assessed using curve fitting techniques for desired cell responses. While designing ESS mechanisms like high temperature, over charge/discharge and under-/overvoltage protection schemes, cell balancing and their redistribution should be considered [122, 123]. To split the current between UC and battery, Karush–Kuhn–Tucker (KKT) and the neural network (NN)-based EMS are used in [124]. The NN-based EMS demonstrates better robustness and performance in terms of the battery state of health. However, KKT offers simpler implementation and excellent computation performance. The artificial neural network (ANN) is very useful in calculating the residual capacity of an UC [125].

The fuzzy logic (FL)-based EMS in a HESS for longer battery life was also adopted. Here, a battery lifetime degradation model was used to develop the relationship between the battery charge/discharge behavior and the impact on its lifetime [126, 127]. The power optimization in a parallel arrangement of battery and UC was carried out using superimposed DC-bus control system which had DC-bus voltage, proportional integral (PI) controllers and a feed-forward load compensator [128, 129]. Wireless charging concept was used to charge the UC effectively in [130]. A rule-based control algorithm was proposed to effectively manage the UC's SOC and offload the current peaks from the battery in [131, 132]. Model predictive controller (MPC) was used to distribute the energy in a HESS in [133]. This scheme satisfied load demand and maintained the output voltage at the desired value.

In order to better utilize the high-power density of UCs, a logic threshold control strategy for HESS was proposed in EVs [134–137]. An adaptive FL-based EMS is used to determine the power split between the battery and the UC pack. An FL controller is used as it can easily manage the complex real-time control issues and does not need the knowledge of the driving cycle ahead of time. It maximizes the efficiency and minimizes the battery current variation [138]. A HESS linear quadratic regulator was designed to

mitigate issues related to battery wear and peak power demands for EVs and HEVs [139].

The equivalent consumption minimization strategy is proposed to distribute the power between the battery and UC in a series HEV [140]. Other HESS like UC with the FC has also been adopted in few cases, and one of such combination is interfaced using the ant colony method in [141]. A dynamic MPC is designed for FC-UC hybrid, which maintains load side requirement and voltage across UC. The single MPC in outer loop is used to find the values of FC and UC currents which are used as references for inner PI control loop [142]. The implementation of HESS has at least three major advantages: cheaper batteries, increased autonomy and extended lifetime [143, 144].

There are various possible configurations to connect the HESS and the electric traction motor, which are given in Fig. 5. Also, a battery and UC can be interfaced by means of bidirectional DC/DC converter in many ways [145]. The topologies are mainly selected based on their advantages and disadvantages as tabulated in Table 5. The boost half-bridge best meets the requirements of a bidirectional cell, thus suitable for battery/UC interface [146].

The passive connection given in Fig. 5a is the simplest configuration with both the battery pack and the UC directly connected to the motor drive without interfacing to a DC/DC converter. Regardless of the system simplicity, the absence of a control on the DC side is the main drawback of this system. This limitation is resolved in the controlled HESS [147] as presented in Fig. 5b, c. The UC is not directly connected to the DC bus, and the bidirectional DC/DC converter controls the power contribution from the UC. The optimal sizing of the DC/DC converter is the main issue here.

In active cascaded battery/UC topology shown in Fig. 5d, UC is directly connected to the terminal of an inverter, whereas the battery is connected through a DC/DC converter. The UC acts as a buffer against a rapid power flow change. As a result, battery is protected and the energy flow can be effectively controlled. However, in this topology, UC voltage needs to be kept constant, limiting the working range of the UC. This topology was used in [148] to reduce the conduction and switching losses and to improve the accuracy.

A new concept having two semi-active configurations, i.e., a semi-active UC and a battery, has been postulated in [149]. A bidirectional nonisolated DC/DC converter performs energy control of one of the storage elements. In this control strategy, UC provides fast dynamic power, and the complement is provided by the battery bank [150], as shown in Fig. 5e.

In case of multi-DC/DC converter topology shown in Fig. 5f, the battery and UC are individually connected to the inverter terminal through their own DC/DC converter.

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This topology shows a good performance, especially for the controllability of current flow.

The two DC/DC converter required in topologies shown in Fig. 5e, f is replaced by a multi-input nonisolated bidirectional DC/DC converter [151]. This topology minimizes the losses and has been analyzed in [152].

The multi-input DC/DC converter is used for the integration of energy sources such as FC, PV and wind for EV applications [153]. The advantage of DC/DC converter is to have low component counts and a simplified structure. Since this converter is capable of operating in different modes of operation such as boost, buck and buck/boost, this topology attains an important role in the energy diversification of different sources in HEV applications [154]. A zero voltage transition buck-and-boost converter can also be employed for UC interface that guarantees soft switching condition for all semiconductor devices in EVs [155].

In [156], a three-level neutral point-clamped converter (NPC) is proposed to optimally couple UC and a battery pack. It minimizes the usage of battery pack in providing peak current in acceleration and deceleration modes. In [157], a half-bridge bidirectional DC/DC multi-input converter is chosen to link the battery and the UC.

5 Motors

There is an extensive need of advanced motors and generators to meet the aggressive targets in terms of efficiency, power density and cost of the drivetrain in HEVs. The specification of the motor/generator depends on its usage, like in light/medium/heavy duty vehicles, off/on highway vehicles and locomotives. The performance of the machine depends mainly on vehicle duty cycle, thermal characteristics and the cooling mechanism implemented. Invention of power converter topologies for drive control has advanced the traction systems for EVs over recent years. The classification of various motors used in traction is shown in Fig. 6. A brief literature review on the motors used for traction in EV/HEVs is presented below. A brief study on control methods of these motors is also presented at the end of this section.

5.1 Switched reluctance motors

These days, the switched reluctance motor (SRM) is receiving much attention in EV/HEV applications. These motors have various advantages such as easier control, rugged construction, better fault tolerance capability and outstanding torque–speed characteristics. An SRM is well suited for applications where constant power is required over a wide operating region. SRM is also reported with

several drawbacks such as electromagnetic interference, torque ripple, high noise and requirement of a special convertor topology [158].

In order to overcome the drawbacks of SRM such as low torque/power density and high torque ripple, a novel modular (M)-SRM with hybrid magnetic paths for simple structure, low cost and improved dynamic performance has been presented for EV applications [159]. An average torque control of SRM for light EVs is proposed to control and estimate the average torque of the motor shaft in [160]. The Seeker optimization algorithm has been presented in [161] to minimize the torque ripple of SRM.

A multistage fast design methodology for SRM is presented in [162]. The process aims to determine the best speed at which the SRM would start in single-pulse mode operation. In [163], SRM was developed with a new propulsion system having good overall efficiency in the total speed range, especially in high speed and excellent generating performance. Generally, PI controllers are used for the speed control of SRM, but have drawbacks of high overshoot and settling time; hence, to overcome them, a fuzzy sliding mode controller has been presented in [164]. SRM is highly suitable to provide the maximum torque for a short time [165]. In [166], SRM has been constructed and test results are presented over the entire speed range and it has been concluded that the output power is significantly enhanced to 100 kW from 60 kW in a high-speed range (5400–13900 rpm) with the same outer diameter and the axial length of the IPMSM. A new design of SRM as a starter/generator for HEV has been presented in [167]. The results show that SRM is capable of starting the vehicle and charging the battery as well. A new modified fuzzy-PI controller is designed to control a high-power SRM, modeled by means of the finite element method (FEM) for HEV applications [168]. This ensures the best efficiencies over the specified operating range.

To improve the efficiency of SRM for HEV, the response surface method and multiobjective genetic algorithm (GA) are applied over various operating modes [169]. Considering the maximum torque capability and maximum power density, SRM seems to be the best candidate for HEV application [170]. In [171], an optimized controller for SRM to reduce undesirable torque ripples for EV and HEV has been discussed. An integrated multilevel converter fed by a modular front-end circuit in SRMs for PHEV has been presented in [172].

The high-speed capabilities of 6-slot/4-pole and 8-slot/6-pole designs have been presented in [173]. The 6/4 designs yield 40% more power at high speed without exceeding the voltage and current ratings of the motors. The SRM definitely shows potential for superior performance to BLDC's and IM's [174]. A split converter-fed four-phase SRM drive to realize flexible integrated

charging functions (DC and AC sources) has been presented for better fault tolerance in [175]. The features of SRM have been described keeping in view their application for vehicles [176].

5.2 Brushless DC motors

BLDC motors are theoretically the result of reversing the position of the stator and rotor of PM DC motors. Their main advantages are high efficiency, compactness and high energy density. In [177], a 5-phase brushless fault-tolerant hybrid-excitation motor was proposed for EV applications. In [178], BLDC was used for EV by means of a fuzzy-tuned PI speed control. In [179], a brushless dual-rotor flux switching permanent magnet motor was employed for PHEV application. A double-stator permanent magnet BLDC (PMBLDC) was engaged for HEV application in [180].

A position sensorless BLDC motor based on the sliding mode control has been presented in [181] for EV applications. The techniques based on flux-weakening control are complex and costly. To circumvent these problems a multispeed winding is designed with sensorless control and presented in [182]. The back electromotive force (EMF) signal of brushless in-wheel hubs can be exploited to simplify their antilock braking system (ABS) arrangement. The experimental results show that the sensorless wheel speed measurement accuracy of a BLDC motor with eight pole pairs is approximately 50% better than the ones produced by the commercial ABS sensor [183].

The integrated starter generator torque booster for a hybrid propulsion system has been presented in [184, 185]. In [186], a promising doubly salient-BLDC generator for HEV application was proposed as it has low cost, high robustness and flexible control. The predictive controller-enabled BLDC motor drive has been presented to improve the motor current response in [187]. In [188], field weakening has been improved, which helps in vehicles where large constant/power speed ratio is required. Digital PWM control for a BLDC drive in both motoring and generating modes of operation is discussed in [189]. This control strategy is simple, robust, current sensorless and computationally less intensive. Chen and Cheng [190] used a low-voltage BLDC motor/alternator with modified converter design in hybrid electric scooters. In [191], the magnetization analysis of the BLDC motor has been presented and it has been concluded that the post-assembly magnetization is preferred in order to overcome the problem of magnetic forces and ferrous debris. The magnetic field-modulated brushless double-rotor machine (MFM-BDRM) is composed of the stator, the modulating ring rotor and the PM HEVs. Compared with traditional double-rotor machines (DRMs), the MFM-BDRM shows more complicated

electromechanical energy conversion relations, due to its special operating principle [192]. The influence of magnetic phase couplings on the performance of multiphase BLDC machines with overlapping phase winding configurations is investigated in [193]. A novel configuration of the BLDC motor with an integrated planetary gear train, which provides functional and structural integrations to overcome inherent drawbacks of traditional designs, has been presented in [194]. The performance of BLDC motor was evaluated in terms of rise time, setting time and overshoot using topologies like fuzzy, PI and their hybrid in [195]. It has been concluded that a hybrid controller is suitable for high-power applications, whereas a PI controller is promising for low-power applications. The generated output power of five-phase BLDC motor is improved under faulty conditions in HEVs [196, 197]. An efficient regenerative braking system in BLDC motor is presented for hybrid vehicles in [198].

5.3 Permanent magnet synchronous motor

PMSMs prove to be strong contenders to IM in HEV applications. Its benefits include lesser heating, higher power density and higher efficiency. That being said, PMSMs suffer from a major drawback of demagnetization due to armature reaction. In [199], the PM motor and IM were compared for HEV application with the help of advanced vehicle simulator (ADVISOR) tool and the results indicate superior performance of PM motors, in terms of standard performance indices such as traction capabilities and fuel efficiency. A PMSM shows better result for HEV when clubbed with HESS.

A novel PMSM drive system with a bidirectional ZSI is proposed and tested by keeping in view the feasibility and effectiveness for an EV system. The application of a bidirectional ZSI to PMSM drive system improves the reliability since it is a single-stage structure and the shoot-through states can no longer destroy the inverter [200]. The PMSM with ZSI and modified vector control considering DC-link capacitor is presented in [201]. To improve the efficiency of a PMSM, a loss optimization control strategy is proposed in [202]. A generalized predictive current control method combined with sliding mode disturbance compensation is proposed for PMSM to satisfy the requirement of fast response in EV system [203]. The hybrid PWM-based discontinuous modulation strategy with DC-link voltage balancing for a three-level NPC traction inverter is presented, and PMSM is considered for traction motor drive in [204]. A test bench has been developed using a surface-mounted PMSM to emulate various electrical machines to understand their real behavior [205, 206].

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To prevent an increase in speed during emergency crash, high-voltage discharge of the capacitor for PMSM drive is presented in [207]. Six typical topologies of compound-structure PMSM (CS-PMSMs) are proposed and evaluated in terms of torque density, manufacturability, heat-dissipating capability and magnetic coupling for an HEV system [208]. The virtual prototyping and optimization of PMSM for HEV drivetrains is presented in [209]. Zheng et al. [210] used an axial–axial flux CS-PMSM, which enables ICE to operate in the optimum efficiency region independent of road conditions. The robust shape model of PMSM for a large-sized HEV is presented in [211]. The numerical computations using the FEM are performed to build the lumped parameter model for PMSM system in [212]. The field-controlled PMSM is proposed for HEV applications in [213]. A new PMSM machine with increased power capability was proposed in [214] with two winding sets in which one of them is dedicated for generator operation and the other for output voltage regulation by flux weakening. To minimize the problem of coupling between d and q axes, a modified current control strategy of the flux-modulated CS-PMSM has been presented in [215].

The PM-assisted synchronous reluctance motors for automotive applications have been examined in [216], but as they use rare earth PMs, the electric motors with less or no rare earth PMs are therefore presented. To reduce the cost of the machine, the flux switching of the PMSM has been presented in [217]. In order to avoid the fault in any component, an onboard diagnostic approach for PMSM drive system has been presented in [218]. Point of common coupling is used to obtain fast torque monitoring and high-performance operation of a PMSM in [219]. A fault-tolerant control system for high-performance PMSM drive is proposed in [220]. Unbalanced magnetic pull plays a key role in nonlinear dynamic behaviors of PMSM. The analysis indicates that these effects are caused by the interaction of the initial phases of forward and backward whirling motions [221]. Reference [222] presents a sensorless algorithm designated for the emergency control of an interior PMSM drive. Two topologies for PMSM (1. battery connected directly to inverter and 2. connected through bidirectional converter) are compared, and it has been concluded that high efficiency of PMSM drive can be obtained by using the second topology [223]. In [224], the design principles of PMSMs for traction applications and its necessary boundary conditions, such as PM flux linkage level and the synchronous inductances, have been discussed; several different topologies capable of producing a low-speed peak torque have been also studied.

To avoid the catastrophic failure of the encoder and sensor, a novel backup universal sensor concept for PMSM with position and current estimation has been presented in [225]. An improved algorithm has been developed for obtaining the maximum torque by accounting the core loss, cross-coupling effect and temperature for PMSM drive [226].

5.4 Induction motor

IMs are widely accepted for the propulsion of EVs, due to their reliability, ruggedness, low maintenance and high efficiency. In addition, from a safety point of view, these motors get de-excited during fault in inverter [227]. IMs offer a higher power density and better efficiency when compared to the DC machine. IM provides a wide range of speed with good efficiency. Some of the usage of IMs in hybrid vehicles is briefed below.

The new design of IM for EVs was proposed with improved speed torque curve in [228]. The field-oriented control (FOC) algorithm needs accurate estimation of motor state variables in order to ensure full-torque performances and good efficiency of IM. For this purpose, a two-rotor resistance estimation method is presented in [229]. Reference [230] presents the motor condition monitoring for HEV and its review with focus on nine commonly used condition monitoring methods of IM. In [231], losses and temperature in IMs are considered and the effects of rotor materials and air-gap length on the performance of these motors are analyzed. It is concluded that the efficiency of the motor with a copper mouse cage rotor is considerably higher than that of the motor with an aluminum rotor. A new sensorless speed control technique for IM-driven EV using a model reference adaptive controller (MRAC) with a basic energy optimization technique known as golden section method has been presented in [232]. The proposed scheme is immune to the variation in stator resistance. The unique formation of the MRAC with the instantaneous and steady-state reactive power eliminates the requirement of any flux estimation in the process of speed estimation. In [233], an energy-efficient and speed-sensorless control scheme for IM of EV has been presented. The IM drive is designed, keeping in view the features like fast dynamic response, high efficiency and low cost. Furthermore, a loss minimization algorithm is associated with the main control strategy to ensure high IM drive efficiency.

An improved direct rotor FOC of seven-phase IM for HEV has been presented with FLC to filter the nonsequential current [234]. This minimizes the loss in IM, which adds to its advantages of high reliability, low cost and high power and torque density. The IPMSM is still an efficient and attractive machine for traction applications from efficiency and size perspective but with increased cost, mainly due to rare earth material [235].

A dual-current loop control algorithm has been proposed for HEV in [236]. The torque and air-gap flux of a doubly

fed induction motor (DFIM) are controlled directly as compared to the singly fed permanent magnet. For IM, the torque–speed operation region for EV/HEV applications is nearly doubled with the proposed algorithm. A compact diagnostic algorithm is presented using advanced speed feedback error management technique for traction motor and generator faults in [237]. The issues addressed are sensor issues, vehicle vibration, hardware tolerances and environmental impacts like temperature, moisture and electromagnetic interferences. A single-electrical-port control scheme, for four-quadrant operation of cascaded DFIM, is proposed in [238], and a new hybrid cascaded H-bridge multilevel inverter for IM has been proposed to improve torque control. An improved motor line-current reconstruction technique by software control for shaft-sensorless EV and HEV propulsion drives has been presented in [239]. This strategy emphasizes on the minimization of the error caused in driveline current.

A new kind of IM called as induction motor with compound cage rotor (IMCCR) has been proposed in [240]. The IMCCR has been suggested as a better choice for the driving systems in EVs and PHEVs. The effects of ambient temperature and output load on motor thermal performance have been considered as well. Table 6 provides the comparison of various motors used in HEV applications.

Based on the literature survey given above, it is found that there is growing interest in the development of advanced traction motors for hybrid vehicles and many traction motors are available in market. However, considering the trade-off based on various parameters like performance, robustness, reliability and cost, the choice is often between IM and permanent magnet AC motor.

5.5 Control of traction motors

A brief study has been carried out on the various methods of controlling the traction motors used in hybrid/electric vehicles and summarized as below:

The driving characteristics of a PM-type antidirectional-twin-rotary (ADTR) motor on the EV driving simulator and traction control for an EV using ADTR motor have been presented in [241]. There are three excitation sources, namely permanent magnetic, armature and axial coils in the motor. Control of these excitation sources to make the motor run in different modes for vehicle applications has been demonstrated [242]. A novel algorithm for designing the set of PI/PID controllers for stabilizing the current and speed loops of a high-speed and high-power flywheel energy storage system using a PMSM is demonstrated in [243]. The improved speed tracking performance of a fuzzy-based indirect FOC of IM drives in comparison with a conventional PI control in HEV applications is presented

in [244]. In [245], a stator flux-oriented (SFO) control scheme of IM using variable-saturation regulators is proposed. The traditional SFO control scheme consists of the d-axis current component, torque, stator flux and speed loops with four PI-type controllers. This control scheme uses two regulators with variable saturation in such a way that the maximum DC-bus voltage utilization is reached and overcurrent problems are prevented. A fuzzy adaptive controller to minimize harmonics introduced by the multilevel converter in traction drives is presented in [246]. A combined control structure of IPMSMs to achieve true maximum voltage utilization is proposed in [247]. The hybrid structure provided a smooth transition from current vector control to modulating voltage-scaled controller mode by deactivating the current regulator in the flux-weakening region. A pressure command control method of engine clutch in a parallel-type HEV is demonstrated in [248], where a dynamic model of an HEV powertrain was also constructed to launch operation with engine power only. A review on different motors used to propel EVs, their control techniques and rotor speed estimation using sensorless methods has been presented in [249].

Direct torque control (DTC) in an IM to achieve better performance has been shown in [250]. As the motor speed varies, the switching frequency also varies, and the maximum sampling frequency is used in DTC. The motor structure and torque equation of a novel claw pole-type half-wave-rectified variable field flux motor, as well as the motor design parameters, are described in [251]. The influence of the rotor structure on the torque characteristic was also evaluated using 3D-FEM. Reference [252] presents a synchronous homopolar motor, which is suitable for sensorless operation over its entire speed range, including zero speed. This ability is necessary for the traction drives, the reliability of which is currently limited due to the presence of the rotor position encoder needed for operation at low speeds. In [253], an attempt was made to build a fast response overvoltage-protecting circuit for traction IPMSM. A good work on the control of salient-pole PMSM for traction in hybrid vehicles has been presented in [254]. In [255], a consensus based on the total amount of cooperative tracking control has been developed to maintain total torque needed for traction. Case studies, particularly with system architecture (sliding mode and PID control methods), extremum-seeking algorithm for the maximum tire-road friction and the corresponding slip value, and experimental validation of the tire model used in the controller were discussed in [256]. The analysis of the three topologies for on-board HESS in EV applications modeled with energetic microscopic representation for voltage stability has been proposed in [257]. A dynamic model, design and novel control strategy for ecotractions supplied by wind generator–supercapacitor hybrid power systems

have been developed in [258]. A novel efficiency improvement method using loss models and gold section search in an IPMSM traction system in EVs has been presented in [259]. The loss models of the IPMSM and the inverter were considered here, and a 2.7% increment in the overall efficiency was recorded. A model reference adaptive system-based estimation algorithm to calculate the rotor resistance of an IM working under dynamic conditions has been reported in [260]. An advanced strategy for life extending control of PMSMs traction drive system in rail vehicles that evaluates and compares the IGBTs damage under different flux conditions offline, has been proposed in [261]. A supertwisting algorithm (STA)-based control scheme for vehicle traction control has been proposed in [262]. The controller is a combination of the STA control law and a nonlinearity observer. The control law was designed based on a sliding mode control method, but the switching control part was replaced with a STA. An integrated vehicle and wheel stability controller which is designed using MPC technique has been proposed in [263]. The prediction model consists of a double-track vehicle model augmented with the wheel dynamics. A novel adaptive wheel control algorithm with slip optimization, considering a balance between maximizing the traction and minimizing the energy consumption, depending on surface conditions has been proposed in [264]. A detailed review on energy optimization strategies in HEVs is given in [3].

6 MPPT algorithms used in HEVs

With the growing demand for switching over to renewable energy resources, PV technology is charging ahead of the other alternatives. The various salient features of it being noiseless, pollution free, immune to direct contamination and its simplicity in operation help make it the preferred choice. The various structures of PV systems and their suitability in hybrid vehicles have been discussed in [265–269].

The I-V characteristics of PV cells are nonlinear, and there exists only one maximum power point (MPP) [270]. By interfacing the power, electronic devices with PV system, the efficiency can be increased along with MPP controller.

Many algorithms have been put forward to track this MPP, but among all, constant voltage tracking method is the most traditional method but has limitations during varying temperature. To overcome them, perturb and observe (P&O) and incremental conductance (IC) methods are most widely used.

In case of P&O, the load impedance varies periodically and senses the change in the direction of power, whereas in IC, $\frac{dp}{dv}$ is monitored to detect whether MPP has reached, where p is the power and v the voltage. In P&O, the system oscillates near MPP; hence, the system works, inefficiently [271]. The IC algorithm is the procedure where the voltage and current curves provide the maximum power level [272]. The advantage with IC is its responsiveness to changing atmospheric conditions, whereas P&O benefits from being more straightforward to implement [273].

A simple charging algorithm with P&O MPPT was proposed for PVHEV in [274]. This is used to extract the maximum power with the help of a boost converter. The charging algorithm drives the converter in constant current and constant voltage mode as needed. The P&O algorithm has also been designed for PVHEV in [275].

An MPPT control algorithm which does not require a current sensing device has been presented for HEV applications in [276]. In this algorithm, MPP can be determined by the PV voltage and switching duty ratio of the converter. In [277], a small-sized PV cell and other hardware components were selected to reduce power loss and cost and to obtain high efficiency. In [278], a solar-thermoelectric hybrid system for HEVs was proposed with P&O-based MPPT. This method is capable of tracking the global MPP with reduced hardware cost [279]. The ANN-based MPPT in PVHEVs was also used. An offline ANN, trained using the backpropagation and gradient descent momentum algorithm, can be used for online estimation of the reference voltage for the feed-forward loop [280]. In [281], it is proposed that one should use P&O algorithm when the vehicle is parked and voltage-based MPPT algorithm is suitable while driving.

The MPPT algorithms, namely P&O, IC and only current, are compared in terms of energy performances in ambient conditions, and IC has proved to be better [282]. For comparison, PV modules were mounted on a moving platform, designed to simulate insulations received by solar systems on a moving vehicle.

A modified P&O algorithm has been proposed to obtain fast transient response with high stability for variations in solar irradiance [283]. P&O- as well as IC-based techniques can be used to handle variable solar irradiance. They provide an optimal solution and a realistic driving scenario. Voltage balancing control is very useful as it allows an independent source for every independent MPPT in a distributed MPPT (DMPPT). When compared to centralized MPPT (CMPPT), the DMPPT offers 6.9–11.1% improvements in annual energy [284]. The single-ended primary inductor converter and estimated P&O were used for charging the battery efficiently, which prolongs the battery life [285]. MPPT algorithms based on the ant colony optimization, FL, ANN, GA and PSO, have been applied to PV systems under changing irradiance

conditions. A new type of algorithm, namely firefly algorithm, was also introduced in [286].

The PHEV loads should be given due consideration while designing a grid-connected residential PV system. The PV arrays and battery packs can be connected in a cascaded manner to power the load. A DC/DC converter can be used to regulate the voltage of the PV arrays by MPPT using the IC method [287]. In grid-connected mode, PV works at its MPP and EV works in the charging mode. However, when the microgrid gets isolated from the utility grid, both PV and EV should deliver active and reactive powers to feed the loads [288]. Table 7 provides the comparison between various MPPT algorithms, which have been used in HEVs. ANN and FL are trending these days because of their advantages over others.

7 HEV: the flipside

Ever since Lohner-Porsche, the first HEV, was developed in 1901, the automobile industry has come a long way. In the recent years, HEV technology has gained tremendous boost in terms of research and development. There is a general sense of optimism in the industry in regard to this new technology. While discussing the many advantages of HEV, often the shortcomings are overlooked. This technology is still in a relative inchoate state and has certain below-mentioned inherent shortcomings that need addressing in order to become a mainstream product.

7.1 Shortcoming

1. *Limited range* An HEV has a comparatively restricted range. Considering that an HEV ought to generate minimal amount of energy from the ICE, the distance per charge is relatively small. There have been improvements apropos of this variable. Further, an HEV requires a minimum of 30 min to charge fully, whereas a traditional car would require barely five minutes to fill the complete tank.

2. *Low power* A traditional vehicle is equipped with a powerful ICE which allows it to provide tremendous speed and torque. In HEV, the combination of ICE, EM and pack of batteries makes it bulky and eats up the extra space. In the bid to reduce the weight and cost, an HEV is equipped with a weaker engine and smaller motor, which gives less speed and torque. Owing to this fact, faster cars have not been able to transit to this eco-friendly technology. There have been attempts to break this image, with a prominent example being Tesla's Model S vehicle, but the cost of the car is well beyond the common man's budget.

Adding fuel to the fire, an ICE is more durable than a motor which has many sensitive components.

3. *Expensive* The major concern that holds back the buyer's intention to purchase a hybrid vehicle is its cost that makes it $5000–$10000 costlier than conventional cars. But, the features of HEV like lower running cost and tax exemptions can compensate for this rise in cost up to large extent.

4. *Maintenance costs* The complex structure of HEV leads to high maintenance cost along with it and also gives rise to the need of highly skilled technicians and mechanics for repair.

5. *Batteries* Considered to be the weakest link in the chain, the battery required to store energy has always posed a challenge in HEV technology. Lithium-ion-based batteries are the most common batteries used in HEVs owing to its high energy density. But such batteries invite a whole set of problems, such as its high sensitivity to external environment, weight and cost. Compared to the traditional ICE, a battery is more susceptible to variations in temperature and is heavier. The final nail in the coffin is that the materials used in the creation of the battery itself are hazardous to the environment, hence vitiating the ultimate objective of being a green technology. The risk of human life during an accident is exacerbated due to the additional risk of electrocution from the batteries present in an HEV.

6. *Security* A HEV requires a controller for the optimum usage of ICE and electric motor power trains. With the increased dependence on smart solutions, security proves to be an ever present danger. Remote exploitation may result in illegal access to unsavory people. It may result in huge losses for an individual if not wary. Unlike a traditional ICE which still requires physical contact to stop or disable a vehicle, an HEV is vulnerable to remote attempts. As such great precautions and protocols need to be developed to keep consumers safe.

7. *Critical analysis* Several critics also claim that an HEV simply delays the inevitable due to its continued consumption of fossil fuels. In order to provide more power or increase the distance, an ICE is coupled with the motor. As such, an HEV only reduces the rate of fuel burning in ICE. With current estimates indicating the exhaustion of fossil fuels in the recent future, some critics are skeptical of the utility of HEVs [289, 290].

7.2 Scope for improvements

There are many fronts where this technology can grow, be it in the adaptation, dissemination or penetration of HEV in

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the market. Being quite advantageous over conventional vehicles, it has some weaknesses in terms of efficiency, refueling, cost and many others. Some important thrusts of focus are listed below.

1. *Battery issues* The battery plays a vital role in HEV performance. They are quite heavy and expensive and thus impact the cost of HEVs. The performance of a battery is affected by temperature variations; therefore, an efficient battery management system is required. It needs long charging time and is sensitive to over/undercharge. Number of charge/discharge cycles decides the durability of battery. Further, disposal of toxic waste of battery is a big issue. Resolving these issues will allow the BEVs to run on the road.

2. *Public awareness* Public awareness and participation is very crucial to infiltrate HEVs in their lives. Various media and education can make people conscious about the advantages of this alternate transport. Participation of government, private players and cost-effective schemes will encourage consumers to use hybrid vehicles.

3. *Smart charging infrastructure* The charging infrastructure needs to be built at regular intervals so that these vehicles can be used for long journeys.

4. *Impact on grid* EVs and PHEVs mostly are charged by being plugged into the power outlet continuously for several hours. So, increase in these vehicles will increase the load on grid and power system performance issues. Hence, the need for extra generating units will arise. The electric power available in vehicles can also be banked at the grid using vehicle to grid (V2G) concept which is relatively unexplored at present. This concept works on the balancing of the 'off-peak' and 'peak' demands.

5. *Cost* Due to high prices of the batteries used in HEVs, EVs and PHEVs, these vehicles are not affordable to middle-income groups who comprise the major portion of the population. The advancement in control strategy, battery management system and less costly component utilization will decrease the purchase and operational costs which will attract more people to buy such vehicles.

7.3 Market share

According to [291], global sales of EVs have climbed from 1.2 million in 2017 to 1.6 million in 2018 and it has been estimated that it will rise to 2 million in 2019, 7 million in 2020, 30 million in 2030 and 100 million in 2050. The share of these vehicles globally is increased from 0.5% in 2014 to 1.7% in 2017. In 2017, China has 48% of market share and Europe has 26%. In terms of EV sales by
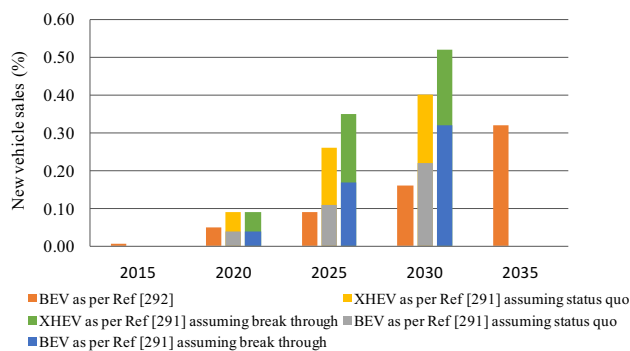
Fig. 7 Medium- and long-term sales of hybrid vehicles

country, China was once again the leader of the pack with over 600,000-unit sales, far ahead of USA which racked up 200,000.

It is expected that the penetration of EV/PHEVs will be around 35–47% of the new cars by 2040. It is observed that agencies have provided different statistics based on the growth rates, and thus, there are no unique data available on the long-term market share of these vehicles. The data on BEVs and XHEVs (including full HEVs and PHEVs) are taken from McKinsey [291] and Morgan Stanley & Co. [292] as they are the player in the vehicle domain statistics and the same is shown in Fig. 7. In [292], data are given for BEVs and XHEV for China, USA and Europe for status quo assumption and with breakthrough assumption till 2030, whereas in [293], the worldwide total data are given for BEVs till 2035. It can easily be inferred that the share of green vehicles will increase over the coming years.

The six European countries, i.e., Germany, France, Norway, Netherlands, UK and Sweden, are expected to share more than 67% of the total BEV market in the year 2020, whereas only four countries (Germany, France, Italy and UK) are expected to share more than 52% of the total market share of PHEVs [294]. According to Pike Research forecast, almost 1.8 million of BEVs, 1.2 million of PHEVs and 1.7 million of HEVs are expected on Europe's roadways by 2020 [295–297].

7.4 Costs involved

Ever since its inception, the cost of HEVs has always been much higher than its traditional counterparts in the same segment. Studying just its model price would be misleading, so it is necessary to realize the various costs, such as maintenance, repair, depreciation and fuel to get the complete picture. Comparisons between various costs involved in vehicle are as follows:

1. *Fuel costs* The main difference between EVs and ICVs is their fuel source, ICVs run on gasoline, while EVs run on electricity. According to a study of the

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University of Michigan's Transportation Research Institute, the operating cost of EV is less than half of gas-powered cars. The average operating cost of an EV is $485/year as against $1,117 for gasoline-powered vehicles in the USA. This figure is subject to the rates of gas and electricity.

2. *Purchase cost* The base price for an EV in general is seen to be higher in comparison with traditional alternatives. Higher costs can be attributed to increased complexity and number of components in an HEV and specialized parts.

3. *Maintenance costs* In ICVs, vehicle maintenance costs can be very high due to engine maintenance which is a huge money sink, which further increases as the car ages. Changing the engine oil, coolant, transmission fluid and belts can add up in value over time. Since an EV does not have these parts, such repair costs are averted. The universal vehicle expenses, i.e., tire and brake changes, insurance and structural repair, are part of owning any vehicle. EVs are also not free of expenses. The highest maintenance cost associated with EVs is due to its battery which is unlike normal batteries. EV has large complex rechargeable batteries, which are quite resistant to any defect but degrade with time, and their replacement is quite expensive.

4. *Depreciation cost* HEVs have seen a higher rate of depreciation compared to ICVs. Deprecation is judged by its resale ability. One possible reason for the higher depreciation cost could be linked to the rapid advancement in HEV technology. An HEV which was once state of the art could become much inferior within a short period due to the recent stress in research in this field.

5. *Electric car rebates and incentives* A great reason which attracts consumers to go for EVs is the country and state incentives available in the form of various subsidies and policies. These rebates help offset the typically higher cost of an electric car to make "going electric" more financially feasible [298].

EVs are not for every lifestyle, but when compared to the myriad costs surrounding ICV purchase and maintenance, choosing an EV can be an intelligent fiscal decision. Table 8 summarizes total costs of ownership (TCO) of the selected drivetrain architectures. They are derived assuming the average German holding period of 4 years and an average yearly driving distance of 10,000 km. The cost breakdown for a midsized conventional car with a gasoline engine versus different hybrid architectures, a full battery electric car and a fuel cell vehicle is summarized in Table 8. The TCO assessment covers all types of expenses accruing for a vehicle owner including one-time cost (e.g., purchase price, expected resale value) as well as operating cost (e.g., fuel/energy, vehicle tax, general/exhaust inspection, maintenance and repair) [299, 300]. It can immediately be inferred that HEVs are economical.

7.5 Affordability

While discussing about HEVs, a natural question that arises is affordability. The government of every country is taking interest to search for an alternative method of transportation which is accessible to the public. As such, there is a rapid deployment of well-managed infrastructure to supplement electric technology. Since the production of the batteries has increased, its cost was shaved by approximately 50% and is expected to be lesser than $200/kWh by 2020. Improvement in battery technology will reduce the cost of the hybrid vehicle and make it accessible to more people. It is expected that EVs can be made affordable by 2022 even if the conventional cars improve their fuel efficiency by 3.5% a year. The analysis uses the US government's projected oil price of $50–$70 (£36–£50) a barrel in the 2020s. If the price is $20, the tipping point is pushed back between 3 and 9 years. Figure 8 depicts the battery pricings over the next 12 years, and it can be inferred that by 2022, EVs are likely to cost the same as ICE vehicle equivalent.

Consequently, EVs will reduce the revenue from ICE vehicle, but it will compensate via the revenue generated from this new window of opportunity for car manufacturers, for charging infrastructure companies and for battery manufacturers. Solid-state batteries will be the key to the enhancement in battery performance as they are 2.5 times denser than lithium-ion batteries.

The past 6 months have witnessed 10 future plans for launching EV from varied automakers. Based on these plans it is expected that about 25 million units would be on the road by 2025. Tesla Gigafactory is currently 35% operational and aims to produce 50 GWh of batteries in 2018. The EV charging station is a big hindrance which has yet not been focused and needs global attention. Currently, charging stations are present in limited areas where EVs sale is higher.

According to 2018 statistics, the total cost of ownership of a Ford Fusion Hybrid would amount to ~ $35,606. This HEV lies comfortably in the midsize market range. In contrast to this, a Honda Accord, which is a traditional vehicle, would cost ~ $35,709. By comparing other car models, it is evident that HEVs are now as price competitive as ICE vehicles. When looking into the compact market, it is seen that an HEV would be about ~ $9,000–$10,000 more expensive. The difference of the pricing in the two segments can be understood due to the higher maintenance and fuel consumption of a midsize IC-driven vehicle compensating for a more expensive battery and
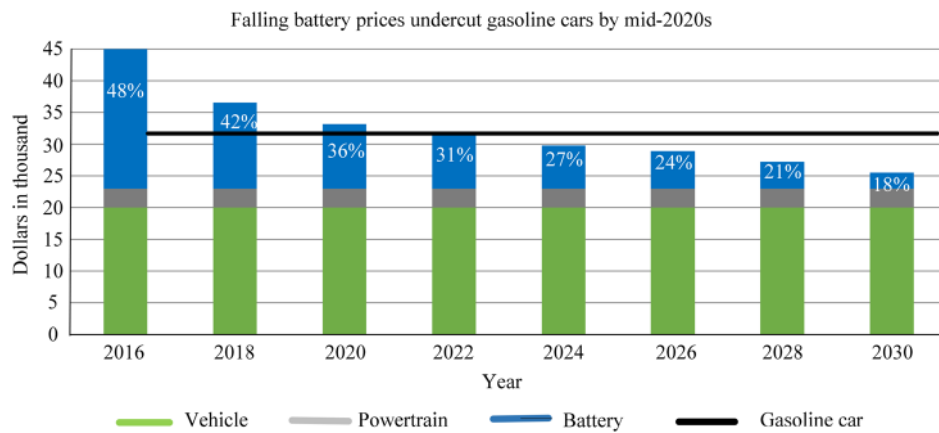
Fig. 8 Price fall status of hybrid vehicles [297]

base price. In a compact vehicle, the fuel consumption is also lower. Apart from that, the depreciation seen in a compact HEV is surprisingly higher which could be due to its lesser demand and product and rapid technology changes in the field. It is evident that HEVs in the midsize market are already price competitive and are affordable choices [301–304].

8 Conclusion

HEVs are rapidly emerging as a potential alternative to the existing state of transportation due to their lower petroleum consumption and toxic emission. Strict CO_2 emission laws and increased public awareness will propel HEVs to be the future of road transportation. Penetration of PHEVs in the market will change the operations of electric grid substantially, and efforts are being made to provide a two-way communication between the user and the grid. A review of various components of HEVs like architecture, bidirectional converter, ESS, motors and MPPT has been presented, and the findings are summarized at the end of each topic in tabular form.

Based on the literature review, it is found that the complex hybrid architecture will provide greater efficiency, trading off on higher costs and more complex designs. As the inverters are needed to interface the motor engine with ESS, their selection is of prime importance and q-ZSI is found to be a promising candidate.

To extend the battery life, it is suggested to combine UC with battery which will further improve the fuel efficiency and performance during varying ambient conditions.

Based on the study carried out, it is observed that there is a growing interest in developing advanced traction motors for hybrid vehicles and many traction motors are

available in the market. However, considering the trade-off based on performance, robustness, reliability and cost, the choice is often between induction motor and permanent magnet AC motor.

PVHEVs are still in infant stage and being explored to minimize gasoline consumption and maximize the usage of renewable energy. Various MPPT algorithms tuned with artificial intelligence techniques like FL, ANN and PSO are also being explored for PVHEV applications.

A comparison of various existing hybrid vehicles is provided in Table 9 which will serve as a guide to choose the best option. This paper provides all necessary information regarding the above-mentioned components and may be considered as a comprehensive document for the researchers and academicians who wish to carry out research in the field of hybrid vehicles.

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