Chapter 2
Literature Review

This chapter provides an exhaustive and systematic review of various essential components used in HEVs. The chapter covers the various architectures of HEV powertrains like series, parallel, series-parallel and complex with their advantages and disadvantages.

The hybrid energy storage system (HESS) which is combination of ultra-capacitor and battery is of prime importance in HEVs. It enhances the driving range of the vehicle and battery life span. Various available topology to integrate ultra-capacitor and battery has been discussed in detail. This combination of the two sources has a lot of potentials to increase the performance of the vehicle. Various topologies used to develop a HESS has been reviewed here.

The choice of a bidirectional converter is very necessary to obtain high efficiency from the system. The various bidirectional converter like current source converter, voltage source converter and impedance source bidirectional converter are discussed here with their application and shortcomings.

Various power optimization strategies used in HEVs are also discussed in this chapter with their suitability and adaptability based on the available environment and model parameters.

This review helps in the identification of suitable control architectures, bidirectional converter, choice of HESS and optimization strategy to improve fuel economy and performance of HEVs.

2.1 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. Since, these vehicles mostly run on internal combustion engine (ICE), the transportation industry is accountable for 25 to 30% of the total greenhouse gases emission [15]. ICE works on the process of fuel combustion resulting in the production of various gases like CO_2, NO_2, NO and CO [16], 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. EVs were tried as a solution in 1881 where battery alone was used to propel the vehicle and therefore required a bulky battery pack. However, absence of an ICE handicapped these vehicles with a short driving range [17]. 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 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 HEV (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 back-up. 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 may also offer grid connectivity.

Robust and affordable batteries are a primary challenge for hybrids vehicles. Various 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: i) singular battery cells, ii) modules, comprised of individual battery cell and iii) 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 ultra-capacitor (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% [18]. The combination of battery and UC forming a hybrid energy storage system (HESS) is higher efficient as compared to their individual performances.

2.1.1 Market share

According to [10], [19], global sales of EVs has 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 country, China was once again the leader of the pack with over 600,000-unit sales, far ahead of US 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 is no unique data available on the long-term market share of these vehicles. The data on BEVs and XHEVs (includes full HEVs and PHEVs) are taken from McKinsey [19] and Morgan Stanley & Co. [20] as they are the player in the vehicle domain statistics and the same is shown in Fig 2.1. In [20], data is given for BEVs and XHEV for China, US and Europe for status quo assumption and with breakthrough assumption till 2030 whereas in [21], the worldwide total data is given for BEVs till 2035. It can easily be inferred that the share of green vehicles will increase over the coming years.

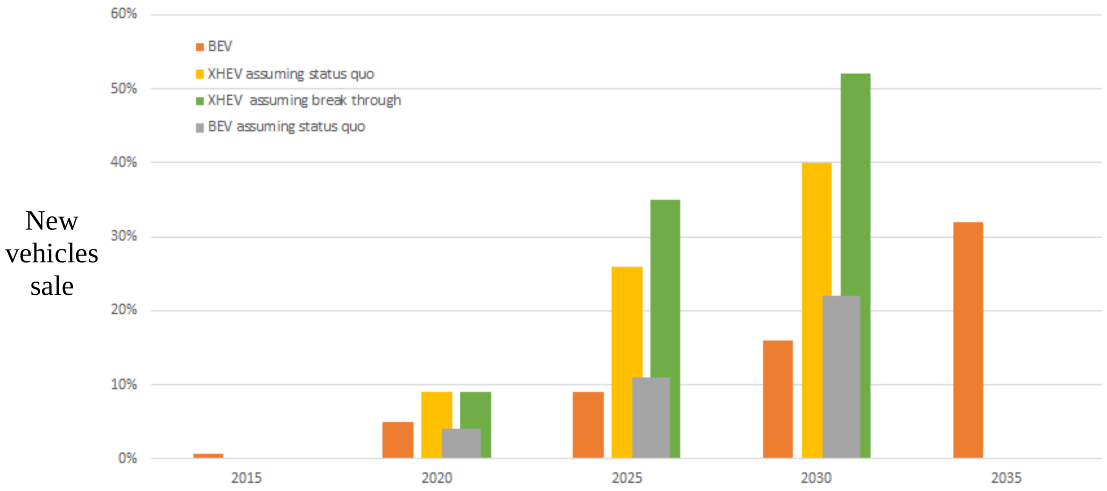


Fig. 2.1 Medium- and long-term sale of Hybrid vehicles

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 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 [22], [23].

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 few models is shown in Table 2.1 [24].

Table 2.1 Saving in fuel consumption in some top models.

Technology	**Non-hybrid/non-electric 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 2.5l (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

The structure of the literature review carried out has been shown in the form of a flowchart in Fig 2.2.

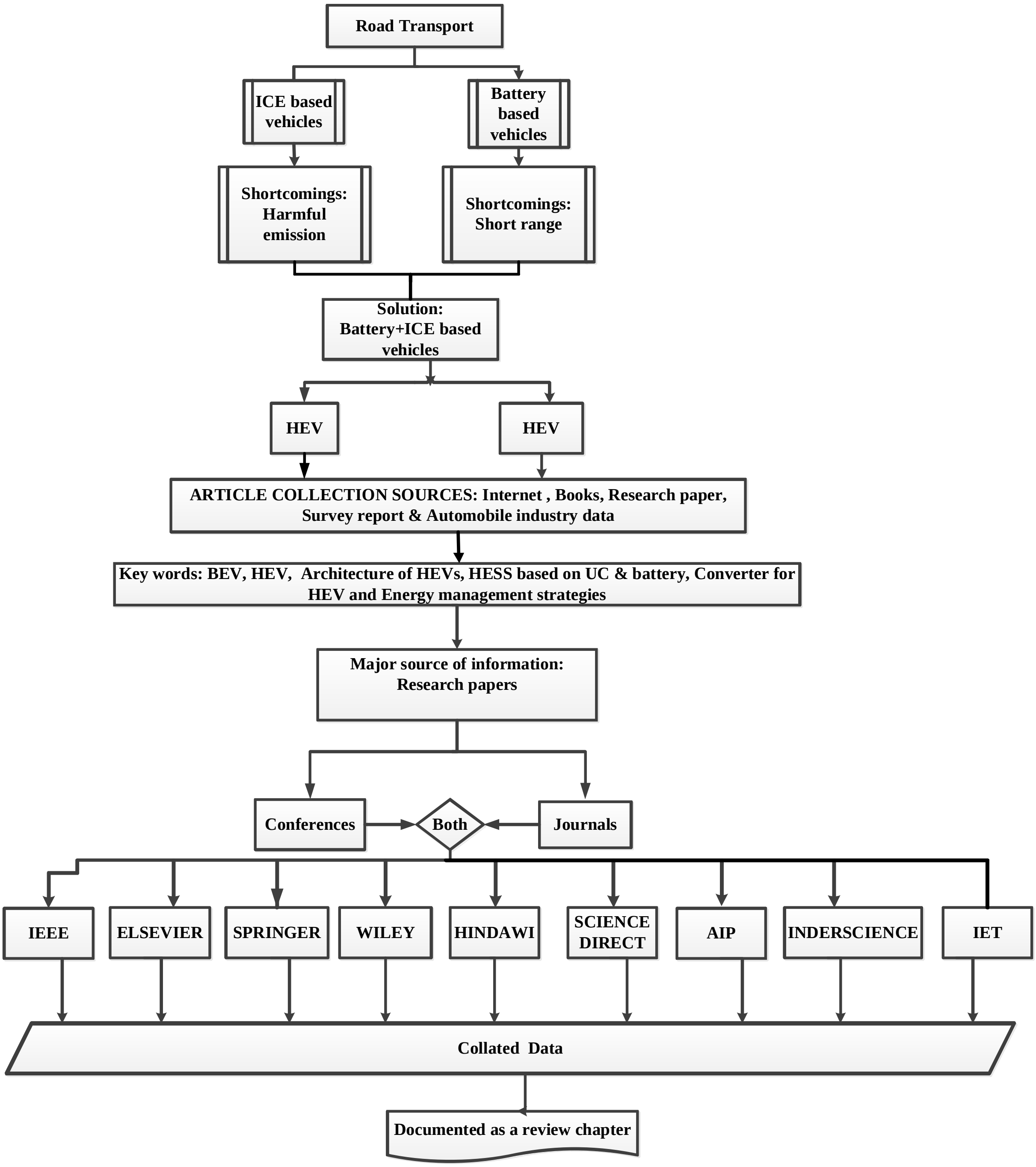


Fig. 2.2 Methodology adopted for carrying out the Literature review.

2.1 Architecture of HEV

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

1. Drive-Trains – 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, drive trains mainly include series, parallel and power split designs. In [25] the HEV's architecture has been classified into six different categories, which are mild / micro parallel, 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 [26]. In parallel HEVs, traction power can be supplied by ICE and EM alone or together by both the sources. The EM is used to charge the HESS by means of regenerative braking [27]. The parallel mild HEV is an ideal option as they provide a prime trade-off between the cost of vehicle and its performance [28]. Complex HEVs incorporate features of both, parallel as well series architecture. They are almost like the series-parallel hybrid except for the variance in power flow of the motor, which is bi-directional 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. 2.3.

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 require a more complex control strategy than a HEV. PHEVs begin operation in CD mode and as soon as the battery reaches to a threshold value of SoC, the battery shifts to CS mode until the vehicle is parked and recharged. The block diagram of PVHEV is shown in Fig. 2.4.

Various patterns of power flow are:

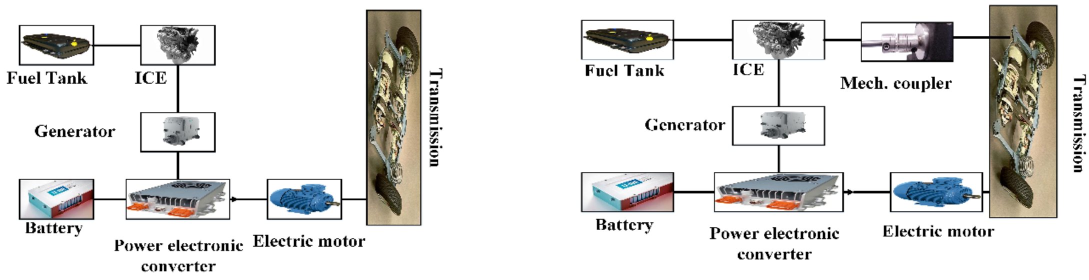
The power flows in HEVs to encounter the load demand is given in Fig. 2.5.

There are many possible patterns as given below [29]:

1) powertrain 1 alone delivers power to load;
2) powertrain 2 alone delivers power to the load;
3) both, powertrain 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;

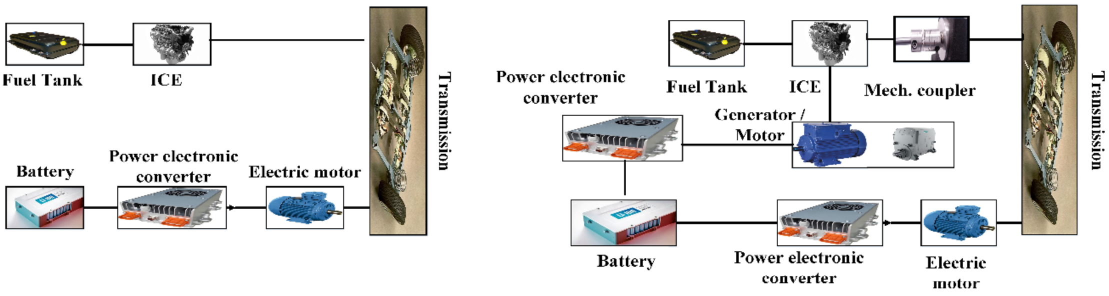
8) powertrain 1 delivers power to powertrain 2, and powertrain 2 delivers power to load;

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



A) Series hybrid

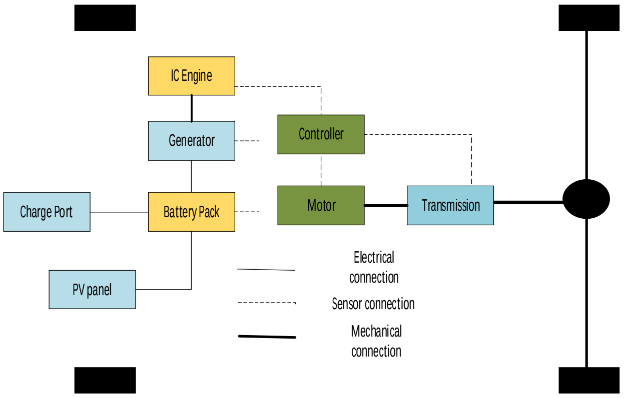
C) Series-Parallel hybrid



B) Parallel hybrid

D) Complex Hybrid

Fig. 2.3 Various architectures of a HEV



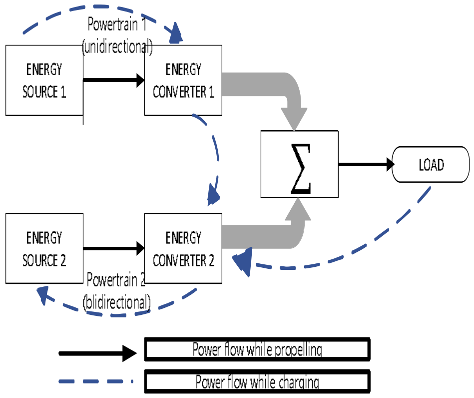


Fig. 2.4 Block diagram of PVHEV

Fig. 2.5 Patterns of power flow

Various papers have been published by researchers on the architecture of hybrid vehicles, and some of them are discussed here. In [30], a small ICE/generator was added to the battery powered EV to develop a series hybrid drivetrain. The prominent benefits of a series hybrid drivetrain are: 1) The ICE and the driven wheels are not coupled mechanically which compel 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 multi gear transmission and 4) Easy drivetrain control, simple structure and easy packaging. However, it suffers from some drawbacks, like 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 lithium battery [31]. In [32], 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-efficiency 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 [33].

In [34], [35] power-split was considered for the analysis of the TTR, a sub-category of parallel architecture. In [36], the split – parallel architecture for TTR and its control challenges are detailed. John M. Miller. [37] 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 mechanical continuous variable transmission (CVT). Series, parallel and power split architecture have been presented in [38]. In [39], the power-split architecture and its modelling in a systematic way is detailed. In [40], an energy management system (EMS) for power split/Parallel architecture of HEV has been employed to improve battery life and powertrain energy efficiency. It was also shown that the proposed two propulsion machines improved the powertrain efficiency by 5% as compared to one propulsion machine. In [41], a parallel active topology was used with a fuzzy logic controller (FLC) which has been implemented for online energy management of an EV. 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 [42]. In [43], 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[44]–[46], the parallel architecture is employed for PHEV and its energy management is presented.

In [47], a model of the power split PHEV powertrain and a TTR hybrid electric powertrain were 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 2.2. Table 2.3 gives the comparison of emissions for EV and HEVs for FTP-75 Urban, Federal highway & Commuter driving cycles. Table 2.4 provides a brief summary of these architectures.

Table 2.2 Summary of architectures & their application

Architecture	Complexity	Efficiency	Application, 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

Low-1, Medium-2, High-3

Table 2.3 Comparison of emission for different driving cycle [48].

Parameters	Conventional	EV	Series Hybrid	Parallel Hybrid
Control complexity	NA	Simple	Medium	Complex
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

Table 2.4 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

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

2.3 Bidirectional DC/AC Converter

Power converters are proliferated in all kind of applications to increase controllability and efficiency in automotive applications [49]. 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 [50], single-stage three-phase, or zero voltage switching inverters [51]. The various motor drives used in EV and HEV have been proposed in [52], [53], [62], [63], [54]–[61].

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.

2.3.1 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. Zhiqiao Wu et al. [65] proposed CSI with interior permanent magnet machine, as it increases the constant power operation regions due to voltage-boosting function. CSI for medium and high-power induction machines were studied in [66]–[70]. A novel space vector pulse width amplitude modulation (SVPWAM) method for a buck–boost CSI was proposed [71]. Due to this technique, the switching loss had reduced by 60%. Furthermore, the power density increased by a factor of 2 to 3. A new type of control strategy known as the nouveau for CSI in battery driven electric vehicle (BEV) has been proposed in[72] for better harmonic performance of the electrical machine. In [73], 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.

2.3.2 Voltage Source Inverter

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 like, the power factor decreases as the speed decreases, it induces harmonics, cogging and jerky start and stop motions. The types, advantages and disadvantages of VSI are as below:

Types of Voltage Source Inverter:

1) Single-phase half-bridge inverter
2) Single-phase full-bridge inverter
3) Three-phase VSI

Advantages:

1) Low power consumption and high-energy efficiency up to 90%
3) High power handling capability
4) No temperature variation-and ageing-caused drifting or degradation in linearity
5) Easy to implement and control
6) 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.

Jun Liu et al.[74] selected an advanced film capacitor to replace the conventional electrolytic bulk capacitors for EV applications. In [75], an adaptive flux observer to adjust itself by online estimation of DC-link voltage and rotor resistance has been proposed for VSI based IM in HEVs. The proposed observer is capable of obtaining simultaneous flux and DC-link voltage observation with online tuning of rotor resistance. Guodong Feng et al. [76] proposed a current injection-based online parameter and VSI nonlinearity estimation method for permanent magnet synchronous motor (PMSM) drives in EVs. The non-linearity of VSI in HEV is discussed in [77]. A new inverter design based on the silicon carbide based semiconductor devices was proposed to fulfil the power and temperature requirements of EVs in [78]. The impact of various modulation schemes on DC-link capacitor of VSI for HEV has been discussed in [79].

2.3.3 Impedance Source Inverter

ZSI has been considered an efficient candidate in vehicle applications such as drive system reliability, which 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, allows working in buck or boost mode using the 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 [80]. 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 [81]. However, the continuous input current by VF-ZSI is suitable for 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 [82]. Dong Caoat et al. has 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 a LC network in its design [83].

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 [84]. The sustainability of inverters at very high temperature (105°C) while operating at high efficiency is another issue to be addressed [85]. The 900V SiC MOSFET technology in the inverter reduces the energy losses and is beneficial in the mild city-style drive cycles [86]. 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 [87]. A high capacity compact power module (J1 series) has been developed with compact size, high performance, lightweight and low self-inductance [88]. 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 [89], 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[90], [91]. 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 [92]. A pulse amplitude modulation (PAM) inverter was introduced in HEV to obtain high performance [93]–[98]. A fault-tolerant 4-leg topology was proposed in [99]. The quasi-ZSI (q-ZSI) [100] can buck and boost the voltage and provide the bidirectional power flow. In [101], [102], 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 is important [103], [104]. The strategy proposed in [105], [106] 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 which allows very high-power densities. In addition, lower stray inductance and package resistance improvements will enable high inverter efficiencies [107].

2.4 Hybrid Energy Storage System

The choice of ESS depends on various parameters including charging speed, energy density, life expectancy, cost, weight and size [108], [109]. The current trend indicates that batteries and UC remain as the main choices for ESS [110]. 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 [111]–[115]. The UCs are robust, have a quasi-infinite cycle life and can sustain highly dynamic power profiles [116], [117]. The UCs are also responsible to reduce the sulfation in lead acid batteries for EVs [118]. Furthermore, the UCs provide high frequency and high magnitude power whereas the batteries fulfil low frequency requirements. It is not possible for an individual energy storage device to fulfil all the requirements [119]. However, a combination of the two can help to overcome their drawbacks [120]–[126].

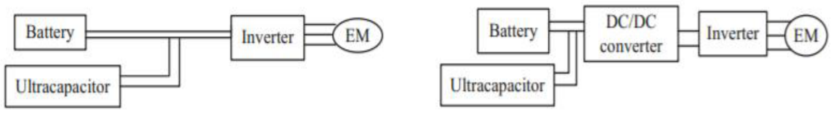
To protect EV batteries and extend their life, an UC is combined with them [127]–[130]. The sudden load variations are absorbed by the UC and hence efficient use of the batteries can be achieved [131], [132]. The batteries can be modelled with 1 RC and multiple RC branches, and an UC is added to make 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/over voltage protection schemes, cell balancing and their redistribution should be considered [133], [134]. To split the current between UC and battery, karush–kuhn–tucker (KKT) and the neural network (NN)-based EMS are used in [135].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 [136].

The fuzzy logic (FL) based EMS in a HESS for longer battery life was also adopted. A battery lifetime degradation model was used to develop the relationship between the battery charge/discharge behavior and the impact on its life time [137], [138]. 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 [139], [140]. Wireless charging concept is used to charge the UC effectively in [141]. A rule based control algorithm is proposed to effectively manage the UC's SoC and offloads the current peaks from the battery in [142], [143]. Model predictive controller (MPC) was used to distribute the energy in a HESS in [144]. 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 [145]–[148] in EVs. 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 [149]. A HESS linear quadratic regulator was designed to mitigate issues related to battery wear and peak power demands for EVs and HEVs [150]. The equivalent consumption minimization strategy is proposed to distribute the power between the battery and UC in a series HEV [151]. Other HESS like UC with the FC, has also been adopted in few cases and one of such combination is interfaced using ant colony method in [152]. 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 [153].The implementation of HESS has at least three major advantages: cheaper batteries, increased autonomy and extended life time [154], [155].

There are various possible configurations to connect the HESS and the electric traction motor, which are given in Fig. 2.6. Also, a battery and UC can be interfaced by means of bidirectional DC/DC converter in many ways [156]. The topologies are mainly selected based on their advantages and disadvantages as tabulated in Table 2.5 below. The boost half-bridge best meets the requirements of a bidirectional cell, thus suitable for battery/UC interface [157].

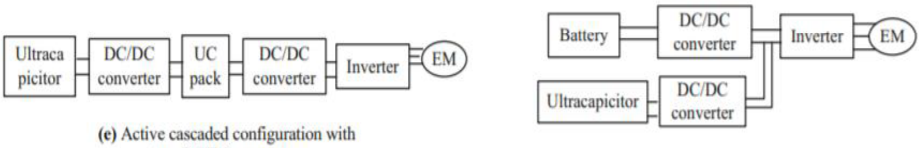


(a) Passive battery/UC configuration

(b) Passive cascaded battery/UC configuration

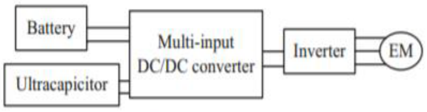
(c) Active cascaded UC/battery configuration

(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. 2.6 Various possible configuration of UC and battery integration [157].

The passive connection given in Fig. 2.6a 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 [158] as presented in Figs. 2.6b & 2.6c. 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. 2.6d, 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 [159] 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 [160]. A bidirectional non-isolated DC-DC converter performs energy control of one of the storage elements. In this control strategy, UC provides fast dynamic power, the complement is provided by the battery bank, [161] as shown in Fig. 2.6e.

In case of multi-DC-DC converter topology shown in Fig. 2.6f, the battery and UC are individually connected to the inverter terminal through their own dc/dc converter. This topology shows a good performance, especially for the controllability of current flow.

The two DC-DC converter required in topologies shown in Figs. 2.6e & 2.6f are replaced by a multi-input non-isolated bidirectional DC-DC converter [162].

The multi-input DC-DC converter is used for the integration of energy sources such as FC, PV and wind for EV applications [163]. 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 [164]. 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 [165].

In [166], 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 [167], a half-bridge bidirectional DC-DC multi input converter is chosen to link the battery and the UC.

Table 2.5 Comparison of various topologies of the HESS [157].

Topologies	Advantages	Disadvantages
Isolated topology in Fig. 2.6b Isolated topology in Fig. 2.6c Isolated topology in Fig. 2.6d	Higher galvanic isolation, higher voltage conversion ratios	Bulky, heavy, costly magnetic core, higher EMI, higher voltage stress across switches
Non-Isolated topology in Fig. 2.6e	Lower transfer capacitor voltage rating	Two large inductors, discontinuous output current, a larger output capacitor and a higher switch/diode voltage rating
Non-Isolated topology in Fig. 2.6f	Reduced input/output current ripples	Having two large inductor higher transfer capacitor voltage ratings
Non-Isolated topology in Fig. 2.6g	One small inductor no transfer capacitor voltage, lower switch/diode voltage ratings, lower switching/conduction losses	Discontinuous output current

The various hybrid electric vehicle has been compared based on the various parameters like driving range in Table 2.6.

Table 2.6 Comparison chart for various existing hybrid vehicles

Vehicle	Driving range	Efficiency	Fuel type	Overall Cost	Structure	Advantage	Disadvantage	ESS	Driving Mode
ICE	high	low	Gasoline	high	Simple	1.Matured technology 2.Better performance 3.Simple and reliable 4.commerciAllized	1.Haramful emission 2. Fuel economy is poor	Fuel tank	City & 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

2.5 Energy Management Strategies (EMS) for HEVs

A high degree of freedom and a lot of opportunities are available in HEVs, specifically in the power- split strategies between motor and the ICE to obtain the ideal mileage. The complex configuration and dynamic nature of the HESS makes this task very complex and calls for smart EMS to split the power between the available on-board sources. Despite the architecture of the HEV, the EMS should be capable to respond instantaneously as per the demand generated by the driver. The classification of these strategies has been shown in Fig. 2.7.

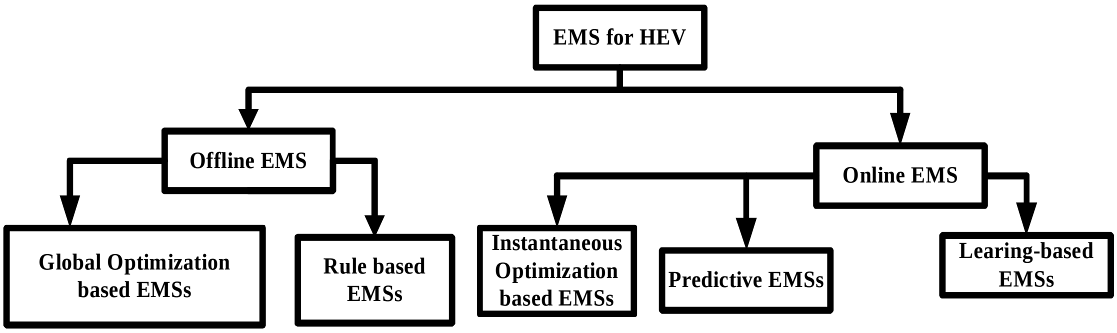


Fig. 2.7 Classification of the optimization strategies used in HEVs

The offline EMS are classified as per the information/ data collected based on the driving conditions of the vehicle. This EMS can further be divided into global optimization based-EMS and rule-based EMS whereas the online EMS can be categorized into instantaneous optimization-based EMS, predictive EMS, and learning-based EMS.

A. Offline EMS

1. The Global optimization-based EMS is used to generate a global optimal point for power- split among various available sources in a provided driving cycle. These EMS cannot be directly applied to the given real-time system as they are associated with computational burden and required prior information/data of the entire trip. These EMS can be used to obtain the control rules and parameters. Few of the examples of the global optimization- algorithms are Pontryagin's minimum principle (PMP), dynamic programming (DP), Stochastic dynamic programming (SDP), Genetic algorithm (GA), Game theory, Pseudospectral method and convex algorithm.

PMP is an analytical advancement strategy to tackle the problems of controlling the flow of power in HEVs. PMP transforms the optimization function into a Hamiltonian matrix. Then the designed optimization will be minimized or maximized based on the kind of problem formulation. The designed objective includes the fuel minimization, lesser degradation of battery SoC and emission reduction mostly. PMP strategy during the urban driving for series HEVs with input like parameters tractive demand and speed has been discussed in [168]. DP optimization breaks the main problem in smaller sub-problems and solve them by recursive manner. This EMS can be used for both constrained and unconstrained problem statements. It can be used with linear and nonlinear systems as well. The curse of dimensionality is the only demerit of this method which result into the increase of computational burden and hence restrict its use to some complex systems [46]. The optimization method which makes use of random variables in the defined problem are considered under stochastic optimization. In SDP, either state or decision is known in terms of probability function [169]. GA starts with a bunch of arrangements (chromosomes) called a population. This bunch also called the set of solutions. The solution are chosen from the population by means of their fitness function. Most reasonable solution will get the chance over the weaker solution to enhance their number [170], [171]. The basic idea of game theory is to identify, through reasoning, strategies of the individual as per the players wish rationally, and the expected outcomes as per their act. This theory has also been implemented in HEV as it is sensitive to the variation in parameters of HEVs. It considers the prediction and real behavior of individuals in a game to provide the result [172].

Pseudospectral method is a branch of operational investigation and is normally used in multi-subject optimization problems [173]. The convex optimization algorithm is used to solve the convex optimization problems [3], where the fitness function and the set constraints are also convex. As compared to other global optimization algorithms this strategy provides optimal solution with a less computation burden. The implementation of EMS to the HEV is mostly consider as a nonlinear problem, which can be converted into a semi convex problem by using a convex optimization method that offers a simplified calculation process and better optimization effect.

2. The rules-based optimizations is a sub-category of the offline EMS as by means of this algorithm the rules are derived prior to the implementation to the real-time system. These rules are derived from the previous trip data or based on human/machine expertise. Rule-based EMS are based on pre-defining a series of control rules to determine the power split while it cannot achieve optimal allocation of power as compared to offline globally optimized energy management. These EMS can further be divided into a deterministic rule-based control strategy and a fuzzy rule-based control strategy.

The deterministic rule-based control strategy is designed by collecting the data of the fuel consumption and emission of the previous trips. The rules are implemented using lookup tables [174]. The fuzzy rule-based control strategy represents phonological as it comprises of the terms such as slow, fast, low, medium, high, and so forth which cannot give the exact value. There exists a fuzziness in parameters. In fuzzy the accuracy of the statement can be marked as per the degree of truthiness in it. Fuzzy control is easy to implement and has a higher degree of robustness in it [175]–[179]. This algorithm is very handy in complex system and the system have higher degree of non-linearity in it.

B. Online EMSs:

This online EMS can be categorized into three.

1. Instantaneous optimization: Instantaneous EMS can minimize the instantaneous fuel consumption at each instant without a prior knowledge of the entire driving cycle and only obtain local optimal results. This can further be divided into equivalent consumption minimization strategy (ECMS), Adaptive equivalent consumption minimization strategy

(A-ECMS) and Robust control. ECMS adds on to the global optimization by adding a feature to work as an instantaneous optimization as well. It is totally based on the performance of equivalent factor designed. This EMS does not require the prior information of the driving cycle to obtain an optimal solution and also can be used in real-time [180]. In Adaptive-ECMS, the equivalent factor is tuned by another algorithm to improve the performance of the EMS. The equivalent factor is normally designed by taking into the account the future power requirement and the current SoC as well. Therefore A-ECMS keeps on refreshing the control parameters by means of trainning [168]. The robust control is used where there an uncertainty in the parameters and disturbances may occur in system parameters and its structure[181].

2. Predictive EMS: In predictive EMS, the main idea is to know the trip information by devices like the global positioning system (GPS) and internet of the things (IoT). [182]. This EMS will predict the best fuel economy based on the trip information, traffic and available source powers. The future power demand over the horizon is calculated via the traffic information received through IoT and GPS. This can further be divided into artificial intelligence (ANN), model predictive control (MPC), stochastic model predictive control (SMPC) and learning based SMPC. The ANN can be categorized into three different forms i.e. back propagation neural network (BPNN), radial basis function neural network (RBFNN) and Elman neural network (ENN) [183]. BPNN is associated with the problems like a) slow training rate b) trapping in local minima, c) complex structure for large size network and, d) usage of hit and trial method for choosing the neurons in a hidden layer [184]. RBFNN is used to overcome the slow learning rate and has comparatively less chances to trap in local minima. For further improvement in forecasting accuracy, ENN is applied due to its virtue of dynamic adaptability [185]–[187]. MPC describes the development of tractable algorithms for uncertain, stochastic, and constrained systems. SMPC method can estimate the expected velocity of the vehicle provided by an exponential estimation or NN. SMPC based strategies are modelled especially for uncertainties and disturbances based on their probabilistic distribution function [188]. In a learning based MPC, the MPC algorithm is combined with a machine learning algorithm. By doing so the performance of the controller get enhanced in a way that the Markov chain function which exist in default MPC gets updated by online learning. Therefore, it can dynamically adapt to the changing driving behaviors, such as environmental changes and varying traffic conditions it is very useful with time-varying condition which exist as the vehicle load and SoC of the battery in HEVs.

3. Learning-based EMS:

The learning-based EMS will normally update the control parameters by means of training the collected data and improves the fuel economy and adaptability as per the changing driving environment. The control parameters get updated online with the change in environmental condition to get adjust to the different traffic conditions. This EMS does not require accurate model [189].

2.6 Summary

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 HEVs 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 and optimization strategies has been presented.

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. Various optimization strategies to decide the power flow between the available on-board source has also been reviewed which play a vital role to enhance the fuel economy and performance of the vehicle.