The electric vehicle: a review

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Abstract: Electric vehicles (EV), as a promising way to reduce the greenhouse effect, have been researched extensively. With improvements in the areas of power electrics, energy storage and support, the plug-in hybrid electric vehicle (PHEV) provides competitive driving range and fuel economy compared to the internal combustion engine vehicle (ICEV). Operating with optimised control strategies or utilising the concept of the energy management system (EMS), the efficiency of the PHEV could be significantly improved. In this review paper, the operating process of the various types of EVs will be explained. Battery technology and supercapacitor technology will also be discussed as a possibility to increase the energy capacity of PHEV.

Keywords: EVs; conventional HEVs; PHEVs; plug-in hybrid electric vehicle; energy transmission; battery technology; FC; PV; internal EMS; EMS; energy management system.

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1 Introduction

The issues of climate change or global warming have been rigorously discussed by many governments since the early 21st century. A great number of relevant reports have revealed the negative impact of climate changes dominantly driven by human activities. With the globally increasing civilisation and industrialisation, a large number of fossil fuel burnings in industries have led to the acute problem of air pollution (Wee, 2010). Simultaneously, the exhaust emissions from automotive vehicles cannot be ignored. Vehicle emissions, which mainly include CO_2, CO, NO_x and particulate matters (PM10 and PM2.5), have been considered as the major contributors to the effect of greenhouse gases, also leading to the increase in different forms of cancers and other serious diseases (Fenton and Hodkinson, 2001; Fajri and Asaei, 2008).

The ever rapidly growing transportation sector consumes about 49% of oil resources. Following the current trends of oil consumption and crude oil sources, the world's oil resources are predicted to be depleted by 2038 (Ehsani et al., 2010). Therefore, replacing the non-renewable energy resources with renewable energy sources and use of suitable energy-saving technologies seems to be mandatory. Electric Vehicles (EVs) as a potential solution for alleviating the traffic-related environmental problems have been investigated and studied extensively (Clement et al., 2009; Hajimiragha et al., 2010; Stephan and Sullivan, 2008). Compared to ICEV, the attractive features of EVs mainly are the power source and drive system.

1.1 Classifications of electric vehicle

Taking the power supplement and propulsion devices into account, EV could be classified into three different types: pure electrical vehicle (PEV), hybrid electrical vehicle (HEV) and fuel cell electrical vehicle (FCEV) (Chan and Chau, 2001; Chau, 2010, 2014). Table 1 shows a brief classification of different EVs. The PEV is purely fed by electricity from the power storage unit, while the propulsion of PEV is solely provided by an electric motor. The driving system of HEV combines the electric motor and the engine, while the power sources involve both electricity and gasoline or diesel. FCEV is driven by an electric motor and could be directly or indirectly powered using hydrogen, methanol, ethanol or gasoline.

Table 1 Comparison of different electrical vehicles

Types	*PEV*	*HEV*	*FCEV*
Drive section	Electric machine	Electrical machine, internal combustion engine (ICE)	Electrical machine
Energy sources	Battery, ultracapacitor	Battery, ultracapacitor, ICE unit	Fuel cell
Energy supplements	Electricity and power system	Electricity and power system, gasoline station	Hydroge-nide

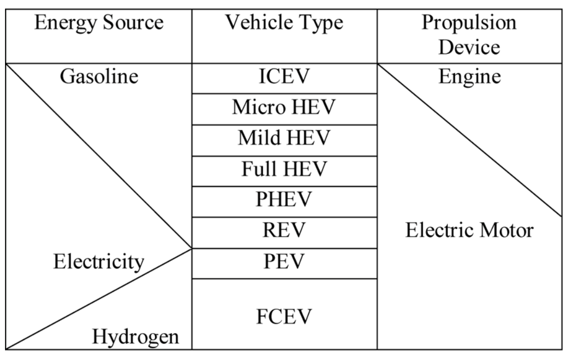
In PEV, loosely named as battery electric vehicle (BEV), energy storage capacity fully depends on the battery technology. Zero discharge emission of PEV should be a significant advantage because the electrical energy is solely supplied from the vehicle-mounted battery. On the other hand, the limitations on the present status of the on-board battery technology of PEV make it less attractive than ICEV under the same economic and driving requirements. Batteries with high power densities but low energy densities result in longer charging time – even with fast charging technologies, one hour to several hours for full charging is necessary. Thus, main challenges of the PEV are limited driving range, high initial cost and lack of charging infrastructures (Hannan et al., 2014). For the practical implementation, the size and location of the battery inside the PEV should also be standardised (Chau and Li, 2014).

FCEVs are attractive because of zero roadside emissions. Even taking the overall emissions into account, which include the emission from chemical plants and on-road reformers, the FCEV seems still competitive. Fuel cell (FC) is the main power supplier and the critical technology for FCEV is an electrochemical device that produces DC electrical energy through a chemical reaction. There are five main components in FC: anode, an anode layer, electrolyte, cathode and a cathode catalyst layer. With suitable parallel/series connection of FC sources, the required amount of power can be produced to drive the car. In terms of driving range, it is comparable to ICEV, thus resulting in a wide range of application of FCs from small scale plants of the order of 200 W to small power plants of the order of 500 kW. However, the high initial cost and lack of refuelling stations are still regarded as significant challenges for the success of FCEV (Rao and Wang, 2011). Also, the supply electricity continuity of FCs is less reliable than conventional battery used in EVs.

The crucial advantage of BEV and FCEV is the 'zero emission' and hence reduced air pollution. However, the 'zero emission' of BEV and FCEV is not absolute considering the emissions during the whole processing. However, "what is critical as the main pollution-contributor and how" are the topics that are hardly discussed. For example, the pollution-contributors include chemical contamination when producing the fuel cell and the battery (or the electrochemical plant for FCs), the emissions during the vehicle manufacture, the pollution from scrap battery processing, etc.

The HEV combines the properties of ICEV and BEV. Driving power sources of HEV include both gasoline/diesel and electricity; the propulsion relies on the engine and electric motor. According to different refuelling or recharging measures, HEVs can be classified as either conventional HEVs or grid-able HEVs. Based on levels of the combination, the conventional HEV could be further developed to three types: micro, mild and full HEV. The grid-able HEV could be either plug-in hybrid electric vehicle (PHEV) or range-extended electric vehicle (REV) (Chau and Li, 2014). Figure 1 shows different categories of EVs based on the energy source and propulsion device.

Figure 1 Classification of EVs

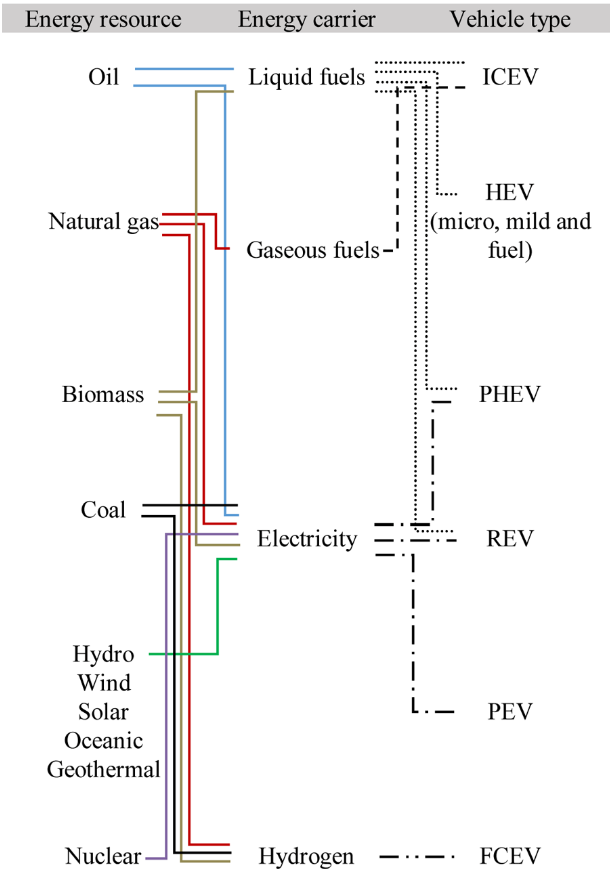


Source: Chau and Li (2014)

As both electricity and petrol propel the HEV, the driving range of HEV is comparable to that of ICEV. The economic practicality of HEV seems to take more advantages than PEV due to the status of present battery technology. However, the need for engine and gasoline is not eliminated in HEV – so there is no zero emission. The combination of electric generator and engine increases the complexity of the manufacturing process and the initial cost. Therefore, the challenges for HEV are focusing on coordinating these two propulsion devices to achieve an optimal efficiency while reducing the design complexity at the same time (Wong, 2013). Going through the overall development of EVs and considering both the economy and the technology, HEV has the most potential to develop and dominate the next few decades.

Taking the energy sources into account, EVs are fully or partially energised from the batteries, which themselves are directly or indirectly charged from either a power station and/or electrochemical reactions. Therefore, various renewable energy sources should be used to improve the overall emission of EVs. Figure 2 gives the energy diversification based on different feeding measures for the EV.

Figure 2 Energy diversification of EVs (see online version for colours)



Source: Chau and Li (2014)

2 Technologies of hybrid electric vehicle

2.1 Conventional HEV

2.1.1 Micro and mild HEV

According to the proportion of the output power from the electric motor, HEV could be divided into micro, mild and full HEV modes. Compared with ICEV, the micro-HEV operates the engine start motor with a belt-alternator start generator (BSG). The BSG probably eliminates the idling of the motor and simultaneously reduces the petrol consumption (Wen and Su, 2016). The micro-HEV cannot be strictly classified as a hybrid electric vehicle because the electric motor does not provide a continuous power.

In mild HEV, the traditional start motor (engine) is replaced by integrated starter-generator (ISG) that is located between the engine and the transmission. As a result, the size of the engine is reduced since ISG assists the engine to propel the vehicle (Lee et al., 2015). One of the notable examples of mild HEV is Buick Lacrosse, introduced in 2006. The working principle of mild HEV is summarised as follows: when the vehicle starts, electric generator comes alive while the petrol engine is shut down. Subsequently, all the working equipment will rely solely on the electric motor. When the brake pedal is released and the vehicle is accelerated, the petrol engine will start and continuously provides the entire propulsion under fast speeds. These processes result in a significant feature: the engine should be shut down once the vehicle stalls, which is known as an idle stop-start feature. The battery is primarily recharged when the vehicle is either decelerating and/or braking. The design of ISG requires both engine and electric motor to work collaboratively when heavy acceleration is required. Honda CR-Z is one of the most typical representatives for mild HEV.

2.1.2 Full and dual-mode HEV

For full HEV, the crucial technology is the electric variable transmission (EVT) which is additionally operated as a power splitter. Power splitting provided by EVT gives access to electric launch which refers to the initial acceleration under electric power only. It maintains almost all of the advantages of different types of conventional HEVs such as idle stop-start, regenerative braking, smaller-size engine and electric launch.

Toyota Prius adopted the full HEV mode in mass production in 1997 and further improved by adding a planetary gear to assist the power splitting (Debnath, 2015). After a successful design and adoption of hybrid power system existing in the vehicle market, a great number of motor companies are dedicating to develop it into more fuel-economic and environment-friendly status (Hermance and Sasaki, 1998). Lexus LS600Hl improved the full hybrid mode and has achieved ‘real zero emission starting’ (Rowley, 2007).

To further address the problem of fuel consumption during start, stop and restart in an urban area, dual-mode based on full hybrid electric vehicle system is introduced to enhance the overall efficiency. ‘Dual-mode’ means that the hybrid system and electric motor cooperate effectively to achieve a premium performance under the conditions of fast acceleration and full speed (Chau, 2009). The new generation motor of Lexus ct200h and BMW x6 are great examples recognised and accepted by the public (Hutchinson et al., 2014). It is important to mention that dual-mode has contributed not only to conventional HEV technologies but also to some plug-in HEV technologies.

Conventional HEV technologies have been researched extensively and have vastly improved (Sabri et al., 2016). When conventional HEV system developed from micro and mild modes into the full mode, the operating characteristics of the vehicles have changed. The micro and mild conventional HEVs give priority to gasoline/diesel machine while electric generator or battery acts as an auxiliary device. In contrast, the full or dual-mode HEV uses electricity as the main energy to propel the vehicle. Currently, HEV has taken a dominating position (Guille and Gross, 2009). Although conventional HEV can be optimised in dual-mode or full HEV to increase the driving range and fuel economy, the disadvantages of burning gasoline/diesel, heavy battery pack and high initial cost cannot be ignored. Additionally, the complexity of the manufacturing process could be another challenge. Thus, conventional HEV is still inappropriate when taking into consideration issues such as transmission loss, gear noise and lubrication (Hermance and Sasaki, 1998). Nevertheless, it should be pointed that HEV has been considered as 'high initial cost' system by researchers. However, these studies that listed the 'high initial cost' as the main drawback had little or no information about the cost of various sections such as the cost of establishing the EVs' production line, the cost of maintenance and cost of building the refuelling or recharging facilities.

2.2 Grid-able HEV (PHEV)

Compared to the fixed amount of electricity from the battery pack in conventional HEV, grid-able HEV can be directly connected to the power grids (Chau and Li, 2014). Researchers have studied the grid-able HEV, also known as the PHEV, for decades (Akhavan-Rezai et al., 2015). Generally, the constructive change in PHEV is to replace the fixed battery pack (used in conventional HEV) with rechargeable batteries. This results in recharging the battery from an external power source and simultaneously allowing an increase in the electricity capacity. PHEV can provide a longer pure electric driving range similar to both PEV and ICEV.

Although it is developed from conventional HEV, the operating mode of PHEV substantially differs from conventional HEV. The conventional HEV is gasoline dependent, which means the electricity from the battery and generator assist partly for the engine. On the contrary, electricity from the rechargeable battery will play a leading role in PHEV while the fuel engine is maintained as the auxiliary propulsion unit.

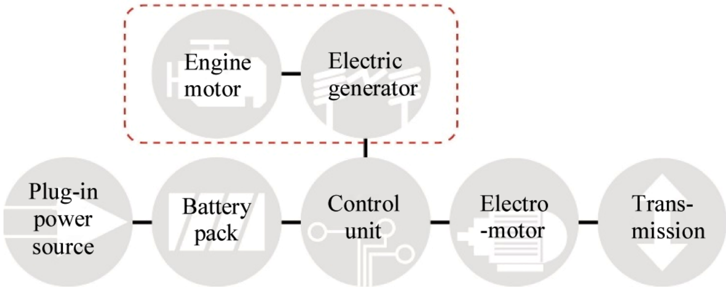
3 Plug-in hybrid electric vehicle technologies

3.1 The propulsion motor technology in PHEV

3.1.1 Connecting status of motors in PHEV

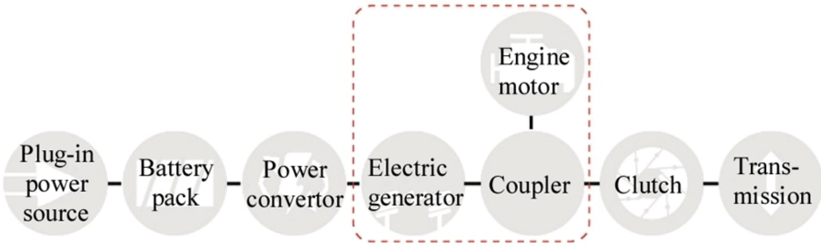
There are three types of hybrid systems based on different connections between ICE (engine motor) and electric generator in PHEV – series connection, parallel connection, and series-parallel connection. The series PHEV is directly driven from the power produced by ICE to the electric generator and the battery. The power goes through a control unit, which will drive the electromotor and will convert into kinetic energy. Figure 3 demonstrates the series system in PHEV. Under the series connection, the function of the battery is to adjust and maintain a balance between the engine and the electric generator.

Figure 3 Series connecting system of PHEV (see online version for colours)



There are two sets of driving systems in parallel connection: traditional ICE system and electric motor system. These two systems could either drive the vehicle independently or propel in cooperation. The advantages of the parallel connection are simple construction and lower initial cost (Van Mierlo et al., 2004). Honda Accord and Civic adopt the parallel HEV mode (PR, 2015). Figure 4 shows the parallel connection mode of PHEV.

Figure 4 Parallel connecting system of PHEV (see online version for colours)

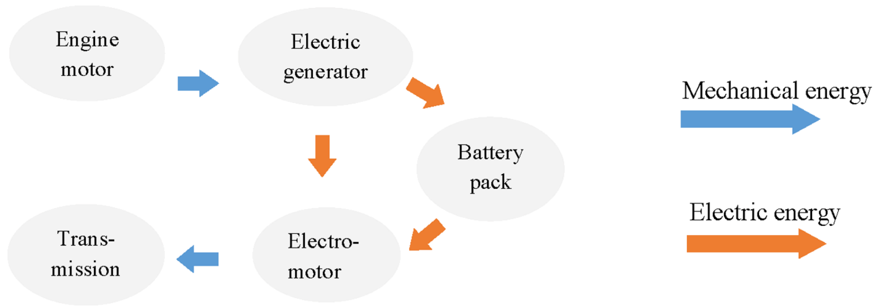


The main feature of a hybrid system with the series-parallel connection is that both ICE and motor drive the system simultaneously. They maintain their own set of mechanically variable-speed institutions separately (Lovatt et al., 1998). The two systems are connected with each other through a gear train or a planetary wheel structure. As a result, PHEV comprehensively regulates the speed relation between the ICE and the electric motor. Compared with the parallel hybrid system, the series-parallel hybrid system is more flexible to adjust the output power from ICE and electromotor according to different working circumstances. Figure 5 shows the mixed transmission of mechanical energy and electric energy in series-parallel PHEV.

3.1.2 Electromotor selection for PHEV

There are two significant factors influencing the selection of the motor for PHEV: driver expectation and vehicle constraints. The driver expectation is defined as driving profile, which represents five characteristics: acceleration, maximum speed, climbing capacity, braking, and the driving range. The vehicle constraints refer to vehicle type, vehicle weight and payload (Amjad et al., 2010).

Figure 5 Parallel connecting system of PHEV (see online version for colours)



Several types of electromotors could be employed in PHEV for different performances. In terms of operational simplicity, direct current (DC) series motor is attractive but suffers from poor power to weight ratio. Higher power to weight ratio exhibits in DC brushless motor, which also has a high efficiency of ~95% (D'Souza et al., 1999). For maintenance-free operation, alternate current (AC) induction motors seem to be an appropriate option with low cost and high reliability. The inherent downside of induction related motors, however, is the difficulties in speed control (Riba et al., 2016). The high-speed operation capability has been demonstrated in switched reluctance motors (Gieras, 2010).

3.2 Range-extended hybrid electric vehicle

One of the controversial issues in the research of PHEV is the range-extended hybrid electric vehicle (REV). In this paper, we define REV as an EV that allocates an extra small-size engine, known as the range-extender, coupled with the electric generator to recharge the battery pack. In terms of grid-ability, REV configures the charging socket that allows charging from external power source. In other words, REV is constructed as a serial mode PHEV. The operating mode in REV is based on PEV with an auxiliary power unit (APU) (Li et al., 2016; Nikowitz, 2016).

Normally, the statistical data indicates that 90% urban driving range is lower than the range of 50–60 km, while the daily driving range greater than 100 km is less than 5%. To cover the 5–10% of the occasionally longer driving range (>100 km), the vehicle has to be designed with more than 150 kg battery bank, which uses Li-ion battery to provide almost 160 km driving range. This results in decreasing the efficiency (Patil et al., 2008; Jorgensen, 2008; Mierlo et al., 2006). Such difficulties have restricted the PEV and full or dual-mode HEV as well. The design of REV, however, incorporates the advantages of both EV and HEV to utilise the range-extender to recharge when the battery runs low.

It is necessary to mention that the range-extender only assists battery without providing any propulsion. GM Chevrolet Volt successfully introduced REV technology, which maintains 64 km pure electric driving range with 16 kWh capacities and a 1.4 l four-cylinder engine. Similarly, the design of Audi A1 REV employs a 15 kW spin motor as the APU when the pure electric driving range is 50 km and the battery capacity is 12 kWh (Newcomb, 2016).

4 The energy mechanism in plug-in hybrid electric vehicle

Based on the components used in EV, the internal energy transfer mechanism can be described by three critical units: energy source, electric power (converter/inverter), and energy storage. The energy source is considered as the supplier or an energy transfer mode to support the running of the whole system. The energy storage should be a significant part of storing the excess energy (regenerative braking and recharged electricity) and maintaining the system when confronting a greater energy demand. Various converters channel the bridge between each component from the energy source to storage. In terms of operating regulations, the state of charging (SOC) will be a critical technology for HEV.

4.1 Energy resources model in HEV

4.1.1 Battery model

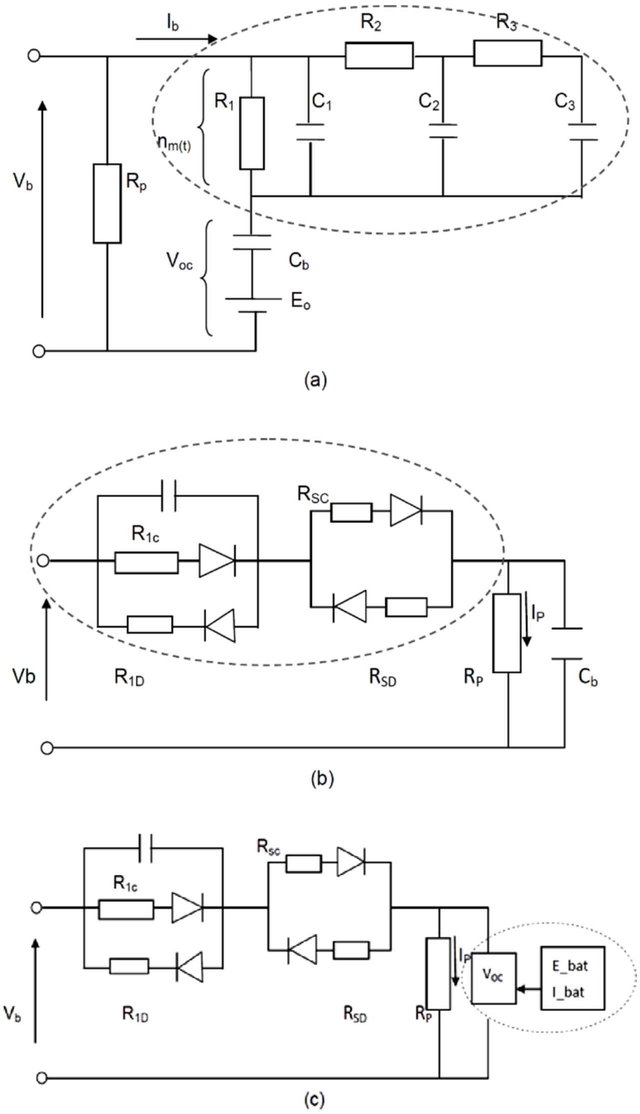
For HEV, three types of energy sources modes can be used. The lead acid battery, which is widely used in HEV, provides propulsion (Wisniewski, 2010). Practically, the characteristics of battery strongly impact the SOC, such as battery capacity, temperature, and lifecycle (Ibrahim et al., 2008). Figure 6 shows three typical battery models – an improved simple battery model, mathematical model and dynamic battery model.

The improved simple battery model consists of a constant resistance and an ideal voltage source in series. R_1, R_2 and R_3 with C_1, C_2 and C_3 replace the constant resistance with a variable resistance to act as the internal resistance (Hannan et al., 2014). The mathematical model (Figure 6(b)) has been developed by Salameeh et al. (1992) to consider the temperature dependence. The mathematic model takes the voltage and current drops differentiate between internal and overvoltage resistances for charging into account (Hannan et al., 2014; Salameh et al., 2014). The dynamic model (Figure 6(c)) introduces two real-time blocks that provide a practical discharging current and the battery energy I_{bat} and E_{bat}, respectively. This block also includes the battery temperature data real-time updating (Salameh et al., 2014).

The battery model can be applied to various categories; the most common application is the polymer Li-ion battery, which originates from the lithium-ion battery with a polymeric material electrolyte replacing the organic solvent (Wang et al., 2016). The storage capacity range of a polymer Li-ion battery is 150–190 W h kg^{-1}, while the power density range is from 300 W kg^{-1} to 1500 W kg^{-1} (Saw et al., 2016). A great number of test system models have adopted polymer Li-ion battery (TCL PL 383562) in simulation studies that involve the dynamic battery model (Chen and Rincon-Mora, 2006).

With the improvement of the battery technology, zinc-bromide batteries are widely accepted in vehicular applications because of higher energy densities (approximately 300 – 600 W kg^{-1}) (Swan et al., 1994). Compared to other batteries, the electrode of the zinc-bromide battery excludes chemical reaction in the charging process. It acts as the medium for zinc metal plating – zinc is dissolved in the electrolyte during the discharging process (Swan et al., 1994; Mania et al., 2010). At the same time, the lifecycle of the zinc-bromide battery is higher than other traditional batteries. For example, the lifecycle which involves the charging and discharging times of nickel-cadmium (Ni-Cd) rechargeable battery is around 500, while zinc-bromide battery could be charged/discharged 1000–1500 times (Mania et al., 2010). The Ni-Cd battery model, as an example for an improved battery model illustrated in Figure 6(a), has been studied with the simulated data by several researchers (Sperandio et al., 2011; Green, 1999; Paatero, 1997). The Ni-Cd model, however, is not ideal for vehicular implementations since the ‘memory effect’ negatively impacts the lifecycle when the battery is not completely exhausted during the discharging process.

Figure 6 (a) improved simple battery model; (b) mathematical model and (c) dynamic model



Source: Hannan et al. (2014)

4.1.2 Fuel cell model

Theoretically, a single FC can produce about 1.23 V under normal operating conditions of 25°C at 1 atm pressure) (Basu, 2007). FC is based on pure chemical reaction and produces DC electrical energy. The voltage generated by a single fuel cell is expressed as follows:

$$E_{\text{cell}} = E_0 + \frac{RT}{2F}\ln\frac{P_{\text{H}_2}\sqrt{PO_2}}{P_{\text{H}_2\text{O}}}. \tag{1}$$

Equation (1) is known as the Nernst equation (Uzunoglu and Alam, 2007), where E_0 is the standard potential of the chemical reaction from internal sources (hydrogen/oxygen), R is the universal gas constant, F is Faraday's constant, T is the absolute temperature, and P_{H2} and P_{H2O} represent the partial pressures of hydrogen and water, respectively. Taking the 'double layer effect' and ohmic overvoltage into account, the total voltage of FC could be expressed as follows:

$$V_{fc} = E_{\text{cell}} + V_{\text{act}} + V_{\text{ohm}}, \tag{2}$$

where E_{cell} is same as the Nernst voltage in equation (1), V_{act} is the activation overvoltage in an electrical domain which has the 'double layer effect', and the V_{ohm} is the ohmic overvoltage because of the membrane resistance (Al Baghdadi, 2005). According to Gao et al. (2011), the reduction in the concentration of oxygen/hydrogen in FC might result in a voltage drop (V_{con}) shown in equation (3) and the total voltage of FC is thus expressed in equation (4).

$$V_{\text{con}} = -B\ln\left(1 - \frac{J}{J_{\max}}\right) \tag{3}$$

$$V_{fc} = E_{\text{cell}} + V_{\text{act}} + V_{\text{ohm}} + V_{\text{con}}, \tag{4}$$

where B is the parametric coefficient that refers to different types of cells and operation state, J (A/cm^2) is the actual current density through the cell, and the range of $J_{\max}$ is from 500 mA/cm^2 to 1500 mA/cm^2.

The advanced technology of the proton exchange membrane fuel cell (PEMFC) can be applied to the comprehensive dynamic model. Equation (5) is a dynamic-model consideration of output stack voltage.

$$E = N\left(E_0 + \frac{RT}{2F}\ln\left\{\frac{P_{\text{H}_2}\left(\frac{P_{\text{O}_2}}{P_{\text{std}}}\right)^{1/2}}{P_{\text{H}_2\text{O}}}\right\} - L\right), \tag{5}$$

where N is the number of cells in the stack, L is the voltage losses which include activation losses, internal current losses, resistive losses, and concentration losses (Correa et al., 2004; Chiu et al., 2004; Pasricha et al., 2007; Pasricha and Shaw, 2010). When FC model acts as the energy source model in HEV or EV, it could couple with power diode since the reverse current might be produced during regenerative braking. In other words, FC model is associated with power electronic devices such as DC/DC converters.

4.1.3 Photovoltaic model

The fundamental principle of the solar cell is utilising the semiconductor solar cell to produce electricity (DC) by absorbing the energy from the solar radiation. A great number of studies have illustrated various significant characteristics of photovoltaics which involve the I-V curve, current/voltage output, impacts of temperature and irradiance, solar harvesting studies, *etc.* (Kaygusuz, 2009; Hannan et al., 2012).

In summary, compared to FC and PV models, the conventional battery model seems to be relatively mature in terms of industrial processing. For the economic practicality, the battery model is also attractive because the high initial cost of FC seems still unacceptable. Another challenge for FC model could be a lack of refilling facilities or the station to exchange FC tank. For PV model, the solar car park is strongly required, which could probably be the main recharging method. Simultaneously, technologies to improve the PV efficiency are also necessary, such as the maximum power point tracking (MPPT). The investments in PV and FC models might pose a significant difficulty for large-scale implementation (Lund et al., 2015; Ehsani et al., 2010; Fernández et al., 2016).

4.2 Energy storage technology of supercapacitor in PHEV

In terms of energy storage technologies, supercapacitor (SC) or ultracapacitor can be an attractive option to extend the storage capacity. Compared with other storage devices, SC provides higher power densities. SC also exhibits a longer charge/discharge lifecycle (500,000 times), while the lead-acid and lithium-ion batteries have an average lifecycle of 1000 and 2000 times, respectively. The SCs are affected by the operating temperature, the depth of discharge, and the number of discharge times (Hannan et al., 2014; Rao and Wang, 2011). Research also indicates that SC maintains a high efficiency of around 90% (Burke, 2000). The properties of minimum heat loss and good reversibility are also considered as advantages of SC (Burke, 2000). Nevertheless, the downside of SCs is the low energy density. Some industries and institutes have developed many new technologies and materials for SCs to improve their energy densities. Experimental data has shown that the SCs potentially achieve over 400 W-h/kg, comparable to the energy densities of lithium batteries (Farcas et al., 2009). Furthermore, the high charging rate of SCs can increase the efficiency of regenerative braking (Zhang et al., 2016).

4.3 Power electronics technology in PHEV

The power electronics refers to converters and inverters – DC/AC converter, AC/DC inverter, AC/AC, and DC/DC converters implemented in different scenarios. To improve the reliability and stability of the internal system in EV and HEV, DC/DC converter should be a significant component. In terms of fuel economy, it is possible to involve a power electronic system (Amjad et al., 2010). For a PHEV, the characteristics of the power electronic system are crucial for effectiveness, which include various features depending on selections of power semiconductor devices, converters/inverters, controlling strategies, packing methods of individual units, and the integration of the whole system (Emadi et al., 2008).

Recent research has revealed that buck converter, boost converter, and cuk converter have been developed with modern technologies, both in terms of packaging and integration (Wilamowski and Irwin, 2011; Chakraborty, 2011; Arora et al., 2016). With the use of such DC/DC converter technologies in various vehicular scenarios, the requirements on high-frequency, high-voltage operations, high operating temperature, high ripple current capability, and low equivalent series resistance should be addressed

(Amjad et al., 2010). Some studies have introduced a multilevel converter coupled with the cascaded cell for higher propulsion demand to integrate the supercapacitor to improve the efficiency and the energy capacity (Shuai et al., 2007a, 2007b).

4.4 Internal energy management in PHEV

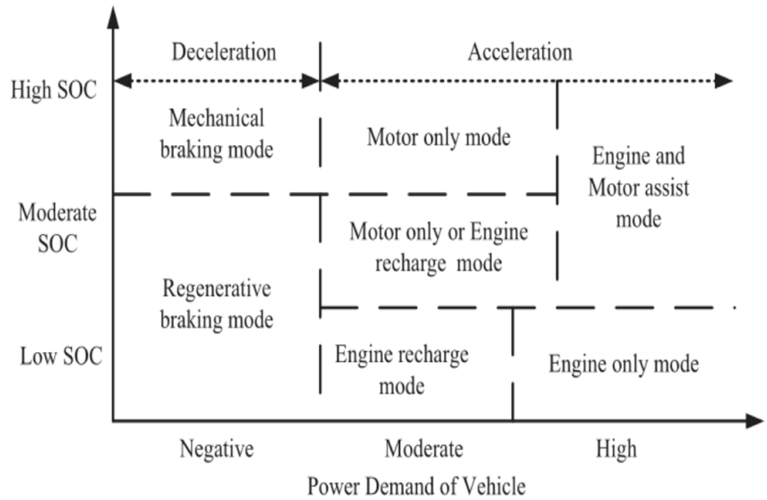
The internal energy management demonstrated for PHEV system is different from the EMS for the whole system that includes the charging processing from a power station or smart grids. The definition of internal energy management for PHEV in this paper is an optimised system to achieve the most effective control on the energy transmission. Firstly, it is necessary to introduce a vital function of SOC. As a critical section in HEV, SOC is a connection between the energy source and the energy storage system. Taking an example of the supercapacitor in HEV or PHEV, the SOC can be expressed as follows:

$$\text{SOC} = \frac{V_{sc,\,oc} - V_{SC,\,\min}}{V_{sc,\,\max} - V_{SC,\,\min}}, \tag{6}$$

where $V_{Sc,OC}$ is the open circuit voltage of SC, $V_{SC,\max}$ and $V_{SC,\min}$ are the maximum and minimum open circuit voltages, respectively. In a realistic or practical scenario in HEV, the design of SOC is as follows: the battery is maintaining when SOC is roughly constant (charge-sustaining mode). When ICE is dominating or during a regenerative braking, the battery is only recharged from onboard electricity (charge-depleting mode). These two modes should be operated synergistically in PHEV (Amjad et al., 2010).

Based on the design of SOC, control strategy is also a significant issue for improving the efficiency of internal energy management in PHEV. For example, the energy source model of a PHEV adopts an FC model – simultaneously the energy storage model uses SC. Figure 7 shows the energy management system (EMS) operating methods.

Figure 7 PHEV energy management system operating methods



Source: Hannan et al. (2014)

4.5 Summary analysis on the PHEV

To minimise the pollution problem and to delay the exhaustion of non-renewable energy sources, there is an urgent and immediate need for replacing the ICEVs with EVs. All studies reviewed so far, however, fail to significantly improve the vehicular functions and driving experiences for various types of EVs. A vital issue is the battery technology. If the battery technology could achieve sufficient energy densities and maintain appropriate power densities at the same time, the use of BEV and FCEV will significantly increase. As a result, the conventional HEVs have adopted sophisticated and complex vehicle-mounted systems at the expense of dramatically increasing the initial cost.

The PHEV is attractive because of technical breakthroughs in rechargeable battery technology. PHEV improves electricity capacity using plug-in charging to provide continuous power. With the additional use of ICE and the external power supply, the size and weight of the battery could be considerably decreased and also reduce the cost.

The problem faced by PHEVs is the optimisation of internal resources. In terms of internal operations, PHEV could achieve the optimal efficiency through establishing or changing a series of operating rules of ICE, electric generator and the battery packs. Another challenge is the EMS for external power sources. The issues of the optimal systems for the networks for charging stations in various circumstances should also be addressed. If it is possible to construct an internal resource optimisation system and the EMS at the same time, the PHEV meets most of the needs for the transport system, even with the restrictions that currently exist in modern battery technologies.

5 Conclusion

The features for different types of EVs have been reviewed in this paper. The PEV and FCEV exhibit the most potential to reduce the road-side emission. However, the PEVs have been restricted by the bottleneck of current battery technologies, while the use of FCEVs show reduced reliablity. For the different levels of the conventional HEVs, the driving expectation seems very close to the ICEVs. However, the limitations on the high initial cost and heavy weight are unacceptiable for the mass market.

The hybrid electric vehicle incorporates most advanced technologies and significantly contributes to the environmental protection. PHEVs are considered as potential candidates to compete with ICEVs in terms of driver expectation, driving range and fuel economy. Research shows that supercapacitor, through its high electricity capacity, seems to be very appropriate for implementation in PHEV. To reduce the overall cost in BEV and PHEV, alternative materials and technologies should be explored and researched. The power electronics technology required for the internal energy transmission should also be researched to improve the overall efficiency.

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