Research on electric vehicles:
Challenges, opportunities and emerging technologies

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Abstract

With ever increasing concern on energy diversification, energy efficiency and environmental protection, electric vehicles (EVs) including the pure EV (PEV), hybrid EV (HEV) and fuel-cell EV (FEV) are becoming attractive for road transportation. Although some of them have become commercially available, there are many challenges and opportunities for EV development and transition. This paper gives an overview of key research on various types of EVs, with emphasis on their challenges, opportunities and emerging technologies. Firstly, the classification of EVs is conducted based on their energy sources and propulsion devices, leading to deduce the PEV, HEV and FEV as well as to subdivide the HEV into the conventional version (the micro HEV, mild HEV and full HEV) and the gridable version (the plug-in HEV and range-extended EV). Then, their energy diversification, energy efficiency and overall harmful emissions are briefly introduced. Secondly, the challenges and opportunities of the PEV, HEV, gridable HEV and FEV are discussed in details. Thirdly, emerging technologies including the energy sources, electric propulsion, battery charging and vehicle-to-grid that are promising for application to EVs are reviewed. For the energy source technology, the batteries, fuel cells, ultracapacitors and ultrahigh-speed flywheels are discussed, while the concept of on-board renewable energy sources is put forward. For the electric propulsion technology, the requirements of electric machines for EVs are identified so that research activities on advanced machines and machine systems are described. For the battery charging technology, the concepts of park-and-charge and move-and-charge are presented, and hence the arrangements of inductive charging and wireless charging are described. For the vehicle-to-grid technology, the corresponding framework and operation are discussed, hence the concept of energy arbitrage is delineated. Finally, a conclusion on research priorities of EV technologies is given.

Key words

battery charging, electric propulsion, electric vehicles, energy sources, vehicle-to-grid

1. Introduction

Electric vehicles (EVs) are nothing new, which were invented 178 years ago but lost the competition for dominance to the internal combustion engine vehicles (ICEVs). Actually, the first EV was a battery-powered tricycle built by Thomas Davenport in 1834 (Wakefield, 1994). In 1900, among an annual sale of 4,200 automobiles in America, 38 % were EVs, 22 % ICEVs, and 40 % steam-powered vehicles. At that time, EVs were the preferred road transportation among the wealthy elite. Their cost was equivalent to a Rolls Royce of today. A man with an idea which finished off the EVs for good was Ford. His mass-produced Ford Model T could offer a range double or triple that of the EVs but at only a fraction of the cost. By the 1930's, the EVs had almost vanished from the scene. The rekindling of interests in EVs started at the outbreak of the energy crisis and oil shortage in the 1970's. Due to the growing concern over air quality and the possible consequences of the greenhouse effect in the 1980's, the pace of EV development was accelerated.

In general, EVs are classified as the pure EV (PEV), hybrid EV (HEV) and fuel-cell EV (FEV) types based on their energy sources and the propulsion devices (Chau et al., 2007). In essence, the PEV is purely fed from electricity source while the propulsion is solely driven by the electric motor; the HEV is sourced from both electricity and gasoline/diesel while the propulsion involves both the electric motor and engine; and the FEV is directly or indirectly sourced from hydrogen while the propulsion is solely driven by the electric motor. Moreover, in order to distinguish the refueling means, the HEV can be further categorized into the conventional HEV and the gridable HEV. The conventional one is solely refueled with gasoline/diesel

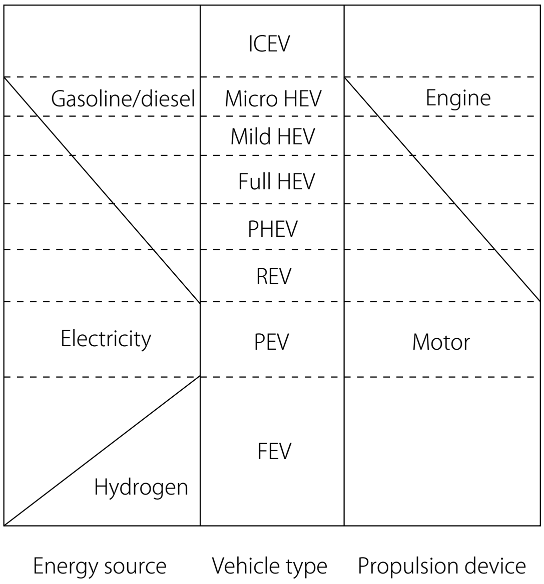


Figure 1: Classification of EVs

in filling stations, whereas the gridable one can be recharged by electricity via charging ports. Based on the hybridization level and the operation feature between the electric motor and engine, the conventional HEV can be further split into the micro HEV, mild HEV and full HEV. Meanwhile, based on the coordination between the electric motor and engine, the gridable HEV can be further split into the plug-in HEV (PHEV) and range-extended EV (REV). This classification is depicted in Figure 1.

Deriving from crude oil, the gasoline and diesel are the major liquid fuels for ICEVs. EVs are an excellent solution to rectify this unhealthy dependence because electricity can be generated by almost all kinds of energy resources. Figure 2 illustrates the merit of energy diversification due to the use of EVs in which electricity can be produced by thermal power, solar power, nuclear power, hydropower, wind power, geothermal power, oceanic power and biomass power. In order to compare the overall energy efficiency of EVs with that of ICEVs, their energy conversion processes from crude oil to road load are depicted in Figure 3, indicating that EVs are more energy-efficient than ICEVs. Moreover, EVs can recover the kinetic energy during braking and utilize it for battery recharging, whereas ICEVs wastefully dissipate this kinetic energy as heat in the brake discs. With this regenerative braking technology, the energy efficiency of EVs can be further boosted by up to 10 % (Chan et al., 2001).

In many metropolises, ICEVs are responsible for over 50 % of harmful air pollutants and smog-forming compounds. In order to reduce air pollution due to road transportation, the use of EVs is the most viable choice. Definitely, the EV offers zero roadside emissions. Even taking into account the emissions generated by refineries to produce gasoline for ICEVs and the emissions by power plants to generate electricity for EVs, the overall harmful emissions of EVs are still much lower than that of ICEV as indicated in Figure 4, where the carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matters (PM_x) and non-methane organic gases (NMOG) are taken into account (Chau, 2010). It should be noted that the overall carbon dioxide (CO_2) emission can also be reduced by about 5 % with the use of EVs

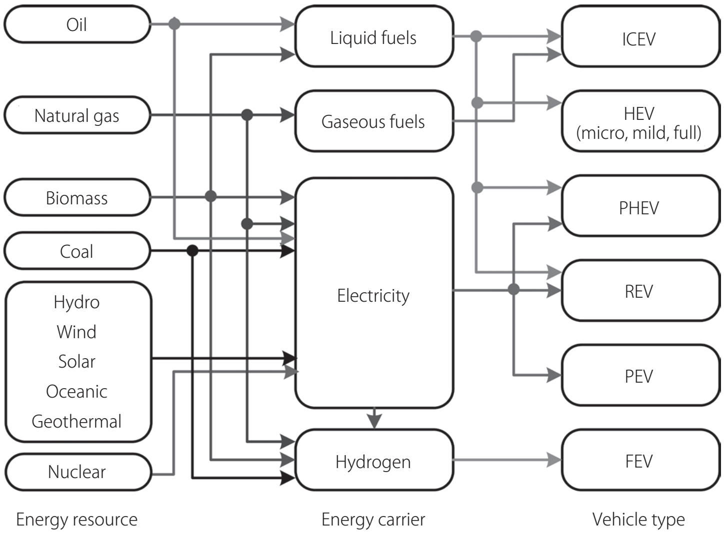


Figure 2: Energy diversification of EVs

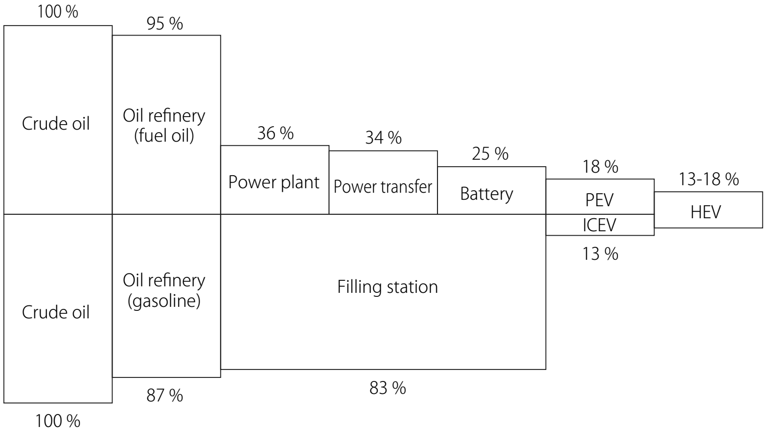


Figure 3: Energy efficiency of EVs

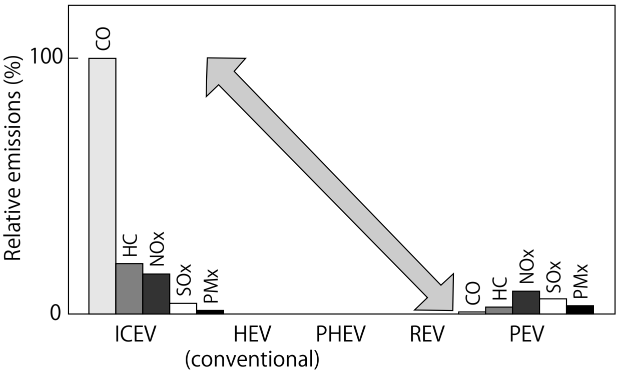


Figure 4: Overall harmful emissions of EVs

and energy-efficient power plants. This improvement may be further increased with the use of higher percentages of clean or renewable power generation, but may even be negative when adopting inefficient coal-fired power plants.

Currently, the conventional HEV has been commercially available and widely accepted as an energy-efficient and environmental friendly vehicle, while the PEV is becoming commercially available and tagged with a zero-emission label. Nevertheless, there are many challenges and opportunities for EV development and transition. The purpose of this paper is to give an overview of key technologies for various types of EVs. In Section 2, key challenges and opportunities of EVs will be revealed. Then, in Section 3, emerging technologies that are promising for EVs will be discussed. Finally, in Section 4, a conclusion on research priorities of EV technologies will be drawn.

2. Challenges and Opportunities

2.1 PEV

The PEV, loosely termed the EV, offers the definite advantages of zero roadside emissions and minimum overall emissions (taking into account the emissions due to electricity generation by power plants). Its major challenges are the limited driving range, high initial cost and lack of charging infrastructure.

Currently, the PEV relies on using batteries as the sole or major energy storage device to store electricity even though there is an attempt to use ultracapacitors as the sole energy storage device. Thus, the PEV is usually named as the battery EV (BEV). At the present status of battery technology, the energy storage capacity of the PEV is far below that of ICEVs. Typically, for a passenger car under urban driving with air-conditioning, a PEV can travel about 100 km per charge whereas an ICEV can offer about 500 km per refuel. With such a short driving range per charge, the PEV will suffer from the problem of range anxiety. Namely, the PEV driver dare not utilize the remaining capacity such as 20 % to travel the trip of 20 km.

With similar performance, the PEV is 2 to 4 times more expensive than the ICEV. Such high initial price is due to the fact that a large number of batteries are necessary to provide a reasonable driving range per charge. Typically, the battery cost is account for 20-40 % of the overall PEV cost. Moreover, the battery life can only last for about 1,500 cycles which is equivalent to about 4 to 5 years of vehicle operation, indicating that all batteries of the PEV need to be renewed in the midway of vehicle life. Thus, the effective cost of the PEV is higher than the initial cost.

Differing from the ICEV, the PEV takes time for battery charging. The corresponding charging period normally ranges from 5 to 8 hours based on a battery charger with the specifications of 110-240 V, 13-40 A and 2-4 kW. This charging period is too long for the PEV to provide continuous operation. When adopting the fast or quick charging technique, it takes about 20 to 30 minutes to charge the batteries up to 80 % capacity based on a battery charger with the specifications of 200-400 V, 100-200 A and 50 kW. Although this charging speed is acceptable for continuous vehicular operation, the installation cost of these fast charging stations is high while the establishment cost of such fast charging infrastructure is huge. Since the power demand for fast charging is high, the fast charging process inevitably causes burden to our existing power system, which violates the merit of using the PEV for load leveling or demand side management. In case the PEV allows for battery swapping, namely replacing the discharged batteries with the fully-charged ones using mechanical means, it takes only a few minutes to mechanically charge up the batteries. Although the required time for battery swapping is comparable to that for gas refueling, the necessary space for each swapping station is much larger. Practically, it involves two implementation challenges, namely the battery size and location inside the PEV have to be standardized, and the single ownership of all batteries needs a new business model.

2.2 HEV

The HEV, loosely termed the hybrid vehicle, refers to the conventional or non-gridable version (Chau et al., 2002). For the micro HEV, the conventional starter motor is eliminated while the conventional generator is replaced by a belt-driven integrated-starter-generator (ISG). Instead of propelling the vehicle, the ISG offers two important hybrid features. One feature is to shut down the engine whenever the vehicle is at rest, the so-called idle stop feature, hence improving the fuel economy for urban driving. Another feature is to recharge the battery primarily during vehicle deceleration or braking, thus offering a mild amount of regenerative braking. For the mild HEV, the ISG is generally placed between the engine and the transmission. This ISG not only provides the hybrid features of idle stop and regenerative braking but also assists the engine to propel the vehicle, thus allowing for a downsized engine (Liu et al., 2010a). However, since the engine and the ISG share the same shaft, it can not offer electric launch (initial acceleration under electric power only). For the full HEV, the key technology is the electric variable transmission (EVT) system which mainly functions to perform power splitting. This EVT can offer all hybrid features, including the electric launch, idle stop, regenerative braking and engine downsizing.

Compared with the PEV, the HEV can offer a comparable driving range of the ICEV and use the existing refueling infrastructure of the ICEV, but sacrificing the merits of zero roadside emissions and energy diversification. Its key challenges are how to reduce the system complexity which involves both the electric motor and engine for propulsion, and how to coordinate these two propulsion devices to achieve optimal efficiency operation. The turning point of HEV development was the advent of Toyota Prius in 1997 (Hermance et al., 1998), which firstly adopted the EVT system as depicted in Figure 5. The key is to employ a planetary gear for power splitting of the engine output power, one via the ring gear to the driveline shaft while one via the sun gear to the generator, then back-to-back converters, motor and finally the driveline shaft. Hence, under varying road load, the engine can always operate at its most energy-efficient or optimal operation line (OOL), resulting in a considerable reduction of the fuel consumption. However, this EVT system suffers from the reliance on planetary gearing which involves transmission loss, gear noise and regular lubrication. Also, the overall system is relatively heavy and bulky.

2.3 Gridable HEV

The PHEV is extended from the conventional HEV by incorporating the additional feature of plug-in rechargeable. Since it incorporates a larger bank of batteries which can be recharged by plugging to an external charging port, it can offer a longer electric-drive range and hence reduce the requirement for refueling from gas stations. On the other hand, the REV is extended from the PEV by incorporating a small engine coupled with a generator to recharge the battery bank. This avoids the range anxiety problem that is always associated with the PEV. So, it can offer energy-efficient operation throughout its electric-drive range and hence significantly reduce refueling from gas stations. Although the PHEV and REV are both a HEV and have similar electric motor and battery ratings, they have different nominal operations. The PHEV generally operates in the blended mode in which the electric motor and the engine are coordinated to work together in such a way that the engine can maintain efficient operation, hence achieving high fuel economy. If necessary, it can operate in the pure-electric mode. In contrast, the REV generally operates in the pure-electric mode all the way, regardless of the driving range or profile. Until the battery pack is depleted to the threshold, it can operate in the extended mode that the engine is turned on which in turn drives the generator to produce the desired electricity.

The key challenges of the gridable HEV is the system complexity and initial cost. Its system complexity is similar to that of the conventional HEV, mainly due to use of both the electric motor and engine. Differing from the conventional HEV, it needs to install the on-board charger to plug in the power grid for battery charging. Its initial cost is much higher than that of the conventional HEV due to the use of a large number of batteries for the pure-electric mode. Of course, when the PHEV operates at the blended mode or the REV operates at the extended mode, they lose the merit of zero roadside emissions.

2.4 FEV

The FEV, loosely termed the fuel-cell vehicle, offers the same advantages as the PEV – namely zero roadside emissions and minimum overall emissions (taking into account the emissions due to hydrogen production by chemical plants or an on-board reformer). Additionally, it can offer the driving range comparable to that of the ICEV. Its major challenges are the very high initial cost and lack of hydrogen refueling

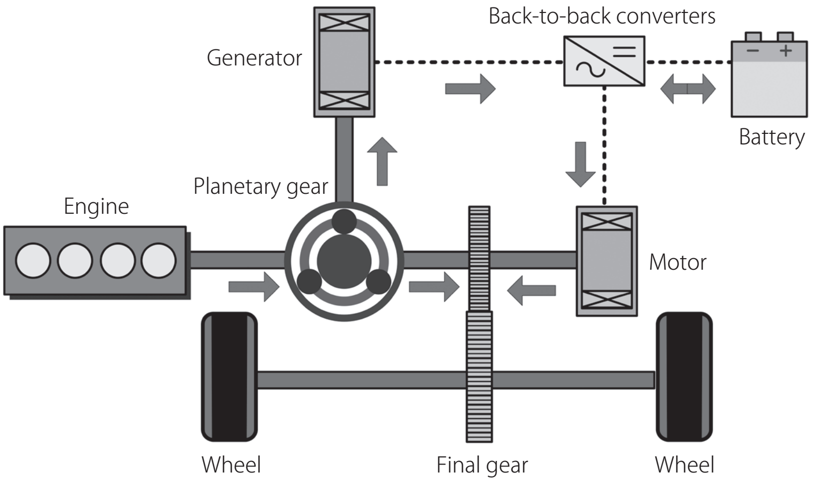


Figure 5: Planetary-geared EVT system

infrastructure. The very high initial cost is due to the use of expensive fuel cells. The hydrogen refueling infrastructure is generally absent in our society, and the establishment of such infrastructure involves a huge investment cost. There are three practical ways to store hydrogen in the FEV, namely the compressed hydrogen gas (CHG), liquid hydrogen (LH) and metal hydride (MH). When adopting the CHG (a pressure of about 350-700 bar) for the FEV, the infrastructure is similar to that of compressed natural gas (a pressure of about 200-248 bar) for some alternative fuel vehicles. When adopting the LH, the infrastructure is very demanding since the hydrogen needs to be cooled to about −253 ℃ while still pressurized. This requires cryogenic storage technology which is even more severe than liquid oxygen. When adopting the MH, it needs to have a similar infrastructure as battery swapping to mechanically replace the discharged MH with the fully-charged MH. Also, it requires additionally energy for providing high temperatures (120-200 ℃) to discharge the hydrogen, and high pressure (over 700 bar) to recharge the hydrogen. Both the CHG and LH enjoy the merit of high specific energy (good energy density by weight) which is desirable for the FEV, but also face the same safety concern which can be an explosion hazard. Meanwhile, the MH takes the merit of safety which is essential for the FEV, but suffers from the problem of low specific energy which deteriorates the driving range.

In the foreseeable future, perhaps next 5 years, the FEV will not be commercially viable unless there is a breakthrough in fuel cell technology in terms of cost per kilowatt and there is a well-established hydrogen refueling infrastructure.

3. Emerging technologies

3.1 Energy source technology

This is the core technology for EVs. Currently, there are 4 viable EV energy sources: batteries, ultracapacitors, ultrahigh-speed flywheels and fuel cells (Chau et al., 1999). The batteries are based on electrochemical means to store electrical energy; the ultracapacitors are based on electrostatic means to store electrical energy; the ultrahigh-speed flywheels are based on electromechanical means to store electrical energy; and the fuel cells are based on electrochemical means to generate electrical energy. None of them can simultaneously offer high specific energy and high specific power, analogous to be suitable for marathon running and 100-m running. Thus, a compromise between these two parameters or a hybridization of two energy sources (one with high specific energy and another with high specific power) are necessary for the PEV or FEV (Chau et al., 2001).

In the foreseeable future, batteries are the major energy source for EVs. Table 1 lists the major types of batteries that have been developed for EVs, including the valve-regulated lead acid (VRLA), nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), zinc/air (Zn/air), sodium/sulfur (Na/S) and lithium-ion (Li-ion). Among them, the VRLA is accepted for low-cost low-end EVs, the Ni-MH is preferred for well-performed EVs, and the Li-ion is attractive for high-performance EVs. At the present status of battery technology, the PEV can only offer acceptable driving range with affordable price. In order to enable the PEV offering comparable price and driving range as the ICEV, the battery specific energy and cycle life need to be greatly increased while the battery initial cost needs to be significantly reduced. Current research on battery technology is being focused on the development of various Li-ion batteries, such as the use of lithium nickel manganese cobalt (NMC) for the positive electrode to improve the specific energy and safety (Omar et al., 2012), and the use of lithium titanate ($Li_4Ti_5O_{12}$) for the negative electrode to improve the cycle life and charging time (Giuliano et al., 2011).

The ultracapacitor technology is promising for EVs since it offers exceptionally high specific power and practically unlimited cycle life. Nevertheless, the ultracapacitor needs significant improvement before practically applicable as the sole energy source for EVs – its specific energy (5-6 Wk/kg) needs to be greatly increased while its initial cost (2,400-6,000 USD/kWh) has to be greatly reduced. Current research on ultracapacitor technology is being focused on the improvement of its specific energy, such as the use of graphene (Liu et al., 2010b) and carbon nanotubes (Du et al., 2006) to increase the usable surface area and hence the energy storage capacity.

The ultrahigh-speed flywheel technology exhibits potentiality for EVs. By providing vacuum environment to remove

Table 1: Viable EV batteries

	Specific energy (Wh/kg)	Specific power (W/kg)	Cycle life (Cycles)	Cost (USD/kWh)
VRLA	30-45	200-300	400-600	150
Ni-Cd	40-60	150-350	600-1200	300
Ni-MH	60-120	150-400	600-1200	200-350
Zn/air	230	105	NA	90-120
Na/S	100	200	800	250-450
Li-ion	90-160	250-450	1200-2000	600-1000

the air friction and magnetic bearings to eliminate the bearing loss, the flywheel can spin up to 60,000 rpm so as to achieve high specific energy and high round-trip efficiency. However, it suffers from the problem of safety concern. When the tensile strength of a flywheel is exceeded or the flywheel is accidentally damaged, the flywheel shatters and instantaneously releases all of its stored energy – so-called flywheel explosion which is as dangerous as a bomb. Current research on ultrahigh-speed flywheel technology is focused on improving its safety precaution such as the use of composite materials which can disintegrate into tiny powder rather than large chunks, or extending its application to energy storage for EV charging stations where the whole flywheel is embedded in the ground (Strasik et al., 2007).

The fuel-cell technology is one of the most active research areas in recent years. Table 2 lists the leading types of fuel cells, including the direct methanol fuel cell (DMFC), alkaline fuel cell (AFC), proton exchange membrane fuel cell (PEMFC), phosphate acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC). Among them, the PEMFC is a natural choice for the FEV because of its solid electrolyte nature, low-temperature operation, quick start-up, proper power level, high power density and good system efficiency. In order to enable the FEV offering affordable price, the fuel-cell initial cost (about 4,800 USD/kW) has to be dramatically reduced. Current research on fuel cell technology is being focused on the reduction of platinum usage for the PEMFC which requires such noble metal as the electrocatalyst (Martin et al., 2010), and the reduction of operating temperature for the SOFC which does not desire noble metal as the electrocatalyst (Wang et al., 2011).

Recently, the concept of on-board renewable energy sources has been attractive for EVs. Since the fuel efficiency of the engine for various HEVs is only around 25 % and about 40 % is lost in the form of the waste heat of exhaust gas, the thermoelectric generator (TEG) can be mounted at the exhaust pipe to recover the waste heat energy and help charge the batteries (Yu et al., 2009). On the other hand, by mounting the solar panel on the roof of EVs, the photovoltaic generator (PVG) can readily collect renewable solar energy and utilize it to help charge the batteries. In general, the TEG and PVG are separately operated, even though they are installed in the same HEV, resulting in higher cost, heavier weight, and larger volume. So, the thermoelectric-photovoltaic (TE-PV) hybrid energy system is promising for application to HEVs. Figure 6 shows the system configuration of this TE-PV hybrid energy system which is composed of the TEG, PVG, maximum power point tracking (MPPT) controller, multiple-input converter (MIC) and battery. The MIC can be a SEPIC-SEPIC converter (Zhang et al., 2011a) or a Ćuk-Ćuk converter (Zhang et al., 2011b). Fig-

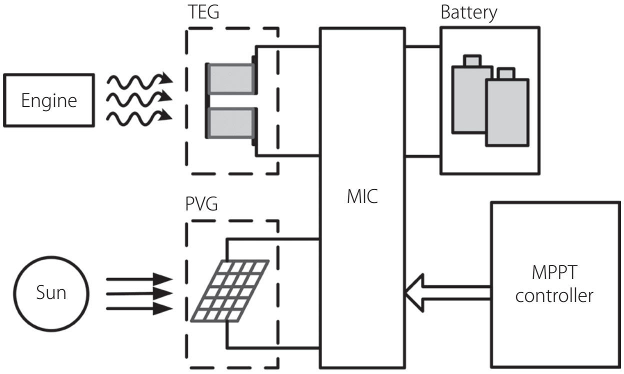


Figure 6: TE-PV hybrid energy system

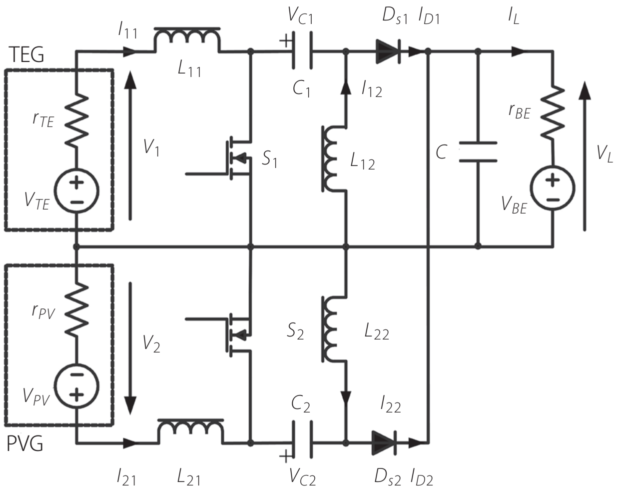


Figure 7: SEPIC-SEPIC MIC

Table 2: Viable fuel cells

	Power level (MW)	Power density (W/cm^2)	Operating temp. (°C)	System efficiency (%)
DMFC	< 0.001	0.04-0.23	90-120	10-20
AFC	< 0.1	0.2-0.3	60-100	62
PEMFC	< 0.5	0.35-0.6	50-120	30-50
PAFC	< 10	0.2-0.25	150-200	40
MCFC	< 100	0.1-0.2	600-650	47
SOFC	< 100	0.24-0.3	500-1100	55-60

ure 7 shows the SEPIC-SEPIC MIC operating in discontinuous capacitor voltage mode. The MPPT controller measures the output voltages and currents of the TEG and PVG, which exhibit nonlinear characteristics at different temperatures and irradiances, respectively, and then generates proper switching signals to the MIC in such a way that the total output power can be maximized.

3.2 Electric propulsion technology

Electric propulsion is another core technology for EVs, while electric machines are the key for electric propulsion. The requirements of electric machines for EVs are much more demanding than those for industrial applications. These requirements are summarized below (Chau, 2009; Zhu et al., 2007):

- high torque density and high power density;
- wide speed range, covering low-speed creeping and high-speed cruising;
- high efficiency over wide torque and speed ranges;
- wide constant-power operating capability;
- high torque capability for electric launch and hill climbing;
- high intermittent overload capability for overtaking;
- high reliability and robustness for vehicular environment;
- low acoustic noise; and
- reasonable cost.

When the electric machine needs to work with the engine for various HEVs, there are some additional requirements:

- high-efficiency generation over a wide speed range;
- good voltage regulation over wide-speed generation; and
- capable of being integrated with the engine.

Figure 8 shows the classification of electric machines in which the bold types are those that have been applied to EVs, including the series DC, shunt DC, separately excited DC, permanent magnet (PM) DC, cage-rotor induction, PM brushless AC (BLAC), PM brushless DC (BLDC) and switched reluctance (SR). Meanwhile, the branches that are not viable for EVs have been pruned. Basically, they are classified into two main groups – commutator and commutatorless. The former simply denotes that they have a commutator and carbon brushes, while the latter have neither commutator nor carbon brushes. It should be noted that the trend is focused on developing new types of PM commutatorless or brushless machines (Chau et al., 2008), especially the class of stator-PM machines and the class of variable reluctance (VR) PM machines.

The stator-PM machine topologies are with PMs located in the stator, and generally with salient poles in both the stator and rotor (Liu et al., 2008). Since the rotor has neither PMs nor windings, this class of machines is mechanically simple and robust, hence very suitable for vehicular operation. According to the location of the PMs, it can be split into the doubly-salient PM (DSPM), flux-reversal PM (FRPM) and flux-switching PM (FSPM) types. Additionally, with the inclusion of independent field windings in the stator for flux control, the class further derives the flux-controllable PM (FCPM) type. On the other hand, the VR PM machine is a class of PM brushless machines dedicated to low-speed high-torque direct-drive applications. The operation principle is that the flux linkage to the armature winding changes along with the interaction between a set of PMs and a set of teeth. Generally, the pole-pair numbers excited by the stator armature winding and the rotor PMs are different. Based on the modulation function of the toothed-pole structure, the heteropolar fields can interact with one another to develop the steady torque (Harris, 1997; Spooner et al., 2003). According to the relationship of motion plane and flux plane, the VR PM machines can be split into the vernier PM (VPM) machine (Li et al., 2011) and the transverse-flux PM (TFPM) machine (Wang et al., 2008) types. Since the aforementioned advanced PM machines are still at the developing stage for application to EVs, their performances have not been

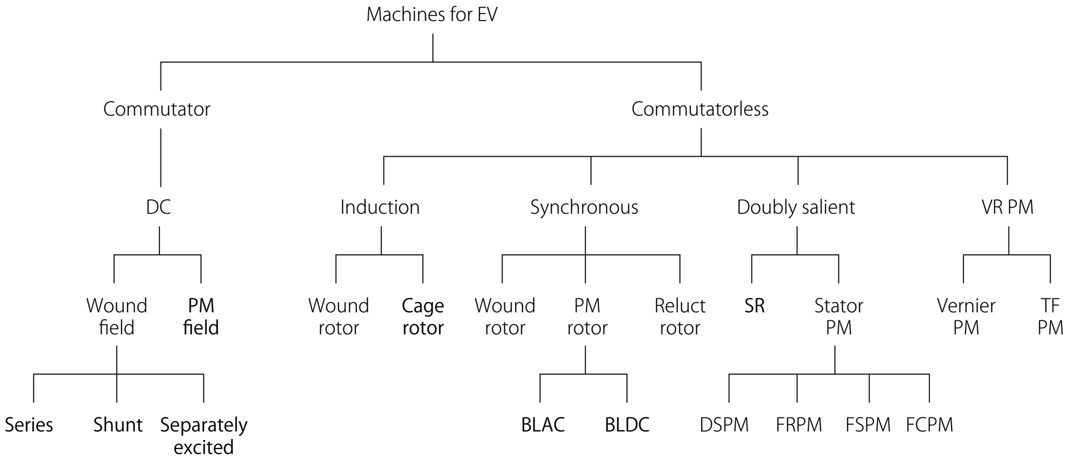


Figure 8: Classification of electric machines for EVs

Table 3: Evaluation of advanced PM machines for EVs

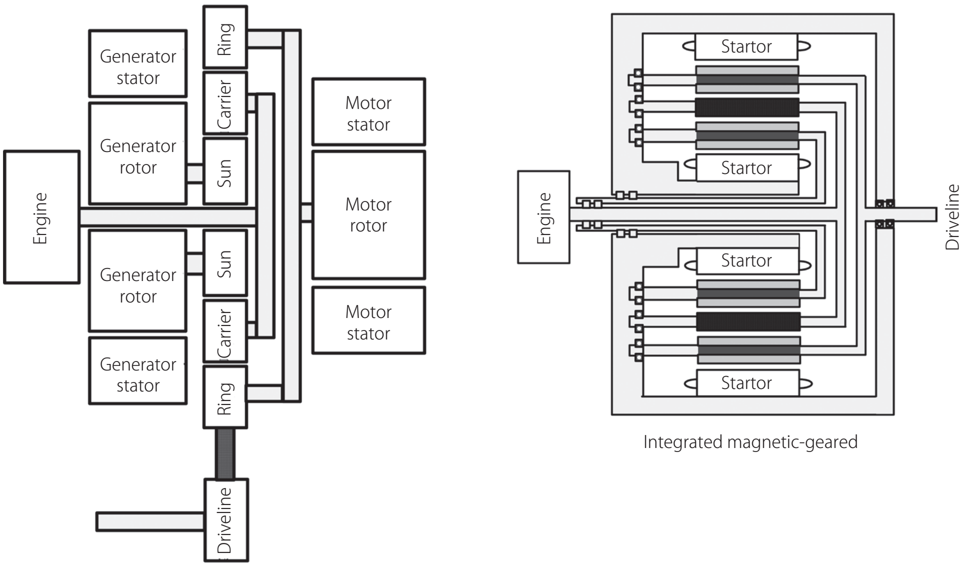
	DSPM	FRPM	FSPM	FCPM	VPM	TFPM
Power density	Medium	Good	Good	Good	Good	Superb
Torque density	Medium	Good	Good	Good	Superb	Superb
Efficiency	Good	Good	Good	Superb	Medium	Medium
Controllability	Medium	Medium	Good	Superb	Good	Good
PM immunity	Medium	Weak	Good	Medium	Medium	Medium
Robustness	Strong	Medium	Medium	Medium	Medium	Weak
Manufacturability	Easy	Medium	Medium	Hard	Medium	Hard
Maturity	High	Medium	Medium	Low	Low	Medium

fully unveiled. Nevertheless, a qualitative comparison among them is given in Table 3, aiming to give an indicative assessment on their suitability for EVs.

Figure 9 gives a comparison of the existing planetary-geared EVT PM brushless machine system which was developed by Toyota for its Prius (Kamiya, 2006) and the integrated magnetic-geared EVT PM brushless machine system (Jian et al., 2009; Jian et al., 2010). The former one inherits the fundamental drawback of planetary gearing, namely the transmission loss, gear noise and need of regular lubrication. On the contrary, the latter one inherits the distinct advantages of magnetic gearing, namely the noncontact torque transmission and speed variation using the modulation effect of PM fields, hence achieving high transmission efficiency, silent operation and maintenance free. Also, the corresponding mechanical torque transmission is straightforward, simply from the engine at one side to the driveline at another side, without requiring any transmission belts.

3.3 Battery charging technology

In recent years, many researchers have proposed various methods to alleviate the problem of short driving range per charge of the PEV, focusing on two strategies – establishing more charging stations and developing fast chargers. These strategies are nothing new, actually based on the traditional refueling concept of gasoline vehicles, since the charging stations and fast chargers are an analogue of the gas stations and powerful pumps, respectively. With the use of electromagnetic theory, batteries can be charged without any physical metallic contacts, hence avoiding electrocution. Thus, inductive charging is becoming more and more attractive for the PEV. As shown in Figure 10, the principle of inductive charging is based on the magnetic coupling between two windings of a high-frequency transformer (Chan et al., 2001). One of the windings is installed in the charger coupler while the other is embedded in the vehicle inlet. Firstly, the main AC supply with a frequency of 50-60 Hz is rectified and converted to a high-



Existing planetary-geared

Integrated magnetic-geared

Figure 9: Comparison of EVT PM brushless machine systems

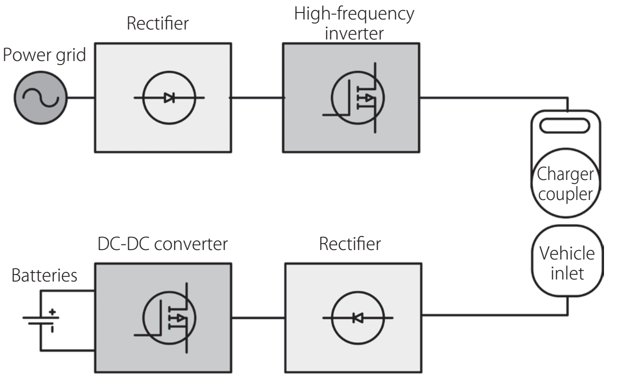


Figure 10: Inductive charging

frequency AC power of 80-300 kHz within the charger module, then the high-frequency AC power is transferred to the PEV side by induction, and finally this high-frequency AC power is converted to DC power for battery charging. This inductive charging approach has a distinct merit over the conductive one – inherently safe under all-weather operation (including rainy, snowy and dirty conditions). The main drawbacks are the high investment cost and inevitable induction losses (up to an efficiency of 86 % only).

In order to further enhance the park-and-charge (PAC) process for the PEV, the inductive charging can be extended to the plugless charging, in which the primary winding is installed on the floor of a garage or in a parking lot and the secondary winding is installed on the vehicle. The driver needs no bothering about those cumbersome and dangerous charging cables. The use of this system is very easy and the charging process takes place automatically once the driver parks the PEV correctly. This PAC offers a means of minimizing the costly recharging infrastructure and providing industry standardization, increases user convenience, and promotes PEV adoption. Of course, this plugless PAC involves additional induction losses due to the existence of larger clearance between the two windings.

Rather than stopping or parking, the PEV highly prefers to wirelessly charge its batteries during moving. Namely, an array of power transmitters are embedded beneath the roadway (so-called the charging zone or lane) while a receiver is mounted at the bottom of the PEV as depicted in Figure 11. Differing from the inductive charging technique, this wireless power transfer is based on resonant inductive coupling. So, the resonant objects, namely the power transmitter and receiver having the same resonant frequency can wirelessly transfer power efficiently with high power density, while dissipating relatively little energy in non-resonant objects such as vehicle bodies or drivers (Imura et al., 2009; Ahn et al., 2011). This move-and-charge (MAC) technology has high potentiality to fundamentally solve the long-term problems of the PEV – high initial cost and short driving range. Namely, there is no need to install so many batteries in the PEV, hence dramatically cutting its initial cost; and the PEV can be conveniently charged at the charging zone during driving, hence automatically extending the driving range.

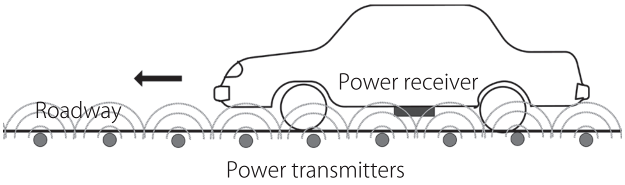


Figure 11: Wireless charging

There are some technical problems to be solved before the realistic application of MAC to the PEV. First, the efficiency of wireless power transfer heavily depends on the distance between the transmitter of the array and the receiver of the vehicle. Since this distance is inevitably time-varying and significantly affected by the road condition and vehicle payload, the resonant frequency of wireless power transfer is not constant, termed the resonance shifting. Thus, the power converter that excites the power transmitter needs to be dynamically tuned to maintain high-efficiency power transfer. Second, the effectiveness of MAC operation heavily depends on the coverage of wireless power transfer as well as the position and speed of vehicles running on the charging zone. The location of power transmitters needs to be optimized in such a way that the electromagnetic field intensities at different locations over the charging zone are uniform.

3.4 Vehicle-to-grid technology

The vehicle-to-grid (V2G) technology is one of the most emerging system-crossover technologies for gridable EVs, including the PEV, PHEV and REV. It is a crossover of EVs, power system and information technology. The gridable EV is no longer a simple transportation means, but serves as a mobile power plant generating electrical energy to the power grid when necessary (Gao et al., 2010). The V2G concept describes a system in which EVs communicate with the power grid to sell services by delivering electricity into the grid or by controlling the charging rate for gridable EVs. Since most gridable EVs are parked with an average of 95 % of the time, their batteries can be used to let electricity flow between the vehicles and the grid. When there is a reasonable penetration rate of gridable EVs (such as 20-40 % vehicles are gridable EVs) and each gridable EV can store or generate electrical energy of 20-50 kWh, the V2G concept will have a significant impact on power system operation. Economically, the V2G concept will be a new business, namely the energy arbitrage between the power utilities and the gridable EV drivers.

Since a gridable EV can store only 20-50 kWh, an individual V2G operation of each gridable EV with the power grid is ineffective and inefficient. So, an aggregator is introduced which is responsible for gathering a number of gridable EVs and

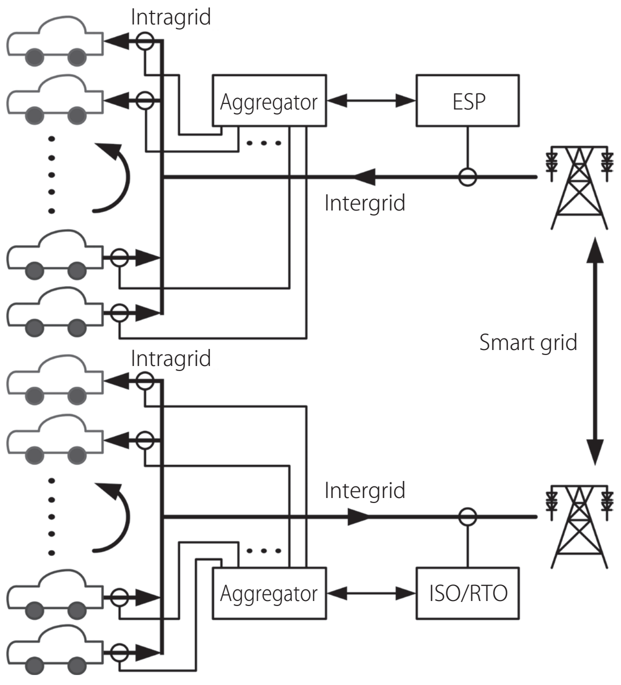


Figure 12: V2G framework

communicating with the power grid. Based on the willingness of drivers and the battery capacity of gridable EVs, the aggregator controls proper gridable EVs to achieve smart charging and discharging (Guille et al., 2009). When an aggregation of gridable EVs is ready for energy arbitrage, it may not be necessary to perform V2G operation. Actually, the corresponding energy arbitrage can be performed internally by the aggregator, so-called the vehicle-to-vehicle (V2V) operation. This dual-grid framework is depicted in Figure 12 in which the ESP is the energy service provider that markets and sells power directly to homes and businesses, the ISO is the independent system operator that oversees the operations of a particular section of the power grid, the RTO is the regional transmission organization that integrates the ISOs into larger operations, and the aggregator functions to aggregate the gridable EVs to deal with the ESP and the ISO/RTO (Wu et al., 2010). Firstly, the aggregator coordinates the intragrid power flow, minimizes the total power demand and total power loss, optimizes the voltage deviation and total harmonic distortion, and calculates prices to maximize the profit of intragrid operation. Secondly, the aggregator coordinates the intergrid power flow, deals with the ISO/RTO to sell power and energy, deals with the ESP to buy power and energy, and calculates prices to maximize the profit of intergrid operation.

The V2G operation has been identified to have two important applications (Gao et al., 2011). First, since renewable power generations, such as wind power and solar power, are intermittent in nature, the use of standby generators to backup the intermittent power outage is expensive, inefficient and sluggish. Although the battery energy storage system can perform the desired efficient and fast backup, it is too expensive and bulky. The V2G operation can fully utilize the EV batteries to backup the intermittent power outage. Second, since the power generation capacity has to match with the load demand, a large fluctuation of load demand will significantly increase the capital cost and operating cost of the power system. As shown in Figure 13, the V2G operation can utilize the EV batteries to absorb or buy electrical energy from the grid during the off-peak period (called load leveling), whereas to generate or sell electrical energy to the grid during peak period (called load shaving). Also, the corresponding charging and discharging processes are much faster than the shutoff and startup processes of standby generators.

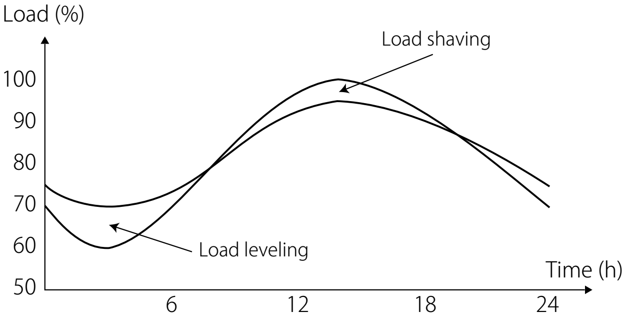


Figure 13: Load leveling and shaving

However, at the present status of battery technology, the batteries still suffer from a limited cycle life. The V2G operation will inevitably degrade their life for normal vehicular operation. Also, since the charging efficiency from the grid to the battery is 70-80 % while the discharging efficiency from the battery to the grid is 80-90 %, the overall charging-discharging efficiency for V2G operation is about 60-70 % which needs to be considered against the potential cost savings.

4. Conclusion

In this paper, a comprehensive overview of key technologies for various types of EVs has been presented, with emphasis on their emerging research activities. Among them, the battery technology is the core for determining whether EVs can be a success or not, which should enjoy the highest research priority. Nevertheless, it is anticipated that a breakthrough in battery technology, in terms of initial cost and specific energy, is unlikely to occur in the foreseeable future. The concept of MAC for battery charging using wireless power transfer is promising to fundamentally solve the long-term shortcomings of EVs, which should have a high research priority. Meanwhile the V2G technology should also be actively researched, which can expand the role or function of EVs, hence significantly increasing their cost effectiveness.

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