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Introduction

With ever-increasing concern on energy diversification, energy efficiency, and environmental protection, electric vehicles (EVs), including pure electric vehicle (PEV), hybrid electric vehicle (HEV), and fuel-cell electric vehicle (FEV) are becoming attractive for road transportation. Although some of them have become commercially available, there are many challenges and hence opportunities for EV research and development.

In this chapter, the classification of EVs is discussed. Then, an overview of EV challenges is given. Consequently, an overview of various technologies developed for EVs is brought forward.

1.1 What Is an Electric Vehicle?

EVs are nothing new; they were invented 178 years ago but lost the competition for dominance to 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 4200 automobiles in the US, 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 that 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 their cost. By the 1930s, the EVs almost vanished from the scene. The rekindling of interests in EVs started at the outbreak of the energy crisis and oil shortage in the 1970s. Owing to the growing concern over air quality and the possible consequences of the greenhouse effect in the 1980s, the pace of EV development was accelerated.

In general, EVs are classified as the PEV, HEV, and FEV types on the basis of their energy sources and the propulsion devices (Chan and Chau, 2001; Chau, 2010, 2014). In essence, the PEV is purely fed from electricity, 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 in filling stations, whereas the gridable one can be recharged by electricity via charging ports. On the basis of 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, on the basis of the coordination between the electric motor and engine, the gridable HEV can be further split into the plug-in hybrid electric vehicle (PHEV) and range-extended electric vehicle (REV). This classification is depicted in Figure 1.1.

Electric Vehicle Machines and Drives: Design, Analysis and Application, First Edition. K. T. Chau.

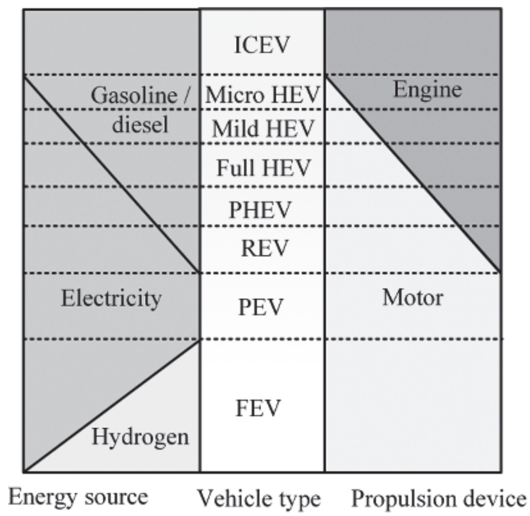

Figure 1.1 Classification of EVs

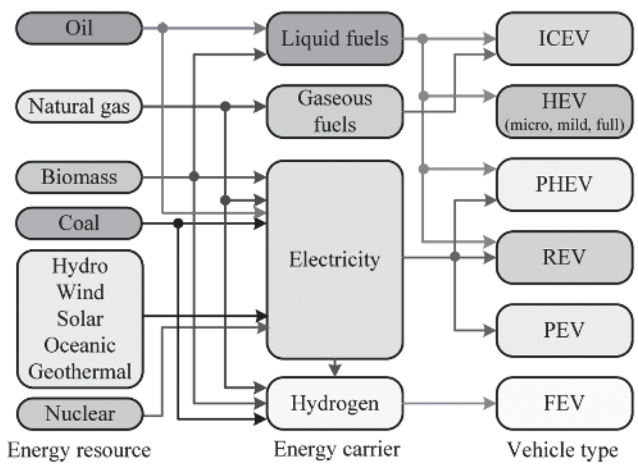

Figure 1.2 Energy diversification of EVs

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 1.2 illustrates the merit of energy diversification due to the use of EVs in which electricity can be produced by thermal power (oil, natural gas, and coal), nuclear power, hydropower, wind power, solar power, oceanic power, geothermal 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 1.3, 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%.

In many metropolises, ICEVs are responsible for more than 50% of harmful air pollutants and smog-forming compounds. To reduce air pollution from road transportation, the use of EVs is the

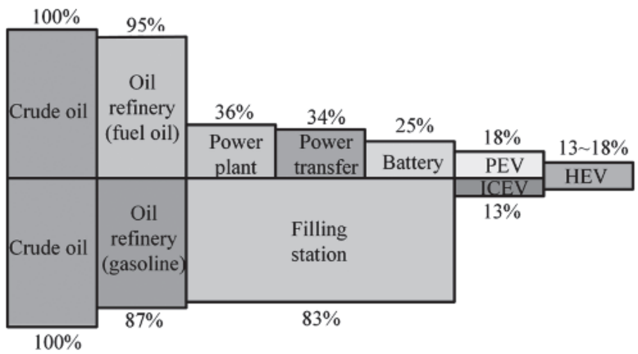

Figure 1.3 Energy efficiency of EVs

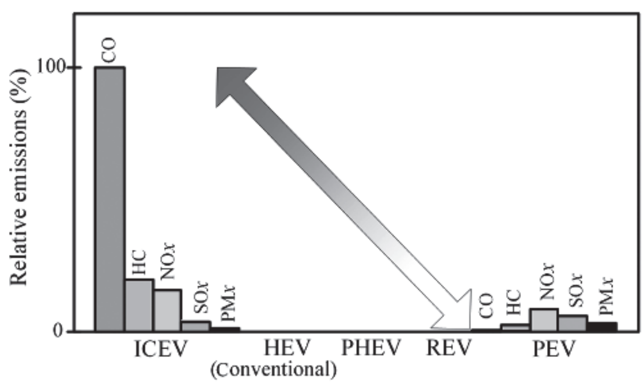

Figure 1.4 Overall harmful emissions of EVs

most viable choice. Definitely, most EVs offer zero roadside emissions. Even taking into account the emissions from refineries to produce gasoline for ICEVs and the emissions from power plants to generate electricity for EVs, the overall harmful emissions of EVs are still much lower than those of ICEVs as indicated in Figure 1.4, where carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matters (PM_x) 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 and energy-efficient power plants. This improvement may be further increased when incorporating with 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 environment-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 research and development.

1.2 Overview of EV Challenges

There are different types of EVs, including the PEV, conventional HEV, PHEV, REV, and FEV. These EVs can be grouped into the PEV, HEV, gridable HEV, and FEV for discussion, with emphasis on their challenges (Chau, 2012).

1.2.1 Pure Electric Vehicle

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 limited driving range, high initial cost, and lack of charging infrastructure.

Currently, the PEV relies on using batteries as their sole or major energy storage device to store electricity even though there is an option to use ultracapacitors as the sole energy storage device. Thus, the PEV is sometimes named as the battery electric vehicle (BEV). At the present status of battery technology, the energy storage capacity of PEVs is far less than that of ICEVs. Typically, for a passenger car under urban driving with air-conditioning, a PEV can travel about 120 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. That is, the PEV driver dare not utilize the remaining capacity such as 20% to travel a trip of 24 km. It should be noted that some PEV models purposely install three to four times the battery capacity to enable their driving range comparable with that of ICEVs, hence solving the short range and range anxiety problems. Of course, these PEV models will be two to three times more expensive than general PEVs, which are actually not targeted for general buyers.

With similar performance, a general PEV is two to four times more expensive than an ICEV. Such high initial cost is because a large number of batteries are necessary to provide a reasonable driving range per charge. Typically, the battery cost accounts for 30–40% of the overall PEV cost. Moreover, the battery life can generally last for about 1500 cycles, which is equivalent to about 4–5 years of vehicle operation, indicating that all batteries of the PEV need to be renewed in the midway of the vehicle life. Thus, the effective cost of the PEV is further 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 20–30 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 and establishment cost of these fast charging stations are very high. 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 time required 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: the battery size and location inside the PEV have to be standardized and the single ownership of all batteries needs a new business model.

1.2.2 Hybrid Electric Vehicle

The HEV, loosely termed the hybrid vehicle, refers to the conventional or nongridable version (Chau and Wong, 2002). For the micro HEV, the conventional starter motor is eliminated, while the conventional generator is replaced by an 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-start 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-start and regenerative braking but also assists the engine to propel the vehicle, thus allowing for a downsized engine (Liu, Chau, and Jiang, 2010a). However, since the engine and the ISG share the same shaft, it cannot 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-start, 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 that involves both an electric motor and an engine for propulsion and how to coordinate these two propulsion devices to achieve optimal efficiency operation (Chau and Wong, 2002). The turning point of HEV development was the advent of Toyota Prius in 1997 (Hermance and Sasaki, 1998), which initially adopted the EVT system. 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 in fuel consumption. However, this EVT system suffers from the reliance on planetary gearing, which involves transmission loss, gear noise, and regular lubrication. In addition, the overall system is relatively heavy and bulky.

1.2.3 Gridable Hybrid Electric Vehicle

The term "gridable" means that the vehicle can be directly connected to the power grid. Therefore, the gridable HEV refers to the vehicles that have gridable capability and HEV features, namely the PHEV and REV. 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 that can be recharged by plugging into an external charging port, it can offer a longer electric drive range and hence reduce the requirement of 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. Therefore, 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 then drives the generator to produce the desired electricity.

The key challenges of the gridable HEV are the system complexity and high initial cost. Its system complexity is similar to that of the conventional HEV, mainly because of the 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 because of 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.

1.2.4 Fuel-Cell Electric Vehicle

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). In addition, it can offer a driving range comparable to that of the ICEV. Its major challenges are the high initial cost and lack of hydrogen refueling infrastructure. The high initial cost is because of the use of expensive fuel cells. Hydrogen refueling infrastructure is generally absent in our society, and the establishment of such an infrastructure involves a huge investment cost. There are three practical ways to store hydrogen in the FEV: 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 °C 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. In addition, it requires more energy for providing necessary temperatures (120–200 °C) to discharge the hydrogen and necessary 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 coming future, the commercialization of the FEV depends on whether there will be a breakthrough in fuel-cell technology in terms of cost per kilowatt and whether there will be a mandate or energy policy to establish the hydrogen refueling infrastructure.

1.3 Overview of EV Technologies

An overview of key technologies for various types of EVs is presented, with emphasis on their emerging research activities. Among them, the motor drive technology is most actively developed in recent years where there are many innovations and advancements in the design, analysis, and control of motor drives. The energy source technology is also actively developed in recent years. Nevertheless, there is no real breakthrough in the battery technology, especially aspiring the simultaneous possession of low initial cost and high specific energy. Rather than waiting for a breakthrough in battery technology, the battery charging technology is being actively developed. Particularly, the concept of move-and-charge (MAC) for battery charging using wireless power transfer (WPT) is promising to fundamentally solve the long-term shortcomings of EVs. Moreover, in order to promote the advantage of EVs to justify their high initial cost, the vehicle-to-grid (V2G) technology is being actively researched, which can expand the role or function of EVs to increase their cost effectiveness.

1.3.1 Motor Drive Technology

Motor drives are the core technology for EVs that convert the on-board electrical energy to the desired mechanical motion. Meanwhile, electric machines are the key element of motor drive technology. The requirements of electric machines for EVs are much more demanding than that for industrial applications. These requirements are summarized as follows (Zhu and Howe, 2007; Chau, 2009):

- 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
- Reasonable cost

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

- High-efficiency power generation over a wide speed range
- Good voltage regulation over wide speed generation
- Capable of being integrated with the engine

Figure 1.5 shows the classification of electric machines for EVs 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) machines. Basically, EV machines 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 commutatorless or brushless machines (Chau, Chan, and Liu, 2008), especially the class of doubly salient machines and the class of vernier machines.

The key feature of doubly salient machines is the presence of salient poles in both the stator and rotor. The SR machine is a kind of doubly salient machines having the simplest structure. When incorporating PMs in the stator of doubly salient machines, a new class of PM brushless machines is resulted – the stator-PM machine (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 doubly salient permanent magnet (DSPM), flux-reversal permanent magnet (FRPM), and flux-switching permanent magnet (FSPM) machines. Additionally, with the inclusion of independent field windings in the stator for flux control, the class can be further split into the flux-controllable (FC) types – the FC-DSPM, FC-FRPM, and FC-FSPM. Furthermore, when the PM poles are replaced with DC field windings aiming to get rid of those expensive PM materials and provide flexible flux control, the resulting doubly salient DC (DSDC), flux-reversal DC (FRDC), and flux-switching DC (FSDC) machines are emerging types of advanced magnetless machines.

The key feature of vernier machines is the use of vernier effect to amplify the output torque while stepping down the speed, leading to be a class of brushless machines dedicated to low-speed high-torque direct-drive application. There are two main classes of vernier machines: vernier permanent magnet (VPM) and vernier reluctance (VR). There are three types of VPM machines depending on the location

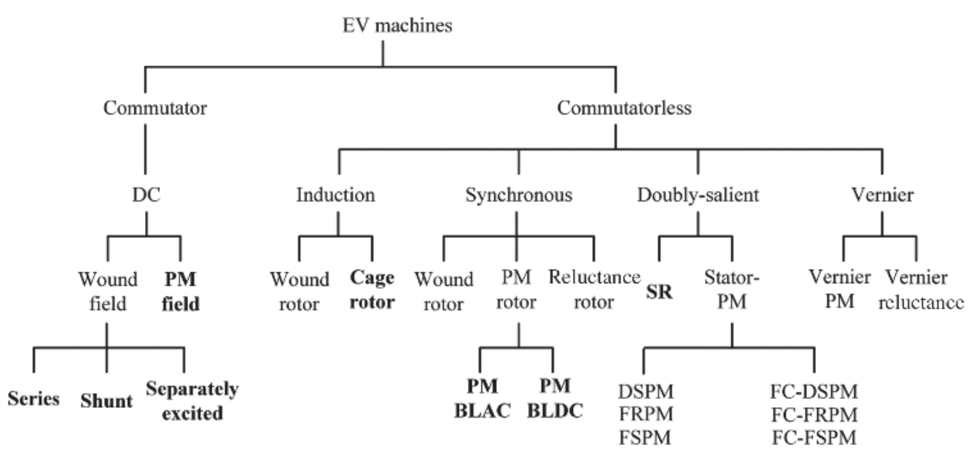

Figure 1.5 Classification of EV machines

of PMs: the rotor-PM type with all PMs mounted on the rotor, the stator-PM type with all PMs mounted on the stator, and the all-PM type with PMs mounted on both the rotor and stator. As the rotor-PM VPM machine is most mature, it is loosely called as the VPM machine (Li, Chau, and Li, 2011). The stator-PM VPM machine is commonly termed the vernier hybrid machine (Spooner and Haydock, 2003). On the other hand, the VR machine is structurally similar to the SR machine, but they operate differently. In essence, the VR machine is fed by three-phase sinusoidal currents to produce the rotating magnetic field, and the rotor runs synchronously at a fraction of the speed of this rotating field (Lee, 1963). Because of its inherently low power factor, an additional supply can be incorporated to feed an additional field winding in the stator of the VR machine, thus resulting in the doubly fed vernier reluctance (DFVR) machine (Taibi, Tounzi, and Piriou, 2006). This additional field winding can be fed by AC or DC current, leading to further create the vernier reluctance AC (VRAC) and vernier reluctance DC (VRDC) machine. The VR and DFVR machines are also classified as emerging types of advanced magnetless machines.

All EV machine topologies developed for the conventional radial-flux morphology can readily be extended to other morphologies such as the axial-flux morphology (Lee, Liu, and Chau, 2014), linear-flux morphology (Du *et al.*, 2011), and transverse-flux morphology (Wang *et al.*, 2008). The axial-flux morphology takes the advantages of higher power density and higher torque density than its radial-flux counterpart, but suffers from the problem of large axial force exerted on the stator by the rotor and limited to pancake shape. As the linear-flux morphology functions to provide linear motion, it is less attractive for EV propulsion. Although the transverse-flux morphology can offer the highest torque density, the corresponding machine structure is very complicated, which limits its manufacturability and practicality for EVs.

Apart from developing EV motor drives for pure electric propulsion, namely for the PEV and FEV, the technological development of EV machines has been extended to hybrid propulsion for HEVs. As depicted in Figure 1.6, there are two main machine systems for hybrid propulsion: the ISG system for the micro and mild hybrids and the EVT system for the full hybrid (Chau and Chan, 2007). The ISG system needs to offer not only the conventional features of engine cranking and electricity generation, but also the hybrid features of idle stop-start, regenerative braking, and power assistance. Therefore, the corresponding machine design, analysis, and control are very demanding (Liu, Chau, and Jiang, 2010a). The EVT functions to offer electrically controllable power transfer from the engine to the wheels with continuously variable transmission, hence providing all hybrid features including the electric launch, idle stop-start, regenerative braking, and power assistance, as well as achieving the highest fuel economy. There are three main types of EVT systems: the planetary-geared electric variable transmission (PG EVT), double-rotor electric variable transmission (DR EVT), and magnetic-geared electric variable transmission (MG EVT). The PG EVT system is almost exclusively used for the commercially available full hybrid, which was first developed by Toyota for its Prius (Kamiya, 2006). However, this PG EVT system inherits the fundamental drawbacks of planetary gearing, namely the transmission loss, gear noise, and need for regular lubrication. In recent years, the concept of double-rotor machines has been developed, which can be used to supersede the planetary gearing, hence forming the gearless DR EVT system (Hoeijmakers and Ferreira, 2006). However, this DR EVT system needs to employ slip rings and carbon brushes to extract the energy from the inner rotor, which suffers from the reliability concern and need for regular maintenance.

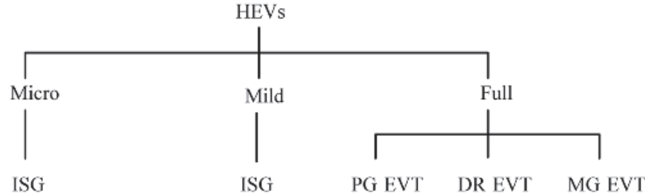

Figure 1.6 EV machine systems for HEVs

Meanwhile, by replacing the planetary gearing with magnetic gearing, the resulting MG EVT system can inherit the distinct advantages of magnetic gearing, namely, the high transmission efficiency, silent operation, and no maintenance, while avoiding the use of slip rings and carbon brushes (Jian and Chau, 2009, 2010). Nevertheless, this pseudo-gearless and brushless EVT system exhibits a complicated structure, and the required precision for manufacture is demanding.

1.3.2 Energy Source Technology

Energy sources are another core technology that provides on-board electrical energy for EVs. Currently, over the last two decades, there are four viable EV energy sources: electrochemical batteries (normally termed batteries), ultracapacitors (also called supercapacitors), ultrahigh-speed flywheels, and fuel cells (Chau, Wong, and Chan, 1999). The batteries are electrochemical devices that store electrical energy during charging and produce electricity during discharging. The ultracapacitors are essentially capacitors with ultrahigh capacitances that store and produce electrical energy by electrostatic means. The ultrahigh-speed flywheels are essentially electric machines spinning at ultrahigh speeds that store and produce electrical energy by electromechanical means, that is, they work as motors during charging and serve as generators during discharging. The fuel cells are electrochemical devices that directly convert chemical fuels into electricity. None of them can simultaneously offer high specific energy and high specific power, analogous to none of athletes can simultaneously be suitable for marathon running and 100-m sprint. 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) is necessary for the PEV or FEV (Chau and Wong, 2001).

In the foreseeable future, batteries are still the major energy source for EVs. Table 1.1 lists the major types of batteries that have been developed for EVs over the past two decades, including 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, VRLA is accepted for low-cost low-end EVs, Ni-MH is preferred for well-performed EVs, and 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, whereas the battery initial cost needs to be significantly reduced. Currently, the main 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, Advani, and Prasad, 2011). Meanwhile, another key research direction is to develop lithium/air (Li/air) battery (Christensen *et al.*, 2012) and lithium/sulfur (Li/S) battery (Zhang, 2013) to significantly improve the specific energy.

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

Table 1.1 Major batteries developed for EVs

	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

practically applicable as the sole energy source for EVs – its specific energy (5–6 Wh/kg) needs to be greatly increased while its initial cost (2400–6000 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 and Pan, 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 air friction and magnetic bearings to eliminate 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 – the so-called flywheel explosion, which is very dangerous. 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 1.2 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, which is also called the solid polymer fuel cell (SPFC), 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 4800 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 metals as the electrocatalyst (Martin, Garcia-Ybarra, and Castillo, 2010), and the reduction of operating temperature for the SOFC, which does not desire noble metals 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 waste heat of exhaust gas, a thermoelectric generator (TEG) can be mounted at the exhaust pipe to recover the waste heat energy and help charge the batteries (Yu and Chau, 2009). On the other hand, by mounting a solar panel on the roof of EVs, the photovoltaic generator (PVG) can readily collect renewable solar energy and utilize it to 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. Therefore, the thermoelectric-photovoltaic (TE-PV) hybrid energy system is promising for application to HEVs. Figure 1.7 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 and Chau, 2011a) or a Ćuk–Ćuk converter (Zhang and Chau, 2011b). The SEPIC–SEPIC MIC operating in discontinuous capacitor voltage mode is shown in Figure 1.8. The MPPT controller measures the output voltages and currents of the TEG and

Table 1.2 Viable fuel cells

	Power level (MW)	Power density (W/cm^2)	Operating temperature (°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

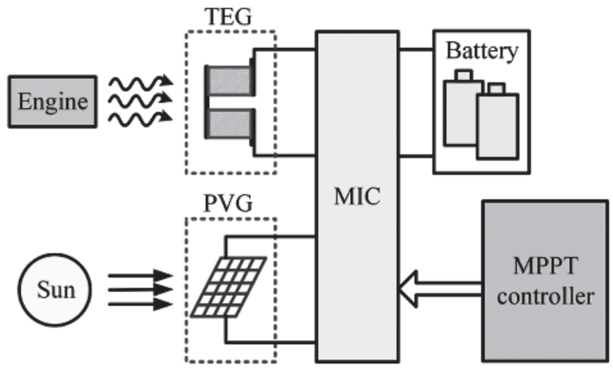

Figure 1.7 Thermoelectric-photovoltaic hybrid energy system

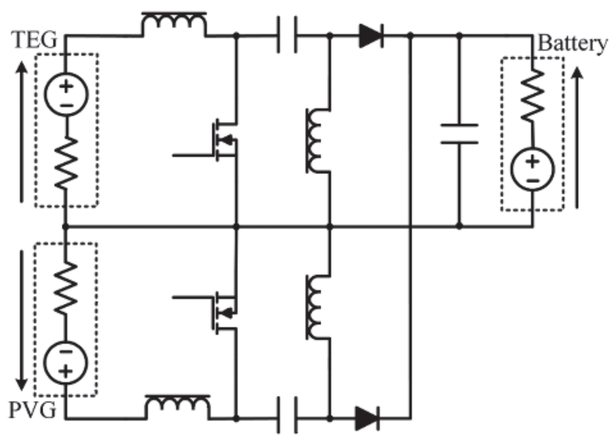

Figure 1.8 SEPIC-SEPIC multiple-input converter

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.

1.3.3 Battery Charging Technology

In recent years, many researchers have proposed various methods to alleviate the short driving range per charge of the PEV, focusing on the development of more convenient chargers. Rather than simply building more charging stations and adopting faster battery chargers, which are analogous to gas stations and powerful pumps, the use of WPT for battery charging can greatly facilitate the charging process. Increasingly, because of the absence of metallic contacts, possible electrocution during the charging process can be totally eliminated, which can enable EVs outperforming ICEVs in terms of user safety for self-service recharging or refueling.

There are two main categories of WPT: the far-field and near-field (Qiu *et al.*, 2014a). The far-field WPT makes use of microwave radiation or laser to transfer high power over long distances. However,

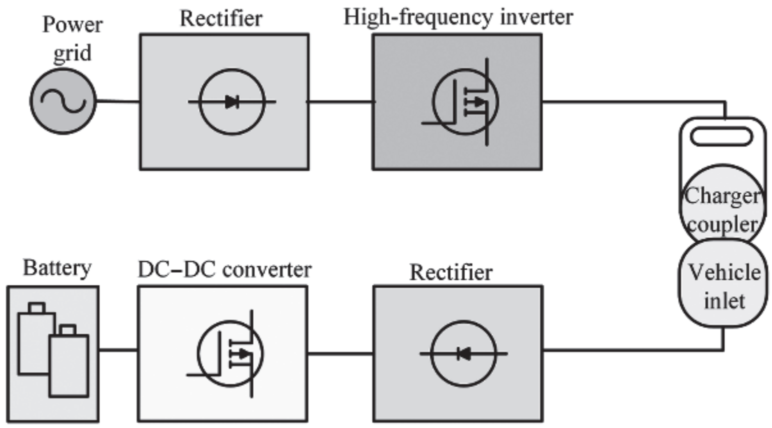

Figure 1.9 Inductive power transfer-based EV charging

it requires complicated tracking strategies and large antennas, which are impractical for EV application. The near-field WPT makes use of electric field or magnetic field for short-range to mid-range power transfer. By using electric field, the capacitive power transfer (CPT) technology takes the advantages that the power transfer is unaffected by metal barriers and causes lower electromagnetic interference (EMI) than the magnetic-field counterpart. However, as the permittivity of air is intrinsically small, it results in inadequate coupling capacitance, so that the power transfer is sensitive to the air-gap length and displacement of coupling plates (Theodoridis, 2012). In addition, since the magnetics involved cannot be scaled down with decreasing power, this CPT technology is advantageous only for low-cost low-power application, and not preferable for EV application (Musavi and Eberle, 2014). On the other hand, by using the magnetic field, the inductive power transfer (IPT) technology can transfer tens of kilowatts, while the magnetic resonant coupling (MRC) technology can extend the air-gap range to tens of centimeters. Thus, the magnetic-field WPT technologies have been identified to be most viable for EV battery charging.

The principle of IPT for EV battery charging is shown in Figure 1.9, based on the magnetic coupling between two coils of a high-frequency transformer. One of the coils 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 or 60 Hz is rectified and converted to a high-frequency AC power of about 80 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 into DC power for battery charging. This IPT can operate over a wide frequency range and can readily be scaled up to meet various power levels for EV charging. However, the corresponding core losses and EMI are of concern. For instance, a well-known but obsolete IPT-based EV charger, Magne Charge, delivered 6.6 kW at an efficiency of 86%.

In order to facilitate the park-and-charge (PAC) process for EVs, the magnetic-field WPT technology is extended to be plugless, in which the primary coil is installed on the floor of a garage or in a parking lot and the secondary coil is installed on the vehicle. The driver needs no bothering about those cumbersome and dangerous charging cables. This system is very easy to use and the charging process takes place automatically once the driver parks the EV correctly. This plugless PAC not only increases user convenience, but also offers a means of overcoming the standardization of charging plugs. Owing to the existence of a large air-gap or clearance between the primary and secondary coils, the IPT technology is ill-suited. On the basis of MRC, the primary and secondary resonant coils having the same resonant frequency can wirelessly transfer power efficiently with high power density, while dissipating relatively little energy in nonresonant objects such as vehicle bodies or drivers. Increasingly, by incorporating one or more resonant coils between the primary and secondary coils as depicted in Figure 1.10, a strongly

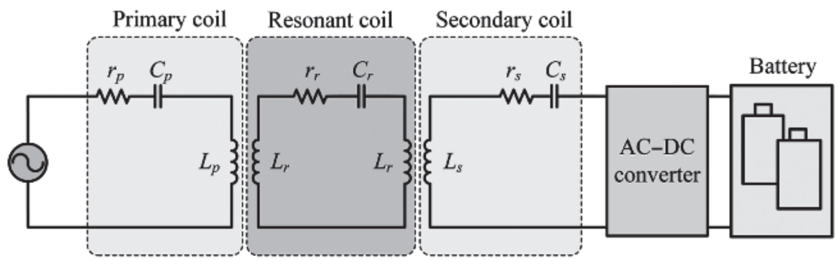

Figure 1.10 Magnetic resonant coupling-based EV charging

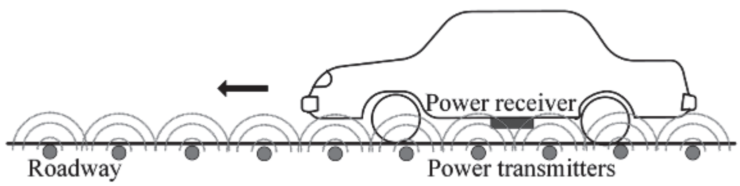

Figure 1.11 EV move-and-charge

coupled magnetic resonance is resulted, which can enable efficient power transfer from the primary coil to the secondary coil with a large air-gap between the floor and vehicle (Cannon *et al.*, 2009; Imura and Hori, 2011). For instance, an on-line electric bus system was demonstrated to transfer 100 kW through an air-gap of 20 cm with an average system efficiency of 75% (Kim *et al.*, 2013). Latest research and development of MRC-based WPT are active and diversified, such as improving the system efficiency, combating the EMI, or compensating the misalignment between magnetic couplers (Qiu *et al.*, 2014b).

Rather than stopping or parking, EVs prefer to be wirelessly charged during moving. An array of power transmitters is embedded beneath the roadway (the so-called charging zone or lane) while a receiver is mounted at the bottom of an EV as depicted in Figure 1.11. This MAC technology has high potentiality to fundamentally solve the long-term problems of the PEV – high initial cost and short driving range. 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. However, there are some technical problems to be solved before the realistic application of MAC to EVs. First, the efficiency of WPT 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 WPT 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 WPT 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. Third, most importantly, as there are many EVs running on the roadway, the MAC operation needs to distinguish which EVs are authorized to retrieve wireless power or to prevent unauthorized vehicles from stealing the energy.

Rather than avoiding the occurrence of chaos, electric drives have positively utilized the chaotic phenomena for various industrial applications (Chau and Wang, 2011) such as industrial mixing (Ye and Chau, 2007) and industrial compaction (Wang and Chau, 2009). Extending from the concept of chaotic modulation (Zhang *et al.*, 2011), the chaotic energy encryption has been developed for EV WPT (Zhang *et al.*, 2014). The key is to employ chaotic sequence to modulate the resonant frequency for WPT, hence encrypting the wireless power transmitted over the roadway. For those authorized vehicles, they know the chaotic sequence that can be used to decrypt the received power for battery charging, whereas the unauthorized vehicles cannot retrieve the power even running on the same roadway.

1.3.4 Vehicle-to-Grid Technology

The 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 whenever necessary (Liu *et al.*, 2013). 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 4.4–85 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 only store a limited capacity, from 4.4 kWh (Toyota Prius PHEV) to 85 kWh (Tesla Model S), an individual V2G operation of each gridable EV with the power grid is ineffective and inefficient. Therefore, an aggregator is introduced, which is responsible for gathering a number of gridable EVs and communicating with the power grid. On the basis of the willingness of drivers and the battery capacity of gridable EVs, the aggregator controls proper gridable EVs to achieve smart charging and discharging (Guille and Gross, 2009). Moreover, the corresponding energy arbitrage can be performed internally by the aggregator, the so-called vehicle-to-vehicle (V2V) operation. For instance, those PEVs preferably perform fast charging for instant usage while those PHEVs preferably sell electricity for profit-making, the aggregator can realize internal V2V operation for energy arbitrage. This dual-grid framework is depicted in Figure 1.12 in which the energy service provider (ESP) sells power directly to homes and businesses, the independent system operator (ISO) oversees the operations of a particular section of the power grid, the regional transmission organization (RTO) 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, Chau, and Gao, 2010b). 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 various potential applications: charging coordination, peak shaving, active regulation, spinning reserve, motor starting, reactive regulation, and renewable transients (Ehsani, Falahi, and Lotfifard, 2012). 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 1.13, the V2G operation preferably performs EV battery charging to absorb or buy electrical energy from the grid during the off-peak period (the so-called coordinated charging), whereas to generate or sell electrical energy to the grid during peak period (the so-called peak shaving). In addition, the corresponding charging and discharging processes of EVs are much faster than the shutoff and start-up processes of standby generators (Wu, Chau, and Gao, 2010a). However, at the present status of battery technology, the EV batteries still suffer from a limited cycle life. Deep discharging of EV batteries for peak shaving will inevitably degrade their life for normal vehicular operation (Gao *et al.*, 2011).

Since renewable power generations such as wind power and solar power are intermittent in nature, the use of standby generators to back up the intermittent power outage is expensive, inefficient, and sluggish. Although the battery energy storage system can provide the desired efficient and fast backup, it is too

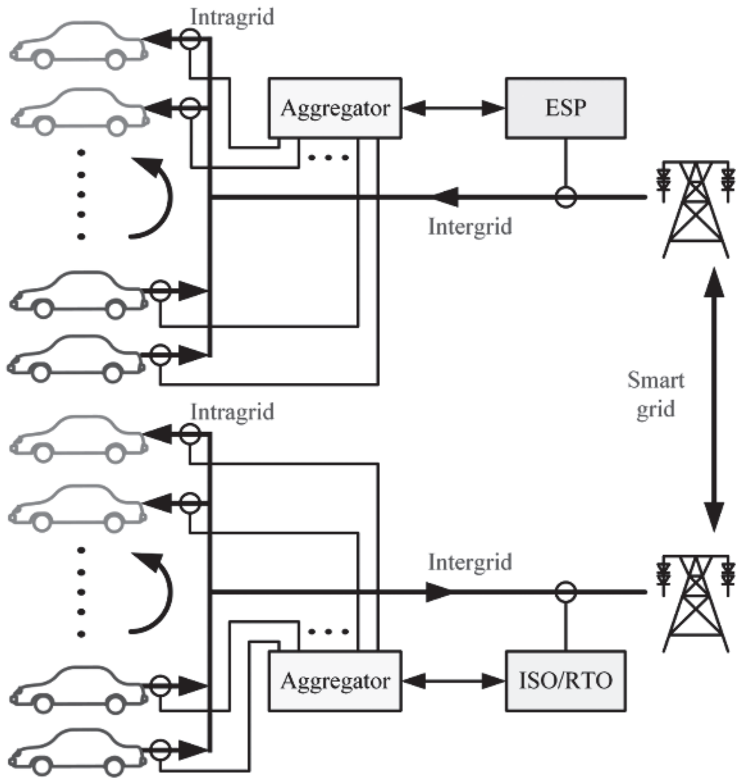

Figure 1.12 Dual-grid framework for vehicle-to-grid operation

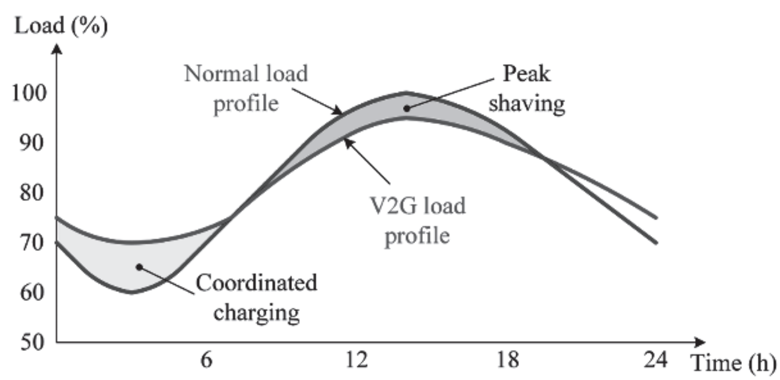

Figure 1.13 Coordinated charging and peak shaving

expensive and bulky. The V2G operation can fully utilize the EV batteries to complement the intermittent outage of power grid with renewables (Gao *et al.*, 2014). Differing from load shaving, the renewable transients will not cause deep discharging of EV batteries or noticeable degradation of battery life. Moreover, by incorporating superconducting magnetic energy storage (SMES) into V2G operation, the system dynamic performance for renewable transients can be further improved (Gao *et al.*, 2012).

Apart from using EV batteries for V2G operation, DC-link capacitors of the off-board bidirectional EV chargers can be fully utilized to perform reactive power compensation for the power grid. In general, the DC-link capacitor is sufficient enough to supply reactive power to the grid even without engaging the EV batteries. Thus, it causes no degradation to the battery life. This feature makes the EV charger very attractive for V2G reactive regulation (Kisacikoglu, Ozpineci, and Tolbert, 2010; Kesler, Kisacikoglu, and Tolbert, 2014). Similar to the active regulation, an aggregation of EV chargers is necessary to provide the desired level of reactive power compensation.

References

Cannon, B.L., Hoburg, J.F., Stancil, D.D. and Goldstein, S.C. (2009) Magnetic resonant coupling as a potential means for wireless power transfer to multiple small receivers. *IEEE Transactions on Power Electronics*, **24**, 1819–1825.

Chan, C.C. and Chau, K.T. (2001) *Modern Electric Vehicle Technology*, Oxford University Press, Oxford.

Chau, K.T. (2009) Electric motor drives for battery, hybrid and fuel cell vehicles, in *Electric Vehicles: Technology, Research and Development* (ed G.B. Raines), Nova Science, New York, pp. 1–40.

Chau, K.T. (2010) Hybrid vehicles, in *Alternative Fuels for Transportation* (ed A.S. Ramadhas), CRC Press, Boca Raton, FL, pp. 361–391.

Chau, K.T. (2012) Research on electric vehicles: challenges, opportunities and emerging technologies. *Studies in Science and Technology*, **1**, 13–24.

Chau, K.T. (2014) Pure electric vehicles, in *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance* (ed R. Folkson), Woodhead Publishing, Amsterdam, pp. 655–684.

Chau, K.T. and Chan, C.C. (2007) Emerging energy-efficient technologies for hybrid electric vehicles. *Proceedings of the IEEE*, **95**, 821–835.

Chau, K.T., Chan, C.C. and Liu, C. (2008) Overview of permanent-magnet brushless drives for electric and hybrid electric vehicles. *IEEE Transactions on Industrial Electronics*, **55**, 2246–2257.

Chau, K.T. and Wang, Z. (2011) *Chaos in Electric Drive Systems–Analysis, Control and Application*, Wiley-IEEE Press, Singapore.

Chau, K.T. and Wong, Y.S. (2001) Hybridization of energy sources in electric vehicles. *Energy Conversion and Management*, **42**, 1059–1069.

Chau, K.T. and Wong, Y.S. (2002) Overview of power management in hybrid electric vehicles. *Energy Conversion and Management*, **43**, 1953–1968.

Chau, K.T., Wong, Y.S. and Chan, C.C. (1999) An overview of energy sources for electric vehicles. *Energy Conversion and Management*, **40**, 1021–1039.

Christensen, J., Albertus, P., Sanchez-Carrera, R.S. *et al.* (2012) A critical review of Li/air batteries. *Journal of the Electrochemical Society*, **159**, R1–R30.

Du, Y., Chau, K.T., Cheng, M. *et al.* (2011) Design and analysis of linear stator permanent magnet vernier machines. *IEEE Transactions on Magnetics*, **47**, 4219–4222.

Du, C. and Pan, N. (2006) Supercapacitors using carbon nanotubes films by electrophoretic deposition. *Journal of Power Sources*, **160**, 1487–1494.

Ehsani, M., Falahi, M. and Lotfifard, S. (2012) Vehicle to grid services: potential and applications. *Energies*, **5**, 4076–4090.

Gao, S., Chau, K.T., Chan, C.C. *et al.* (2011) Optimal control framework and scheme for integrating plug-in hybrid electric vehicles into grid. *Journal of Asian Electric Vehicles*, **9**, 1473–1481.

Gao, S., Chau, K.T., Liu, C. *et al.* (2014) Integrated energy management of plug-in electric vehicles in power grid with renewables. *IEEE Transactions on Vehicular Technology*, **63**, 3019–3027.

Gao, S., Chau, K.T., Liu, C. *et al.* (2012) SMES control for power grid integrating renewable generation and electric vehicles. *IEEE Transactions on Applied Superconductivity*, **22**, 5701804-1–5701804-4.

Giuliano, M.R., Advani, S.G. and Prasad, A.K. (2011) Thermal analysis and management of lithium-titanate batteries. *Journal of Power Sources*, **196**, 6517–6524.

Guille, C. and Gross, G. (2009) A conceptual framework for the vehicle-to-grid (V2G) implementation. *Energy Policy*, **37**, 4379–4390.

Hermance, D. and Sasaki, S. (1998) Hybrid electric vehicles take to the streets. *IEEE Spectrum*, **35**, 48–52.

Hoeijmakers, M. and Ferreira, J. (2006) The electric variable transmission. *IEEE Transactions on Industry Applications*, **42**, 1092–1100.

Imura, T. and Hori, Y. (2011) Maximizing air gap and efficiency of magnetic resonant coupling for wireless power transfer using equivalent circuit and Neumann formula. *IEEE Transactions on Industrial Electronics*, **58**, 4746–4752.

Jian, L. and Chau, K.T. (2009) A novel electronic-continuously variable transmission propulsion system using coaxial magnetic gearing for hybrid electric vehicles. *Journal of Asian Electric Vehicles*, **7**, 1291–1296.

Jian, L. and Chau, K.T. (2010) Design and analysis of a magnetic-geared electronic-continuously variable transmission system using finite element method. *Progress in Electromagnetics Research*, **107**, 47–61.

Kamiya, M. (2006) Development of traction drive motors for the Toyota hybrid system. *IEEE Transactions on Industry Applications*, **126**, 473–479.

Kesler, M., Kisacikoglu, M.C. and Tolbert, L.M. (2014) Vehicle-to-grid reactive power operation using plug-in electric vehicle bidirectional off-board charger. *IEEE Transactions on Industrial Electronics*, **61**, 6778–6784.

Kim, J., Kim, J., Kong, S. *et al.* (2013) Coil design and shielding methods for a magnetic resonant wireless power transfer system. *Proceedings of the IEEE*, **101**, 1332–1342.

Kisacikoglu, M.C., Ozpineci, B., and Tolbert, L.M. (2010) Examination of a PHEV bidirectional charger for V2G reactive power compensation. Proceedings of IEEE Applied Power Electronics Conference and Exposition, pp. 458–465.

Lee, C.H. (1963) Vernier motor and its design. Proceedings of IEEE Winter General Meeting, pp. 343–349.

Lee, C.H.T., Liu, C. and Chau, K.T. (2014) A magnetless axial-flux machine for range-extended electric vehicle. *Energies*, **7**, 1483–1499.

Li, J., Chau, K.T. and Li, W. (2011) Harmonic analysis and comparison of permanent magnet vernier and magnetic-geared machines. *IEEE Transactions on Magnetics*, **47**, 3649–3652.

Liu, C., Chau, K.T. and Jiang, J.Z. (2010a) A permanent-magnet hybrid brushless integrated starter-generator for hybrid electric vehicles. *IEEE Transactions on Industrial Electronics*, **57**, 4055–4064.

Liu, C., Yu, Z., Neff, D. *et al.* (2010b) Graphene-based supercapacitor with an ultrahigh energy density. *Nano Letters*, **10**, 4863–4868.

Liu, C., Chau, K.T., Jiang, J.Z. and Niu, S. (2008) Comparison of stator-permanent-magnet brushless machines. *IEEE Transactions on Magnetics*, **44**, 4405–4408.

Liu, C., Chau, K.T., Wu, D. and Gao, S. (2013) Opportunities and challenges of vehicle-to-home, vehicle-to-vehicle, and vehicle-to-grid technologies. *Proceedings of the IEEE*, **101**, 2409–2427.

Martin, S., Garcia-Ybarra, P.L. and Castillo, J.L. (2010) Electrospray deposition of catalyst layers with ultra-low Pt loadings for PEM fuel cells cathodes. *Journal of Power Sources*, **195**, 2443–2449.

Musavi, F. and Eberle, W. (2014) Overview of wireless power transfer technologies for electric vehicle battery charging. *IET Power Electronics*, **7**, 60–66.

Omar, N., Daowd, M., Hegazy, O. *et al.* (2012) Standardization work for BEV and HEV applications: critical appraisal of recent traction battery documents. *Energies*, **5**, 138–156.

Qiu, C., Chau, K.T., Ching, T.W. and Liu, C. (2014a) Overview of wireless charging technologies for electric vehicles. *Journal of Asian Electric Vehicles*, **12**, 1–7.

Qiu, C., Chau, K.T., Liu, C. *et al.* (2014b) Quantitative comparison of dynamic flux distribution of magnetic couplers for roadway electric vehicle wireless charging system. *Journal of Applied Physics*, **115**, 17A334-1–17A334-3.

Spooner, E. and Haydock, L. (2003) Vernier hybrid machines. *IEE Proceedings – Electric Power Applications*, **150**, 655–662.

Strasik, M., Johnson, P.E., Day, A.C. *et al.* (2007) Design, fabrication, and test of a 5-kWh/100-kW flywheel energy storage utilizing a high-temperature superconducting bearing. *IEEE Transactions on Applied Superconductivity*, **17**, 2133–2137.

Taibi, S., Tounzi, A. and Piriou, F. (2006) Study of a stator current excited vernier reluctance machine. *IEEE Transactions on Energy Conversion*, **21**, 823–831.

Theodoridis, M.P. (2012) Effective capacitive power transfer. *IEEE Transactions on Power Electronics*, **27**, 4906–4913.

Wakefield, E.H. (1994) *History of the Electric Automobile: Battery-Only Powered Cars*, Society of Automotive Engineers, Warrendale, PA.

Wang, Z. and Chau, K.T. (2009) Design, analysis, and experimentation of chaotic permanent magnet DC motor drives for electric compaction. *IEEE Transactions on Circuits and Systems II*, **56**, 245–249.

Wang, J., Chau, K.T., Jiang, J.Z. and Yu, C. (2008) Design and analysis of a transverse flux permanent magnet machine using three dimensional scalar magnetic potential finite element method. *Journal of Applied Physics*, **103**, 7F107-1–7F107-3.

Wang, X., Ma, Y., Li, S. *et al.* (2011) Ceria-based nanocomposite with simultaneous proton and oxygen ion conductivity for low-temperature solid oxide fuel cells. *Journal of Power Sources*, **196**, 2754–2758.

Wu, D., Chau, K.T. and Gao, S. (2010a) Cost-emission analysis of vehicle-to-grid system. *World Electric Vehicle Journal*, **4**, 767–773.

Wu, D., Chau, K.T., and Gao, S. (2010b) Multilayer framework for vehicle-to-grid operation. Proceedings of IEEE Vehicle Power and Propulsion Conference, pp. 1–6.

Ye, S. and Chau, K.T. (2007) Chaoization of DC motors for industrial mixing. *IEEE Transactions on Industrial Electronics*, **54**, 2024–2032.

Yu, C. and Chau, K.T. (2009) Thermoelectric automotive waste heat energy recovery using maximum power point tracking. *Energy Conversion and Management*, **50**, 1506–1512.

Zhang, S.S. (2013) Liquid electrolyte lithium/sulfur battery: fundamental chemistry, problems, and solutions. *Journal of Power Sources*, **231**, 153–162.

Zhang, X. and Chau, K.T. (2011a) Design and implementation of a new thermoelectric-photovoltaic hybrid energy system for hybrid electric vehicles. *Electric Power Components and Systems*, **39**, 511–525.

Zhang, X. and Chau, K.T. (2011b) An automotive thermoelectric-photovoltaic hybrid energy system using maximum power point tracking. *Energy Conversion and Management*, **52**, 641–647.

Zhang, Z., Chau, K.T., Liu, C. *et al.* (2014) An efficient wireless power transfer system with security considerations for electric vehicle applications. *Journal of Applied Physics*, **115**, 17A328-1–17A328-3.

Zhang, Z., Chau, K.T., Wang, Z. and Li, W. (2011) Improvement of electromagnetic compatibility of motor drives using hybrid chaotic pulse width modulation. *IEEE Transactions on Magnetics*, **47**, 4018–4021.

Zhu, Z.Q. and Howe, D. (2007) Electrical machines and drives for electric, hybrid and fuel cell vehicles. *Proceedings of the IEEE*, **95**, 746–765.