Electric Vehicles

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7.1 Introduction

In the past, there were various definitions of electric vehicles (EVs). They used to be classified into two types: the pure EV which was purely powered by batteries and only propelled by an electric motor, and the hybrid EV (HEV) which was powered by both batteries and liquid fuel and propelled by both the engine and the electric motor. After the invention of other energy sources, namely the fuel cells, ultracapacitors and ultrahigh-speed flywheels (Chau *et al.*, 1999), this classification became inappropriate. In recent years, there has been a consensus that the EVs refer to vehicles with at least one of the propulsion devices being the electric motor. Then, when the energy source is only batteries and the propulsion device is only an electric motor, they are named the battery EV (BEV) or even loosely called the EV; when the energy source involves fuel cells working together with batteries and the propulsion device is only an electric motor, they are named the fuel cell EV (FCEV) or simply called the fuel cell vehicle; when both batteries and liquid fuel are the energy sources as well as both the engine and the electric motor are the propulsion devices, they are named the hybrid EV (HEV) or simply called the hybrid vehicle. Figure 8-1 depicts the classification of the existing internal combustion engine vehicle (ICEV), HEV, BEV and FCEV based on the energy source and the propulsion device.

The first EV, actually a BEV, was built by Thomas Davenport in 1834. With the drastic improvement in the ICEV, the BEV almost vanished from the scene by the 1930's. The rekindling of interests in BEVs was resulted from the outbreak of energy crisis and oil shortage in the 1970's. The actual revival of BEVs was due to the growing concerns on energy conservation and environmental protection throughout the whole world in the 1990's. In essence, BEVs offer higher energy efficiency, better energy diversification, load equalization of power systems, zero local exhaust emissions and quieter operation than ICEVs. However, there are two major barriers hindering the popularization of BEVs — short driving range and high initial cost. These barriers can not be easily solved by the available energy source technologies (including batteries, fuel cells, ultracapacitors and ultrahigh-speed flywheels) in the near future.

People may not buy a BEV, no matter how clean, if its range between charges is only one hundred kilometres. By the same token, people may not buy a FCEV, no matter how clean, if its price is over ten times the ICEV counterpart.

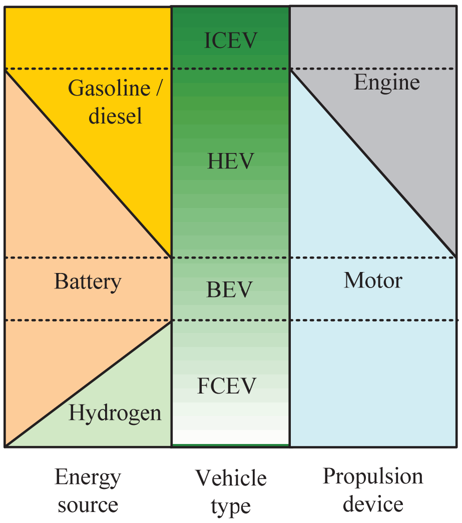


Figure 7-1 Classification of vehicles.

The HEV, incorporating the engine and the electric motor, was introduced as an interim solution before the full implementation of pure EVs at which there is a breakthrough in energy sources. The distinctive advantages of the HEV are to greatly extend the original BEV driving range by two to four times, and to offer rapid refuelling of liquid fuel. An important issue is that it does not require any change in the refuelling infrastructure. The key drawbacks of the HEV are the loss of zero-emission vehicle concept and the increased complexity. Nevertheless, the HEV is vastly less polluting and exhibits less fuel consumption than the ICEV while having the same range. These merits are due to the fact that the engine of the HEV can always operate in its most efficient mode, yielding low exhaust emissions and low fuel consumption (Chau *et al.*, 2007). Also, the HEV can be purposely operated as a BEV in the zero-emission zone. It is becoming a consensus that the HEV is not only an interim solution before the implementation of pure EVs but also a practical solution for realization of the class of super-ultra-low-emission vehicles (SULEVs).

The concept of HEVs is nothing new. Actually, it was patented in 1905 that a battery-powered electric motor was used to boost the acceleration of an ICEV. However, over the years, the development of HEVs had been slow. The major reason was due to their complexity, especially on how to coordinate and combine the mechanical driving forces from both the engine and the electric motor. The turning point of HEV development was the hybrid synergy drive developed for the Toyota Prius in 1997. Subsequently, the development of HEVs has been accelerated dramatically (Chau *et al.*, 2002).

Based on the hybridization level and the operation feature between the engine and the electric motor, HEVs have been further split into the micro hybrid, the mild hybrid and the full hybrid. Recently, this classification has been further extended to include the plug-in hybrid EV (PHEV) and the latest range-extended EV (REEV). Figure 7-2 depicts their classification in terms of the energy source and the propulsion device (Chau, 2010).

For the micro hybrid, the conventional starter motor is eliminated while the conventional generator is replaced by a belt-driven integrated-starter-generator (ISG). This ISG is typically 3–5 kW. 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, so-called the 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. The battery voltage is generally 12 V.

For the mild hybrid, the ISG is generally placed between the engine and the transmission. This ISG is typically 7–12 kW. It can provide the hybrid features of idle stop and regenerative braking. Also, the ISG can assist the engine to propel the vehicle, thus allowing for a downsized engine. However, since the engine and the ISG share the same shaft, it can not offer electric launch, namely initial acceleration under electric power only. The battery voltage is typically 36–144 V.

For the full hybrid, 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, the idle stop, the regenerative braking and the engine downsizing. The corresponding electric motor and battery ratings are typically 30–50 kW and 200–500 V, respectively. Instead of downsizing the engine, the electric motor can be utilized to produce additional torque and hence better acceleration performance than a conventional ICEV with the same size of engine.

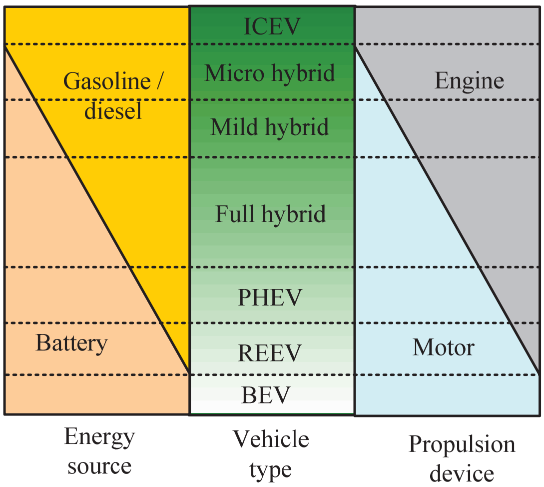


Figure 7-2 Classification of HEVs.

For the PHEV, it provides all features of the full hybrid, while having an additional feature of plug-in rechargeable. Since it incorporates a large bank of batteries which can be recharged by plugging to an external charging port, it can offer a long electric-drive range and hence reduce the requirement for refuelling from gas stations. The corresponding electric motor and battery ratings are typically 30–50 kW and 300–500 V, respectively.

For the REEV, it provides all features of the plug-in hybrid, but having a small engine coupled with a generator to recharge the battery bank when its capacity is lower than a threshold. This avoids the range anxiety problem that is always associated with the BEV. So, it can offer energy-efficient operation throughout its initial pure-electric range and hence significantly reduce the requirement for refuelling from gas stations. The corresponding electric motor and battery ratings are similar to that of the plug-in hybrid, typically 30–50 kW and 300–500 V.

The use of EVs, no matter the BEV, HEV or FCEV, can enjoy two major benefits. Namely, the energy benefit resulting from better energy diversification and higher energy efficiency, as well as the environmental benefit resulting from better air quality and lower noise pollution.

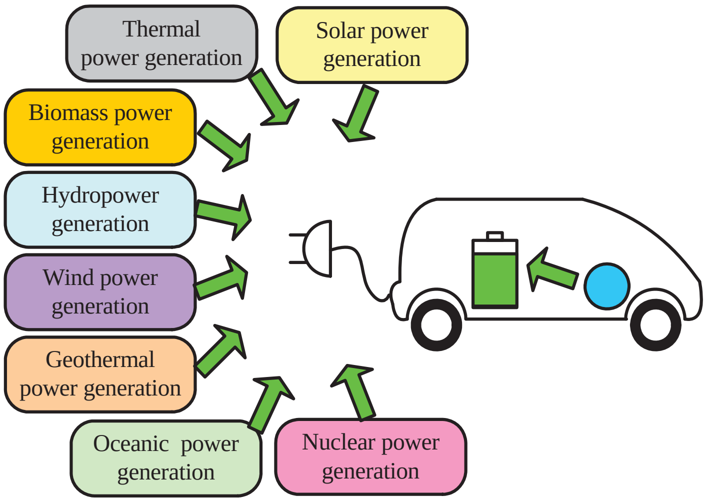


Figure 7-3 Generation of electricity for BEV, PHEV and REEV.

7.2 Energy Benefit

Deriving from oil, gasoline and diesel are the major liquid fuels for ICEVs. Although the development of biofuels has taken on an accelerated pace in recent years, our road vehicles are still heavily dependent on crude oil. EVs are an excellent solution to rectify this unhealthy dependence because electricity can be generated by almost all kinds of energy resources. Figure 7-3 illustrates the merit of energy diversification for three types of EVs (namely the BEV, PHEV and REEV) in which electricity can be derived from the power grid via thermal power generation, solar power generation, nuclear power generation, hydropower generation, wind power generation, geothermal power generation, oceanic power generation and biomass power generation, as well as from the generator coupled with the engine and the electric motor via regenerative braking.

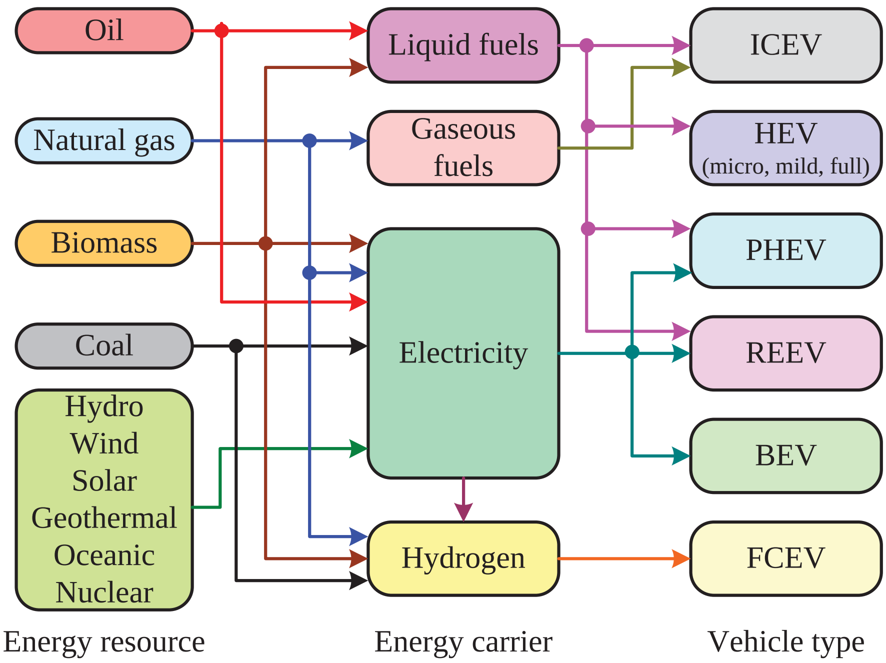


Figure 7-4 Energy conversions for various EVs.

Taking into account various energy resources including the oil (both conventional and non-conventional), the natural gas, the coal, the renewable energies (biomass, hydro, wind, solar, geothermal and oceanic) and the nuclear energy, and various types of EVs including the ICEV, the conventional HEV (micro, mild, full), the PHEV, the REEV, the BEV and the FCEV, the relevant energy conversion processes are depicted in Figure 7-4. It can be found that electricity is the most convenient energy carrier between various energy resources and various EVs, while liquid fuels including the gasoline, the diesel, the liquefied petroleum gas (LPG) and biofuels are the major energy carrier for the ICEV and various HEVs. Hence, it can be identified that the latest two types of HEVs, namely the PHEV and the REEV, can benefit the greatest energy diversification from accepting both liquid fuels and electricity as their energy carriers.

Besides the definite merit of energy diversification resulting from the use of EVs, another important advantage is the high energy efficiency offered by EVs. In order to compare the overall energy efficiency of the BEV with the ICEV, their energy conversion processes from crude oil to road load are depicted in Figure 7-5, where the numerical data are indicative only. By taking the energy capacity of crude oil as 100%, the overall energy efficiencies for the BEV and ICEV are 18% and 13%, respectively. Therefore, even when all electricity are generated by oil-fired power plants, the BEV is more energy efficient than the ICEV by about 38%. For the HEVs, the corresponding energy efficiencies are between the BEV and ICEV. Typically, they are 20–30% higher energy efficiency or fuel economy than the ICEV. It should be noted that since ICEVs currently consume over 60% of oil demand in advanced countries, the use of EVs can significant reduce the consumption of oil, hence saving in both energy and money.

Moreover, all EVs possess one distinct advantage over the ICEV in energy recovery, namely regenerative braking. As shown in Figure 7-6, EVs can recover the kinetic energy during braking or deceleration and utilize it for battery recharging, whereas the ICEV wastefully dissipates this kinetic energy as heat in the brake discs and drums. With this technology, the energy efficiency of EVs can be further boosted by up to 10%.

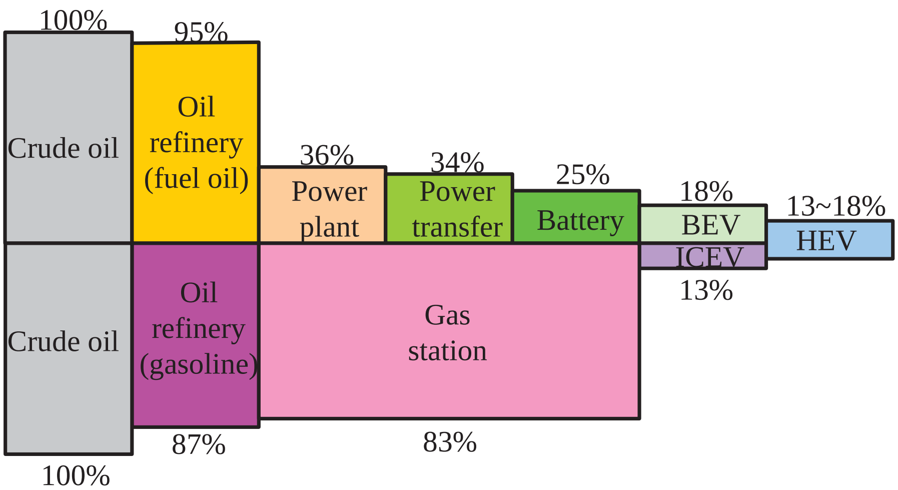


Figure 7-5 Comparison of energy efficiencies between BEV and ICEV.

Figure 7-6 Energy recovery by regenerative braking.

7.3 Environmental Benefit

In many metropolises, ICEVs are responsible for over 50% of harmful air pollutants and smog-forming compounds. Although the engine of ICEVs is continually improved to reduce the emitted pollutants, the increase in the number of ICEVs is much faster than the reduction of emissions per vehicle. Thus the total emitted pollutants due to ICEVs, including the carbon monoxide (CO), the hydrocarbons (HC), the nitrogen oxides (NO_x), the sulphur oxides (SO_x), the particulate matter (dust) and the non-methane organic gases (NMOG), continue to grow in worrying trend.

In order to reduce or at least slow down the growth of air pollution due to road transportation, the use of EVs is the most viable choice (Chan *et al.*, 2001). Figure 7-7 shows an indicative comparison of harmful emissions locally generated by the ICEV and the BEV, while those of the HEVs lie between them. As expected, the BEV offers zero local emissions at all. Taking into account the emissions generated by refineries to produce liquid fuels for the ICEV as well as the emissions by power plants to generate electricity for the BEV, an indicative comparison of global harmful emissions is shown in Figure 7-8. It can be found that the global harmful emissions of the BEV are still much lower than those of the ICEV. For the HEVs, the corresponding global harmful emissions are between the BEV and the ICEV.

Nowadays, many automobile companies produce HEVs, which are not only commercially available but also economically sustainable. The latest flagships include the Chevrolet C15 Silverado Hybrid, the Ford Fusion Hybrid, the Honda Civic Hybrid, the Mercedes Benz S400 Hybrid, the Nissan Altima Hybrid, the Saturn VUE hybrid and the Toyota Prius. In general, they exhibit significant reduction in exhaust emissions as compared with their ICEV counterparts. Nevertheless, different HEV models have different emission levels of different pollutants. For instance, as listed by the Air Resources Board of the California Environmental Protection Agency in 2009, the Toyota Prius offers a very low level of CO emission while the Mercedes Benz S400 Hybrid provides a very small content of NMOG emission.

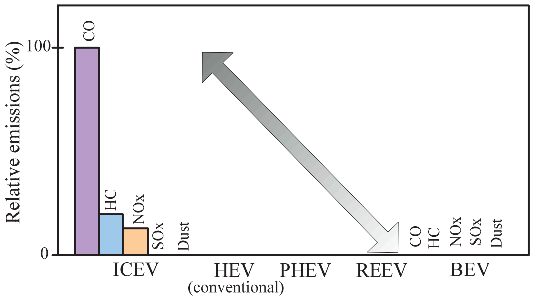


Figure 7-7 Comparison of local harmful emissions.

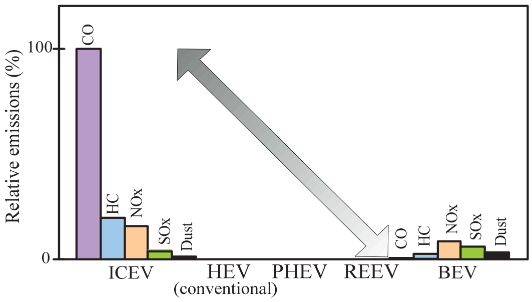


Figure 7-8 Comparison of global harmful emissions.

It should be noted that the global carbon dioxide (CO_2) emission can be reduced by about 5% with the use 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.

EVs have another definite advantage over ICEVs on the suppression of noise pollution. Different from the ICEV that its combustion engine and complicated mechanical transmission produce severe noise problems to our surroundings, the BEV is powered by an electric motor operating with very low acoustic noise. Moreover, the BEV offers either gearless or single-speed mechanical transmission so that the corresponding annoying noise is minimal. Figure 7-9 gives an indicative comparison of noise created by the ICEV and the BEV during launching, running, climbing and braking. Of course, the noise of those HEVs lies between them.

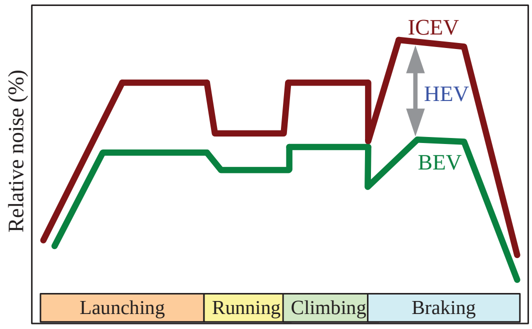


Figure 7-9 Comparison of vehicle noises between BEV and ICEV.

7.4 HKU's Role

The University of Hong Kong (HKU) kicked off the research and development of EVs in the early 1980's. The first EV of Hong Kong, named Mark1, was developed by HKU. This Mark1 was converted from an existing ICEV, namely replacing the engine by the induction motor and adopting lead acid batteries as the energy source. The community became aware of the development of EVs as reflected from the cover page of the HKIE's *Hong Kong Engineer* in December 1984 as shown in Figure 7-10.

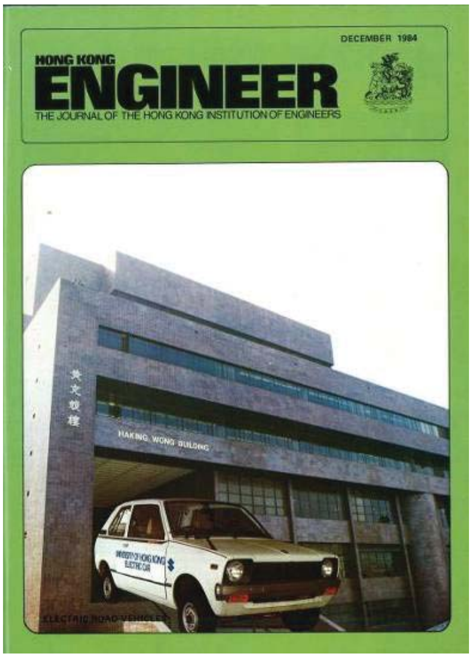


Figure 7-10 Our EV appeared on HKIE's *Hong Kong Engineer* in 1984.

Subsequently, the International Research Centre for Electric Vehicles (IRCEV) was established in HKU in 1986. Its mission is to pursue excellence in research and technology transfer in EV technology. As shown in Figure 7-11, the IRCEV is currently led by Prof. K.T. Chau with the manpower of about 10 researchers and research students.

Over the years, the IRCEV has developed five BEVs as shown in Figure 7-12 in which the Mark1, the Mark2, the Mark3 and the U2001 were based on ICEVs' conversion whereas the eV Light was based on the Reva's ground-up EV. Each EV prototype had its unique features, especially the electric propulsion system. For instance, the Mark1 adopted the variable-voltage variable-frequency (VVVF) induction motor drive, the Mark2 used the vector-controlled induction motor drive, the Mark3 employed the permanent magnet (PM) synchronous motor drive, the U2001 tested our self-developed PM hybrid motor drive and the eV Light tested our self-developed stator-PM brushless motor drive. Also, both the U2001 and the eV Light have installed the variable temperature seats to enhance energy-efficient temperature control.

IRCEV-HKU

Figure 7-11 Our IRCEV was established in 1986.

Mark1

Mark2

Mark3

U2001

Figure 7-12 EV developed in HKU.

Rather than simply promoting EVs using prototypes for demonstration, the IRCEV has made extraordinary contributions to and lasting impact on the field of EV technology:

(i) Defined the concept of EV drives and identified their performance requirements (Chau *et al.*, 2010).

(ii) Pioneered the development of AC propulsion systems, especially permanent magnet (PM) brushless motor drives (Chau *et al.*, 2008), for EVs.

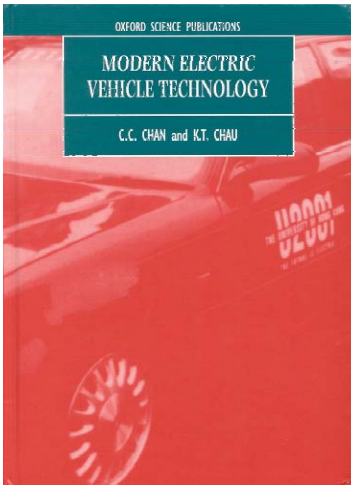
(iii) Developed the class of flux-controllable stator-PM brushless machine drives for EVs, which can offer the advantages of high efficiency, high power density, high controllability and high reliability (Chau, 2009).

(iv) Educated over 40 PhD/MPhil graduates in the field of EVs serving academia and industries in Hong Kong, mainland and overseas.

(v) Published over 400 papers in learned journals and conference proceedings in various topics of EV technology.

(vi) Authored two monographs in the area of EV technology as shown in Figure 7-13. The *Modern Electric Vehicle Technology* (Oxford University Press, 2001) was the first comprehensive monograph in the field of EV technology, which was highly commended by the Power Engineering Journal – "Their backstage work has been assiduous and careful over the last 20 years. …… Their comprehensive exposition of the technology will form a handy reference: it has the ring of authority". The *Advanced EV Drive Technology* in Chinese (China Machine Press, 2010) was a monograph covering research and development of various EV drive systems with emphasis on advanced energy-efficient motor drives and power electronics, which was highly desired by EV researchers and engineers.

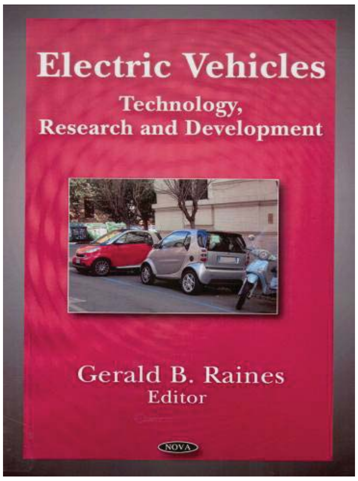
(vii) Wrote two monograph chapters in the area of EV technology as shown in Figure 7-14. The chapter *Electric Motor Drives for Battery, Hybrid and Fuel Cell Vehicles* in *Electric Vehicles: Technology, Research and Development* (Nova Science Publishers, 2009) focused on the latest research and development of electric motor drives for various types of EVs. The chapter *Hybrid Vehicles* in *Alternative Fuels for Transportation* (CRC Press) focused on the research and development of hybrid power trains for different types of HEVs.



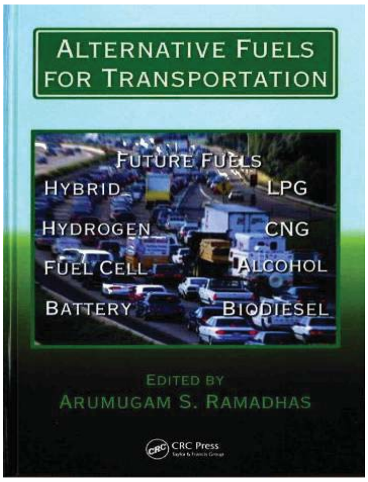
Oxford University Press

China Machine Press

Figure 7-13 Authored books about EVs.



Nova Science Publishers



CRC Press

Figure 7-14 Authored books chapters about EVs.

7.5 Research & Development

Currently, many automobile companies throughout the world accelerate the development of EVs for the coming huge market. It is anticipated that the HEVs will be a practical and sustainable solution for the class of super-ultra-low-emission vehicles (SULEVs), while the BEV and the FCEV will share the market of zero-emission vehicles. In view of the fact that the micro hybrid is virtually a motor-assisted ICEV while the REEV is essentially an engine-assisted BEV, the HEVs will be dominant in the automotive market in the near future.

The research and development trends of EVs are twofold: device integration and system crossover. Two emerging device-integration technologies – namely the integration of magnetic gearing and PM brushless motor drives for BEVs or FCEVs, and the integration of PM brushless motor drives and electric variable transmission for HEVs – are elaborated below.

For BEVs and FCEVs, PM brushless motor drives are very attractive since they inherently offer high power density and high efficiency. In particular, in-wheel PM brushless motor drives can play the role of electronic differential (Chan *et al.*, 2001). As the wheel speed is only about 600 rpm, the in-wheel motor drive is either a low-speed gearless outer-rotor one or a high-speed planetary-geared inner-rotor one. Although the outer-rotor one takes the advantage of gearless operation, its low-speed operation causes bulky size and heavy weight. On the other hand, although the inner-rotor one takes the merits of reduced overall size and weight, the planetary gear inevitably involves transmission loss, acoustic noise and regular lubrication. Recently, magnetic gears are becoming attractive because they inherently offer the merits of high efficiency, reduced acoustic noise and maintenance free. By artfully integrating the magnetic gear into the PM brushless motor drive, the low-speed requirement for direct driving and the high-speed requirement for motor design can be achieved simultaneously (Chau, 2009). Figure 7-15 gives a comparison of the existing planetary-gear inner-rotor topology and the integrative magnetic-geared outer-rotor topology for in-wheel motor drives. This integrative topology not only offers reduced size and weight but also eliminates all drawbacks due to the mechanical gear. The artfulness is the share of the outer rotor of the PM brushless motor and the inner rotor of the magnetic gear.

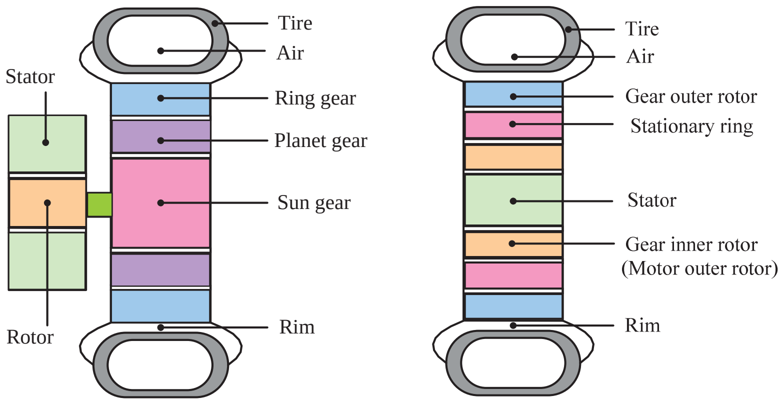
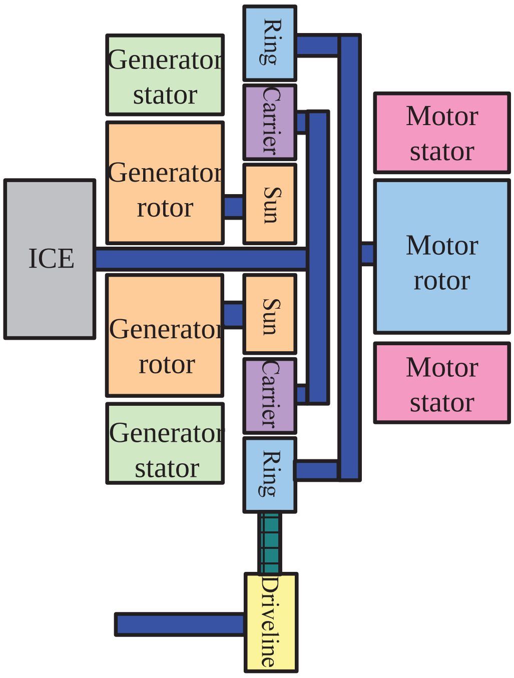
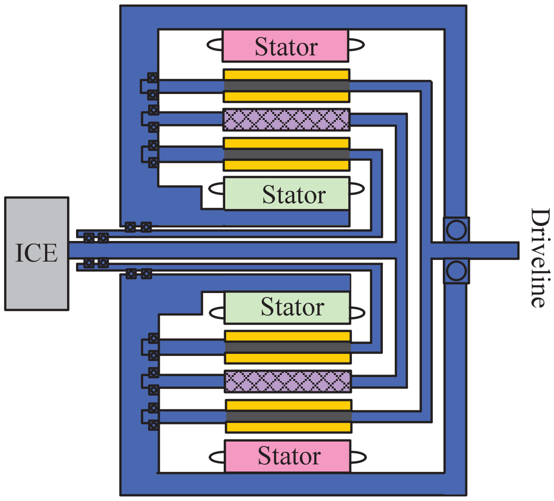


Figure 7-15 Comparison of in-wheel motor drives.

For HEVs, the electric variable transmission (EVT) system functions to perform power splitting of the engine output – one power flow path is mechanically coupled with the motor output and another power flow path is electrically connected with the motor input via power converters (Chau, 2010). Hence, a continuously variable ratio between the engine speed and the wheel speed can be achieved. In the presence of this electronic continuously variable ratio, the engine can always operate at its most energy-efficient operating point, resulting in a considerable reduction of fuel consumption. Figure 7-16 gives a comparison of the existing planetary-geared EVT system which was developed by Toyota for its Prius and the newly developed magnetic-geared EVT system. Both of them adopt the PM brushless motor drive. 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 gears, namely non-contact 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.



Planetary-geared integration



Magnetic-geared integration

Figure 7-16 Comparison of EVT systems.

The vehicle-to-grid (V2G) technology is one of the most emerging system-crossover technologies for EVs. It is a crossover of EVs, power system and information technology. The gridable EV (GEV), which may be a PHEV, REEV or BEV, is no longer a simple transportation means. It can serve as a bidirectional portable power plant for the power grid. Although each GEV can only store or generate a relatively small amount of electrical energy (5-10 kWh for a PHEV, 10-20 kWh for REEV or 20-50 kWh for a BEV) as compared with the whole power grid, a reasonable penetration rate of GEVs (such as 20-40% vehicles are GEVs) will have a significant impact on power system operation. For instance, the V2G has been identified to have two important functions:

(1) 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 use of a battery energy storage system (BESS) can perform the desired efficient and fast backup, this BESS is too expensive and bulky. The V2G technology can fully utilize the batteries installed in GEVs. Namely, when GEVs are parking at their lots, they can provide or sell instantaneous power to the grid so as to backup the intermittent power outage while avoiding the installation of the BESS.

(2) 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.

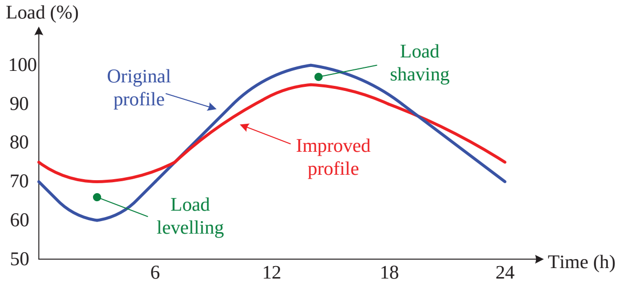


Figure 7-17 Load levelling and load shaving.

As shown in Figure 7-17, the V2G technology can utilize the batteries in GEVs to absorb or buy electrical energy from the grid during the off-peak period (called load levelling), 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.

The key to achieve the aforementioned two functions is the V2G framework. The latest aggregated dual-grid framework is depicted in Figure 7-18 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 GEVs to deal with the ESP and the ISO/RTO. 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.

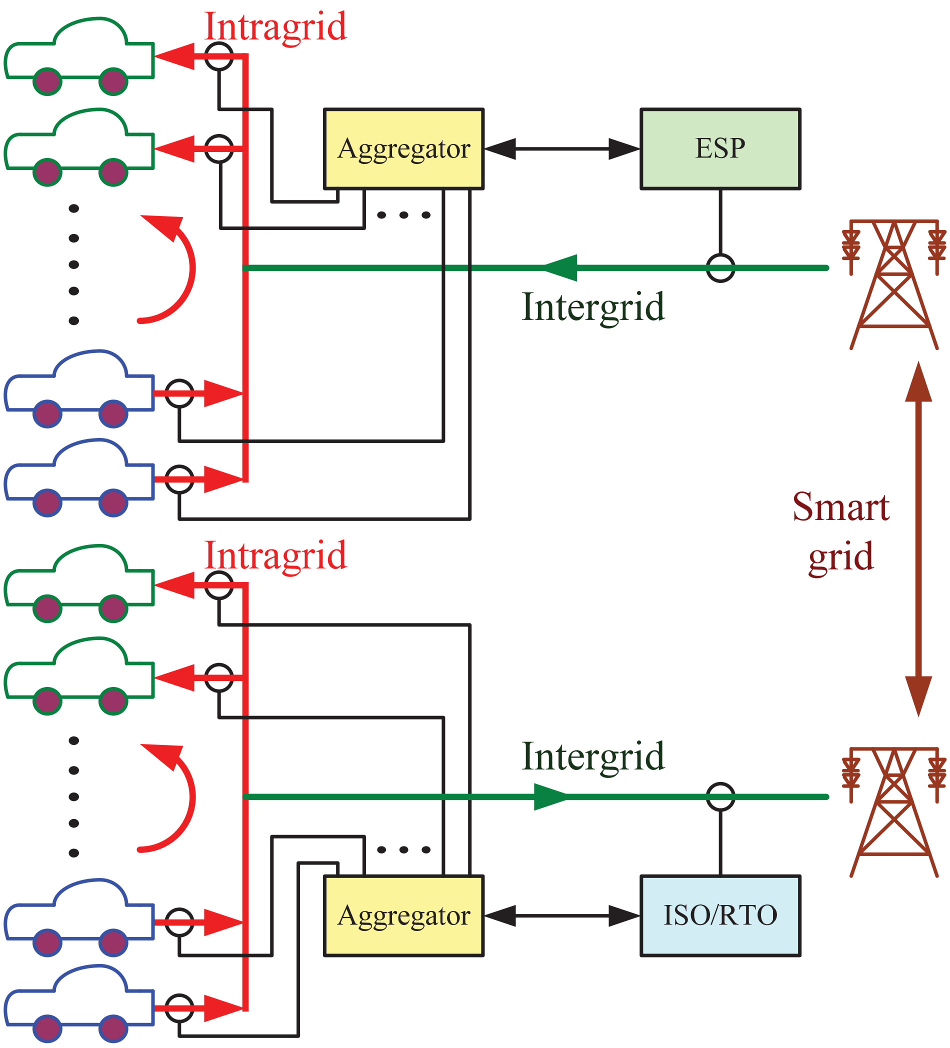


Figure 7-18 Aggregated dual-grid V2G framework

7.6 Vision

Among all types of EVs, the PHEV will be popular in the next five years, whereas the FCEV will not be popular in the next five years unless there is a breakthrough in fuel cell technology. Most vehicles will be sorts of EVs, at least micro hybrid, and the BEV, HEV and FCEV will coexist in future. The V2G energy arbitrage will be the key to further boost the research and development of EVs.

Acknowledgement

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