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The Sate of the Art of Electric Vehicles

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Abstract

In a world where environment protection and energy conservation are growing concerns, the development of electric and hybrid vehicles (EV/HEV) has taken on an accelerated pace. The dream of having commercially viable electric/hybrid vehicles is becoming a reality. EVs and HEVs are gradually available in the market. This article reviews the present status of electric and hybrid vehicles worldwide and their state of the art, with emphasis on the engineering philosophy and key technologies. The importance of the integration of technologies of automobile, electric motor drive, electronics, energy storage and controls, and the importance of the integration of society strength from government, industry, research institutions, electric power utilities and transportation authorities are addressed. The challenge of EV commercialization is discussed.

Keywords

electric and hybrid vehicles, electric propulsion, electric drives

1. INTRODUCTION

Electric vehicle (EV) is a road vehicle which involves with electric propulsion. With this broad definition in mind, electric vehicles may include battery electric vehicles (BEV), hybrid electric vehicle (HEV) and fuel cell electric vehicle (FCEV). Electric vehicle is a multidisciplinary subject which covers broad and complex aspects. However, it has core technologies, namely chassis and body technology, propulsion technology and energy source technology. The article begins with reviewing the status of BEV and HEV, then focusing on the engineering philosophy of EV development. Subsequent to the illustration of the configurations of both BEV and HEV, it discusses rather detail the major technologies, namely the propulsion technology, energy source technology and infrastructure technology. Finally the commercialization aspects are discussed. The conclusion summarizes the state of the art and the challenges of BEV, HEV and FCEV.

Table 1 Characteristics of BEV, HEV and FCEV

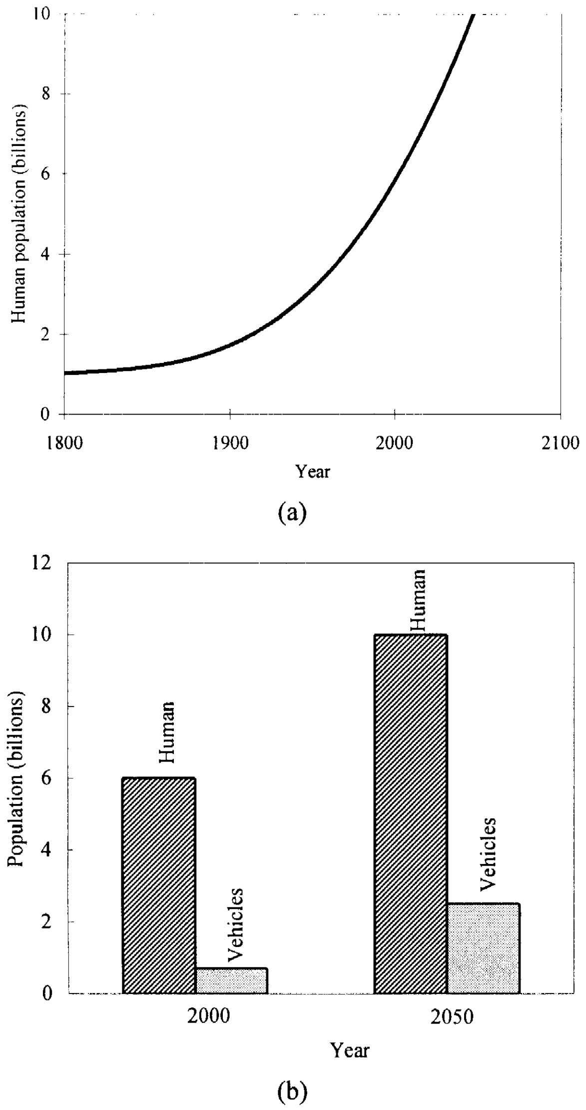
Types of EVs	Battery EVs	Hybrid EVs	Fuel Cell EVs
Propulsion	• Electric motor drives	• Electric motor drives • Internal combustion engines	• Electric motor drives
Energy system	• Battery • Ultracapacitor	• Battery • Ultracapacitor • ICE generating unit	• Fuel cells
Energy source & infrastructure	• Electric grid charging facilities	• Gasoline stations • Electric grid charging facilities (optional)	• Hydrogen • Methanol or gasoline • Ethanol
Characteristics	• Zero emission • Independence on crude oils • 100-200 km short range • High initial cost • Commercially available	• Very low emission • Long driving range • Dependence on crude oils • Complex • Commercially available	• Zero emission or ultra low emission • High energy efficiency • Independence on crude oils • Satisfied driving range • High cost now • Under development
Major issues	• Battery and battery management • High performance propulsion • Charging facilities	• Managing multiple energy sources • Dependent on driving cycle • Battery sizing and management	• Fuel cell cost • Fuel processor • Fueling system

Today BEV, HEV and FCEV are in different stages of development, facing different challenges and require different strategies. In order to assist the readers appreciate the features and issues of these vehicles before reading the whole text, the major characteristics of these three types vehicles are given in Table 1. It can be seen that the critical issue of BEV is the battery. Therefore, BEV is mainly suitable for small EV for short range low speed community transportation, thus requires only smaller battery size. HEV can meet consumers' meet but cost is the major issue. FCEV has long term potential for future main stream vehicles, however the technology is still in early development stage, its cost and refueling system are the major concerns.

2. WHY ELECTRIC VEHICLES?

Let us begin with the investigation of the growth of population and vehicles as shown in Figure 1. In the next 50 years, the global population will increase from 6 billions to 10 billions and the number of vehicles will increase from 700 millions to 2.5 billions. If all these vehicles are propelled by internal combustion engines, where will the oil come from? and where should the emissions be disseminated? Would the sky be permanently grey? The gloomy answers to these questions compel people to strive for sustainable road transportation for the 21st century.

In a world where environmental protection and energy conservation are growing concerns, the development of electric vehicle (EV) technology has taken on an accelerated pace to fulfil these needs. Concerning the environment, EVs can provide emission-free urban transportation. Even taking into account the emissions from the power plants needed to fuel the vehicles, the use of



(a)

(b)

Fig. 1 Growth of population and vehicles

EVs can still significantly reduce global air pollution. From the energy aspect, EVs can offer a secure, comprehensive and balanced energy option that is efficient and environmentally friendly, such as the utilisation of various kinds of the renewable energies. Furthermore, EVs will have the potential to have a great impact on energy, environment and transportation as well as hi-tech promotion, new industry creation and economic development.

3. PAST, PRESENT AND FUTURE OF EVS

3.1 Past years development

EV was invented in 1834. During the last decade of the 19th Century, a number of companies produced EVs in America, Britain, and France. Figure 2 shows the London Electric Cab Company's taxi. Due to the limitation of driving range associated with the batteries and on the other hand the rapid advancement in internal combustion engine (ICE) vehicles, EVs have almost vanished from the scene since 1930.

In the early 1970's, some countries, compelled by the energy crisis, started the rekindling of interests in EVs. In 1976, the USA launched the Electric and Hybrid Vehicle Research, Development and Demonstration Act, Public Law 94-413. At that time, the main question to be answered was "Can EVs do the job in our modern society?", although EVs did work well in the late 1800's and early 1900's. The development of EVs for over years has answered the above question - yes. For example, an experimental EV in 1968 racing from California Institute of Technology (Caltech) to Massachusetts Institute of Technology (MIT) suffered from failures in virtually every critical component; whereas a commercially built EV in 1998 running from Los Angeles to Detroit exhibited a success with no component failures. Within the 1970's, EVs were still in research and development stage, and most of them were conversion of internal combustion engine vehicles (ICEVs). Today, major automobile manufacturers are offering EVs for sale or lease. Most of them are the purpose-built EV, not conversion EV.

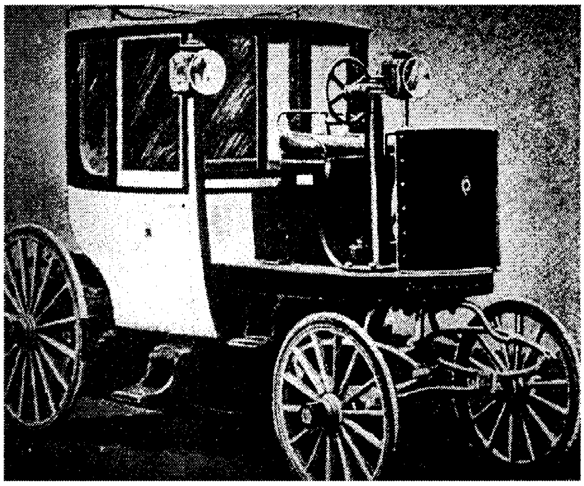


Fig. 2 London Electrical Cab Company's taxi (Courtesy of Scientific American Supplement; Photo courtesy of History of the Electric Automobile by Ernest H. Wakefield)

3.2 Present major issues

At present, the major driving force for EVs is the environment issue, such as mandate by California rule, rather than the previous energy issue. Thus, the main question to be answered becomes "Can EVs be made affordable?". The major factors that make EV affordable are the range and cost. To tackle the range, the development of advanced batteries such as the nickel-metal hydride, zinc/air, lithium-ion, and lithium polymer are in progress. However, since both specific energy and energy density of batteries are much lower than that of gasoline, the development of fuel cells for EVs has taken on an accelerated pace in recent years. Meanwhile, the development of commercial hybrid electric vehicles (HEVs) is also going on rapidly. HEVs essentially improve the range and performance of EVs at higher complexity and cost because of the additional energy source, engine and other accessories. Nevertheless HEVs have added value by optimising the engine and motor systems and providing redundancy. To tackle the cost, efforts are being made to improve various EV subsystems, such as electric motors, power converters, electronic controllers, energy management units, battery chargers, batteries and other EV auxiliaries, as well as EV system level integration and optimisation.

3.3 Development trends

In order to see the development trends of various EV aspects, a survey has been made with respect to the number of papers published on various topics in leading EV related international conferences from 1984 to 2000. With regard to propulsion system, it was observed that the research papers on induction motor drives (IM) and permanent magnet motor drives (PM) are highly dominant, whereas those on DC motor drives (DC) are drooping while those on switched reluctance motor drives (SR) are still in a crawling stage. With regard to the development trend of various energy sources, including lead-acid batteries (LA), nickel-based batteries (NB), lithium-based batteries (LB), fuel cells (FC) and capacitors/flywheels (CF); the number of papers published in LB, FC and CF are becoming more and more attractive, though LA and NB are still undergone continual improvement. With regard to the configurations of EVs, it was observed that the conversion EV is becoming less attractive than the purpose-built EV while the HEV is of growing interests for the coming EV markets. It was also observed that EVs are on the verge of commercialisation, since more and more papers were published on the topics of demonstration as well as standardisation and marketing of EVs.

In the next few decades, it is anticipated that both EVs and HEVs will be commercialised, and they will have their market shares. EVs will be well accepted by some niche markets, namely the users for community transportation, the places where electricity is cheap and ease of access, and the places with zero-emission mandate. EVs can be integrated with the intelligent transportation system to improve the driving range. On the other hand, HEVs will have a niche market for those users desiring long driving ranges. The ultimate penetration of EVs and HEVs will mainly depend on their respective costs. Particularly, the research and development of FCEVs will be accelerated in the next two decades, since they have the good potential to deliver the same range and performance as our ICEVs.

In summary, electric propulsion and energy sources will still be the key technologies to be addressed, EVs and HEVs will still be coexistent, while energy, environment and economy will still be the key issues for EV commercialisation. Figure 3 illustrates the development trends of EVs and HEVs. It should be noted that some core technologies can be shared among ICEVs, EVs and HEVs. Our ultimate goal is the use of clean, efficient and intelligent energy to achieve sustainable transportation system for the 21st century.

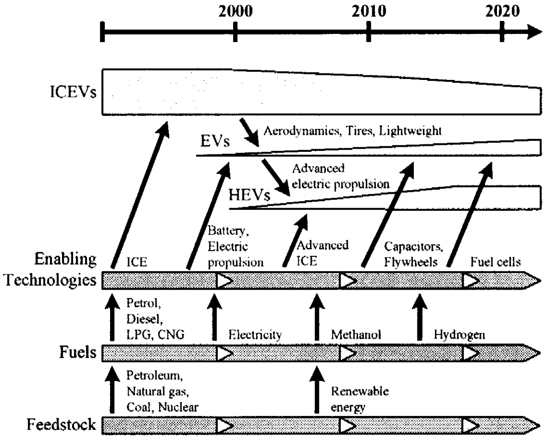


Fig. 3 Development trends of EVs and HEVs (Courtesy of EVAA)

4. PRESENT STATUS

After many years development, EV technologies are becoming mature. Many advanced technologies are employed to extend the driving range and reduce the cost. For examples, the use of advanced induction motor drives and permanent-magnet brushless motor drives to improve the electric propulsion system, the employment of advanced valve-regulated lead-acid (VRLA) battery, nickel-metal hydride (NiMH) battery, lithium-ion (Li-Ion) battery, lithium-polymer battery, fuel cells and ultracapacitors to improve the EV energy source, application of light body technology with light but rigid material, low drag coefficient body to reduce the aerodynamic resistance and low rolling resistance tires to reducing running resistance at low and medium driving speed, as well as the adoption of advanced charging, power steering or variable temperature seats to enhance the EV auxiliaries. In the following paragraphs, some of recently developed EV, HEV and FCEV are illustrated with the intention to show the achievable technology, despite particular vehicle model eg. EV1 has been discontinued, and some models are for demonstration purpose only.

Figure 4 shows an electric vehicle named U2001, which was developed by the University of Hong Kong. It is a four-seater electric car which adopted a 45-kW motor and a 264-V battery pack. This specially designed EV motor could offer high efficiencies over a wide operating range. It also incorporated a number of advanced EV technologies, such as the adoption of thermoelectric variable temperature seats to minimise the energy used for air-conditioning, the use of an a navigation system to facilitate safe and user-friendly driving, and the use of an intelligent energy management system to optimise the energy flow within the vehicle. It is essentially a ECarLab, which serves as a moving laboratory. Its powertrain architecture, types of motor and battery, etc can be changed from time to time depending on the research topics. The objectives of this ECarLab are: (1) to benchmark the energy consumption, emissions and driveability; (2) to research into propulsion systems, control strategies and various energy storage systems; (3) to use as a platform for the development and demonstration of new technologies; and (4) to assess the possible market applications.

Fig. 4 HKU U2001

The world's first mass-production HEV was the Toyota Prius as shown in Figure 5. Its motive power was sourced from both a four-cylinder ICE and a permanent-magnet brushless motor. Since it was an ICE-heavy HEV, a power split device, namely the planetary gear, sent part of the ICE power to the wheels and part to a generator. The generated electrical energy could supply the electric motor to increase the motive power, or could be stored in the 28-module, 21kW, batteries. The Prius could offer an acceleration from zero to 60 mph in 10.5 s, and a fuel economy of 55 mpg for combined city and highway operation. Both of its fuel economy and exhaust emissions were much better than that of any conventional ICEVs.

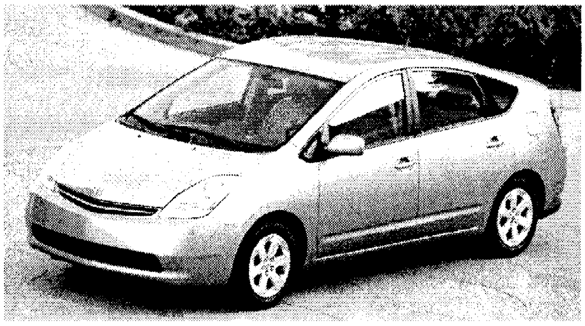


Fig. 5 Toyota Prius

The Honda Insight, shown in Figure 6, went on sale in December 2000. It employed an ICE-heavy hybrid system, combining a three-cylinder ICE (50 kW at 5700 rpm) and a permanent-magnet synchronous motor (10 kW at 3000 rpm). The electric motor was powered by a 144-V nickel-metal hydride battery pack which was recharged by regenerative braking during normal cruising and downhill driving. The Insight was claimed to be the most fuel-efficient HEV with the fuel economy of 60-65 mpg. Also, it satisfied the stringent ultra-low-emission vehicle (ULEV) standard in California.

Fig. 6 Honda Insight

Figure 7 shows the Ford Escape Hybrid. The Ford Escape Hybrid is the first "full" hybrid SUV to be built in North America. It combines near-zero emissions and the fuel economy of a full hybrid-electric system with the go-anywhere capability, toughness and cargo capacity. It adopts 2.3-litre 16 v engine, 70 kW permanent magnet synchronous motor, continously variable transmission, and 330-V nickel metal hydride battery pack.

Fig. 7 Ford Escape Hybrid

Electric and hybrid vehicles have distinct advantages in military applications since they are quiet, excellent dynamic performance, can be designed as four wheel drives, secure, cannot be detected by enemy's heat sensor, etc. Therefore they can be converted to military applications as shown in Figure 8.

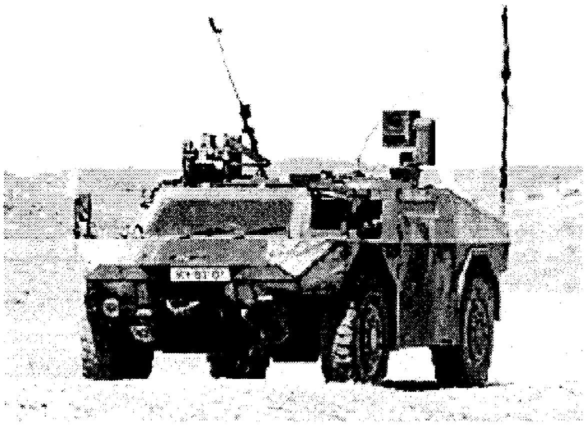


Fig. 8 Hybrid electric vehicles for military applications (Source: TNO)

Figure 9 shows the GM Hy-wire concept vehicle. It combines fuel cell and by-wire technology. The fuel cell propulsion system, and the by-wire acceleration, steering and braking controls are entirely housed in a flat, skateboard-like chassis. With no engine, steering column or other conventional vehicle components.

Fig. 9 GM hy-wire concept vehicle

5. ENGINEERING PHILOSOPHY OF EV DEVELOPMENT

5.1 EV concept

Although the EV was around before the turn of the 20th century, the modern EV is a completely new machine that is totally different from the classical EV. It is not only a transportation vehicle, but also a new type of electric equipment. The modern EV concept is summarised as follows.

(1) The EV is a road vehicle based on modern electric propulsion which consists of the electric motor, power converter and energy source, and it has its own distinct characteristics.
(2) The EV is not just a car but a new system for our society, realising clean and efficient road transportation.
(3) EV users' expectations must be studied, hence appropriate education must be conducted.

The system architecture of EVs has its own distinct features which may different from that of ICEVs, similar to the fact that the system architecture of quartz-based electronic watches is very different from that of spring-based mechanical watches. In short, their appearances are very similar whereas their principles are very different. The unique features of EVs must be fully appreciated.

5.2 EV engineering philosophy

The EV engineering philosophy essentially is the integration of automobile engineering and electrical engineering. Thus, system integration and optimisation are prime considerations to achieve good EV performance at affordable cost. Since the characteristics of electric propulsion are fundamentally different from those of engine propulsion, a novel design approach is essential for EV engineering. Moreover, advanced energy sources and intelligent energy management are key factors to enable EVs competing with ICEVs. Of course, the overall cost effectiveness is the fundamental factor for the marketability of EVs.

The design approach of modern EVs should include state-of-the-art technologies from automobile engineering, electrical and electronic engineering and chemical engineering, should adopt unique designs particularly suitable for EVs, and should develop special manufacturing techniques particularly suitable for EVs. Every effort should be made to optimise the energy utilisation of EVs. The following points are those typical considerations for EV design:

(1) Identify the niche market and environment.
(2) Determine the technical specifications including the driving cycle.
(3) Determine the infrastructure required including the recycling of batteries.
(4) Determine the overall system configuration - BEV, HEV or FCEV configurations.
(5) Determine the chassis and body.
(6) Determine the energy source - generation or storage, single or hybrid.
(7) Determine the propulsion system - motor, converter and transmission types, single or multiple motors, gearless or geared, mounting methods, and ICE systems in case of an HEV.
(8) Determine the specifications of electric propulsion

(power, torque, speed) and energy source (capacity, voltage, current) according to various driving cycles; for example, Figure 10 shows that the torque-speed requirement of Federal Urban Driving Schedule (FUDS) is very different from that of Federal Highway Driving Schedule (FHDS). In the figure, the density of dots represents the frequency of operating condition. Hence, in FUDS, the powertrain often operates at low speed, high torque; while in FHDS, it operates at high speed, low torque profile.

(9) Adopt intelligent energy management system.

(10) Analyse the interaction of EV subsystems by using the quality function matrix as shown in Figure 11, hence understanding the degree of interaction that affects the cost, performance and safety.

(11) Optimise the efficiency of the motor drive according to the selected driving pattern and operating conditions.

(12) Optimise the overall system using computer simulation.

It should be noted that there are a number of design and safety issues which are distinctive to electric vehicles, both because of the necessity of conserving battery energy for propelling the vehicle and because of its special characteristics. These include the provision of heating and air-conditioning subsystems, the maintenance of the auxiliary power subsystems, the special requirements for the braking, suspension and wheel systems and the safety of batteries, connectors and other electrical systems in the vehicle.

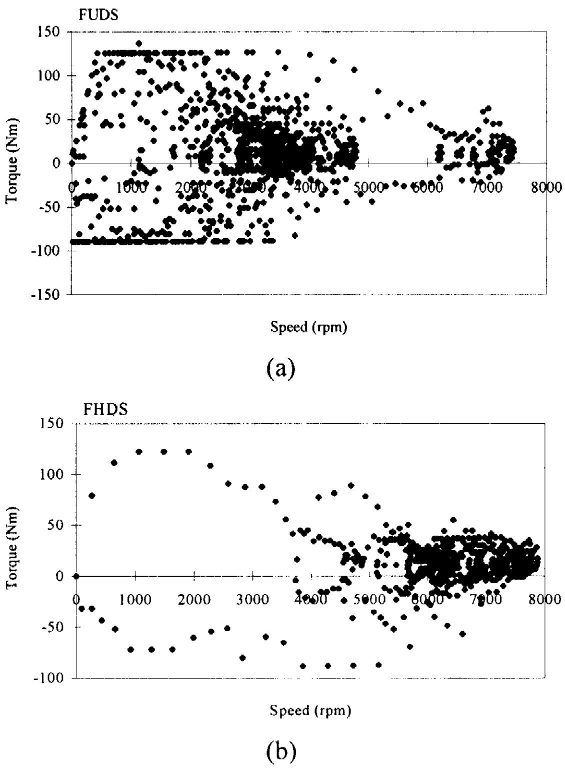


Fig. 10 Torque-speed requirements of typical driving cycles

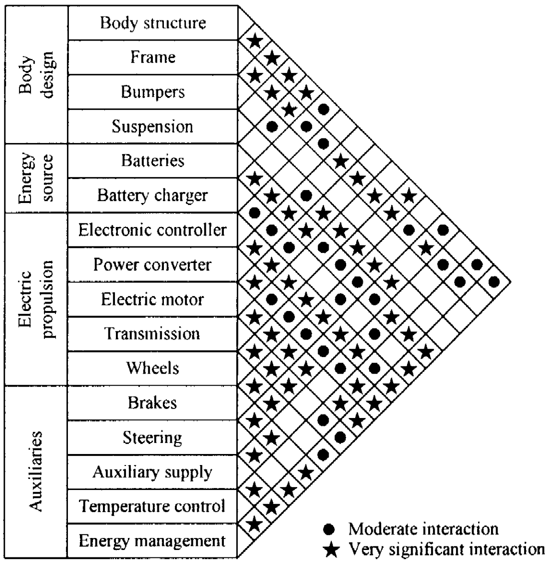


Fig. 11 Interactions among EV sybsystems

5.3 Key EV technology

The key technologies of EVs include automotive technology, electrical technology, electronic technology, information technology and chemical technology. Although the energy source is the most crucial area, body design, electric propulsion, energy management and system optimisation are equally important. In fact, the integration of all these areas is the key to success. For the ease of editing, only body design, energy management and system optimisation technologies are discussed in this section. While the major technologies of electric propulsion and energy source will be discussed separately in the subsequent sections.

5.3.1 Body design

There are two basic approaches for producing EVs - either conversion or purpose-built. For the conversion EV, the engine and associated equipment of an existing ICEV are replaced by the electric motor, power converter and battery. This offers some economy for a small volume production because the existing ICEV chassis can be utilised. However, in most conversions, the resulting EV suffers from a greater curb weight, a higher centre of gravity and an unbalanced weight distribution. Therefore, this approach is gradually fading out. At present, the modern EVs are mostly purpose-built, sometimes called ground-up design. This purpose-built EV takes the definite advantage over the conversion ones because they allow the engineers having the flexibility to coordinate and integrate various EV subsystems so that they can work together efficiently.

There are some design concepts for purpose-built EVs so that the overall performances such as range, gradeability, acceleration and top speed can be improved. These concepts include the consistent weight-saving design, low drag coefficient body design, and low rolling resistance concept. Firstly, the vehicle weight directly affects the performance of EVs, especially the range and gradeability. To reduce the curb weight, the use of lightweight materials such as aluminium and composite material for the body and chassis can be adopted. Secondly, low drag coefficient body design can effectively reduce the vehicle aerodynamic resistance, which has a significant effect on extending the range of EVs in highway driving or cruising. In general, the aerodynamic resistance can be reduced by tapering front and rear ends, adopting undercover and flat under-floor design, optimising airflow around the front and rear windows, using rear spats, providing airflow streaks along the front and rear tires, and employing slanted front nose design. Thirdly, low rolling resistance tires are particularly effective in reducing running resistance at low and medium driving speeds, and play an important role in extending the range of EVs in city driving. This can be achieved through the use of a newly developed blended tire polymer, together with an increase in tire pressure. The mass and the position of the mass centre are very important design parameters. The most important design principle of EV is to minimize the vehicle mass while to satisfy the required vehicle performance and safety. As the vehicle weight increases 1 kg, the energy consumption would increase 5-10 Wh. For every kilogram of payload, it needs at least 0.3 kg supporting structure. The position of mass centre will directly effect the vehicle stability, smoothness and braking characteristics. If the position of mass centre is too high, the vehicle will be unstable, particularly when cornering.

5.3.2 Energy management

Compared with ICEVs, EVs offer a relatively short driving range. Thus, in order to maximise the utilisation of on-board stored energy, an intelligent energy management system (EMS) needs to be adopted. Making use of sensory inputs from various EV subsystems, including sensors for temperatures of outside and inside air, current and voltage of the energy source during charging and discharging, current and voltage of the electric motor, vehicle speed and acceleration as well as external climate and environment, the EMS can realise the following functions:

(1) Optimise the system energy flow.
(2) Predict the remaining available energy and hence the residual driving range.
(3) Suggest more efficient driving behaviour.
(4) Direct regenerative energy from braking to receptive energy sources such as batteries.
(5) Modulate temperature control in response to external climate.
(6) Adjust lighting brightness in response to external environment.
(7) To propose a suitable battery charging algorithm.
(8) Analyse the operation history of the energy source, especially the battery.
(9) Diagnose any incorrect operation or defective components of the energy source.

Figure 12 shows the block diagram of energy management system. When the EMS is coupled with a navigation system, it can plan energy efficient routes, locate charging facilities for extended trips, and modify range predictions on the basis of traffic conditions. In summary, the EMS has the distinct features of integrated multi-functions, flexibility and adaptability (just like the brain of EVs) such that the limited on-board energy can be used wisely.

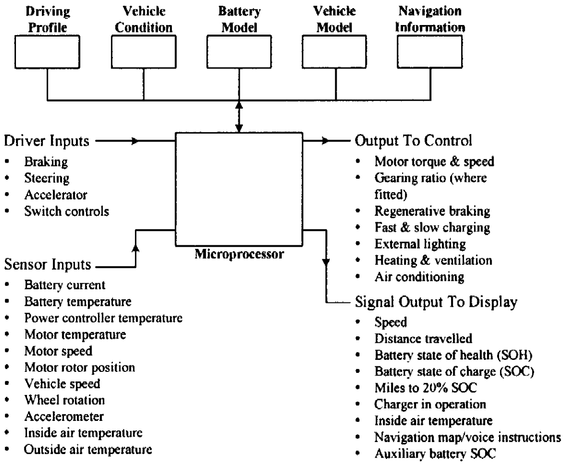


Fig. 12 Block diagram of energy management system (Source: The Electric Car, The Institute of Electrical Engineers)

5.3.3 System optimisation

As mentioned before, the EV system has a complex architecture that contains multidisciplinary technologies. Since the EV performance can be affected by many multidisciplinary interrelated factors, computer simulation is the most important technology to carry out the optimisation for performance improvement and cost reduction. Also, EV simulation can help those manufacturers to minimise prototyping cost and time, and to provide rapid concept evaluation. Since the whole EV system consists of various subsystems clustered together by mechanical link, electrical link, control link and thermal link, the simulation should be based on the concept of mixed-signal simulation. Hence, the system optimisation can be carried out in the system level in which there are many trade-offs among various subsystem criteria. Generally, numerous iterative processes are involved for the preferred system criteria.

In summary, the system-level simulation and optimisation of EVs should consider the following key issues:

(1) As the interactions among various subsystems greatly affect the performance of EVs, the significance of those interactions should be analysed and taken into account.

(2) As the model accuracy is usually coherent with the model complexity but may be contradictory to the model usability, trade-offs among the accuracy, complexity and usability as well as simulation time should be considered.

(3) As the system voltage generally causes contradictory issues for EV design, including the battery weight (higher voltage requires higher number of battery modules in series, hence more weight for the battery case), motor drive voltage and current ratings, acceleration performance, driving range and safety, it should be optimised on the system level.

(4) In order to increase the driving range, multiple energy sources may be adopted for modern EVs. The corresponding combination and hybridisation ratio should be optimised on the basis of the vehicle performance and cost.

(5) Since EVs generally adopt fixed gearing, the gear ratio can greatly affect the vehicle performance and driveability. An optimal ratio should be determined through iterative optimisation under different driving profiles.

6. EV AND HEV CONFIGURATIONS

6.1 EV configurations

Compared with the ICEV, the configuration of the EV is rather flexible. This flexibility is due to several factors unique to the EV. Firstly, the energy flow in the EV is mainly via flexible electrical wires rather than rigid & mechanical links. Thus, the concept of distributed subsystems in the EV is really achievable. Secondly, different EV propulsion arrangements involve a significant difference in the system configuration. Thirdly, different EV energy sources (such as batteries and fuel cells) have different characteristics and different refueling systems.

Figure 13 shows the composition of the EV, consisting of three major subsystems - electric propulsion, energy source and auxiliary. The electric propulsion subsystem comprises the electronic controller, power converter, electric motor, mechanical transmission and driving wheels. The energy source subsystem involves the energy source, energy management unit and energy refuelling unit. The auxiliary subsystem consists of the power steering unit, temperature control unit and auxiliary power supply. In the figure, a mechanical link is represented by a double line, an electrical link by a thick line and a control link by a thin line. The arrow on each line denotes the direction of electrical power flow or control information communication. Based on the control inputs from the brake and accelerator pedals, the electronic controller provides proper control signals to switch on or off the power devices of the power converter which functions to regulate power flow between the electric motor and energy source. The backward power flow is due to regenerative braking of the EV and this regenerative energy can be stored provided that the energy source is receptive. Notice that most available EV batteries (except some metal/air batteries) as well as capacitors and flywheels readily accept regenerative energy. The energy management unit cooperates with the electronic controller to control regenerative braking and its energy recovery. It also works with the energy refuelling unit to control refuelling and to monitor usability of the energy source. The auxiliary power supply provides the necessary power with different voltage levels for all EV auxiliaries, especially the temperature control and power steering units.

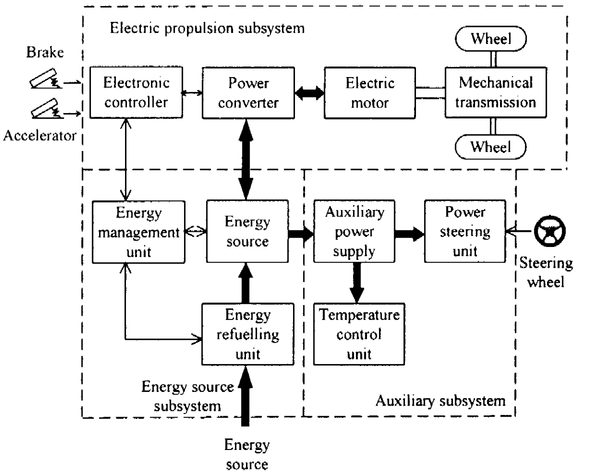


Fig. 13 EV composition

At present, there are many possible EV configurations due to the variations in electric propulsion and energy sources. Focusing on those variations in electric propulsion, there are six typical alternatives as shown in Figure 17:

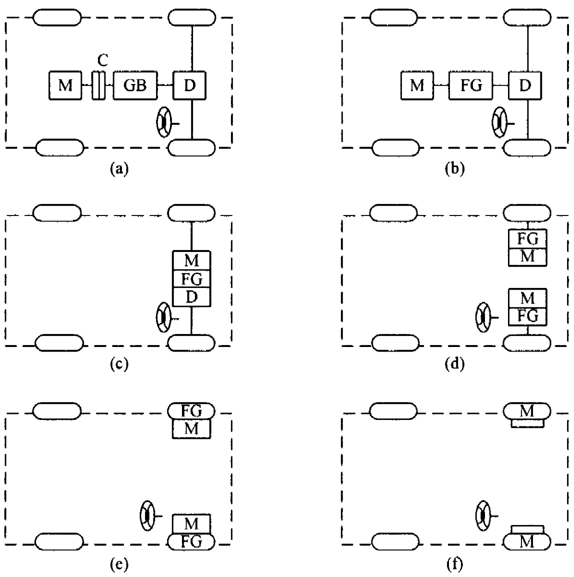
(1) Figure 14 (a) shows the first alternative which is a direct extension of the existing ICEV adopting longitudinal front-engine front-wheel drive. It consists of an electric motor, a clutch, a gearbox and a differential. By incorporating both clutch and gearbox, the driver can shift the gear ratios and hence the torque going to the wheels. The wheels have high

torque low speed in the lower gears and high speed low torque in the higher gears. The differential is a mechanical device which enables the wheels to be driven at different speeds when cornering - the outer wheel covering a greater distance than the inner wheel. This configuration was mostly used in conversion type of EVs to maximize utilization of existing components. However, this configuration usually cannot achieve the optimization among weight, performance and cost.

(2) By replacing the gearbox with fixed gearing and hence removing the clutch, both the weight and size of the mechanical transmission can be greatly reduced. Figure 14 (b) shows this arrangement which consists of an electric motor, fixed gearing and a differential. Notice that this EV configuration is not suitable for the ICEV as the engine by itself, without the clutch and gearbox, cannot offer the desired toque-speed characteristics.

(3) Similar to the concept of transverse front-engine front-wheel drive of the existing ICEV, the electric motor, fixed gearing and differential are integrated into a single assembly, while both axles point at both driving wheels. Figure 14 (c) show this configuration which is in fact most commonly adopted by modern EVs.

(4) Besides the mechanical means, the differential action of an EV when cornering can be electronically provided by two electric motors operating at different speeds. Figure 14 (d) shows this dual-motor configuration in which two electric motors separately drive the driving wheels via fixed gearing.



C : Clutch
D : Differential
FG : Fixed gearing
GB : Gearbox
M : Electric motor

Fig. 14 EV configuration due to variations in electric propulsion

(5) In order to further shorten the mechanical transmission path from the electric motor to the driving wheel, the electric motor can be placed inside a wheel. This arrangement is the so-called in-wheel drive. Figure 14 (e) shows this configuration in which fixed planetary gearing is employed to reduce the motor speed to the desired wheel speed. It should be noted that planetary gearing is favoured in this arrangement since it offers the advantages of a high speed-reduction ratio as well as an in-line arrangement of input and output shafts.

(6) By fully abandoning any mechanical gearing, the in-wheel drive can be realised by installing a low-speed outer-rotor electric motor inside a wheel. Figure 14 (f) shows this gearless arrangement in which the outer rotor is directly mounted on the wheel rim. Thus, speed control of the electric motor is equivalent to the control of the wheel speed and hence the vehicle speed.

The selection of the above configurations mainly depends on the size and application of EVs, the major criteria for selection are compactness, performance, weight and cost. Presently, the popular configurations are Figure 14 (b) or (c), where configuration Figure 14 (e) or (f) have been used for demonstration or small scale production.

6.2 HEV configurations

What exactly is a HEV? The definition available is so general that it anticipates future technologies of energy sources. As proposed by Technical Committee 69 (Electric Road Vehicles) of the International Electrotechnical Commission, a HEV is a vehicle in which propulsion energy is available from two or more kinds or types of energy stores, sources or converters, and at least one of them can deliver electrical energy. Based on this general definition, there are many types of HEVs, such as the gasoline ICE & battery, diesel ICE & battery, battery & fuel cell, battery & capacitor, battery & flywheel, and battery & battery hybrids. However, the above definition is not well accepted. Ordinary people have already borne in mind that a HEV is simply a vehicle having both an ICE and electric motor. To avoid confusing readers or customers, specialists also prefer not using the HEV to represent a vehicle adopting energy source combinations other than the ICE & battery hybrid. For examples, they prefer to call a battery & fuel cell HEV simply as a fuel cell EV and a battery & capacitor HEV as an ultracapacitor-assisted EV. As we prefer general perception to loose definition, the term HEV in this paper refers only to the vehicle adopting the ICE and electric motor.

The major challenges for HEV design are managing multiple energy source, highly dependent on driving cycles, battery sizing and battery management. HEVs take the advantages of electric drive to compensate the inherent weakness of ICE, namely: (1) to avoid idling, (2) to increase the ICE efficiency and reduce emission during starting and low speed operation, (3) to increase the ICE efficiency and reduce emission at high speed operation, and (4) to use regenerative braking instead of mechanical braking during deceleration and down slope driving. Figure 15 shows the relationship between the battery capacity and emissions.

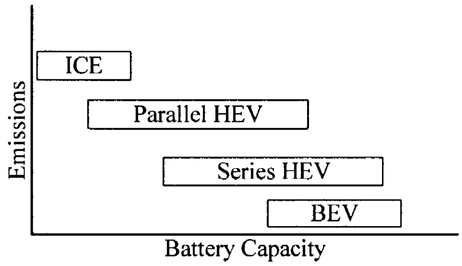


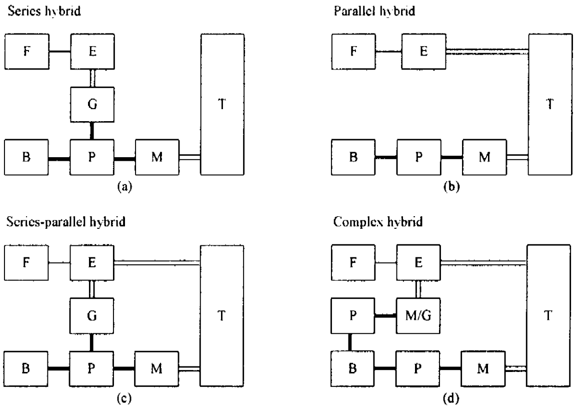
Fig. 15 Battery capacity versus emssions

HEV can meet customers' need but cost is the major issue. Therefore, with some incentives from governments to reduce initial cost burden, HEV may have substantial share in mainstream automobile production.

Traditionally, HEVs were classified into two basic kinds - series and parallel. Recently, with the introduction of some HEVs offering the features of both the series and parallel hybrids, the classification has been extended to three kinds - series, parallel and series-parallel. It is interesting to note that some newly introduced HEVs cannot be classified into these three kinds. Hereby, HEVs are newly classified into four kinds:

(1) series hybrid,
(2) parallel hybrid,
(3) series-parallel hybrid, and
(4) complex hybrid.

Figure 16 shows the corresponding functional block diagrams, in which the electrical link is bidirectional, the hydraulic link is unidirectional and the mechanical link (including the clutches and gears) is also bidirectional. It can be found that the key feature of the series hybrid is to couple the electric power from the ICE/generator and the battery, together to supply the electric motor to propel the wheels to meet the demand of the vehicle, whereas the key feature of the parallel hybrid is to couple the mechanical power from the ICE and the electric motor to propel the wheels to meet the demand of the vehicle. The series-parallel hybrid is a direct combination of both the series and parallel hybrids. On top of the series-parallel hybrid operation, the complex hybrid can offer additional and versatile operating modes. Figure 17 shows the energy flow of HEVs.



B : Battery
E : ICE
F : Fuel tank
G : Generator
M : Motor
P : Power converter
T : Transmission (including brakes, clutches and gears)

▬ Electrical link
— Hydraulic link
═ Mechanical link

Fig. 16 Classification of HEVs

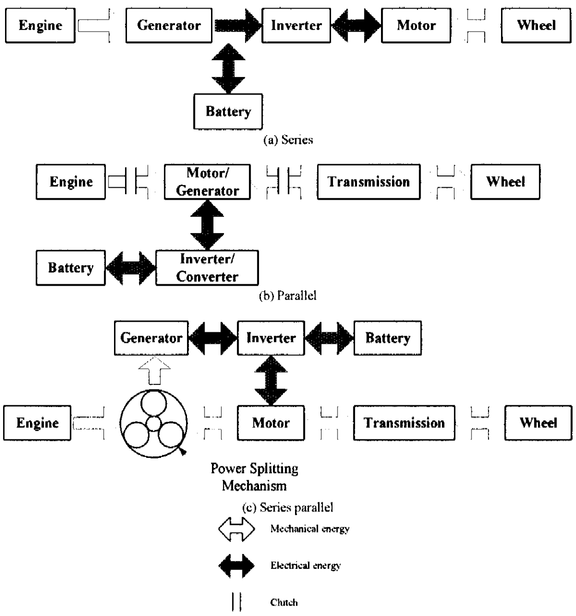


Fig. 17 Energy flow of HEVs

6.2.1 Series hybrid system

The series hybrid is the simplest kind of HEV. Its ICE mechanical output is first converted into electricity using a generator. The converted electricity either charges the battery or can bypass the battery to propel the wheels via the same electric motor and mechanical transmission. Conceptually, it is an ICE-assisted EV which aims to extend the driving range comparable with that of the ICEV. It combines the electric power from ICE/generator and battery then convert to mechanical power to meet the power demand of the vehicle. Due to the decoupling between the engine and the driving wheels, it has the definite advantage of flexibility for locating the ICE-generator set. Although it has an added advantage of simplicity of its drivetrain, it needs three propulsion devices - the ICE, the generator and the electric motor, therefore the efficiency of series HEV is generally lower. Another disadvantage is that all these propulsion devices need to be sized for the maximum sustained power if the series HEV is designed to climb a long grade, making series HEV expensive. On the other hand, when it is only needed to serve such short trips as commuting to work and shopping, the corresponding ICE-generator set can adopt a lower rating.

6.2.2 Parallel hybrid system

Differing from the series hybrid, the parallel HEV allows both the ICE and electric motor to deliver power in parallel to drive the wheels, thus combining mechanical power through gearbox. Hence, it may need continuous variable transmission (CVT). Since both the ICE and electric motor are generally coupled to the drive shaft of the wheels via two clutches, the propulsion power may be supplied by the ICE alone, by the electric motor or by both. Conceptually, it is inherently an electric assisted ICEV for achieving lower emissions and fuel consumption. The electric motor can be used as a generator to charge the battery by regenerative braking or absorbing power from the ICE when its output is greater than that required to drive the wheels. Better than the series HEV, the parallel hybrid needs only two propulsion devices - the ICE and the electric motor. Another advantage over the series case is that a smaller ICE and a smaller electric motor can be used to get the same performance until the battery is depleted. Even for long-trip operation, only the ICE needs to be rated for the maximum sustained power while the electric motor may still be about a half.

6.2.3 Series-parallel hybrid system

In the series-parallel hybrid, the configuration incorporates the features of both the series and parallel HEVs, but involving an additional mechanical link compared with the series hybrid, and also an additional generator compared with the parallel hybrid. Although possessing the advantageous features of both the series and parallel HEVs, the series-parallel HEV is relatively more complicated and costly. Nevertheless, with the advances in control and manufacturing technologies, some modern HEVs prefer to adopt this system.

6.2.4 Complex hybrid system

As reflected by its name, this system involves a complex configuration which cannot be classified into the above three kinds. As shown in Figure 19(d), the complex hybrid seems to be similar to the series-parallel hybrid, since the generator and electric motor are both electric machinery. However, the key difference is due to the directional power flow of the electric motor in the complex hybrid and the unidirectional power flow of the generator in the series-parallel hybrid. This bidirectional power flow can allow for versatile operating modes, especially the three propulsion power (due to the ICE and two electric motors) operating mode which cannot be offered by the series-parallel hybrid. Similar to the series-parallel HEV, the complex hybrid suffers from higher complexity and costliness. Nevertheless, some newly introduced HEVs adopt this system for dual-axle propulsion.

6.2.5 Power flow control

Due to the variations in HEV configurations, different power control strategies are necessary to regulate the power flow to or from different components. These control strategies aim to satisfy a number of goals for HEVs. There are four key goals:

(1) maximum fuel economy,
(2) minimum emissions,
(3) minimum system costs, and
(4) good driving performance.

The design of power control strategies for HEVs involves different considerations. Some key considerations are summarized below:

(1) Optimal ICE operating point. The optimal operating point on the torque-speed plane of the ICE can be based on the maximization of fuel economy, the minimization of emissions, or even a compromise between fuel economy and emissions.
(2) Optimal ICE operating line. In case the ICE needs to deliver different power demands, the corresponding optimal operating points constitute an optimal operating line. Figure 21 shows a typical optimal operating line of an ICE, in which the optimization is based on the minimum fuel consumption which is equivalent to the maximum fuel economy.
(3) Optimal ICE operating region. The ICE has a preferred operating region on the torque-speed plane, in which the fuel efficiency remains optimum.
(4) Minimum ICE dynamics. The ICE operating speed needs to be regulated in such a way that any fast fluctuations are avoided, hence minimizing the ICE dynamics.
(5) Minimum ICE speed. When the ICE operates at low speeds, the fuel efficiency is very low. The ICE should be cut off when its speed is below a threshold

value.

(6) Minimum ICE turn-on time. The ICE should not be turned on and off frequently; otherwise, it results in additional fuel consumption and emissions. A minimum turn-on time should be set to avoid such drawbacks.

(7) Proper battery available. The battery available capacity needs to be kept at a proper level so that it can provide sufficient power for acceleration and can accept regenerative power during braking or downhill. When the battery available capacity is too high, the ICE should be turned off. When the available capacity is too low, the ICE should increase its output to charge the battery as fast as possible.

(8) Safety battery voltage. The battery voltage may be significantly altered during discharging, generator charging or regenerative charging. This battery voltage should not be over-voltage or under-voltage; otherwise, the battery may be permanently damaged, therefore battery management is critical issue.

(9) Relative distribution. The distribution of power demand between the ICE and battery can be optimized during the driving cycle.

(10)Geographical policy. In certain cities or areas, the HEV needs to be operated in the pure electric mode. The changeover should be controlled manually or automatically.

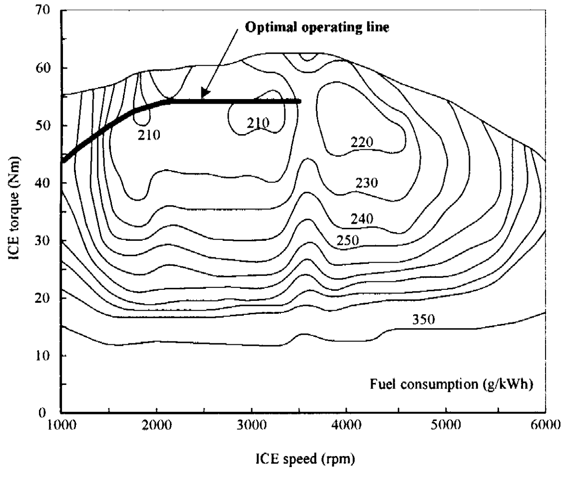
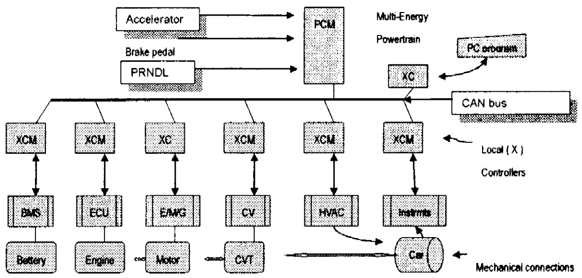


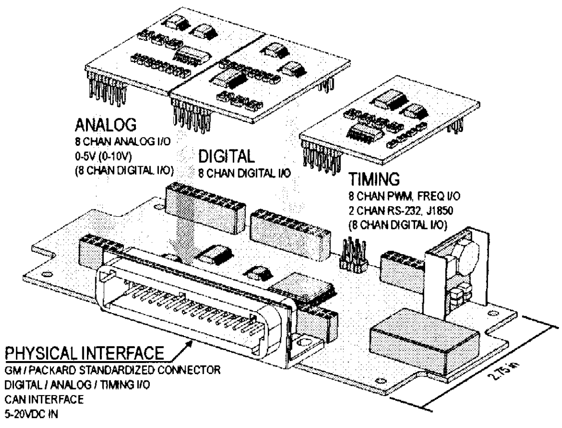
Fig. 18 Optimal operating line on an ICE fuel consumption map

6.2.6 Multi-energy powertrain control

In HEVs, it is essential to have multi-energy powertrain control with effective control algorithm. The control system is implemented through CAN (Controller Area Network) bus to reduce wires while increasing reliability. Figure 19 shows the block diagram and the hardware of coordinated multi-energy powertrain control system.



(a) Block diagram



(b) Controller hardware

Fig. 19 Block diagram of coordinated multi-energy powertrain control system
(Source: A. Burke: Plug-In HEV)

6.2.7 Advanced HEV system performance

Figure 20 shows a new parallel hybrid HEV system. This HEV system not only possesses the features of the parallel hybrid, but also incorporates a unique advantage of the series hybrid (namely the ICE can independently operate at the mode of minimum fuel consumption). The key is to employ a planetary gear which offers two degrees of freedom for mechanical transmission.

In city driving, the HEV system is characterized by the features of a parallel hybrid and the advantage of a series hybrid. When the vehicle is at full-throttle acceleration, the power is simultaneously delivered by the ICE and electric motor. While the vehicle at normal driving (steady speed operation), the power is collaboratively fed by the ICE and electric motor via the planetary gear with two degrees of freedom in such a way that the fuel consumption of the ICE is minimum. This means that the ICE operates at minimum torque and power, and the majority of power is supplied by the electric motor.

During regenerative braking, the planetary gear operation is reduced to one degree of freedom by disconnecting the clutch and braking the sun gear shaft. Thus, the kinetic energy is converted to electrical energy and hence

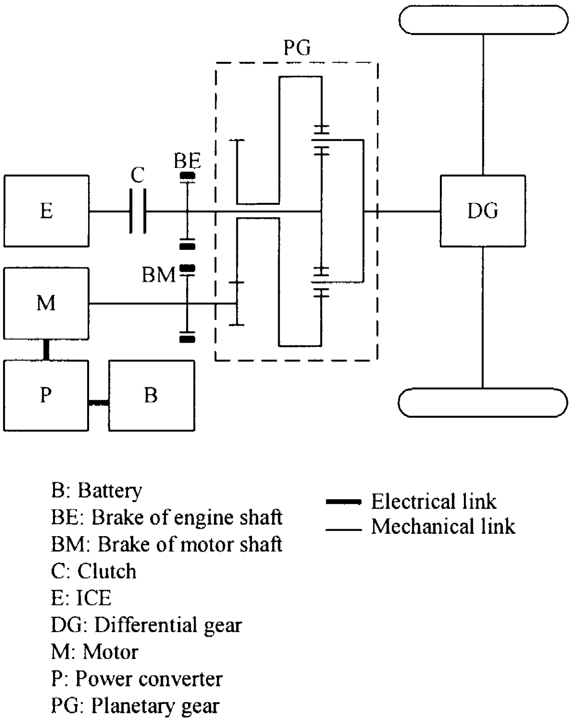


Fig. 20 New HEV system with planetary gear (Courtesy of A. Szumanowski)

recharges the battery while the electric motor operates as an generator.

During suburb driving, the HEV operates as an ICEV. In this case, the electric motor is switched off and the ring gear shaft is braked, which means that the planetary gear operation is also reduced to one degree of freedom.

The power distribution using planetary gearing provides the merits of significant torque and power stabilization of ICE operation, hence achieving high efficiency of the whole HEV system.

7. ELECTRIC PROPULSION

7.1 General Consideration

The electric propulsion system is the heart of EV. It consists of the motor drive, transmission device and wheels. The transmission device sometimes is optional. In fact, the motor drive, comprising of the electric motor, power converter and electronic controller, is the core of the EV propulsion system. The major requirements of the EV motor drive are summarised as follows:

(1) High instant power and high power density.
(2) High torque at low speeds for starting and climbing, as well as high power at high speed for cruising.
(3) Very wide speed range including constant-torque and constant-power regions.
(4) Fast torque response.
(5) High efficiency over wide speed and torque ranges.
(6) High efficiency for regenerative braking.
(7) High reliability and robustness for various vehicle operating conditions.
(8) Reasonable cost.

The choice of electric propulsion systems for EVs mainly depends on three factors - driver expectation, vehicle constraint and energy source. The driver expectation is defined by a driving profile which includes the acceleration, maximum speed, climbing capability, braking and range. The vehicle constraint depends on the vehicle type, vehicle weight and payload. The energy source relates with batteries, fuel cells, capacitors, flywheels and various hybrid sources. Thus, the process of identifying the preferred features and packaging options for electric propulsion has to be carried out at the system level. The interactions between subsystems and those likely impacts of system trade-offs must be examined.

The development of electric propulsion systems has been based on the growth of various technologies, especially electric motors, power electronics, microelectronics and control strategies. Figure 21 shows EV propulsion system overview, including the possible types of motor, computer aided design methodology, power converter devices/topology, control hardware, software and strategy. Toady, with regards to motor technology, CAD FEM analysed induction motors and PM brushless motors are most favourable. With regard to power converter technology, PWM/IGBT inverters are most popular. With regard to control technology, microprocessor or DSP based vector controls are very common.

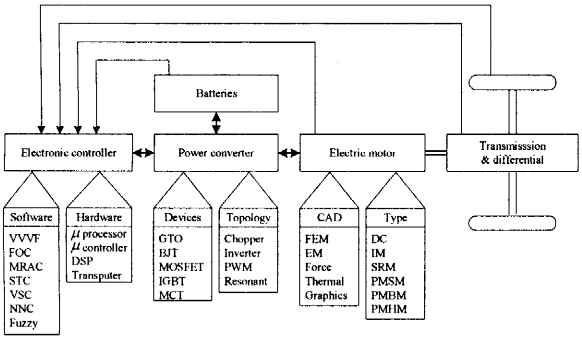
Traditionally, DC motors have ever been prominent in electric propulsion because their torque-speed characteristics well suit traction requirement and their speed controls are simple. However DC motor has commutator hence it requires regular maintenance. Recently, technological developments have pushed commutatorless motors to a new era, leading to take the advantages of higher efficiency, higher power density, lower operating cost, more reliable and maintenance-free over DC motors. As high reliability and maintenance-free operation are prime considerations for electric propulsion in EVs, commutatorless motors are becoming attractive. Induction motors are a widely accepted commutatorless motor type for EV propulsion because of their mature, high reliability and free from maintenance. Alternatively, permanent magnet (PM) brushless motors are also promising because they use PM to produce the magnetic field, hence higher efficiency and higher power density can be achieved. Switched reluctance (SR) motors also have potential because their simple and robust construction. Table 2 shows the application of different types motors for major EVs. The evaluation of EV motors is shown in Table 3, a point grading system is adopted. The grad-

Table 2 Applications of EV motors

EV models	EV motors
Fiat Panda Elettra	Series dc motor
Mazda Bongo	Shunt dc motor
Conceptor G-Van	Separately excited dc motor
Suzuki Senior Tricycle	PM dc motor
Fiat Seicento Elettra	Induction motor
Ford Th!nk City	Induction motor
GM EV1	Induction motor
Honda EV Plus	PM brushless motor
Nissan Altra	PM brushless motor
Toyota RAV4	PM brushless motor
Chloride Lucas	Switched reluctance motor

Table 3 Evaluation of EV motors

	DC motor	Induction motor	PM brushless motor	SR motor	PM hybrid motor
Power density	2.5	3.5	5	3.5	4
Efficiency	2.5	3.5	5	3.5	5
Controllability	5	4	4	3	4
Reliability	3	5	4	5	4
Maturity	5	5	4	4	3
Cost	4	5	3	4	3
Total	**22**	**26**	**25**	**23**	**23**



VVVF - Variable voltage variable frequency
FOC - Field oriented control (vector control)
MARC - Model reference adaptive control
STC - Self-tuning control
VSC - Variable structure control
NNC - Neural network control
Fuzzy - Fuzzy control
DSP - Digital signal processor

GTO - Gate turn-off thyristor
BJT - Bipolar-junction transistor
MOSFET - Metal-oxide field-effect transistor
IGBT - Insulated-gate bipolar transistor
MCT - MOS-controlled thyristor
PWM - Pulse width modulation

CAD - Computer aided design
FEM - Finite element method
EM - Electromagnetic
DC - Direct current motor
IM - Induction motor
SRM - Switched reluctance motor
PMSM - Permanent magnet synchronous motor
PMBM - Permanent magnet brushless motor
PMHM - Permanent magnet hybrid motor

Fig. 21 EV propulsion system overview

ing system consists of six major characteristics and each of them is graded from 1 to 5 points, 5 points means the best. It can be seen that induction motor drives and permanent magnet (PM) brushless motor drives are the main stream in today's EV electric propulsion.

7.2 Vector controlled induction motor drives

Today induction motor drive is the most mature technology among various commutatorless motor drives. Figure 22 shows the characteristics of induction motor drives. In order to improve the dynamic performance of induction motor drives for EV propulsion, vector control is preferred. Although vector control may offer wide speed range up to (3-4) times of base speed, but the efficiency at high speed range may suffer. Figure 23 shows the efficiency-optimising of vector controlled induction motor drive for EVs. This control scheme is able to control the torque component current and field component current hence to minimize the total losses at any loading condition.

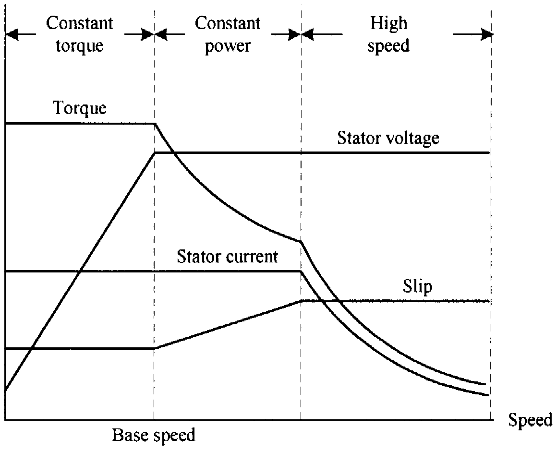


Fig. 22 Characteristics of induction motor drives

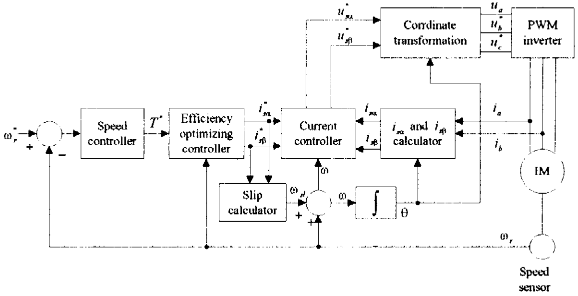


Fig. 23 Efficiency optimising vector controlled EV induction motor drive

7.3. PM brushless motor drives

Among those modern motor drives, Permanent magnet brushless motor drives are most capable of competing with induction motor drives for electric propulsion. Their advantages are summarised below:

(1) Since the magnetic field is excited by high-energy PMs, the overall weight and volume can be significantly reduced for a given output power, leading to

higher power density.

(2) Because of the absence of rotor copper losses, their efficiency is inherently higher than that of induction motors.

(3) Since the heat mainly arises in the stator, it can be more efficiently dissipated to surroundings.

(4) Since PM excitation suffers from no risk of manufacturing defects, overheating or mechanical damage, their reliability is inherently higher.

(5) Because of lower electromechanical time constant of the rotor, the rotor acceleration at a given input power can be increased

In order to increase the speed range and improve the efficiency of PM brushless motor, the conduction angle of the power converter can be controlled at above the base speed. Figure 24 shows the torque-speed characteristic of a PM brushless motor with conduction angle control. The speed range may reach (3-4) times of base speed. However, at very high speed range the efficiency may drops, the PM may suffer from demagnetization and possible fault.

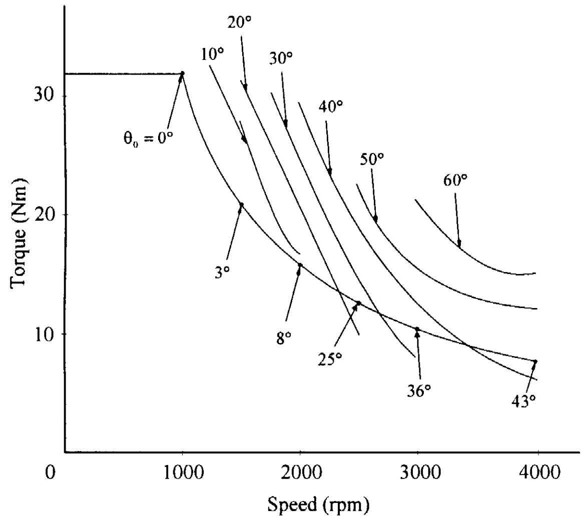


Fig. 24 Torque-speed characteristics of a PM brushless motor drive with conduction angle control

There are various configurations of PM brushless motors. Depending on the arrangement of the PM, basically they can be classified as surface magnet mounted or buried magnet mounted. The surface magnet designs may use less magnet, while the buried magnet designs may achieve higher airgap flux density. The commonly used PM is Neodymium-iron boron (Nd-Fe-B). Another configuration is so called permanent magnet hybrid motor, where the airgap magnetic field is obtained through the combination of PM and field winding. In the broader term, PM hybrid motor may also include the motor whose configuration utilize the combination of PM motor and reluctance motor. PM hybrid motors offer wider speed range and higher overall efficiency but more complex construction.

7.4 SR motor drives

Switched reluctance (SR) motors have been recognized to have potential for EV applications. Basically, they are direct derivatives of single-stack variable-reluctance stepping motors. SR motors have the definite advantages of simple construction, low manufacturing cost and outstanding torque-speed characteristics for EV propulsion. Although they possess the simplicity in construction, it does not imply any simplicity of their design and control. Because of the heavy saturation of pole tips and the fringe effect of poles and slots, their design and control are difficult and subtle. Also they usually exhibit acoustic noise problems. Recently, an optimum design approach to SR motors has been developed, which employs finite element analysis to minimize the total motor losses while taking into account the constraints of pole arc, height and maximum flux density. Also, fuzzy sliding mode control has been developed for those EV SR motors so as to handle the motor non-linearities and minimize the control chattering.

8. ENERGY SOURCE

8.1 General consideration

The EV energy source has been identified to be the major obstacle of EV Commercialization. Thus, the present and foreseeable future most important EV development issue is on how to develop various EV energy sources. Those development criteria are summarised as follows:

(1) High specific energy (kWh/kg) and energy density (kWh/liter).

(2) High specific power (kWh/kg) and power density (kW/liter).

(3) Fast charging and deep discharging capabilities.

(4) Long cycle and service lives.

(5) Minimum self discharging rate and high charging efficiency.

(6) Safety and cost effectiveness.

(7) Maintenance free.

(8) Environmental sound and recyclable.

Rather than based on one energy source, the use of multiple energy sources, so-called hybridisation of energy sources, can eliminate the compromise between the specific energy and specific power. For the hybridisation of two energy sources, one is selected for high specific energy while the other for high specific power. For examples, there are the battery & battery hybrid, battery & ultracapacitor hybrid, battery & ultrahigh-speed flywheel hybrid (flywheel is still in the research stage, major issues include safety, complexity and weight), and fuel cell & battery hybrid. In fact, the HEV is a special case of this hybridisation, namely the gasoline is of high specific energy for the long driving range while the battery is of high specific power for assisting fast acceleration and providing emission-free operation. Figure 25 shows the characteristics of various EV energy sources.

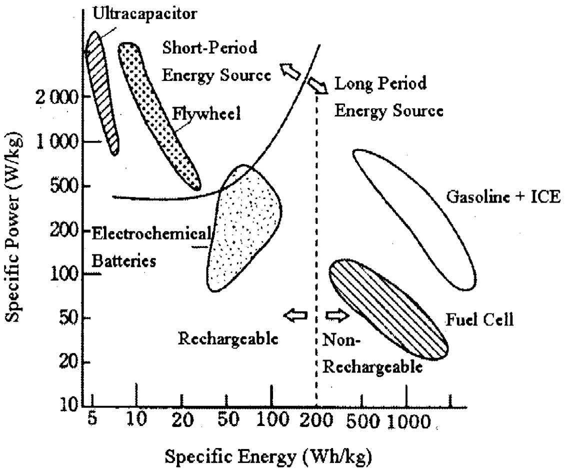


Fig. 25 Characteristics of various EV energy sources (Source: Most Recent Electric Vehicle Technology, Japan Institute of Electrical Engineering)

8.2 Batteries

The working conditions of batteries in BEV, HEV and FCEV are quite different with that in other applications. Therefore the performance requirements of EV batteries should be fully understood. Table 4 shows the key parameters of EV batteries as compared with the goal figures by the United States Advanced Battery Consortium (USABC). Table 5 shows the specific advantages and comparison of various EV batteries. Table 6 shows the comparison of EV batteries at the deep cycles condition.

At present, the viable EV batteries include the valve-regulated lead-acid (VRLA), nickel-cadmium (Ni-Cd), nickel-zinc (Ni-Zn), nickel-metal hydride (Ni-MH), zinc/air (Zn/Air), aluminium/air (Al/Air), sodium/sulphur (Na/S), sodium/nickel chloride (Na/NiCl2), lithium-polymer (Li-Polymer) and lithium-ion (Li-Ion) types. Detailed chemistries of the aforementioned batteries can be found in relevant battery handbooks. It should be noted that these parameters are only for indicative purposes since the data may have wide variations among different battery manufacturers. Even for the same manufacturer, different models of the same battery may also have significant variations because of different trade-offs among the specific energy, specific power and cycle life. Moreover, these data always change with the advancement of battery technology.

In order to meet the California mandate of on zero-emission vehicles, the development of EV batteries has to be continued and accelerated. It is noted that those batteries with near-term high potentiality are the VRLA, Ni-Cd and Ni-MH. Since the features of the Ni-MH are

Table 4 Key parameters of EV batteries

	Specific energy [a] (Wh/kg)	Energy density [a] (Wh/l)	Specific power [b] (W/kg)	Cycle life [b] (Cycles)	Projected cost [d] (US$/kWh)
VRLA	30-45	60-90	200-300	400-600	150
Ni-Cd	40-60	80-110	150-350	600-1200	300
Ni-Zn	60-65	120-130	150-300	300	100-300
Ni-MH	60-70	130-170	150-300	600-1200	200-350
Zn/Air	230	269	105	NA [c]	90-120
Al/Air	190-250	190-200	7-16	NA [c]	NA
Na/S	100	150	200	800	250-450
Na/NiCl$_2$	86	149	150	1000	230-350
Li-Polymer	155	220	315	600	NA
Li-Ion	90-130	140-200	250-450	800-1200	>200
USABC	200	300	400	1000	<100

NA: Not available
[a] At C/3 rate
[b] At 80% DOD
[c] Mechanical recharging
[d] For reference only

Table 5 Specific advantages of batteries

Advantages Of / On		Lead Acid	Nickel Cadmium NiCd	Nickel Metal Hydride NiMH	Lithium-Ion	
					Conventional	Polymer
Lead Acid			• Gravimetric energy density • Volumetric energy density • Operating temperature range • Self discharge rate • Reliability (progressive extinction)	• Gravimetric energy density • Volumetric energy density • Self discharge rate	• Gravimetric energy density • Volumetric energy density • Voltage output • Self discharge rate	• Gravimetric energy density • Volumetric energy density • Self discharge rate • Design characteristics
Nickel Cadmium NiCd		• Higher cyclability • Voltage output • Price		• Gravimetric energy density • Volumetric energy density	• Gravimetric energy density • Volumetric energy density • Voltage output • Self discharge rate	• Gravimetric energy density • Volumetric energy density • Self discharge rate • Design characteristics
Nickel Metal Hydride NiMH		• Higher cyclability • Voltage output • Price	• Operating temperature range • Higher cyclability • Self discharge rate • Price		• Gravimetric energy density • Volumetric energy density • Operating temperature range • Higher cyclability • Voltage output • Self discharge rate	• Gravimetric energy density • Volumetric energy density • Operating temperature range • Self discharge rate • Design characteristics
Lithium-Ion	Conventional	• Higher cyclability • Price • Safety • Recyclability	• Operating temperature range • Higher cyclability • Price • Safety • Recyclability	• Price • Safety • Discharge rate • Recyclability		• Gravimetric energy density • Volumetric energy density (potential) • Design characteristics • Safety • Price
	Polymer	• Higher cyclability • Price	• Operating temperature range • Higher cyclability • Price	• Volumetric energy density • Higher cyclability • Price	• Operating temperature range • Higher cyclability	
Absolute advantages		• Higher cyclability • Price	• Operating temperature range • Price	• Volumetric energy density	• Gravimetric energy density • Volumetric energy density • Self discharge rate • Voltage output	• Gravimetric energy density • Volumetric energy density (potential) • Self discharge rate • Voltage outout • Design characteristics

(Source: Christopher Pillot: The Worldwide Rechargeable Battery Market 2003-2008, Proceedings of the sixth China International Battery Fair, Beijing, China, April, 2004)

Table 6 Comparison of deep cycle batteries

High Energy Design in Deep Cycle Application		Lead Acid	Nickel Metal Hydride	Lithium-Ion
Energy density	(Wh/kg)	35	55	>80
Power density	(W/kg)	150	230	1,000
Charge acceptance	(W/kg)	50	200	600
Life time (number of cycles)	at 80% swing	125	3,000	2,500
	at 5% swing	50,000	300,000	140,000
Cost level	USD/kWh	150	450	500

(Source: Christian Rosenkranz: Deep Cycle Batteries For Plug-in Hybrid Application. EPRI Hybrid Electric Vehicle Working Group, Nov.15, 2003) superior to those of the Ni-Cd except maturity, the Ni-Cd is being superseded by the Ni-MH. Actually, some manufacturers used to produce the Ni-Cd for EV applications have redirected their efforts to the Ni-MH. Thus, in near term, the VRLA is still popular due to its maturity and cost-effectiveness, whereas the Ni-MH is attractive because of its good performances. On the other hand, those batteries with mid-term high potentiality include the Ni-Zn, Zn/Air, Na/NiC12, Li-Polymer and Li-Ion. The Li-Ion has been identified by many battery manufacturers to be the most promising mid-term EV battery. The Zn/Air may also promising because of its excellent specific energy and fast mechanical refuelling. However, this mechanically rechargeable battery cannot accept energy resulting from regenerative braking. Since the major drawback of the Ni-Zn, namely short cycle life, is being alleviated in recent development, it may have the potential to compete with the Ni-MH in mid term. The Na/NiC12 is relatively the acceptable high-temperature battery for EV applications. It is promising in mid term provided that the battery performances can be further improved. The Li-Polymer has demonstrated to exhibit good performances for EV applications. It is promising in mid term provided that more battery manufacturers are involved to accelerate its research and development.

It should be noted that, in addition to the required performance of the batteries, the battery management system is also prime important to ensure the charging and discharging of batteries are in proper conditions. The replacement and recycling of batteries must also be taken care.

8.3 Fuel cells

The fuel cell is an electrochemical device which converts the free-energy change of an electrochemical reaction into electrical energy. In contrast to a battery, the fuel cell generates electrical energy rather than stores it, and continues to do so as long as a fuel supply is maintained. Its advantageous features are efficient conversion of fuel to electrical energy, quiet operation, zero or very low emissions, waste heat recoverable, rapid refuelling, fuel flexibility, durable and reliable.

As shown in Figure 26, a fuel cell basically consists of three major components, namely the anode (A), cathode (C) and electrolyte (E). The anode (fuel electrode) provides a common interface for the fuel and electrolyte, catalyses the fuel oxidation reaction, and drives electrons to the external circuit. On the other hand, the cathode (oxygen electrode) provides a common interface for the oxygen and electrolyte, catalyses the oxygen reduction reaction, and receives electrons from the external circuit. Between the anode and cathode, the electrolyte functions to transport one of the ionic species involved in the fuel and oxygen electrode reactions, and also prevents the conduction of electrons.

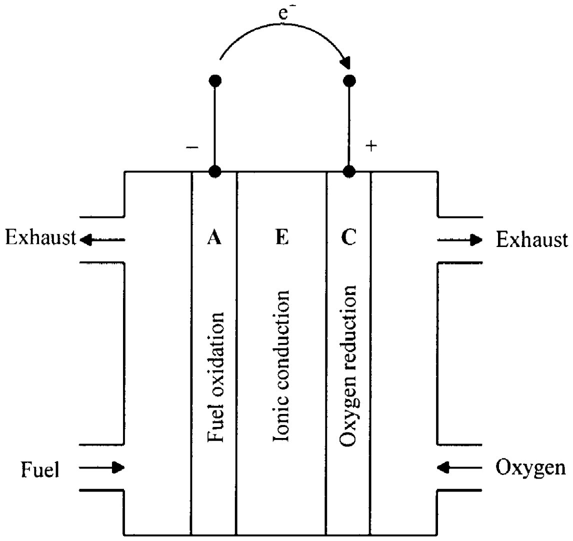


Fig. 26 Basic principle of fuel cells

Hydrogen seems to be an ideal nonpolluting fuel for the fuel cell because it has the highest energy content per unit of weight of any fuel, and the by-product as a result of the fuel cell reaction is just plain water:

$$2H_2 + O_2 \Rightarrow 2H_2O \qquad (1)$$

Since hydrogen is not a primary fuel, it is generally derived from various primary fuels such as hydrocarbons, methanol and coal by means of a fuel processor. There are three major ways of storing hydrogen. Firstly, it can be stored as a compressed gas, so-called compressed hydrogen gas (CHG). Similar to the compressed natural gas, the CHG can be stored at 20-34.5 MPa in fibreglass-reinforced aluminium containers. Secondly, it can be chilled below its boiling point (-253 C) to form liquid hydrogen, which is then stored in cryogenic containers. Thirdly, it can be brought to react with some metals such as magnesium and vanadium to form metal hydrides. The reaction is reversible, depending on the temperature of dissolution (up to about 300 C). Table 7 shows the theoretical energy contents of some prominent fuels, including hydrogen stored in various forms, liquid methanol and liquid petrol. The CHG storage offers the advantages of lightweight, low cost, mature technology and fast refuelling capability, but suffers from bulky size and safety concerns. The liquid hydrogen offers both high specific energy and fast refuelling capability, but has the drawbacks of expensive production and distribution costs as well as high volatility. Although the metal hydrides can provide the merits of compact size and inherent safety, they suffer from either too high

Table 7 Theoretical energy contents of prominent fuels

	Specific energy (Wh/kg)	Energy density (Wh/l)
Compressed hydrogen gas [a]	33600	600
Liquid hydrogen [b]	33600	2400
Magnesium hydride	2400	2100
Vanadium hydride	700	4500
Methanol	5700	4500
Petrol	12400	9100

temperature of dissociation such as magnesium hydride (287 C) or relatively low specific energy such as vanadium hydride (700 Wh/kg).

Because of a vast number of variables among the fuel cell systems, such as the type of fuel, type of electrolyte, type of fuelling and operating temperatures, many classifications have appeared in the literature. Having done some of streamlining over the years, they are generally classified by the type of electrolyte, namely acid, alkaline, molten carbonate, solid oxide and solid polymer. Instead of using hydrogen as the fuel, carbon monoxide and methanol have also been adopted by some fuel cells. However, the by-product of these fuel cells becomes carbon dioxide, rather than plain water (Blomen et al, 1993).

Detailed chemistries of the aforementioned fuel cells can be found in relevant reference books (Blomen et al, 1993). Typical characteristics of the aforementioned fuel cells are summarised in Table 8. Accordingly, both the Molten Carbornate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) suffer from very high-temperature operation, respectively over 600 C and 900 C, making them practically difficult to be applied to EVs. For the Direct Methanol Fuel Cell (DMFC), the corresponding technology is still immature although it has been developed for over 30 years. Also, its available power level and power density are too low for practical application to EVs. The others, namely the Phosphoric Acid Fuel Cell (PAFC), Alkaline Fuel Cell (AFC) and Solid Polymer Fuel Cell (SPFC) also known as Proton Exchange Membrane (PEM) fuel cell, are all technically possible for EV applications - termed EV fuel cells.

Table 8 Typical characteristics of fuel cells

	PAFC	AFC	MCFC	SOFC	SPFC	DMFC
Working temp. (°C)	150-210	60-100	600-700	900-1000	50-100	50-100
Power density (W/cm^2)	0.2-0.25	0.2-0.3	0.1-0.2	0.24-0.3	0.35-0.6	0.04-0.23
Projected life (kh)	40	10	40	40	40	10
Projected cost (US$/kW)	1000	200	1000	1500	200	200

PAFC - Phosphoric acid fuel cell

AFC - Alkaline fuel cell

MCFC - Molten carbonate fuel cell

SOFC - Solid oxide fuel cell

SPFC - Solid polymer fuel cell also known as proton exchange membrane fuel cell

DMFC - Direct methanol fuel cell

With the advancement of SPFC (PEM) technology, the SPFC (PEM) takes advantages over the AFC for EV applications. The major reasons are due to its higher power density and longer projected life while maintaining the low working temperature and economical projected cost. Thus, recent research and development on fuel cells for EVs have been focused on the SPFC (PEM) technology. Ballard Power Systems and Daimler-Benz jointly produced a PEM fuel cell bus in 1997, namely the NEBUS. At present, the major challenge is how to significantly reduce the material cost of solid polymer membrane and platinum-electrocatalysed electrodes. By retaining the definite advantage of liquid fuel while avoiding those shortcomings of the DMFC, the concept of methanol-fuelled PEM fuel cell system is becoming more and more attractive for EVs. As shown in Figure 27, methanol and water are firstly mixed, vaporised, and then converted into hydrogen and carbon dioxide gases via an on-board reformer. The resulting hydrogen gas is

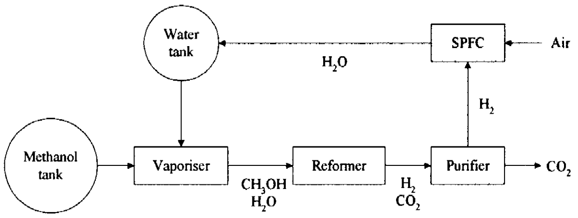


Fig. 27 Methanol-fuelled SPFC system

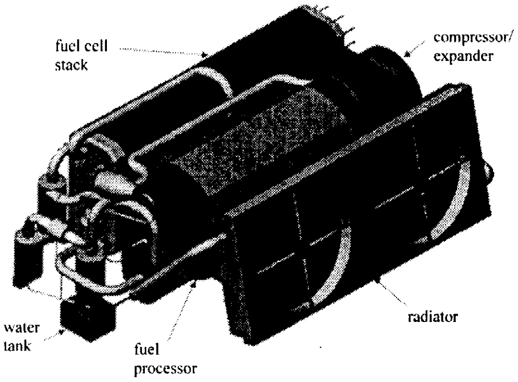


Fig. 28 50 kW automative FC system

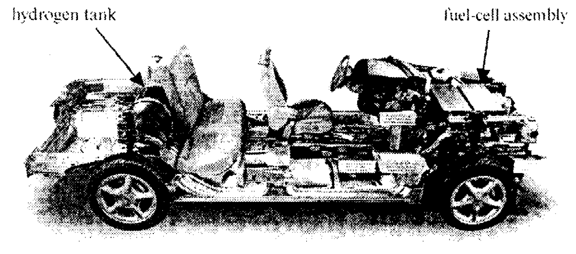


Fig. 29 FCEV configuration

(Source: The Electric Car, The Institute of Electrical Engineers) fed to the PEM fuel cell to generate the desired electricity and the reusable pure water. The purifier functions to prevent any undesirable reformer by-products such as carbon monoxide gas from poisoning the precious electrocatalysts of the PEM fuel cell. Although this technology seems to be contradictory to the pursuit of zero-emission vehicles, it is still environmentally friendly as it does not generate harmful emissions such as carbon monoxide, nitrogen oxides and hydrocarbons. Recently, Daimler-Benz and Ballard Power Systems has presented the first methanol-fuelled PEM fuel cell powered EV, namely the NECAR 3, which can travel over 400 km using 38 liters of liquid methanol. Toyota has also announced that its fuel cell RAV4 EV has achieved the range of 500 km per tank of methanol. Even so, these methanol-fuelled PEM fuel cell EVs are still in the development stage. Figure 28 shows a 50kW automative FC system and Figure 29 shows a FCEV configuration. Further extending the concept of liquid-fuelled fuel cell EVs, research on extracting hydrogen from gasoline using an on-board reformer has been launched. The argument of this research is simple - hundreds of billion dollars have been invested in the way gasoline is distributed, and it is impossible to change this infrastructure just because there are fuel cell EVs that run in hydrogen or methanol. No matter this argument is agreeable or not, the success of this concept can definitely move the fuel cell EVs approaching to reality. Recently, Chrysler has decided to realise this concept by demonstrating a gasoline-fuelled fuel cell EV within the next few years. Definitely, there are still much to be done in research and development of gasoline-fuelled fuel cell EVs before they become commercially viable.

8.4 Ultracapacitors

Because of frequent start/stop operation of EVs, the discharge profile of the battery is highly variable. The average power required from the battery is relatively low while the peak power of relatively short duration required for acceleration or hill climbing is much higher. The ratio of the peak power to the average power can be as high as 16:1 for a high-performance EV. In fact, the amount of energy involved in the acceleration and deceleration transients is roughly 2/3 of the total amount of energy over the entire vehicle mission in the urban driving. Therefore, based on present battery technology, the design of batteries has to carry out the trade-offs among the specific energy, specific power and cycle life. The difficulty of simultaneously obtaining high values of specific energy, specific power and cycle life has lead to some suggestions that EVs may best be powered by a pair of energy sources. The main energy source, usually a battery, is optimised for the range while the auxiliary source for acceleration and hill climbing. This auxiliary source can be recharged from the main source during less demanding driving or regenerative braking. An auxiliary energy source which has received wide attention is the ultracapacitor.

In the foreseeable development of the ultracapacitor, it cannot be used as a sole energy source for EVs because of its exceptionally low specific energy. Nevertheless, there are a number of advantages that can be resulted from using the ultracapacitor as an auxiliary energy source. The promising application is the so-called battery & ultracapacitor hybrid energy system for EVs. Hence, the specific energy and specific power requirements of the EV battery can be decoupled, thus affording an opportunity to design the battery that is optimised for the specific energy and cycle life with little attention being paid to the specific power. Due to the load levelling effect of the ultracapacitor, the high-current discharge from the battery is minimised so that the available energy, endurance and life of the battery can be significantly increased. Moreover, compared to the battery, the ultracapacitor can provide much faster and more efficient energy recovery during regenerative braking of EVs. Therefore, as a combined effect of load levelling and efficient energy recovery, the vehicle range can be greatly extended. Notice that system integration and optimisation should be made to coordinate the battery, ultracapacitor, electric motor and power converter. The power converter and corresponding controller should take care both the electric motor and ultracapacitor.

According to the goals set by the US Department of Energy for the inclusion of ultracapacitors in EVs, the near-term specific energy and specific power should be better than 5 Wh/kg and 500 W/kg, respectively, while the advanced performance values should be over 15 Wh/kg and 1600 W/kg. So far, none of the available ultracapacitors can fully satisfy these goals. Nevertheless, research and development of ultracapacitors for EV applications are actively engaged by some companies.

9. EV INFRASTUCTURE

9.1 General consideration

To support the commercialization of EVs, an EV infrastructure is the underlying foundation, which includes the basic facilities and services to support the operation of a large number of EVs. In this section, only the infrastructure for battery EVs is discussed. The infrastructure for HEV will be much simpler because the size of battery is much smaller, it may also use the existing gasoline infrastructure. The infrastructure for fuel cell EV will be quite different depending on the fuel used. In order to develop a successful battery EV infrastructure, we should pay attention on the following aspects:

(1) Availability of charging stations.
(2) Convenience of payment for charging.
(3) Standardisation of EV batteries and charging.
(4) Regulation of clean and safe charging.
(5) Support from training and promotion.
(6) Impacts on power utilities.

9.2 Charging infrastructure

The design of EV charging systems mainly depends on the level of charging currents to charge the EV batteries. There are three major current levels:

(1) Normal charging current. The EV batteries can be charged by a rather low charging current, about 15 A, and the charging period may last for over six hours. The operation and installation costs of the corresponding charger are relatively low since the power and current ratings involved are not of critical values. This charging current usually benefits to increase the charge efficiency and to extend the battery life.

(2) Medium charging current. The EV batteries can be charged by a medium current of 30-60 A, and the charging period may last for a few hours. The operation and installation costs of the corresponding charger are relatively higher than that for normal charging current because of the necessity to upgrade the charging equipment.

(3) Fast charging current. The EV batteries can be charged up within a short time based on a high charging current of 150-400 A. In contrast to that using normal or medium charging current, the corresponding charger offers relatively low charge efficiency. Definitely, the corresponding operation and installation costs are high.

The normal charging current are adopted in both domestic and public charging infrastructures, whereas both the medium and fast charging currents are only found in the public charging infrastructure. Moreover, the fast charging current should only be adopted in those dedicated public charging stations because the corresponding current demand may cause detrimental effect on the power system network, and maybe the impact of large current to the battery life.

9.3 Impacts on power system

EVs bring both good and bad influences on power system. Positively, the batteries of EVs can be charged at off-peak periods or at night so that the overall power demand can be levelled and the utilisation of power system facilities can be improved. Negatively, the EV battery chargers are nonlinear devices which generate harmonic contamination to our power system, while the battery recharging of EVs at normal or peak periods creates additional current demand burdens on our power system.

9.3.1 Harmonic compensation

In order to compensate the harmonic contamination on our power system, there are many possible measures proposed by researchers and engineers. Basically, these measures can be categorised into two groups - device and system levels. In the device level, many new topologies of battery chargers are being proposed in such a way that the input harmonic current distortion is aimed to be minimal. These approaches rely on the invention of new battery chargers with minimum harmonic contamination and economically viable. In the system level, it can further be divided into two subgroups - passive and active filters. The passive filters can be simply phase-shifting transformers to suppress certain low-frequency harmonics or different combinations of inductor-capacitor sets to reduce those undesirable harmonics. On the other hand, the active filters are advanced power electronic systems which can on-line measure and diagnose the system harmonics so that they can instantaneously generate the same magnitude but anti-phase harmonics to neutralise the system harmonic content. As expected, these active filters need additional power source and sophisticated real-time control technology. Recently, a new way for compensating harmonics generated by EV chargers has been proposed. It is neither based on the invention of new EV chargers (device level) nor the adoption of new filters (system level). Rather than adding something to our power system, the basic idea is simply to coordinate the number of EV chargers per charging station. Since the phase angles of those harmonic currents generated by one EV charger are normally different from those by another EV charger, there is a natural effect that harmonic compensation or even cancellation may occur. The more the number of chargers are being used per station, the higher the possibility to compensate the overall harmonic currents flowing to

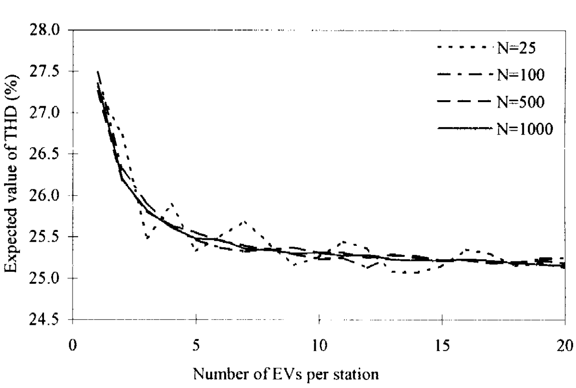


Fig. 30 Expected THD versus number of EVs at a charging station

that charging station can be resulted. However, there is a practical limitation on the number of EV chargers per station because of the availability of space. Figure 30 shows the expected Total Harmonic Distortion (THD) versus number of EVs at a charging station.

9.3.2 Current demand minimisation

In order to reduce the peak current demand due to the recharging of EVs, the concept of charging coordination has recently been proposed. The key of such concept is based on the coordination between charging current and charging time to charge a group of EVs at the same charging station, hence reducing the total maximum current demand, charging up the batteries as soon as possible and achieving a flat load profile as far as possible. Basically, there are two types of coordination approaches:

(1) distributive coordination, and
(2) centralised coordination.

In case of the distributive coordination, each EV needs to install a distributive coordination controller which functions to maximise its individual charging current provided that the total current demand of the whole charging station is within the specified limit. Whenever there is any remaining current due to the charge-up or the leave of a particular EV, this unused current will be picked up by another EV based on the first-come-first-serve (FCFS) arbitration. Since each EV simply knows the total current demand and aims to grasp the unused current to shorten its individual charging time, this approach takes the advantages of simplicity and low-cost implementation. However, the FCFS arbitration cannot re-distribute the remaining current to other EVs in a balance way, thus the charging times of those EVs spread around. Also, since each EV charger knows only the total current demand of the charging station and nothing about the conditions of other EV chargers, some complicated control algorithms are not applicable to such approach.

In case of the centralised coordination, the charging station needs to install a central computer which gathers the necessary information, such as the battery capacity, state of charge, current and voltage ratings as well as expected charging times, from all EV chargers. Hence, intelligent arbitration made by the central computer is adopted so that the total current demand can be minimised while the EV charging times can be equalised as far as possible. This central coordination approach takes the advantages over the distributive counterpart that the current demand fluctuation can be reduced, the spread of charging times can be optimised, and those sophisticated control algorithms can be implemented. The drawback is the increase in implementation complexity and cost, which can be well outweighed by the associated advantages.

10. EV COMMERCIALIZATION

The hurdles and barriers of EV commercialization are listed in Table 9. The key issues of successfully commercializing and promoting EVs lie in how to produce low-cost, good performance EVs; how to leverage the initial investment; and how to provide an efficient infrastructure. The overall strategy should take into account how to fully utilize the competitive edge, to share the market and resources, and to produce EVs that can meet the market demand. Although specific strategies may vary with different manufacturers and countries, and are very complex, the key element is the willingness and commitment of manufacturers and their industrial partners, governments and public authorities, electric utilities and users. It is negative to say, "Let the market decide". Market forces are just abstract concept, derived from individuals who have different interests. Therefore, a wise initial strategy and agreement on market penetration are essential. Of course, the general expectation of the consumers must be fully considered

The key of success is two integrations. First is the integration of society strength, which includes government's policy support, financing and venture capital's interest, incentives for industry, and technical support from academic institutions. Second is the integration of technical strength, that is the effective integration of the state-of-the-art technologies of automobile, electrical, electronic, chemical and material engineering.

At the beginning, EVs cannot compete with ICEVs in every application. Therefore, it is important to identify the niche markets that are feasible, eg. small BEV for community transportation, while HEV for wider applications, consequently to identify the required technical specifications, and to adopt the system integration and optimization. In order to achieve cost effectiveness, a unique design approach and a unique manufacturing process should be developed. Excellent after-sales ser-

Table 9 Hurdles and barriers for the application of alternative propulsion systems

Battery Electric Vehicle	weight, durability, range , cost, recycling, size, recharge time
Hybrid	battery, durability, size, weight, cost
Mid hybrid/ISG	cost, weight, reliability
42V board net voltage	safety, cost
Fuel cell (hydrogen onboard)	infrastructure, cost, hydrogen production, storage, reliability, durability, customer acceptance of hydrogen
Fuel cell (reformer)	warm up time, efficiency, emissions, CO poisoning, transient operation
APU	size, weight, safety, durability, reliability, cost, efficiency, cooling
Storage for mechanical energy	flywheel, safety, weight, hydraulic, noise, cost

vice and effective infrastructure are also essential.

11. CONCLUSION

Environment protection and energy conservation have urged the development of EVs. However, the commercialisation of EVs was not successful. The main reason was because they could not satisfy the consumers' need due to high cost and short range. Consequently, HEV and FCEV are recently rapidly emerging. Looking ahead in the next few decades, with the aid of new technologies, battery and advanced propulsion will continue to develop, BEV will mainly designed for small vehicles for niche market, such as community transportation. HEV can meet consumers need and will grow in faster rate. The key issue of HEV is how to optimise the multiple energy source to obtain best performance at lower cost. FCEV will have long term potential to be the main stream vehicles in the future, because it is almost zero emission and comparible driving range to ICEV. However, it is still in early development state today, the major challenge of FCEV is how to develop low cost fuel cell, efficient fuel processor and refuelling system. A proper engineering philosophy is essential for the guidance of strategic development of electric vehicles

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