INVITED PAPER

The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles

With their superior fuel economy and performance, hybrid vehicles will likely increase in popularity in coming years; further development of control theory for hybrids is essential for their progress.

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ABSTRACT | With the more stringent regulations on emissions and fuel economy, global warming, and constraints on energy resources, the electric, hybrid, and fuel cell vehicles have attracted more and more attention by automakers, governments, and customers. Research and development efforts have been focused on developing novel concepts, low-cost systems, and reliable hybrid electric powertrain. This paper reviews the state of the art of electric, hybrid, and fuel cell vehicles. The topologies for each category and the enabling technologies are discussed.

KEYWORDS | Electric drives; electric machines; electric vehicle; fuel cell vehicles; hybrid electric vehicle (HEV); modeling; power electronics

I. INTRODUCTION

Compared to conventional vehicles, hybrid electric vehicles (HEVs) are more fuel efficient due to the optimization of the engine operation and recovery of kinetic energy during braking. With the plug-in option (PHEV), the vehicle can be operated on electric-only modes for a driving range of up to 30–60 km. The PHEVs are charged overnight from the electric power grid where energy can be generated from renewable sources such as wind and solar energy and from nuclear energy. Fuel cell vehicles (FCV) use hydrogen as fuel to produce electricity, therefore they are basically emission free. When connected to electric power grid (V2G), the FCV can provide electricity for emergency power backup during a power outage. Due to hydrogen production, storage, and the technical limitations of fuel cells at the present time, FCVs are not available to the general public yet. HEVs are likely to dominate the advanced propulsion in coming years. Hybrid technologies can be used for almost all kinds of fuels and engines. Therefore, it is not a transition technology. Fig. 1 shows the road map of hybrid technologies.

In HEVs and FCVs, there are more electrical components used, such as electric machines, power electronic converters, batteries, ultracapacitors, sensors, and microcontrollers. In addition to these electrification components or subsystems, conventional internal combustion engines (ICE), and mechanical and hydraulic systems may still be present. The challenge presented by these advanced propulsion systems include advanced powertrain components design, such as power electronic converters, electric machines and energy storage; power management; modeling and simulation of the powertrain system; hybrid control theory and optimization of vehicle control.

This paper provides an overview of the state of the art of electric vehicles (EVs), HEVs and FCVs, with a focus on HEVs. Section II tries to answer a fundamental question: why EV, HEV, and FCV? It also looks at the key issues of HEVs and FCVs. Section III reviews the history of EVs, HEVs, and FCVs. Section IV highlights the engineering philosophy of EVs, HEVs, and FCVs. Section V presents the architectures of HEVs and FCVs. Section VI provides an overview of the current status of HEVs and FCVs. Section VII discusses the key technologies, including electric motor technology, power converter technology, control and power management technology, and energy storage devices. Finally, conclusions are given in Section VIII.

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II. WHY EVs, HEVs, AND FCVs?

Vehicles equipped with conventional internal combustion engines (ICE) have been in existence for over 100 years. With the increase of the world population, the demand for

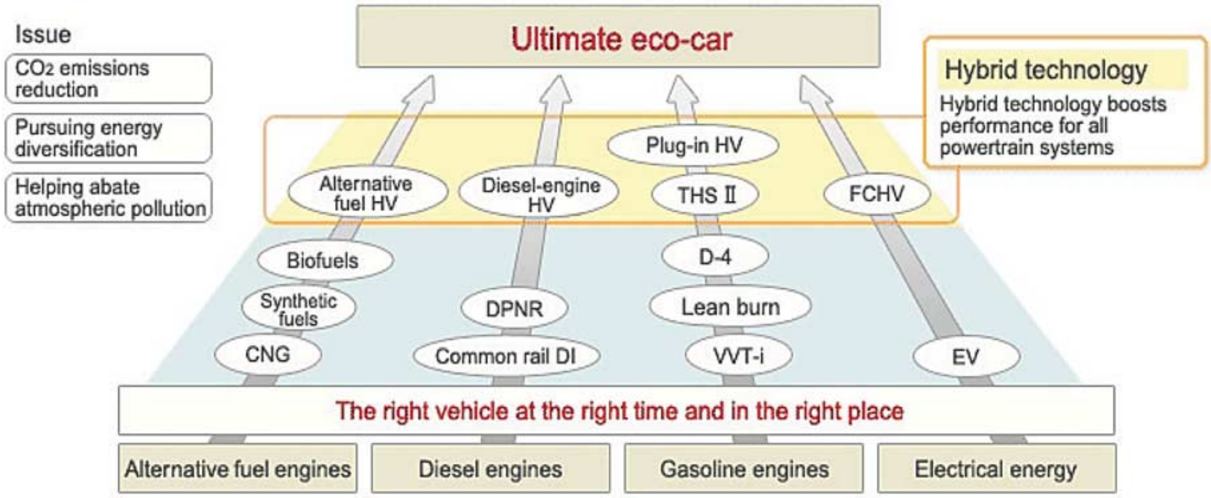

Fig. 1. ***Road map of hybrid technology (Courtesy of Toyota).***

vehicles for personal transportation has increased dramatically in the past decade. This trend of increase will only intensify with the catching up of developing countries, such as China, India, and Mexico. The demand for oil has increased significantly.

Another problem associated with the ever-increasing use of personal vehicles is the emissions. The green house effect, also know as global warming, is a serious issue that we have to face. There have been increased tensions in part of the world due to the energy crisis.

Government agencies and organizations have developed more stringent standards for the fuel consumption and emissions. Nevertheless, with the ICE technology being matured over the past 100 years, although it will continue to improve with the aid of automotive electronic technology, it will mainly rely on alternative evolution approaches to significantly improve the fuel economy and reduce emissions.

Battery-powered electric vehicles were one of the solutions proposed to tackle the energy crisis and global warming. However, the high initial cost, short driving range, long charging (refueling) time, and reduced passenger and cargo space have proved the limitation of battery-powered EVs.

The HEV was developed to overcome the disadvantages of both ICE vehicles and the pure battery-powered electric vehicle. The HEV uses the onboard ICE to convert energy from the onboard gasoline or diesel to mechanical energy, which is used to drive the onboard electric motor, in the case of a series HEV, or to drive the wheels together with an electric motor, in the case of parallel or complex HEV.

The onboard electric motor(s) serves as a device to optimize the efficiency of the ICE, as well as recover the kinetic energy during braking or coasting of the vehicle. The ICE can be stopped if the vehicle is at a stop, or if vehicle speed is lower than a preset threshold, and the electric motor is used to drive the vehicle along. The ICE operation is optimized by adjusting the speed and torque of the engine. The electric motor uses the excess power of the engine to charge battery if the engine generates more power than the driver demands or to provide additional power to assist the driving if the engine cannot provide the power required by the driver.

Due to the optimized operation of the ICE, the maintenance of the vehicle can be significantly reduced, such as oil changes, exhaust repairs, and brake replacement. In addition, the onboard electric motor provides more flexibility and controllability to the vehicle control, such as antilock braking (ABS) and vehicle stability control (VSC).

FCVs use fuel cells to generate electricity from hydrogen. The electricity is either used to drive the vehicle or is stored in an energy storage device, such as battery pack or ultracapacitors. Since fuel cells generate electricity from chemical reaction (isothermal), they do not burn fuel and therefore do not produce pollutants. The byproduct of a hydrogen fuel cell is water. An FCV provides quiet operation and more comfort for the ride.

Although HEVs possess many advantages, they also have certain limitations. The main concerns include increased cost due to the introduction of motors, energy storage system, and power converters; reliability and warranty related issues due to the lack of electrician in the car shops; safety concerns due to the introduction of high voltage in the vehicle system; and electromagnetic interference caused by high-frequency high-current switching in the electric powertrain system.

Issues related to FCV include the high cost of the fuel cell, storage of hydrogen, production and transportation of hydrogen, and life cycle of the fuel cells. Table 1 shows

Table 1 Characteristics of BEVs, HEVs, and FCVs

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 • Need battery / ultracapacitor to enhance power density for starting.
Energy source & infrastructure	• Electric grid charging facilities	• Gasoline stations • Electric grid charging facilities (for Plug In Hybrid)	• Hydrogen • Hydrogen production and transportation infrastructure
Characteristics	• Zero emission • High energy efficiency • Independence on crude oils • Relatively short range • High initial cost • Commercially available	• Very low emission • Higher fuel economy as compared with ICE vehicles • Long driving range • Dependence on crude oil (for non Plug In Hybrid) • Higher cost as compared with ICE vehicles • The increase in fuel economy and reduce in emission depending on the power level of motor and battery as well as driving cycle. • Commercially available	• Zero emission or ultra low emission • High energy efficiency • Independence on crude oil (if not using gasoline to produce hydrogen) • Satisfied driving range • High cost • Under development
Major issues	• Battery and battery management • Charging facilities • Cost	• Multiple energy sources control, optimization and management. • Battery sizing and management	• Fuel cell cost, cycle life and reliability • Hydrogen infrastructure

a comparison of the major characteristics of EVs, HEVs, and FCVs.

III. HISTORY OF EVs, HEVs, AND FCVs

A. History of EV

The EV was invented in 1834. During the last decade of the 19th century, a number of companies produced EVs in America, Britain, and France. In London, there were Electric Cab Company's taxis. However, due to the limitations associated with the batteries and the rapid advancement in ICE vehicles, EVs have almost vanished from the scene since 1930. Nevertheless, in the early 1970s, some countries, compelled by the energy crisis, started the rekindling of interests in EVs. In 1976, the U.S. launched the Electric and Hybrid Vehicle Research, Development and Demonstration Act, Public Law 94-413. In the beginning of the 21st century, California had a mandate on the use of zero emission vehicles. Today, EVs are mainly used for small vehicles and short distance applications due to the limitation of batteries. In London, due to a new mandate of using zero emission vehicles in the down town, around 900 small EVs recently have been used. With the aid of intelligent transportation systems, EVs can be used as a car sharing system, when the user will travel for longer distances, the user can change to another fully charged EV at the midway service station.

B. History of HEV

In 1898, the German Dr. Ferdinand Porsche built his first car, the Lohner Electric Chaise. It was the world's first front-wheel-drive car. Porsche's second car was a hybrid, using an ICE to spin a generator that provided power to electric motors located in the wheel hubs. On battery alone, the car could travel nearly 40 miles.

By 1900, American car companies had made 1681 steam, 1575 electric, and 936 gasoline cars. In a poll conducted at the first National Automobile Show in New York City, patrons favored electric as their first choice, followed closely by steam.

In the first few years of the 20th century, thousands of electric and hybrid cars were produced. This car, made in 1903 by the Krieger company, used a gasoline engine to supplement a battery pack.

Also in 1900, a Belgian carmaker, Pieper, introduced a 3-1/2 horsepower "voiturette" in which the small gasoline engine was mated to an electric motor under the seat. When the car was "cruising," its electric motor was in effect a generator, recharging the batteries. But when the car was climbing a grade, the electric motor, mounted coaxially with the gas engine, gave it a boost. The Pieper patents were used by a Belgium firm, Auto-Mixte, to build commercial vehicles from 1906 to 1912.

In 1904, Henry Ford overcame the challenges posed by gasoline-powered cars—noise, vibration, and odor—and began assembly-line production of low-priced, lightweight, gas-powered vehicles. Henry Ford's assembly line and the advent of the self-starting gas engine signaled a rapid decline in hybrid cars by 1920. Within a few years, the electric vehicle company failed. In 1905, an American engineer named H. Piper filed a patent for a petrol-electric hybrid vehicle. His idea was to use an electric motor to assist an ICE, enabling it to achieve 25 mph.

Two prominent electric vehicle makers, Baker of Cleveland and Woods of Chicago, offered hybrid cars. Woods claimed that their hybrid reached a top speed of 35 mph and achieved fuel efficiency of 48 mpg. The Woods Dual Power was more expensive and less powerful than its gasoline competition and therefore sold poorly.

Hybrid and electric vehicles faded away until the 1970s with the Arab oil embargo. The price of gasoline soared, creating new interest in electric vehicles. The U.S. Department of Energy ran tests on many electric and hybrid vehicles produced by various manufacturers.

The world started down a new road in 1997 when the first modern hybrid electric car, the Toyota Prius, was sold in Japan. Two years later, the U.S. saw its first sale of a hybrid, the Honda Insight. These two vehicles, followed by the Honda Civic Hybrid, marked a radical change in the type of car being offered to the public: vehicles that bring some of the benefits of battery electric vehicles into the conventional gasoline powered cars and trucks we have been using for more than 100 years.

Along the line, over 20 models of passenger hybrids have been introduced to the auto market.

C. History of FCV

Fuel cells started with Sir William Grove in 1839. It was not too successful initially because electricity was not known enough. The first success was by Francis Bacon in 1932 (alkaline fuel cell system with porous electrodes). In the 1950s, fuel cells were used in the Apollo space program. The reason for space use was that it was the best choice: nuclear too dangerous, solar too bulky, and batteries too heavy. Fuel cells were used in Apollo, Gemini, and space shuttles.

In 1967, General Motors developed a six-passenger Electrovan, but only for use on company property due to safety reasons.

In more recent decades, a number of manufacturers including major auto makers and various government agencies have supported ongoing research into the development of fuel cell technology for use in fuel cell vehicles and other applications. Fuel cell energy has the potential to gradually replace the traditional power sources, from micro fuel cells to be used in cell phones to high-powered fuel cells for vehicle applications and stationary power generation.

IV. ENGINEERING PHILOSOPHY OF EVs, HEVs, AND FCVs

The overall EV engineering philosophy essentially is the integration of automobile engineering and electrical engineering. Thus, system integration and optimization 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. It should adopt unique designs that are particularly suitable for EVs and should develop special manufacturing technology that is particularly suitable for EVs. Every effort should be made to optimize the energy utilization of EVs.

The EV engineering philosophy is the marriage of automotive engineering and electrical engineering which includes the motor, power electronic converter, controller, battery or other energy storage device, and energy management system. Marriage implies that the bride and the groom have fully understood the character of the partner and are able to cope together harmoniously and best perform to achieve the required driveability at maximum energy efficiency and minimum emission.

The HEV engineering philosophy is $1+1>2$. This implies the added value gained from the integration of engine propulsion and motor propulsion, fully seizes the advantages and flexibility of electrical, electronic, and control technologies and will not only increase energy efficiency and reduce emission, but also driving comfort and safety. Just like a mule is the hybrid of horse and moke, a mule possesses the best DNA of horse and moke and is more powerful with more endurance. In HEV, the prime key technology is the control algorithm and optimization.

The FCV engineering philosophy is the integration of automotive engineering, electrical engineering, and fuel cell engineering. Since the fuel cell is a new kind of energy device which is quite different with gasoline and batteries, every effort should ensure that the overall system of the fuel cell is efficient, reliable, optimum, and long lasting at reasonable cost. Other high power density devices such as a lithium-ion battery or ultracapacitor may be used in conjunction with the fuel cell to improve the starting performance of the vehicle. The electric propulsion system and fuel cell system must cope very well to achieve the required driveability at maximum energy efficiency and minimum emission.

V. ARCHITECTURE OF HEVs AND FCVs

HEVs are propelled by an ICE and an electric motor/generator (EM) in series or parallel configurations. The ICE provides the vehicle an extended driving range, while the EM increases efficiency and fuel economy by regenerating energy during braking and storing excess energy from the ICE during coasting. Design and control of such powertrains involve modeling and simulation of intelligent control algorithms and power management strategies, which aim to optimize the operating parameters to any given driving condition.

Traditionally, there are two basic categories of HEV, namely series hybrids and parallel hybrids. In series HEV, the ICE mechanical output is first converted to electricity using a generator. The converted electricity either charges the battery or bypasses the battery to propel the wheels via an electric motor. This electric motor is also used to capture the energy during braking. A parallel HEV, on the other hand, has both the ICE and an electric motor coupled to the final drive shaft of the wheels via clutches. This configuration allows the ICE and the electric motor to deliver power to drive the wheels in combined mode, or ICE alone, or motor alone modes. The electric motor is also used for regenerative braking and for capturing the excess energy of the ICE during coasting. Recently, series–parallel and complex HEVs have been developed to improve the power performance and fuel economy.

A. Series HEV

In series HEVs, the 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 that aims to extend the driving range comparable with that of conventional 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.

There are six possible different operation modes in a series HEV:

1) battery alone mode: engine is off, vehicle is powered by the battery only;
2) engine alone mode: power from ICE/G;
3) combined mode: both ICE/G set and battery provides power to the traction motor;
4) power split mode: ICE/G power split to drive the vehicle and charge the battery;
5) stationary charging mode;
6) regenerative braking mode.

B. Parallel HEV

Differing from the series hybrid, the parallel HEV allows both the ICE and electric motor to deliver power in parallel to drive the wheels. 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 both lower emissions and fuel consumption. The electric motor can be used as a generator to charge the battery by regenerative braking or by 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. The following are the possible different operation modes of parallel hybrid:

1) motor alone mode: engine is off, vehicle is powered by the motor only;
2) engine alone mode: vehicle is propelled by the engine only;
3) combined mode: both ICE and motor provides power to the drive the vehicle;
4) power split mode: ICE power is split to drive the vehicle and charge the battery (motor becomes generator);
5) stationary charging mode;
6) regenerative braking mode (include hybrid braking mode).

C. Series–Parallel HEV

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.

D. Complex HEV

As reflected by its name, this system involves a complex configuration that cannot be classified into the above three kinds. As shown in Fig. 2(d), the complex hybrid seems to be similar to the series–parallel hybrid, since the generator

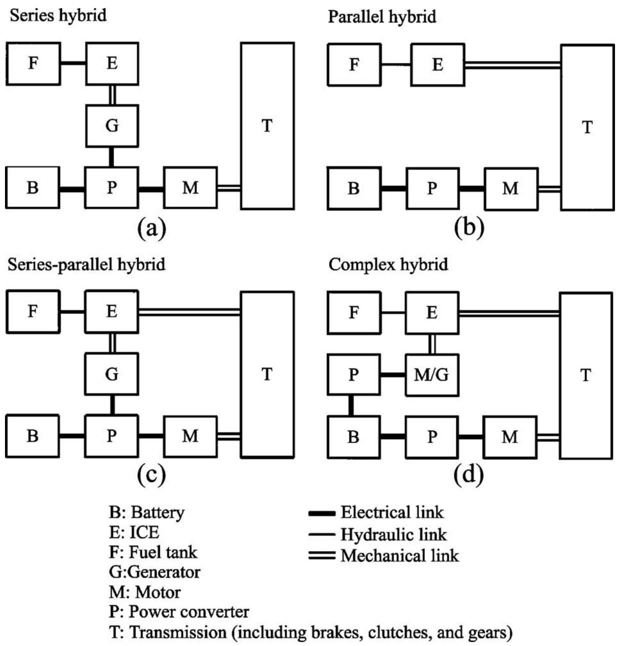

Fig. 2. *Four common architectures of HEV.*

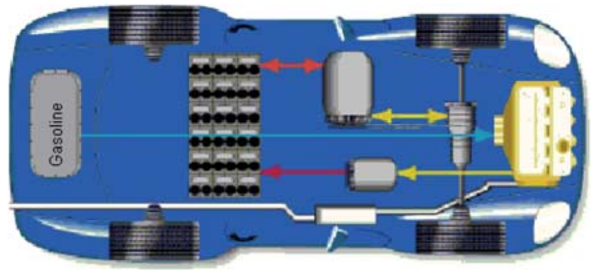

Fig. 3. *Architecture of series HEV.*

and electric motor are both electric machinery. However, the key difference is due to the bidirectional 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.

E. Heavy Hybrids

Vehicles used typically for delivery are one special kind of vehicle, usually referred to as heavy vehicles. When hybridized, these vehicles are referred to as heavy hybrids. Heavy hybrids can be either series or parallel. Heavy hybrids may run on gasoline or diesel.

F. FCV

Fuel cell vehicles can be considered as series-type hybrid vehicles. The onboard fuel cell produces electricity, which is either used to provide power to the propulsion motor or stored in the onboard battery for future use.

VI. PRESENT STATUS OF HEVs AND FCVs

Major automakers have developed many hybrid vehicles. The available models encompass passenger vehicles, SUVs, delivery trucks, transient buses, and line-haul trucks.

According to the level of electric power and the function of the electric motor, HEVs can be classified into following categories.

1) Micro hybrid: The typical electric motor power for a sedan micro hybrid is about 2.5 kW at 12 V. It is essentially the integration of starter and alternator in the conventional ICE vehicle. The main function of the electric motor is for start and stop, hence the energy saving gained mainly is due to using the motor for start and stop. In city driving where there are frequent starts and stops, the energy saving may reach about 5% to 10%. The cost of a micro hybrid is only few percent higher than that of conventional vehicle, since the motor is small and the structure is simple. In the market, there is the C3 Citroen micro hybrid using the Valeo motor system.
2) Mild hybrid: The typical electric motor power for a sedan mild hybrid is about 10–20 kW at 100–200 V. In this case, the motor is designed in a flat shape and is directly coupled with the engine. The high ratio of diameter to length of the motor enables the motor to have high inertia such that the original flywheel of the engine can be removed. The motor can join the propulsion as in parallel hybrid architecture. In city driving,

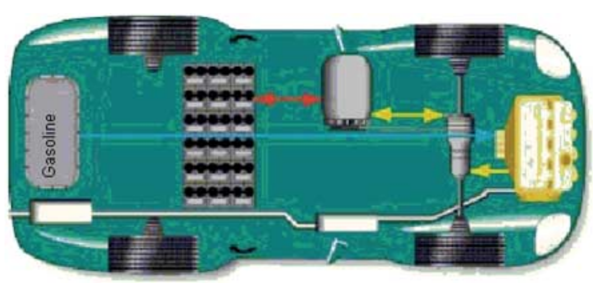

Fig. 4. *Architectures of parallel HEV.*

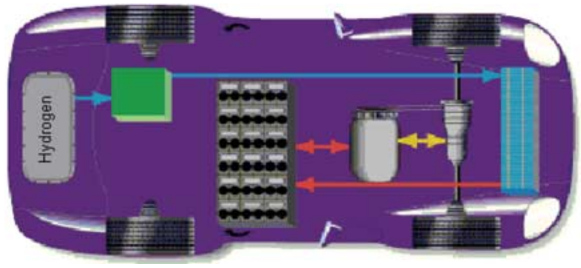

Fig. 5. *Architectures of fuel cell HEV.*

typically it can save energy 20%–30%, but the cost will also increase 20%–30%. Available models are the Honda Civic and Honda Insight that belong to the mild hybrid category.

3) Full hybrid: The typical electric motor power for a full sedan hybrid is about 50 kW at 200–300 V. Normally, there is a motor, generator, and engine, adopting series–parallel or a complex hybrid architecture. With the aid of power split devices such as a planetary gear, the power flow among engine, motor, generator, and battery is flexible in order to achieve optimum drive performance at maximum energy efficiency and minimum emission. The propulsion can be executed by motor only (for start and stop), engine only (for cruising whenever the engine at optimum operation region), or a combination of motor and engine (for sudden acceleration or normal driving when the required propulsion power is less than the engine optimum power range, thus the engine will drive the generator to charge the battery, and hence the engine will deliver more power than the required propulsion power such as that to reach optimum operation region). Typically, a full hybrid in city driving can save energy about 30%–50%, while the cost increases about 30%–40%.

The full hybrid vehicles can be further subdivided into Synergy Hybrid and Power Hybrid. Synergy Hybrid compromises the drive performance, energy efficiency, and emission reduction. In this subcategory, the engine is downsized as compared with conventional vehicle, such as in the Toyota Prius. Power Hybrid is aiming to have better driving performance, thus the engine is not downsized, and with the conjunction of the motor, the vehicle will have better drive performance as compared with a conventional vehicle, such as in the Toyota Highlander.

According to the method of the refueling the energy, HEVs can also be classified into the following categories.

1) Gas station refueling: The vehicle is refueled by gasoline at the gas station. The majority of present HEVs available in the market belong to this category.
2) Plug-In Hybrid (PHEV): The vehicle is mainly refueled by electricity grid. The PHEV can be designed with all-electric ranges of 30–60 km using lithium-ion batteries. The effective energy efficiency of PHEV can be very high and there is zero emission when running at all-electric ranges. PHEV contribute to the independency from oil. Recently, auto makers have paid further attention to PHEV, and its commercial success will mainly depend on the cost of batteries, since PHEV uses more batteries than a gas station refueling HEV.

In summary, presently, the development direction of the HEV is going in two directions. One direction is a full hybrid aiming for high energy efficiency and low emission, but the cost is the major barrier. Another direction is where micro and mild hybrids are aiming for simple structure and low cost. Today, HEVs are sold more in the U.S. and Japan as compared to Europe, since in Europe HEVs will compete with diesel engine vehicles in terms of energy efficiency. Hence, in Europe, micro and mild hybrids would be preferable. PHEV will attract more attention in coming years as the oil reserve becomes limited and the oil prices may continue to increase. Several models of HEV that are available in the market are given in the following.

Fig. 6. *The 2005 Model Prius.*

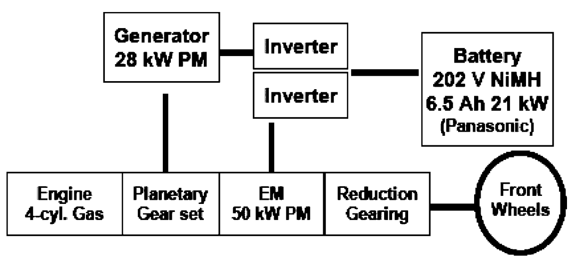

Fig. 7. *Powertrain layout of Toyota Prius.*

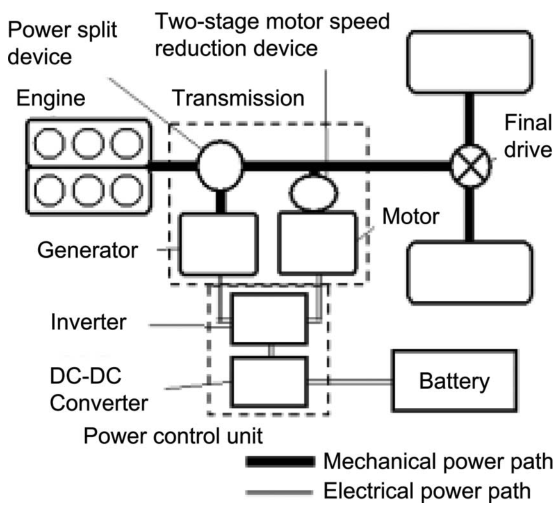

Fig. 8. *Toyota THS-II hybrid system configuration.*

Fig. 9. *Honda Civic.*

A. Toyota Prius

The Toyota Prius is the world's first commercially mass-produced and marketed HEV. It went on sale in Japan in 1997 and worldwide in 2001. In 2005, it sold over 100 000 units in the U.S. alone. In Latin, prius means "before" or "first." The 2000 to 2003 model Prius was certified as a Super Ultra Low Emission Vehicle (SULEV) by the California Air Resources Board (CARB). The 2004 model Prius was redesigned as a midsize hatchback and certified as an Advanced Technology Partial Zero-Emissions Vehicle (AT-PZEV). The third generation of the Prius HEV is between the Corolla and Camry. Prius has won numerous awards including Car of the Year awards for Europe, Japan, and North America.

The Prius uses a planetary gear set as a power splitting device. There are two permanent magnet motors, one primarily used as a motor and the other primarily used as a generator. The 6.5-Ah 21-kW nickel-metal hydride battery is charged by the generator during coasting and by the motor during regenerative braking. The four-cylinder engine is shut off during low vehicle speed. The vehicle has significant fuel improvement over the conventional vehicles, with a remarkable 60 mpg for city and 51 mpg for highway driving.

Toyota has adopted the same technology in its 2006 model Camry, the best selling sedan in North America. Other hybrids from Toyota, such as the Highlander and the Lexus RX400h and RX450h, used the same planetary gear concept, with a third motor added to the rear wheel to further improve the performance of the hybrid vehicle.

Fig. 8 shows the system configuration of the Toyota most recently developed THS-II for front engine, rear-wheel drive system used in the luxury GS 450h hybrid car. The 3.5-l six-cylinder engine, the motors, and the generator are connected through the power split device to drive the rear wheels. The system is based on the THS-II for SUV, but to make it more compact and increase its power, a two-stage motor speed reduction device has been inserted between the motor output shaft and the power split device. This reduction device can select one of two reduction ratios between the motor and the power split device. Therefore, the needed torque to the motor has become small. So, the size of motor has become small, too. This allows the motor to reach a maximum speed of more than 1400 r/min, approximately 1.2 times the maximum speed of the THS-II for SUV system used in the RX 400h. The maximum speed of the generator is set to more than 13 000 r/min, so that it can handle the output of the 3.5-l engine. The specifications of the different units are shown in Table 2.

B. Honda Civic

The Honda Civic hybrid adopts a different topology. The electric motor is mounted between the ICE and the transmission. The 12-kW PM motor either provides assistance to the engine in high vehicle power demand or splits the power of the engine during low vehicle power demand. The hybrid offers 66% and 24% fuel efficiency improvement in city and highway driving over its counterpart, respectively. Honda also has adopted this technology in its Accord hybrid.

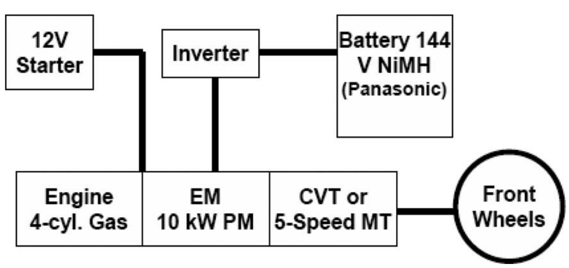

Fig. 10. *Powertrain layout of Honda Civic hybrid.*

Fig. 11. ***Ford Escape SUV hybrid.***

Fig. 13. ***ISE hybrid transient buses.***

C. Ford Escape

Ford produced the first SUV hybrid in the world—the Escape. The Escape hybrid also adopted the planetary gear concept as its power splitting device. With a significantly reduced sized engine, this full size SUV hybrid provides the same performance as its counterpart. The second generation hybrid SUV at Ford, the Mercury Mariner, has an improved power train design which offers exceptional drivability and dynamic performance.

D. Saturn Vue

The Saturn Vue simply added a 4-kW electric motor through a belt to its existing powertrain. The small electric motor is powered by a 36-V 10-kW nickel-metal hydride battery. The motor provides 5 kW of electricity in a generating mode either from the engine during opportunity charging or from the vehicle braking. The surprising 20% fuel economy improvement justifies the small investment into the hybrid. The drawback is that due to the small size motor, the engine cannot be shut off at low vehicle speed. The air conditioning is operated by the engine, therefore, there will be no A/C even though the engine can be turned off during idle.

E. ISE Transient Bus

The transient buses are usually considered ideal candidates for hybridization. The transient buses have fixed routes and are almost driven in the stop-and-go pattern. It is shown that an average 50% or more of fuel can be saved with either parallel or series hybrids.

F. Honda FCX

There has been continuous progress in the fuel cell vehicle development. One of the fuel cell vehicles that has been commercially available is the Honda FCX. In 2002, Honda's FCX was certified by the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB), making it the first and only fuel cell car in history to be approved for commercial use. CARB and the EPA have also certified the FCX as a Zero-Emission Vehicle (ZEV), Tier-2 Bin 1.

The 2005 and 2006 Honda FCX is powered by Honda designed and manufactured fuel cell stacks. With an EPA city/highway rating of 62/51 mpkg (57 mpkg combined), it can achieve an EPA-rated driving range of 210 miles. In terms of energy efficiency, one mile per kilogram (mpkg) of hydrogen is almost equivalent to one mile per gallon (mpg) of gasoline.

Fig. 12. ***Saturn Vue.***

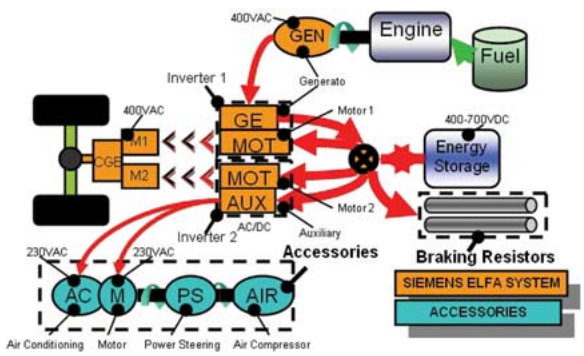

Fig. 14. ***ISE series hybrid system.***

Fig. 15. *Honda FCX fuel cell car.*

VII. KEY TECHNOLOGIES OF EVs, HEVs, AND FCVs

A. Propulsion Motor

Electric motors and drives play an important role in the success of EVs, HEVs, and FCVs. There are three major types of electric motors that are suitable for EV, HEV and FCV applications: 1) PM synchronous or PM brushless motors; 2) induction motors; and 3) switched reluctance motors. Typical requirements for motor and drive technology include: high torque density and power density; wide speed range including constant torque and constant power operations; high efficiency over wide speed range, high reliability, and robustness; all at a reasonable cost.

Induction machines are used for EV, HEV and FCV powertrain due their simplicity, robustness, and wide speed range. Besides, induction machines do not have back emf to deal with at high speeds. Field-oriented control makes an induction machine behave just like the way a dc machine behaves. The efficiency is generally lower than a PM machine due to the inherent rotor loss. For the same reason, the size of an induction machine is generally bigger than a PM machine with the same power and speed rating.

Permanent magnet machines possess unique characteristics such as high efficiency, high torque, and high power density. However, PM motors inherently have a short constant power range due to its rather limited field weakening capability, resulting from the presence of the PM field, which can only be weakened through production of a stator field component, which opposes the rotor magnetic field. Besides, the back emf can be an issue at high speed: the inverter must be able to withstand the maximum back emf generated by the stator winding. In the case of a stator winding short circuit fault, the system can run into problems due to the existence of a rotor PM field.

The switched reluctance motor (SRM) is gaining interest as a candidate of electric propulsion for EVs, HEVs, and FCVs because of its simple and rugged construction, simple control, ability of extremely high speed operation, and hazard-free operation. These prominent advantages are more attractive for traction application than other kinds of machines. However, since SRM is not yet widely produced as a standard motor, its cost may be higher than the induction motor.

B. Power Converters

Typical power electronic circuits used in HEVs include rectifiers, inverters, and dc/dc converters. The issues that need to be addressed in the design of HEV power electronics circuits include:

- *Electrical design*: includes the main switching circuit design, controller circuitry design, switching device selection, switching frequency optimization, and loss calculations;
- *Control algorithm design*: includes the control algorithm design to achieve the desired voltage, current, and frequency at the output, and to realize bidirectional power flow;
- *Magnetic design*: includes the design of inductors, capacitors, and other magnetic components needed for filtering, switching, and the gate driver units;
- *Mechanical and thermal design*: includes modeling the loss of power devices and magnetic components, design of the cooling system, heat sink, and enclosure, and integration of the power electronics unit.

Table 2 Specifications of Generator and Motors

		GS450h	RX400h
Generator	Max. power	134 [kW]	109 [kW]
	Max. speed	More than 13000 [rpm]	More than 13000 [rpm]
	Max. torque	114/-114 [Nm]	110/-80 [Nm]
Motor	Max. power	147 [kW]	123 [kW]
	Max. speed	More than 14000 [rpm]	12400 [rpm]
	Max. torque	275 [Nm]	333 [Nm]
Rear motor	Max. power	-	50 [kW]
	Max. speed	-	10000 [rpm]
	Max. torque	-	130 [Nm]

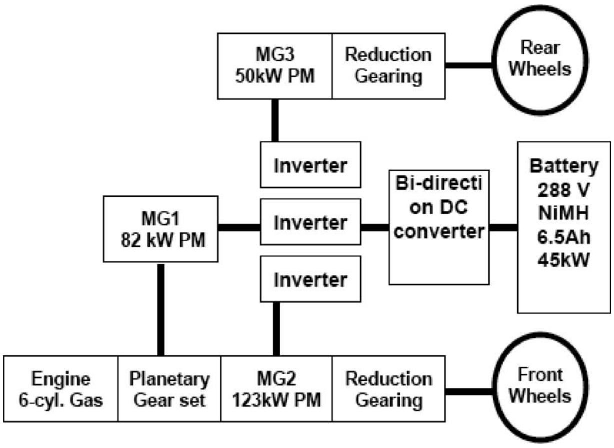

Fig. 16. *Full hybrid SUV with front hybrid powertrain and separate rear motor.*

Fig. 16 shows the configuration of a parallel HEV powertrain used for the Toyota Highlander Hybrid SUV. In this configuration, the front wheel is driven by a hybrid powertrain while the rear wheel is driven by a separate electric motor (MG3) to achieve all-wheel driving capability without the need of a conventional differential. The front hybrid powertrain contains a planetary gear set, an ICE, and two electric machines MG1 and MG2. MG1 serves primarily as a generator to split the engine power, and MG2 serves primarily as a motor to drive the vehicle and recover the regenerating braking energy.

Fig. 17 shows the integrated power electronics unit used to control the hybrid vehicle shown in Fig. 16. The unit consists of a bidirectional dc/dc converter that links the lower voltage hybrid battery and the higher voltage dc bus; three motor drive circuits control the front and rear motor/generators. In addition, there is also a motor drive circuit for the air conditioner (A/C) unit, and a dc–dc converter linking the hybrid battery and the auxiliary battery, which are not shown in the circuit.

There are typically two bidirectional dc–dc converters in hybrid vehicle applications. One of the dc–dc converters is a high-power converter that links the hybrid powertrain battery at a lower voltage with the high-voltage dc bus. A second low-power dc–dc converter links the hybrid battery with the low voltage auxiliary battery.

Fig. 18 shows the electrical system of THS-II for GS450h. It is basically the same boost converter system used in the Prius, and the system voltage is the same 650 V dc that is used in the RX 400h, which has the advantage of

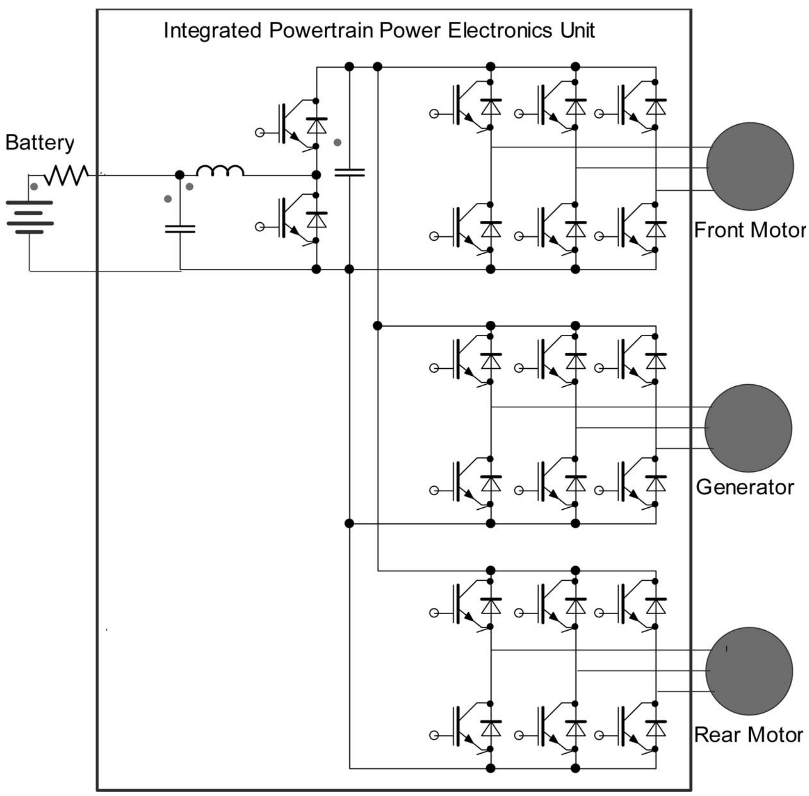

Fig. 17. *Integrated powertrain power electronics.*

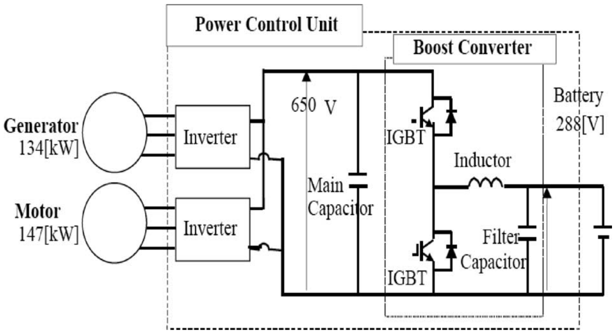

Fig. 18. *High-voltage power system of THS-for GS450h.*

increasing the motor power. The motor and generator are permanent magnet machines. Fig. 19(a) and (b) shows the power characteristics of the motor used in the GS 450h. Raising the system voltage in this way means that the motor power increases as the voltage applied to the motor increases. However, the system parts must be able to withstand the higher voltage. Therefore, an inverter, a boost converter, and a motor were developed to use 650 V for GS 450h. As shown in Fig. 18, the motor power is 147 kW, approximately 1.2 times the RX 400h's 123 kW, but the battery power has been reduced to around 83% as compared with that of RX 400h. The lower battery capacity helps to reduce the weight of the battery and the space it requires, but it also makes maintaining the power balance between the generator and motor more critical than ever. In order to reduce the space required for the inverter, a single capacitor handles both inverter systems. But this means that if the power of motor or generator fluctuates, the resulting fluctuation in the inverter voltage will affect the generator or motor. It is therefore necessary to keep motor power fluctuations to a minimum to avoid this problem.

In the THS-II for the front engine, rear-wheel drive system, it is extremely important to maintain the energy balance between the motors and the generator. The battery and generator must supply power to match what the motors consume, and if too much power is consumed, the excess is drawn from the battery, creating the risk of an overcurrent in the boost converter and a drop in the battery voltage. Particularly, in a high-power motor system, large transient power imbalances occur when the tires slip, and these imbalances must be corrected immediately. Ordinarily, the hybrid CPU controls the power balance by sending torque commands to the motor CPU. But communication delays between the hybrid CPU and the motor CPU sometimes create delays in the hybrid CPU's recognition of how much power the motors are consuming. In a high-power system, this sort of delay would be fatal for the power balance control, so a technique was implemented whereby the motor CPU monitors the power balance to prevent too much power from being consumed. A limit was also set on the amount of power the motors can consume.

C. Hybrid Control Technology

Presently, the hybrid control algorithm is mainly designed by simulation and experience. However, as control is the prime key technology in HEVs, further research on the control theory of hybrid is essential. There are basically two control topics in HEVs. The first is energy management control, aiming to optimize the energy efficiency and emission. Second is drivability control, aimed to optimize drive performance, comfort, and safety performance. Fig. 20 shows the control scheme of parallel hybrid architecture, such as in the Honda Civic. Fig. 21 shows the control strategy and power management for series–parallel or complex hybrid architecture, such as in the Toyota Prius.

From the point of view of control technology, a hybrid system is a discrete event and continuous dynamics. Under these circumstances, what is the performance specification, how to determine the control law, how to determine the torque command, how to distribute the torque command to motor and engine, respectively, what is the proper policy in control strategy decision, and what is the relation

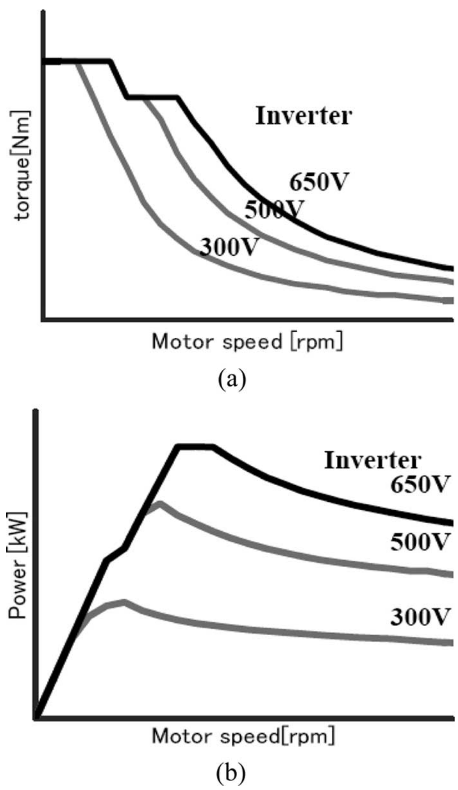

Fig. 19. *Motor characteristics: (a) torque speed and (b) output power speed.*

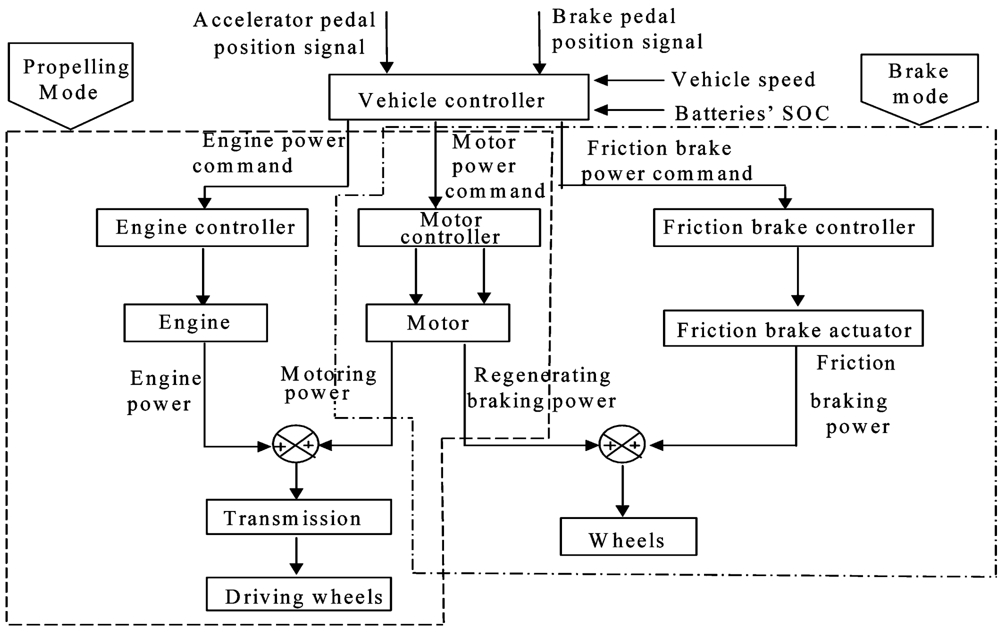

Fig. 20. *Control scheme of parallel HEV.*

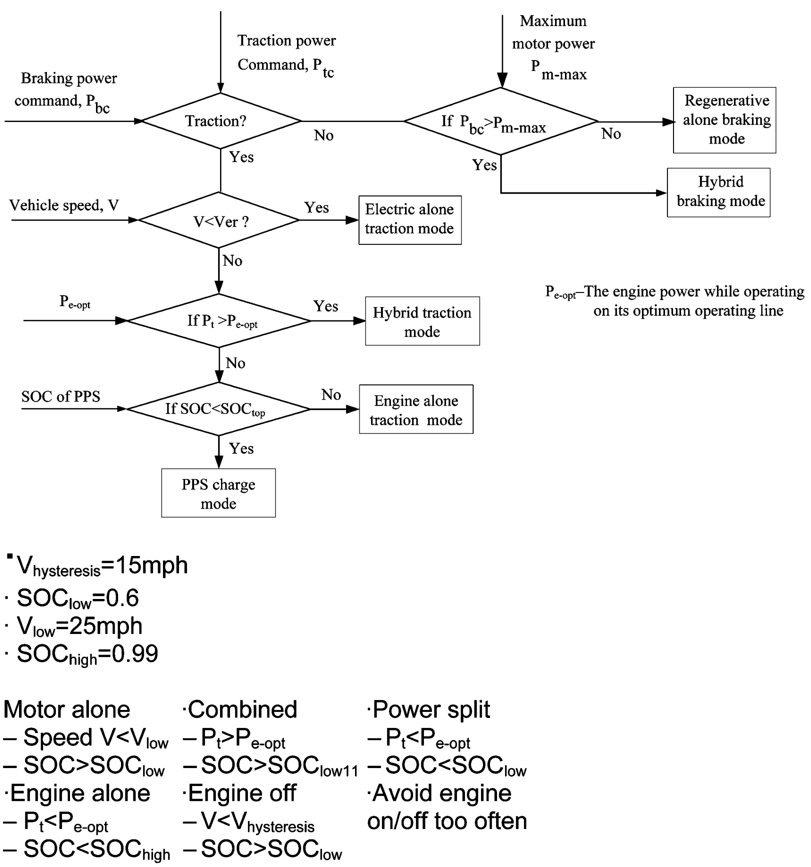

Fig. 21. *Control strategy and power management of HEV.*

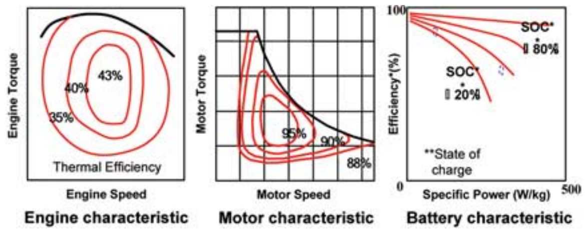

Fig. 22. *Steady-state model of engine, motor, and battery.*

between the control and the performance, are all issues that should be addressed.

Fig. 22 shows the steady-state model of three major components, namely engine, motor, and battery. It is important to ensure that these three major components will operate within their optimum operation region. Furthermore, the dynamic model of these three major components as well as the whole hybrid system must be thoroughly studied.

D. Battery and Ultracapacitors

Batteries and ultracapacitors store energy that is either from the kinetic braking or from the engine during costing. It also provides energy/power to the propulsion system, including during sudden power demand of the vehicle.

Fig. 23 shows the characteristics of batteries, ultracapictors, flywheels, and fuel cell as compared with gasoline. It can be seen that the specific energy of fuel cell is comparable with that of gasoline; however, its specific power is much less than that of gasoline, therefore the starting performance of a fuel cell vehicle could be worse than a conventional vehicle. Consequently, the battery or ultracapacitor may be used in conjunction with the fuel cell to improve the starting performance of the vehicle. Batteries are using electrochemistry principles to store electric energy, as inherently their specific energy is much less than that of gasoline. Ultracapacitors use static electricity principles to store electric power; therefore, they have high specific power. The major difference between battery and fuel cell is twofold. Firstly, a battery is an electric energy storage device, while a fuel cell is an electric energy generation device. A fuel cell combines oxygen and hydrogen to produce electricity. Secondly, secondary batteries are rechargeable and self-contained, while a fuel cell is a complex system including fuel cell stack, heat exchanger, compressor, etc., just like a power plant system. Therefore, fuel cell commercialization is more complex, since it has more auxiliary systems including the hydrogen infrastructure.

The electrical energy storage units must be sized so that they store sufficient energy (in kilowatt hours) and provide adequate peak power (in kilowatts) for the vehicle

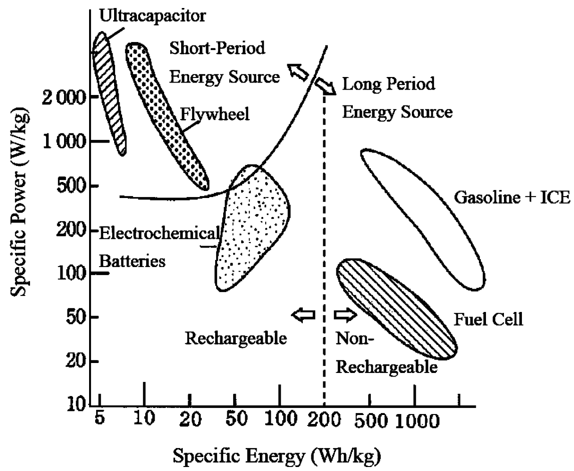

Fig. 23. *Characteristics of various energy sources.*

to have a specified acceleration performance and the capability to meet appropriate driving cycles.

Batteries that are suitable for use in EVs, HEVs, and FCVs include the lead acid battery, nickel-metal hydride battery, lithium-ion battery, etc. Batteries generally have high energy density but less power density compared to ultracapacitors. Ultracapacitors have very high power density but hold very little energy. Hybrid energy storage that combines a battery and an ultracapacitor pack can provide both the power and energy needs of an HEV. Fig. 24 shows the block diagram of hybrid energy storage.

According to the present state of the art of battery technology and the vehicle performance requirements, the following summary on battery and ultracapacitor technologies can be drawn: 1) The energy density and power density characteristics of both batteries and ultracapacitor technologies are sufficient for the design of attractive EVs, HEVs, and PHEVs. The primary questions concerning these technologies are calendar and cycle life and cost. 2) Battery-powered vehicles (EVs) using lithium-ion batteries can be designed with ranges up to 240 km with reasonable size battery packs. The acceleration performance of these vehicles would be comparable or better than conventional ICE vehicles. 3) Charge-sustaining engine powered HEVs can be designed using either batteries or ultracapacitors with fuel economy improvements. The level of fuel economy improvement depends on the size of motor and battery, namely whether micro hybrid or mild hybrid or full hybrid. 4) Plug-in hybrids (PHEVs) can be designed with effective all-electric ranges of 30–60 km using lithium-ion batteries that are relatively small. The effective fuel economy of the PHEVs can be very high, resulting in a large fraction of the energy used by the vehicle being from grid electricity, thus reforming the energy structure and contributing to the independence from oil.

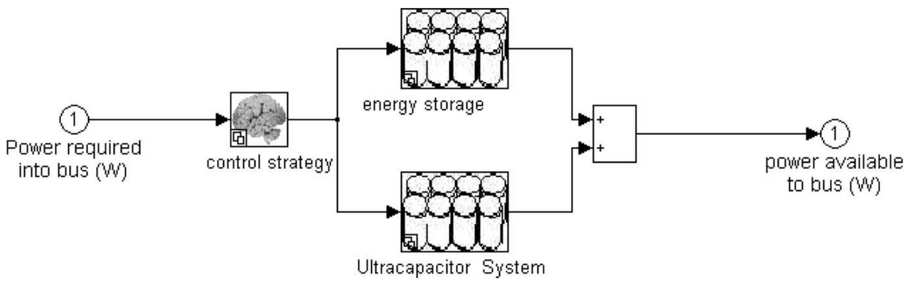

Fig. 24. *Block diagram representation of new battery subsystem that consists of battery and ultracapacitor. Input/output relation with the rest of the system is left unchanged.*

VIII. CONCLUSION

This paper has presented an overview of the state of the art of EVs, HEVs, and FCVs.

With the ever more stringent constraints on energy resources and environmental concerns, HEVs will attract more interest from the automotive industry and the consumer. Although the market share is still insignificant today, it can be predicted that HEVs will gradually gain popularity in the market due to the superior fuel economy and vehicle performance. Modeling and simulation will play important roles in the success of HEV design and development. Control is the prime key technology in HEVs, hence the control theory of HEVs should be further advanced. ■

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