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Introduction

In recent decades, hybrid electric technology has advanced significantly in the automotive industry. It has now been recognized that the hybrid is the ideal transitional phase between the traditional all-petroleum-fueled vehicle and the all-electric vehicles of the future. In popular concepts, a hybrid electric vehicle (HEV) has been thought of as a combination of an internal combustion engine (ICE) and an electric motor.

The most important feature of hybrid vehicle system technology is that fuel economy can be increased noticeably while meeting increasingly stringent emission standards and drivability requirements. Thus, hybrid vehicles could play a crucial role in resolving the world's environmental problems and the issue of growing energy insecurity. In addition, hybrid technology has been a catalyst in promoting the technology of electric motors, power electronics, and batteries to maturity (Powers and Nicastri, 1999; Chan, 2002).

An HEV is a complex system of electrical and mechanical components. Its powertrain control problems are complicated and often have conflicting requirements. Moreover, they are generally nonlinear, exhibit fast parameter variation, and operate under uncertain and changing conditions; for example, the vehicle has to run well on a cold January day in northern Ontario as well as on a sweltering day in Death Valley. Many control design objectives are very difficult to formalize, and many variables that are of the greatest concern are not measurable. The HEV system control is also fundamentally a multivariable problem with many actuators, performance variables, and sensors. It is often important to take advantage of these interactions with multivariable designs; however, multivariable designs may make control strategies less robust to parameter variation and uncertainties, and thus may be more difficult to calibrate. In this book, we will systematically introduce HEVs' control problems from powertrain architecture and modeling to design and performance analysis.

Hybrid Electric Vehicle System Modeling and Control, Second Edition. Wei Liu.

1.1 Classification of Hybrid Electric Vehicles

In order to cover automotive needs, various hybrid electric vehicle concepts have been proposed and developed. According to the degree of hybridization, nowadays hybrid electric vehicles can be classified as micro hybrid, mild hybrid, full hybrid, or plug-in hybrid electric vehicles as well as fully electric vehicles. These hybrid electric vehicles are described briefly in the following sections and a classification summary is given in Table 1.1.

1.1.1 Micro Hybrid Electric Vehicles

Micro hybrid electric vehicles are normally operated at low voltages between 12 V and 48 V. Due to the low operational voltage, the electric power capability is often under 5 kW, and thus micro hybrid electric vehicles primarily have auto start–stop functionality. Under braking and idling circumstances, the internal combustion engine is automatically shut down, so fuel economy can be improved by 5–10% during city driving conditions. With the power capability increase of a 12 V battery, some micro hybrid vehicles even have a certain degree of regenerative braking capability and are able to store the recovered energy in the battery. Most micro hybrid electric systems are implemented through improving the alternator–starter system, where the conventional belt layout is modified and the alternator is enhanced to enable the engine to be started and the battery to be recharged. Valve-regulated lead–acid batteries (VRLAs) such as absorbent glass mat (AGM) batteries and gel batteries are widely used in micro hybrid electric vehicles. The biggest advantage of the micro hybrid vehicle is the lower cost, while the main drawback is the inability to recover all regenerative braking energy.

1.1.2 Mild Hybrid Electric Vehicles

Compared with micro hybrid electric vehicles, mild hybrid electric vehicles normally have an independent electric drivetrain providing 5–20 kW of electric propulsion power, and the electric drive system typically operates at voltages between 48 V and 200 V. Mild hybrid

Table 1.1 The main features and capabilities of various hybrid electric vehicles

Type of vehicle	Features and capabilities				
	Start–stop	Regenerative braking	Boost	Electric-only mode	Electric range (miles)
Micro hybrid	Yes	Possible	No	No	No
Mild hybrid	Yes	Yes	Yes	No	No
Full hybrid	Yes	Yes	Yes	Possible	Possible (<2)
Plug-in hybrid	Yes	Yes	Yes	Yes	Yes (20–60)
Pure electric	Yes	Yes	Yes	Yes	Yes (80–150)

electric vehicles can make use of an electric motor to assist the internal combustion engine during aggressive acceleration phases and enable the recovery of most regenerative energy during deceleration phases. Therefore, mild hybrid electric vehicles have great freedom to optimize vehicle fuel economy and vehicle performance, and improve driving comfort. Mild hybrid electric architecture is often implemented in several ways depending on the degree of hybridization. The belt starter–generator, mechanically coupled via the alternator belt in a similar manner to micro hybrids, and the starter–generator, mechanically coupled via the engine crankshaft, are typical implementations. Nickel–metal hydride and lithium-ion batteries are often employed in mild hybrid electric vehicles. One distinguishing characteristic of mild hybrid electric vehicles is that the vehicle does not have an exclusive electric-only propulsion mode. The fuel economy improvement is mainly achieved through shutting down the engine when the vehicle stops, using electrical power to initially start the vehicle, optimizing engine operational points, and minimizing engine transients. Typical fuel savings in vehicles using mild hybrid drive systems are in the range of 15 to 20%.

1.1.3 Full Hybrid Electric Vehicles

Full hybrid electric vehicles (HEVs) are also called strong hybrid electric vehicles. Here, the electric drive system normally has in excess of 40 kW of power and operates on a voltage level above 150 V for the sake of the operational efficiency of the electrical system and the component/wire size. The electric powertrain of a full hybrid electric vehicle is capable of powering the vehicle exclusively for short periods of time when the combustion engine runs with lower efficiency, and the energy storage system is designed to be able to store the free regenerative braking energy during various deceleration scenarios. These vehicles can also provide a purely electric driving range of up to two miles to meet some special requirements such as silent cruising in certain areas and zero emissions for driving in tunnels and indoors. The ideal application scenario for full hybrid electric vehicles is continuous stop-and-go operation; therefore, they are widely used as city buses and delivery trucks. Compared with traditional internal combustion engine vehicles, the overall fuel economy of a full hybrid electric vehicle in city driving could improve by up to 40%.

1.1.4 Electric Vehicles

Electric vehicles (EVs) are operated with electrical power only. Presently, most electric vehicles employ lithium-ion batteries as the energy storage system, with a plug to connect to the electric grid to charge the battery. The capacity of the energy storage system plays a crucial role in determining the electric driving range of the vehicle. However, enlarging the energy storage capacity would result in an increase in vehicle mass and volume, and would also require quite a long time to charge the battery without a fast-charging facility. Most electric vehicles on the market have an 80–150 mile electric range, while in the near future, 300–400 mile ranges could be achieved with a cutting-edge battery system with more than 80 kWh storage capability.

A major concern with such battery-powered electric vehicles (BEVs) is the range limitation, and technical challenges currently preventing progress with battery-powered electric vehicles include the need to reduce plug-in charging times significantly and to predict the energy remaining in the battery precisely. In the long term, a fuel-cell-powered electric vehicle could be a solution and could emerge on the automotive markets if the remaining technical and economic barriers are overcome and a hydrogen infrastructure established.

1.1.5 Plug-in Hybrid Electric Vehicles

Plug-in hybrid electric vehicles (PHEVs) share the characteristics of both full hybrid electric vehicles and all-electric vehicles with the capability of charging the battery through an AC outlet connected to the electric grid. The electric powertrain of PHEVs normally has an 80–150 kW electrical power capability that allows the vehicle to operate in exclusively electric mode with an electric range of 20–60 miles on most daily driving routes. Similar to BEVs, a PHEV also uses power from the grid to charge the battery. During a driving route, the vehicle normally first operates in electric mode using the energy stored in the battery; once the battery is depleted to a certain level, the internal combustion engine starts to propel the vehicle and the battery provides supplemental electric power and stores regenerative braking energy like a full HEV to improve fuel economy and dynamic performance and also to reduce emissions.

1.2 General Architectures of Hybrid Electric Vehicles

There are two fundamental architectures of hybrid electric vehicles:

1. The series hybrid vehicle, in which the engine, coupled with a generator, powers the generator for recharging the batteries and/or supplying electrical energy to the electric motor. The motor, in turn, provides all torque to the wheels.
2. The parallel hybrid vehicle is propelled by either an engine or an electric motor, or both. The electric motor works as a generator to recharge the batteries during regenerative braking or when the engine is producing more power than is needed to propel the vehicle.

Although possessing the advantageous features of both series and parallel HEVs, the series–parallel HEV is relatively more complicated and costly. Nevertheless, this system has been adopted by some modern HEVs, as advanced control and manufacturing technologies can be applied.

1.2.1 Series Hybrid

A series HEV, as shown in Fig. 1.1, has power sources in electromechanical series. The electric powertrain only provides propulsion power to the drive wheels, and an

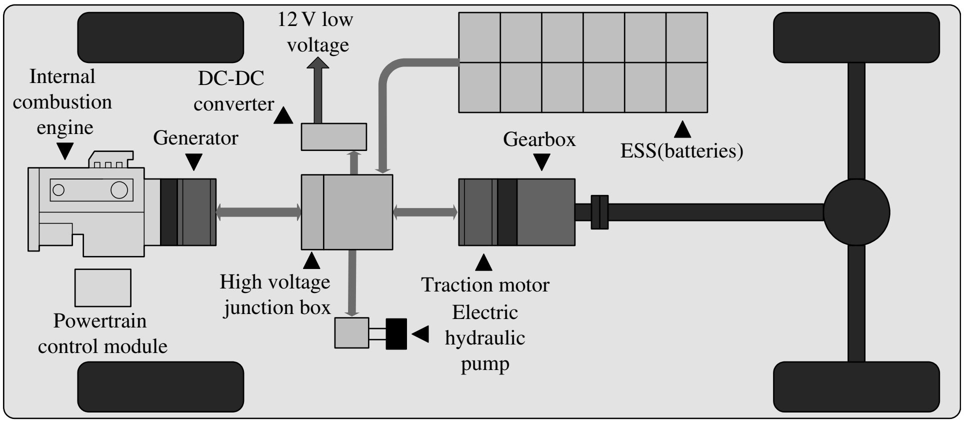

Figure 1.1 A rear-wheel-drive series hybrid electric vehicle layout

engine–generator pair unit (genset) provides electrical power and energy with a high-voltage bus. The energy storage system (ESS) is charged or discharged to achieve optimal fuel economy, while the electric motor propels the vehicle to realize vehicle performance requirements. Therefore, in simple terms, a series hybrid vehicle is an electric vehicle with a genset to supply electrical energy when the ESS lacks sufficient energy to power the vehicle.

Because of the simplicity of dynamic control, this type of hybrid vehicle has many practical uses, especially in the form of heavy/medium-duty delivery trucks and shuttle buses. In this type of system, the primary function of the genset is to extend the range of the electric vehicle beyond what is possible with the battery alone. The key technical challenge of this type of hybrid electric vehicle is to manage energy sources and power flow optimally.

1.2.2 Parallel Hybrid

In contrast to a series HEV, a parallel HEV essentially blends ICE power output with electric motor/generator power output. There are multiple potential points connecting these two power sources to the drivetrain depending on the availability of the components. In a parallel HEV configuration, as shown in Fig. 1.2, an electric powertrain system is added to the conventional powertrain system through a clutch that enables the vehicle to be driven by the electric motor or engine either separately or together. The maximal power rating of the electric powertrain is normally smaller than that of the engine powertrain in a parallel hybrid vehicle. The size of the electric powertrain is determined such that the electric motor and ESS can deliver the required power for a given drive cycle. In addition, the conventional powertrain must be able to provide sufficient flexible torque that can be smoothly and efficiently combined with the torque from the electric motor to meet the torque requirements to propel the vehicle. The engine may be turned on and off frequently in response to the system control strategy.

1.2.3 Series–Parallel Hybrid

The series–parallel architecture is a combination of the two described above. The electric motor, the electric generator, the internal combustion engine, and the wheels of the vehicle can be linked together through a device such as a planetary gear set. Figure 1.3 shows a conceptual layout of the series–parallel hybrid vehicle system, in which the power provided by the engine is split up and transmitted to the wheels through two paths: *series* and *parallel* paths. The *series path* leads through the electric generator jointed with the ESS to the electric motor to the wheels. In this path, the mechanical power of the engine is converted to electrical power through the generator, and the electrical power can partly flow to the ESS or

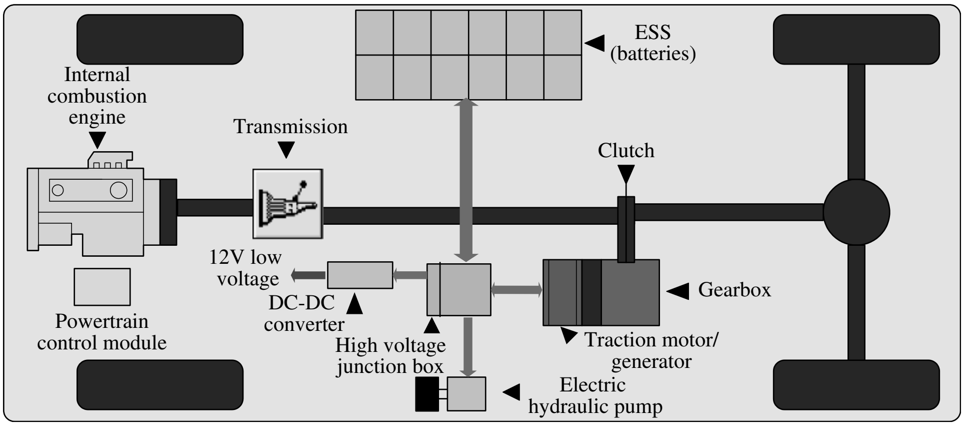

Figure 1.2 A rear-wheel-drive parallel hybrid electric vehicle layout

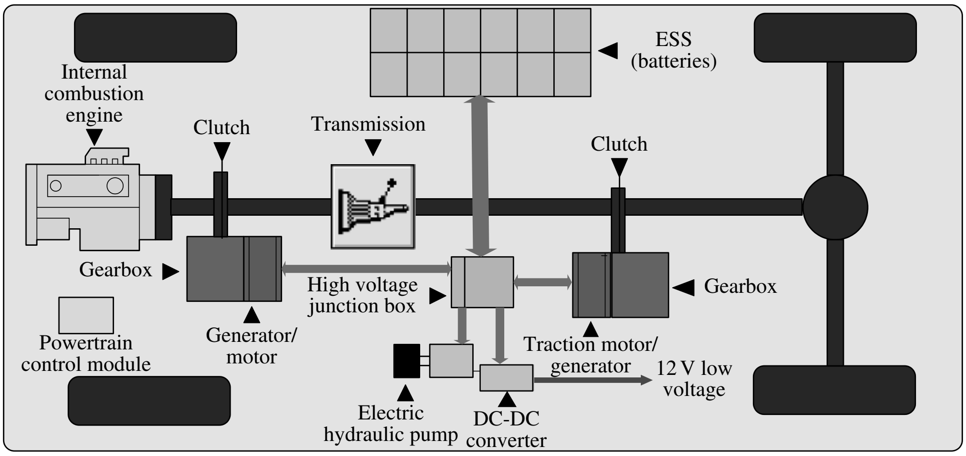

Figure 1.3 A rear-wheel-drive series–parallel hybrid electric vehicle layout

entirely to the wheels through the electric driveline. In the second path, the *parallel path*, the engine is connected through a gear set to the conventional drivetrain. In this path, the mechanical power of the engine is partly or entirely transmitted mechanically to the wheels, and the part not transmitted to the wheels is converted to electrical power through the electric motor to charge the battery. If the entire mechanical power of the engine cannot meet the vehicle's power demand, the electric motor drivetrain supplies supplemental power to the wheels. The series–parallel hybrid electric configuration acts at all times as a combination of the series and parallel configurations. It allows the electric motor drivetrain to adjust the engine load to achieve optimal fuel economy. The percentage of power flowing through the series and parallel paths is determined in real time to achieve the optimal vehicle performance. Although the power flow can be set by controlling the speeds of the planetary gear set, a sophisticated control system is needed to control the power flow to achieve the best fuel efficiency.

The comparison of series and parallel architectures described above leads to the conclusion that, in city driving conditions, series hybrid behavior is preferable, while in highway driving conditions, a parallel hybrid action is generally desired. Therefore, the series–parallel hybrid architecture combines the positive aspects of the series hybrid architecture – the independence of the engine operation from the driving conditions – with the advantage of the parallel hybrid architecture – efficient mechanical transmission. The complexity of the control task for the series–parallel configuration is the main distinct point compared to the individual series or parallel systems.

1.3 Typical Layouts of the Parallel Hybrid Electric Propulsion System

The basic parallel hybrid electric architecture shown in Fig. 1.2 is actually often implemented in several ways. There are several mechanical points in the drivetrain that can be used to implement hybridization. Figure 1.4 shows typical parallel hybrid arrangements. Based on the location of the hybrid joint points, these parallel hybrid architectures are called P0, P1 … P4, respectively from front to rear.

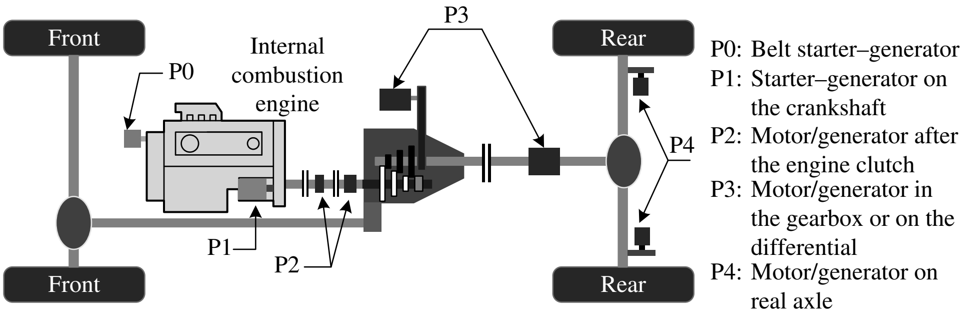

Figure 1.4 Typical parallel hybrid electrified powertrain arrangements

The P0 hybrids are commonly implemented through an enhanced belt starter–generator system to handle frequent start–stop operation. The P1 hybrid joint point is on the crankshaft, where the starter in a traditional vehicle is replaced by a starter–generator which can support start–stop and recover some regenerative braking energy. P0 and P1 are typical architectures of micro hybrid electric vehicles and a 12 V battery system is normally employed as the energy storage device. The P2 hybrid joint is on the input gear shaft of the transmission; most mild hybrid electric vehicles use the P2 architecture, and a set of planetary gears is usually employed to distribute ICE power and electric motor power to the output shaft of the transmission. Compared with P2 architecture, the hybrid joint of P3 is on the transmission output shaft. Since the electric motor is mounted on the output shaft, the propulsion efficiency is improved. P2 and P3 are often combined in strong hybrid electric vehicles, and multiple operational modes can be implemented to achieve superior fuel economy and performance in either city driving or highway driving. Since the motor/generators are mounted on the rear axle, P4 architecture is the most efficient implementation to recover regenerative braking energy and boost the vehicle. This type of parallel hybrid is also called parallel-through-road, since the ICE power and electric motor power are coupled through the road. Therefore, the battery can only be charged when the vehicle is running; that is, the ability to recharge the battery is limited.

1.4 Hybrid Electric Vehicle System Components

Compared with traditional vehicles, the ESS, electric motors, transmission systems, and power-electronics-related components such as converters and inverters are key components in hybrid vehicle systems. In order to size these components and analyze hybrid system performance, it is necessary to establish their models based either on physical principles or test data.

- **The ESS:** This is one of the most important subsystems in hybrid vehicles, which directly affects the efficiency and other performance factors of the vehicle. In hybrid vehicle applications, the batteries need to have high energy density, low internal resistance, and long cycle and calendar life. Depending on the design objective, higher power density batteries are generally used for traditional HEVs and higher energy density batteries are needed for plug-in HEVs. Another energy storage component attracting R&D attention for HEV applications is the ultracapacitor, which lasts indefinitely and has extremely high charge and discharge rates. These advantages make ultracapacitors ideal for providing the surges required for accelerating an electrically powered vehicle and for accumulating charges during regenerative braking. Due to their low energy density and high self-discharge rates, ultracapacitors are not considered as an energy storage device for plug-in HEVs. However, the combination of ultracapacitors and higher energy density batteries may have considerable potential for all types of HEV, as this combination has both power and energy density advantages and decreases the size of the entire ESS. On the other hand, with significant reductions in manufacturing cost, lithium-ion (Li-ion) batteries have been widely regarded as the best choice for hybrid and purely electric vehicles.

- **Transmission:** Hybrid vehicle systems carry some specific demands for transmission design. Generally speaking, the hybrid vehicle transmission must be able to manage ICE driving, electric-only driving, and combinations of the two. Functionally, it has to support functions of stop–start, regenerative braking, and shifting the operational zone of the ICE; furthermore, the transmission must also be able to adjust its parameters to match the actual drive scenarios. That is, a hybrid vehicle system mainly relies on the transmission to implement an optimal performance for multiple types of drive cycle rather than a particular cycle. Other challenges for hybrid transmission design include minimizing additional weight, cost, and packaging.
- **Electric motors:** Efficient, light, powerful electric motors also play a key role in hybrid technology. Depending on the architecture of an HEV, the electric motor can be used as a peak power regulation device, a load-sharing device, or a small transient source of torque. Electric motors also operate well in two modes – normal mode and extended mode. In the 'normal' mode, the motor exerts constant torque throughout the rated speed range. Once past the rated speed, the motor enters its 'extended' mode, in which torque decreases with speed. In HEVs, the electric motor is primarily designed to deliver the necessary torque for adequate acceleration during its normal mode before it changes to its extended mode for steady speeds. Depending on the design objectives, direct current (DC), brushless DC, and alternating current (AC) induction motors can be selected for HEVs.

  The second function of electric motors is to capture the energy from regenerative braking. The electric motors for HEV applications need to have the capacity to operate equally well as a generator when driven by some external rotational force. Applying the brake pedal in an HEV normally signals to the control system for the motor to generate negative torque, switch off the ICE or let the vehicle's momentum drive the electric motor via the drivetrain. In the case where the electric motor generates negative torque, the mechanical energy of the vehicle will be converted to AC electrical energy by the motor, and then the inverter system on the motor assembly will invert the AC to DC to recharge the battery system. The control system tasks include optimizing the regenerative braking strength in combination with activating the conventional hydraulic braking system in accordance with the pressure applied to the brake pedal. Gentle deceleration generally maximizes the use of the regenerative system, but emergency braking sometimes needs to utilize the conventional braking system. As stop–start urban driving involves frequent acceleration and deceleration, the regenerative braking system and control strategy are crucial technologies for the improvement of the fuel efficiency of a hybrid vehicle.
- **Power electronic components:** In addition to batteries, electric motors, and the transmission, DC–DC converters and DC–AC inverters are key components in hybrids. The function of a DC–DC converter in HEVs/EVs is to convert the high voltage supplied by the ESS to a lower voltage, which normally supplies 12 V electrical power to various accessories such as headlamps and wipers. The function of the inverter in HEVs/EVs is to convert the DC voltage of the ESS to a high AC voltage to power the AC electric propulsion motor. Under regenerative braking, this process is reversed; the output AC power of the motor, operating as a generator, is converted to DC power to charge the battery. The efficiencies of these power electronic components have significant impact on the overall efficiency of the vehicle.

1.5 Hybrid Electric Vehicle System Analysis

1.5.1 Power Flow of Hybrid Electric Vehicles

Different types of HEV configuration have different power flow paths. In series hybrid power flow, as shown in Fig. 1.5, the propulsion power comes from an electric motor which converts electrical energy into the mechanical energy required by the vehicle, while the motor can be powered by either a generator or the ESS. The engine and generator pair can either power the electric motor or charge the ESS. During regenerative braking, the motor works as a generator which converts braking mechanical energy into electrical energy to charge the ESS. When cranking the engine, the battery will provide electrical energy to the generator. In parallel hybrid power flow, the vehicle can be powered by either the engine or the electric motor or both, depending on the system state and the control objectives. During regenerative braking, the captured braking energy will be converted into electrical energy by the electric motor and stored in the ESS. The ESS will power the motor/generator to crank the engine when the key starts. The power flow path of a parallel hybrid system is shown in Fig. 1.6.

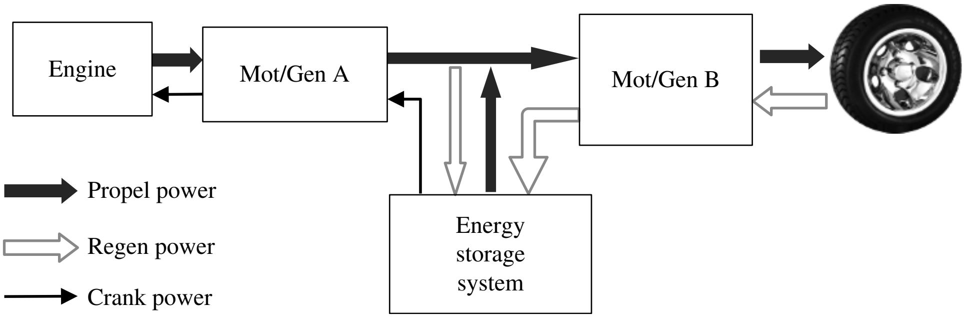

Figure 1.5 Power flow of a series hybrid electric vehicle

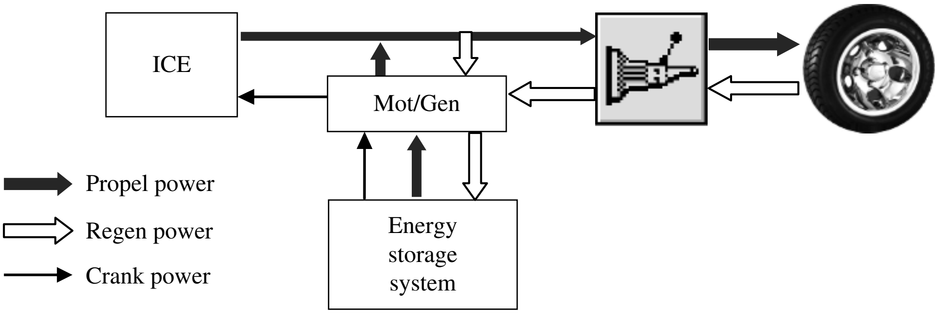

Figure 1.6 Power flow of a parallel hybrid electric vehicle

1.5.2 Fuel Economy Benefits of Hybrid Electric Vehicles

Figure 1.7 illustrates the fuel economy improvement of a P2-type hybrid electric vehicle from an ICE-only conventional vehicle in typical urban cycles. For one unit of energy to be delivered at the wheels, if we assume that the final drive efficiency is 92%, the transmission efficiency is 85%, and the conversion efficiency of fossil fuel energy to mechanical energy is about 28% for an ICE in the conventional powertrain, 4.6 units of fossil energy are required to propel the vehicle in a typical urban cycle, shown by the dotted lines in Fig. 1.7. Typically, 60% of the energy at the wheels is consumed by aero drag and rolling resistance and the other 40% is converted into kinetic energy and eventually consumed by braking in urban cycles. Since the overall vehicle mass increases with hybridization, to achieve the same performance as a conventional vehicle, the hybrid vehicle requests 1.05 units of energy at the wheels. However, most kinetic energy consumed by braking in a conventional vehicle can be recovered by regenerative braking in a hybrid electric vehicle.

As shown by the dashed line in Fig. 1.7, there is 0.38 of a unit of energy available at the wheels for regenerative braking; this amount of energy is reduced to 0.35 of a unit at the output shaft of the transmission, and further reduced to 0.3 of a unit when it reaches the motor/generator shaft due to efficiency loss. If we assume that the one-way efficiencies of the motor/invertor and the battery are 92% and 96% respectively, the 0.38 of a unit of regenerative energy at the wheels will be converted into 0.26 of a unit of chemical energy stored in the battery, which can contribute 0.23 of a unit of mechanical energy at the input shaft of transmission to propel the vehicle afterwards.

On the other hand, the second electrical power source provides the opportunity to operate the ICE in optimal states and shut down the ICE when the vehicle is still, which saves about 0.68 of a unit of fossil fuel energy. Overall, the hybridization shown can improve fuel economy by about 24% in typical urban cycles, shown by the pale grey line in Fig. 1.7.

1.5.3 Typical Drive Cycles

Since a vehicle's fuel economy and emissions are strongly affected by environmental factors such as road condition, traffic, driving style, weather, etc., it is not a good idea to try and judge whether a vehicle really improves fuel economy or emissions based on actual fuel consumption and emissions measured on the road. To get around this problem, the automobile industry and governments have developed a series of standard tests whereby the fuel consumption and emissions of a vehicle can be measured under completely repeatable conditions, and different vehicles can be compared fairly to each other. These tests are described as drive cycle tests and are conducted as a matter of routine on all new car designs. Most drive cycle tests will be described in Chapter 10.

1.5.4 Vehicle Drivability

Drivability can be understood as the capacity of a vehicle to deliver the torque requested by the driver at the time expected. It is often evaluated subjectively but can also be quantified

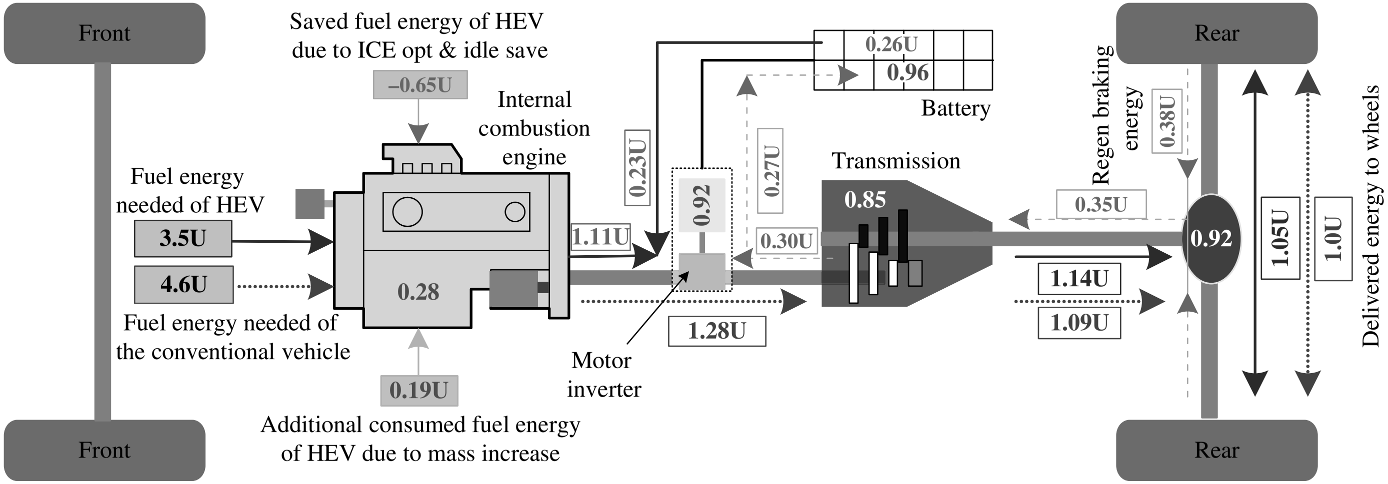

Figure 1.7 Typical urban cycle energy flows of a conventional powertrain and a hybrid electrified powertrain

objectively through accelerometers. Problems such as hesitation, powertrain excitation during acceleration (acceleration pedal tip-in) and deceleration (acceleration pedal back-out) maneuvers are identified in this attribute. Compared with conventional vehicles, hybrid vehicles have more operational modes. The delivered torque is associated not only with the states of the internal combustion engine (ICE), the electric motor/converter and the ESS, but also with the energy management strategy determining how to split the vehicle's required power between the ICE and the electric motor. In order to achieve the maximal fuel economy and meet emission standards under different driving situations, an HEV has to employ more complex control strategies to meet the drivability requirements. The complexity of the control and powertrain systems makes it a challenge to analyze an HEV's drivability.

1.5.5 Hybrid Electric Vehicle Fuel Economy and Emissions

The actual fuel consumption and emissions of ICE-driven vehicles can be measured directly. Since HEVs, especially plug-in HEVs, can make use of an external electrical source (such as the public grid), the electrical energy withdrawn from that source must be separately accounted for when performing fuel consumption and emissions calculations.

1.6 Controls of Hybrid Electric Vehicles

Since a hybrid vehicle is a complex system of electrical and mechanical components which contains multidisciplinary technologies, modern control system techniques and methodologies are playing important roles in hybrid technology (Powers and Nicastri, 1999). An HEV's performance is affected by many interrelated multidisciplinary factors; therefore, advanced control strategies could significantly improve its performance and lower its costs. The overall control objective of a hybrid vehicle is to maximize fuel economy and minimize emissions. In order to achieve the objectives, some key system variables must be optimally governed; these primarily include the energy flow of the system, the availability of energy and power, the temperatures of subsystems, and the dynamics of the engine and the electric motor. Some typical HEV control issues are as follows:

- **Make sure the ICE works at the optimal operating points:** Each ICE has optimal operating points on its torque–speed plane in terms of fuel economy and emissions. If the ICE operates at these points, maximal fuel economy, minimal emissions, or a compromise between fuel economy and emissions can be achieved. Ensuring that the HEV's ICE operates at these points under various operating conditions is a challenging control objective.
- **Minimize ICE dynamics:** As an ICE has inertia, additional energy is consumed to generate the related kinetics whenever the operating speed changes. Therefore, the operating speed of the ICE should be kept constant as much as possible and any fast fluctuations should be avoided. HEVs make it possible to minimize the dynamics under changing load, road, and weather conditions.

- **Optimize ICE operational speed:** According to the working principle of an ICE, its fuel efficiency is low if the ICE operates at low speed. The ICE speed can be independently controlled with the vehicle speed and can even be shut down when its speed is below a certain value, in order to achieve maximal benefits.
- **Minimize ICE turn on/off times:** The ICE in an HEV can be turned on and off frequently as it has a secondary power source; furthermore, the times at which the ICE is turned on/off can be determined based on an optimal control method to minimize fuel consumption and emissions.
- **Optimally manage the battery's state of charge (SOC):** The battery's SOC needs to be controlled optimally so that it is able to provide sufficient energy to power the vehicle and accept regenerative energy during braking or while traveling downhill as well as maximizing its service life. The simplest control strategy is to turn the ICE off if the battery's SOC is high and turn the ICE on if the SOC is too low. A more advanced control strategy will be able to regulate the output power of the ICE based on the actual SOC level of the ESS.
- **Optimally control the voltage of the high-voltage bus:** The actual voltage of the high-voltage bus of an HEV has to be controlled during discharging and charging to avoid being over or under limits; otherwise, the ESS or other components may be permanently damaged.
- **Optimize power distribution:** Since there are two power sources in an HEV, the most challenging and important control task is to split the vehicle's power demand between the ICE and the electric motor based on the driving scenario, road and weather conditions, as well as the state of the ESS, to achieve the best fuel economy, minimal emissions, and maximal service life of the ESS.
- **Follow zero emissions policy:** In certain areas such as tunnels or workshops, some HEVs may need to be operated in the purely electric mode.
- **Optimally control the HEV transmission system:** The most recent HEV systems not only possess the features of the parallel hybrid but also incorporate unique advantages of the series hybrid. The key for this implementation is to employ an advanced transmission system that provides at least two mechanical transmission channels through the clutch control. In city driving, the HEV system maximally uses the advantage of a series hybrid. If full-throttle acceleration is needed, the required power is simultaneously delivered by the ICE and the electric motor, but the ICE is operated at steady speed as much as possible. While the vehicle is driving normally, the power is collaboratively fed by the ICE and the electric motor to achieve the maximal fuel economy.

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