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INTRODUCTION

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

The paramount importance of hybrid vehicle system technology is that the fuel economy can be noticeably increased while meeting the increased stringent emission standards and drivability requirements. Thus, hybrid vehicles can play a crucial role in resolving the world's environmental problems and growing energy insecurity. In addition, hybrid technology has been promoting the technology of the electric motor, power electronics, and batteries to maturity (Chan, 2002; Powers and Nicastri, 2000).

The 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 a sweltering day in Death Valley. Many of the control design objectives are very difficult to formalize and many of the variables of greatest concern are not measurable. The HEV system control is a fundamentally 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

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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 the HEV control problems, from powertrain architecture and modeling to design and performance analysis.

1.1 GENERAL ARCHITECTURES OF HYBRID ELECTRIC VEHICLE

There are basically two different hybrid architectures: (i) The series hybrid, in which the engine, coupled with a generator, powers the generator that recharges the batteries and/or supplies electric energy to the electric motor. The motor, in turn, provides torque to the wheels. (ii) The parallel hybrid vehicle is propelled by either the engine or the 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 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 architecture has been used in some modern HEVs as advanced control and manufacturing technologies can be applied.

1.1.1 Series Hybrid

A series HEV, as shown in Fig. 1-1, has power sources in electromechanical series. The electrical powertrain only provides propulsion power to the drive wheels, and an engine–generator pair unit (Genset) recharges the energy storage system (ESS) that provides energy to the electrical powertrain. Therefore, generally speaking a series hybrid vehicle is an electric vehicle with a Genset to supply electrical energy when the vehicle's battery lacks sufficient energy to power the vehicle.

Because of the simplicity of its control, this type of hybrid vehicle can be found in practical uses, especially in heavy/medium-duty delivery trucks and shuttle

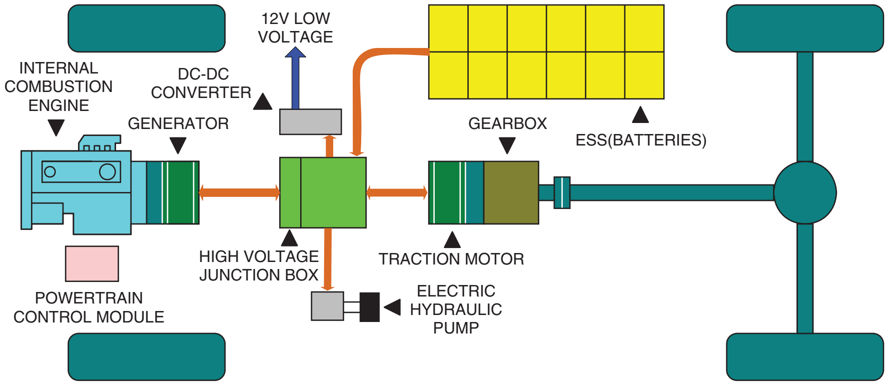

Fig. 1-1. Rear-wheel-drive series hybrid electric vehicle layout.

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 on a battery alone. This type of HEV can globally optimize the energy sources, but the implementation cost is high.

1.1.2 Parallel Hybrid

In contrast to the series HEV, a parallel HEV 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 availabilities of the components. In a parallel HEV configuration, shown in Fig. 1-2, an electrical powertrain system is connected to the conventional powertrain system through a clutch that enables the vehicle to be driven by the electric motor or engine separately or together. The maximum power rating of the electrical powertrain is normally smaller than that of the engine-based conventional powertrain in a parallel hybrid vehicle. The principle of sizing the electric powertrain is 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 of propelling the vehicle. The engine may be turned on and off frequently in response to the system control strategy.

1.1.3 Series–Parallel Hybrid

In a series–parallel configuration the electric motor, the electric generator, the internal combustion engine, and the wheels of the vehicle can be linked together through one or multiple planetary gear sets or other devices. Figure 1-3 shows the series–parallel configuration in which the power provided by the engine gets split and transmitted to the wheels through two paths: series and parallel. The

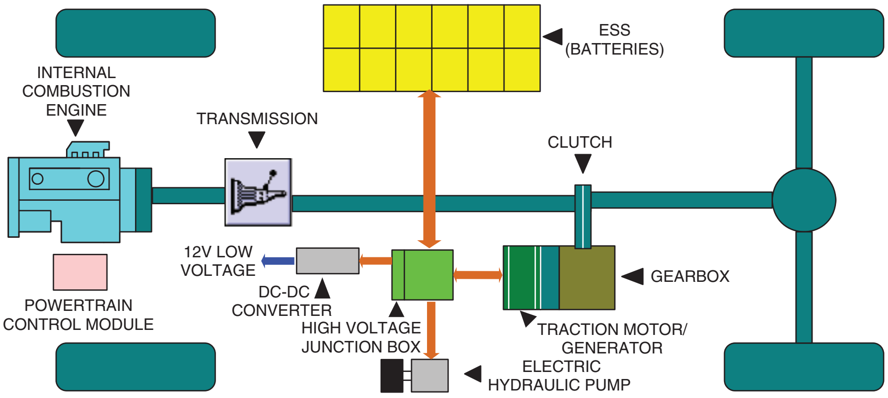

Fig. 1-2. Rear-wheel-drive parallel hybrid electric vehicle layout.

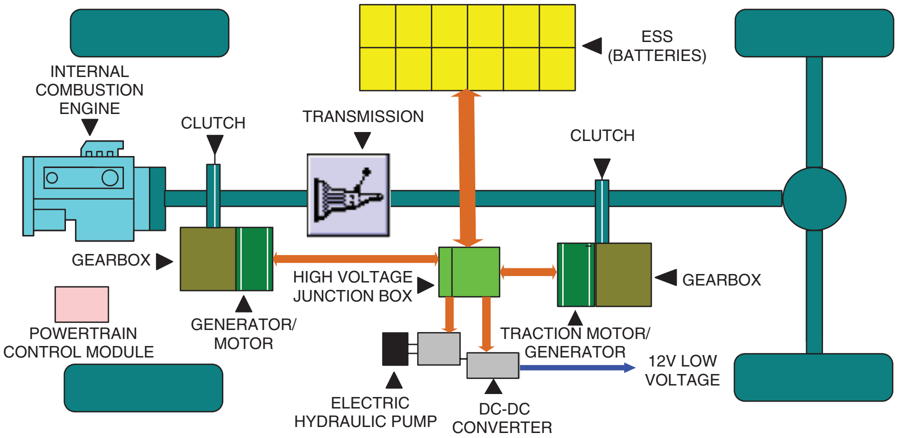

Fig. 1-3. Rear-wheel-drive series–parallel hybrid layout.

series path leads through the electric generator connected to the ESS to the electric motor to the wheels. In this path, the mechanical power of the engine gets converted to electric power through the generator, and the electric power can partly flow to the ESS or entirely to the wheels through the electrical driveline. In the *parallel path*, the engine is connected through the ring gear 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 will be converted to electric power through the electric motor to charge the battery; if the entire mechanical power of the engine cannot meet the vehicle demand power, the electric motor drivetrain will supply additional torque to the wheels. The series–parallel hybrid electric configuration acts at all times as a combination of the series and the parallel configurations. It allows the electric motor drivetrain to adjust the engine load to achieve the optimal fuel economy. The percentage of power flowing through the series and parallel paths determines the performance of a series–parallel hybrid vehicle. Although the power flow can be set by controlling the speed of the planetary gear set, a sophisticated control system is needed to control the power flow to achieve the best fuel efficiency.

The above comparison of the series and parallel configurations leads to the conclusion that, in city driving conditions, series hybrid behavior is preferable but, during highway driving conditions, a parallel hybrid action is generally desired. Therefore, the series–parallel configuration combines the positive aspects of the series configuration—independence of engine operation from the driving conditions—with the advantage of the parallel configuration—efficient mechanical drivetrain. The complexity of the control task for the series–parallel configuration is the main distinct point compared to the series or parallel system.

1.2 HYBRID VEHICLE SYSTEM COMPONENTS

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

(a) *The ESS* One of the most important subsystems in hybrid vehicle, the ESS directly affects the efficiency 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 rapid charge and discharge rates. These advantages make ultracapacitors ideal for providing the surges required for accelerating an electrically powered vehicle and for efficiently accumulating charge during regenerative braking. Due to the low energy density and high self-discharge rate, ultracapacitors are not considered an energy storage device for plug-in HEVs. However, the combination of ultracapacitors and higher energy density batteries may have considerable potential for all HEVs as it both provides power and energy density advantages and decreases the size of the entire ESS. On the other hand, with significant reduction in manufacturing cost, lithium-ion (Li-ion) batteries have been widely regarded as the best choice for hybrid and pure electric vehicles.

(b) *Transmissions* Hybrid vehicle systems bring 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 ICE working range; therefore, the transmission must also be able to adjust its parameters to match the actual driving scenarios. That is, a hybrid vehicle system mainly relies on the transmission to implement optimal performance for multiple types of drive cycles rather than a particular cycle. Other challenges for hybrid transmission design include minimizing additional weight, cost, and packaging.

(c) *Electric Motors* Efficient, light, powerful electric motors also play key roles 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. The HEV electric motors need to operate well in two modes—normal and extended. In the "normal" mode, the motor exerts constant torque throughout the rated speed range. Above the rated speed, the motor enters its "extended" mode in which torque decreases with speed. In HEVs, the electric motor delivers 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 alternative 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 the control system motor to generate negative torque, switch off the ICE, or let the vehicle's momentum drive the electric motor via the drivetrain. When the electric motor generates negative torque, the mechanical energy of the vehicle will be converted to AC electric energy by the motor, and then the inverter system on the motor assembly inverts the AC to DC to recharge the battery system. The control system tasks include optimizing the regenerative braking strength while 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 for improving the fuel efficiency of a hybrid vehicle.

(d) *Power Electronic Modules* Similar to batteries, electric motors, and transmissions, DC–DC converters and DC–AC inverters are very important devices in hybrids. The function of the 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 electric 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 high AC voltage to power 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 devices have significant impact on the overall efficiency of the vehicle.

1.3 HYBRID VEHICLE SYSTEM ANALYSIS

1.3.1 Power Flow of Hybrid Vehicles

Different types of HEV configuration have different power flow path. In series hybrid power flow, shown in Fig. 1-4, the propulsion power comes from the electric motor which converts electric energy to the required mechanical energy, while the motor can be powered by either the generator or the ESS. The engine–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 to electric energy to charge the ESS. When cranking

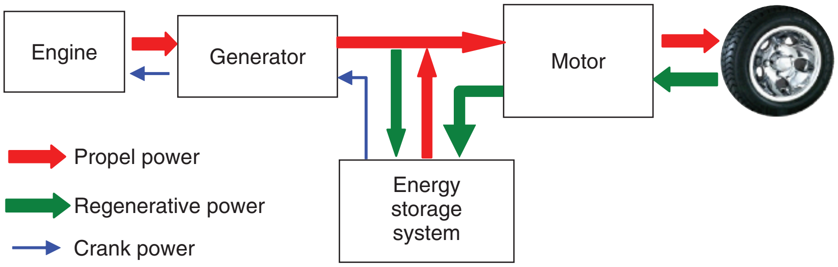

Fig. 1-4. Power flow of series hybrid vehicle.

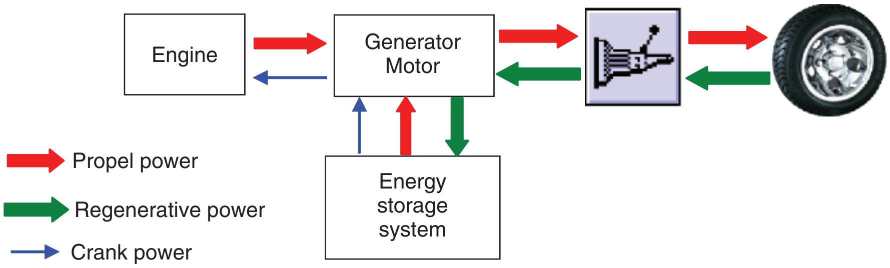

Fig. 1-5. Power flow of parallel hybrid vehicle.

the engine, the battery will provide electric energy to the generator which works as a motor. In a parallel hybrid, the vehicle can be powered by either the engine or electric motor or both depending on the system state and control objectives. During regenerative braking, the captured brake energy will be converted into electric energy by the electric motor and stored in the ESS. The ESS will power the Generator/motor to crank the engine when key started. The power flow path of a parallel hybrid system is shown in Fig. 1-5.

1.3.2 Typical Drive Cycles

Since the vehicle's fuel economy and emissions are strongly affected by environmental factors such as road condition, traffic, driving style, and weather, it is not a good way to judge a vehicle's 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 to measure the fuel consumption and emission of a vehicle under repeatable conditions where different vehicles are compared fairly to each other. These tests are called drive cycle tests and are routinely conducted on all new car designs. Most test drive cycles will be described in Chapter 9.

1.3.3 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 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 ICE, electric motor/converter, and ESS but also with the energy management strategy determining how to divide the vehicle required power between the ICE and the electric motor. To achieve the maximum 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.

1.3.4 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 electric source (such as the public electric grid), the electric energy withdrawn from that source must be separately accounted for when performing fuel consumption and emissions calculations.

1.4 CONTROLS OF HYBRID VEHICLE

Since the hybrid vehicle is a complex system of electrical and mechanical components which contain multidisciplinary technologies, modern control system techniques and methodologies are playing important roles in hybrid technology (Powers and Nicastri, 2000). An HEV's performance is affected by many multidisciplinary interrelated factors; therefore, advanced control strategies could significantly improve performance and lower cost. The overall control objectives of a hybrid vehicle are to maximize fuel economy and minimize emission. In order to achieve the objectives, some key system variables must be optimally governed, including mainly energy flow of the system, availability of energy and power, temperature of subsystems, and dynamics of the engine and electric motor. Some typical HEV control problems are as follows:

(a) *Have the ICE work on 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 on these points, the maximum fuel economy, the minimum emissions, or a compromise between fuel economy and emissions can be achieved. It is a challenging control objective for an HEV to have the ICE operate on these points at various operating conditions.

(b) *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.

(c) *Optimize ICE operation 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 even can be shut down when its speed is below a certain value in order to achieve maximum benefits.

(d) *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, when ICE should be turned on/off can be determined based on an optimal control method to minimize fuel consumption and emissions.

(e) *Optimally manage battery* state of charge *(* SOC*)* The battery's SOC needs to be controlled optimally so as to provide sufficient energy to power the vehicle and accept regenerative energy during braking or downhill as well as maximize its service life. The simplest control strategy is to turn the ICE off if the battery's SOC is too high and turn the ICE on if the SOC is too low. A more advanced control strategy should be able to regulate the output power of the ICE based on the actual SOC level of the ESS.

(f) *Optimally control the voltage of the high-voltage bus* Actual voltage of the high-voltage bus of an HEV has to be controlled during discharging and charging to avoid being over or under the limits; otherwise, the ESS or other components may be permanently damaged.

(g) *Optimize power distribution* Since there are two power sources in an HEV, the most challenging and important control task is to split the vehicle demand power to the ICE and the electric motor based on the driving scenario, road and weather conditions, and state of the ESS to achieve the best fuel economy, minimum emissions, and maximum service life of the ESS.

(h) *Follow zero-emission policy* In certain areas such as tunnels or workshops, some HEVs may need to be operated in the pure electric mode.

(i) *Optimally control 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. Key in this implementation is to employ an advanced transmission system that provides at least two mechanical transmission channels through 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 electric motor, but the ICE is operated at the steady speed as much as possible. During normal driving, the power is collaboratively fed by the ICE and electric motor to achieve maximum fuel economy.

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