1. Introduction to Hybrid and Electric Vehicles

1.1 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-fuelled 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.

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 vehicles
- mild hybrid vehicles
- full hybrid, or plug-in hybrid electric vehicles
- fully electric vehicles

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. 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. 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 drive-train 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 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. Nickel–metal hydride and lithium-ion batteries are often employed in mild hybrid electric vehicles. 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. 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.

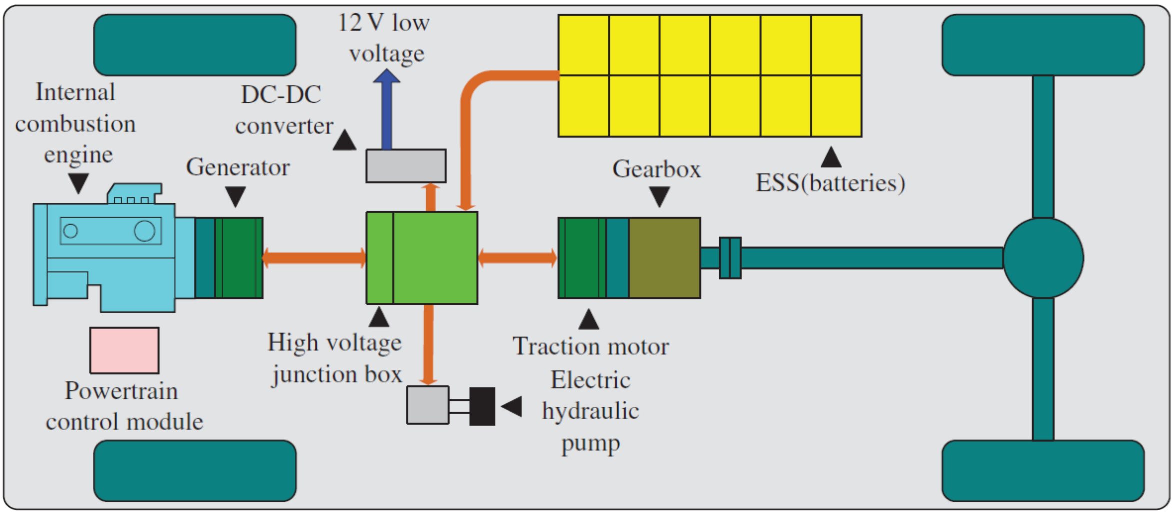
1.1.5 Plug-in Hybrid Electric Vehicles

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.

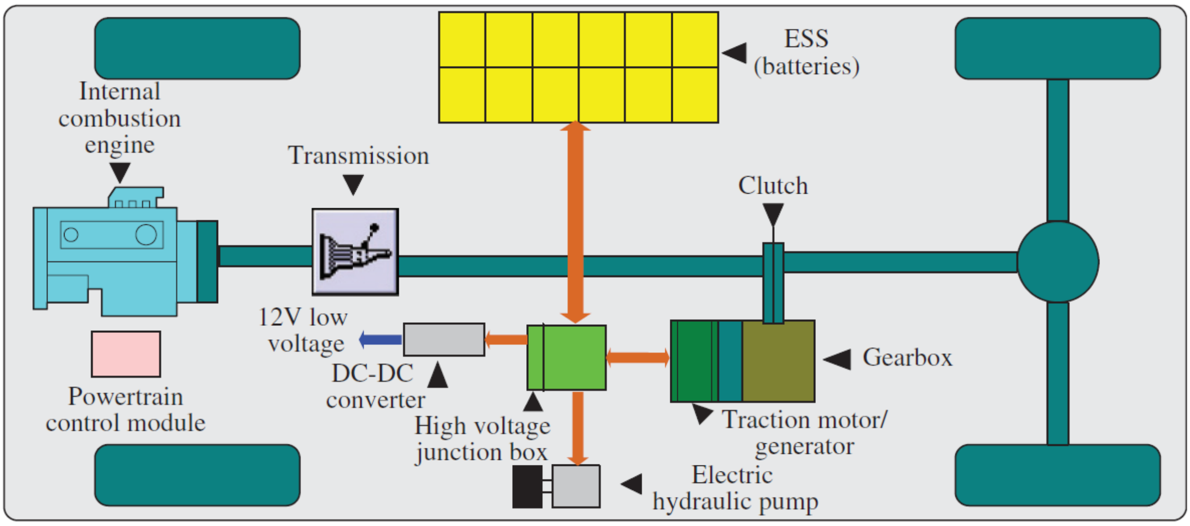
1.2 General Architectures of Hybrid Electric Vehicles

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.



1.3 Electric Vehicles (EV)

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

1.3.1 Modern EV concept

The modern EV concept is summarized as follows:

- The EV is a road vehicle based on modern electric propulsion which consists of the electric motor, power converter and energy source, and it has its own distinct characteristics;
- The EV is not just a car but a new system for our society, realizing clean and efficient road transportation;
- The EV system is an intelligent system which can readily be integrated with modern transportation networks;
- EV design involves the integration of art and engineering;
- EV operating conditions and duty cycles must be newly defined;
- EV users' expectations must be studied, hence appropriate education must be conducted.

1.3.2 EV Design considerations

The following points are those typical considerations for EV design:

- To identify the market and environment;
- To determine the technical specifications including the driving cycle;
- To determine the infrastructure required including the recycling of batteries;
- To determine the overall system configuration-EV, HEV or fuel cell EV configurations;
- To determine the chassis and body;
- To determine the energy source-generation or storage, single or hybrid;
- To determine the propulsion system-motor, converter and transmission types, single or multiple motors, gearless or geared, mounting methods, and ICE systems in case of an HEV;
- To determine the specifications of electric propulsion (power, torque, speed) and energy source (capacity, voltage, current) according to various driving cycles;
- To adopt intelligent energy management system;
- To analyse the interaction of EV subsystems for understanding the degree of interaction that affects the cost, performance and safety;
- To optimize the efficiency of the motor drive according to the selected driving pattern and operating conditions;
- To optimize the overall system using computer simulation.

1.3.3 EV motor drive

The major requirements of the EV motor drive are summarized as follows:

- High instant power and high power density;
- High torque at low speeds for starting and climbing as well as high speed at low torques for cruising;
- Very wide speed range including constant-torque and constant-power regions;
- Fast torque response;
- High efficiency over wide speed and torque ranges;
- High efficiency for regenerative braking;
- High reliability and robustness for various vehicle operating conditions;
- Reasonable cost

To satisfy these special requirements, the power rating and torque-speed require-ments of the motor drive should be determined on the basis of driving cycles and system-level simulation. New motor design technologies and control strategies are being pursued to extend the speed range, to optimize the system efficiency and to enlarge the high-efficiency region. Newly developed electronic products are also adopted to improve the system performance and to reduce the total cost.

Based on the technological growth of electric motors, power electronics, micro-electronics and control strategies, more and more kinds of motor drives become available for EVs. De motor drives have been traditionally used for EV propulsion because of their ability to achieve high torque at low speeds and easy to control. However, the de motor needs careful maintenance due to its commutator and brushes. Recent technological developments have enabled a number of advanced motor drives to offer definite advantages over those de motor drives, namely high efficiency, high power density, efficient regenerative braking, robust, reliable, and maintenance free. Among them, the vector controlled induction motor drive is most popular and mature, though it may suffer from low efficiency at light-load ranges. On the other hand, permanent magnet (PM) brushless motors possess the highest efficiency and power density over the others, but may suffer from a difficulty in flux weakening control for the constant-power high-speed region. The PM hybrid motor is a special type of PM brushless motors. In this motor, an auxiliary de field winding is so incorporated that the air-gap flux is a resultant of the PM flux and field-winding flux. By adjusting the field-winding excitation current, the air-gap flux can be varied flexibly, hence offering optimal efficiency over a wide speed range. Switched reluctance (SR) motors offer promis-ing features for EV applications because of their simplicity and reliability in both motor construction and power converter configuration, wide speed range, favour-able thermal distribution, 'limp-home' capability, and efficient regenerative braking. However, they may suffer from torque ripples and acoustic noise problems.

In summary, for EV motor drives, de motor drives have been gradually super-seded by induction motor drives, PM brushless motor drives with various config-urations and SR motor drives. These advanced motor drives must be specially designed to meet the EV special requirements. For transmission devices, conven-tional gearing can no longer satisfy the needs of EVs. Recently, planetary gearing has been accepted as the transmission device of the latest EVs.

1.3.4 EV Energy sources

At present, the main obstacles of the commercialization of EVs are the relatively high initial cost and short driving range. The EV energy source has been identified to be the major cause of these problems. Thus, the present and foreseeable future most important EV development issue is on how to develop various EV energy sources. Those development criteria are summarized as follows:

- High specific energy and energy density;
- High specific power and power density;
- Fast charging and deep discharging capabilities;
- Long cycle and service lives;
- Low self discharging rate and high charging efficiency;
- Safety and cost effectiveness;
- Maintenance free;
- Environmental sound and recyclable

Currently, there is no sole EV energy source that can fully satisfy all of these criteria. When batteries are selected, there are various compromises among those criteria. For examples, the lead-acid battery offers the merits of relatively low cost and high specific power, and the demerits of relatively short cycle life and low specific energy; whereas the nickel-metal hydride battery exhibits the relatively high specific energy but with relatively high cost. In general, all batteries face a compromise among the specific energy, specific power and cost. In the foreseeable future, the lithium-based batteries such as lithium-ion and lithium-polymer should have good prospects for modern EVs. On the other hand, emerging energy sources including ultracapacitors and ultrahigh-speed flywheels provide promising EV applications because of their exceptionally high specific power. Recently, fuel cells have been identified as one of the most important EV energy sources that can fundamentally solve the key EV problem-short driving range. Provided that the high initial cost of fuel cells can be significantly reduced, it is anticipated that fuel cell EVs can directly compete with the existing ICEVs in the next generation of road transportation.

Rather than based on one energy source, the use of multiple energy sources, so-called hybridization of energy sources, can eliminate the compromise between the specific energy and specific power. For the hybridization of two energy sources, one is selected for high specific energy while the other for high specific power. For examples, there are the battery & battery hybrid, battery & ultracapacitor hybrid, battery & ultrahigh-speed flywheel hybrid, and fuel cell & battery hybrid. In fact, the HEV is a special case of this hybridisation, namely the petrol is of high specific energy for the long driving range while the battery is of high specific power for assisting fast acceleration and providing emission-free operation.

1.3.5 Energy management

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

- to optimize the system energy flow;
- to predict the remaining available energy and hence the residual driving range;
- to suggest more efficient driving behaviour;
- to direct regenerative energy from braking to receptive energy sources such as batteries;
- to modulate temperature control in response to external climate;
- to adjust lighting brightness in response to external environment;
- to propose a suitable battery charging algorithm;
- to analyse the operation history of the energy source, especially the battery;
- to diagnose any incorrect operation or defective components of the energy source.

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

1.3.6 System optimization

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

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

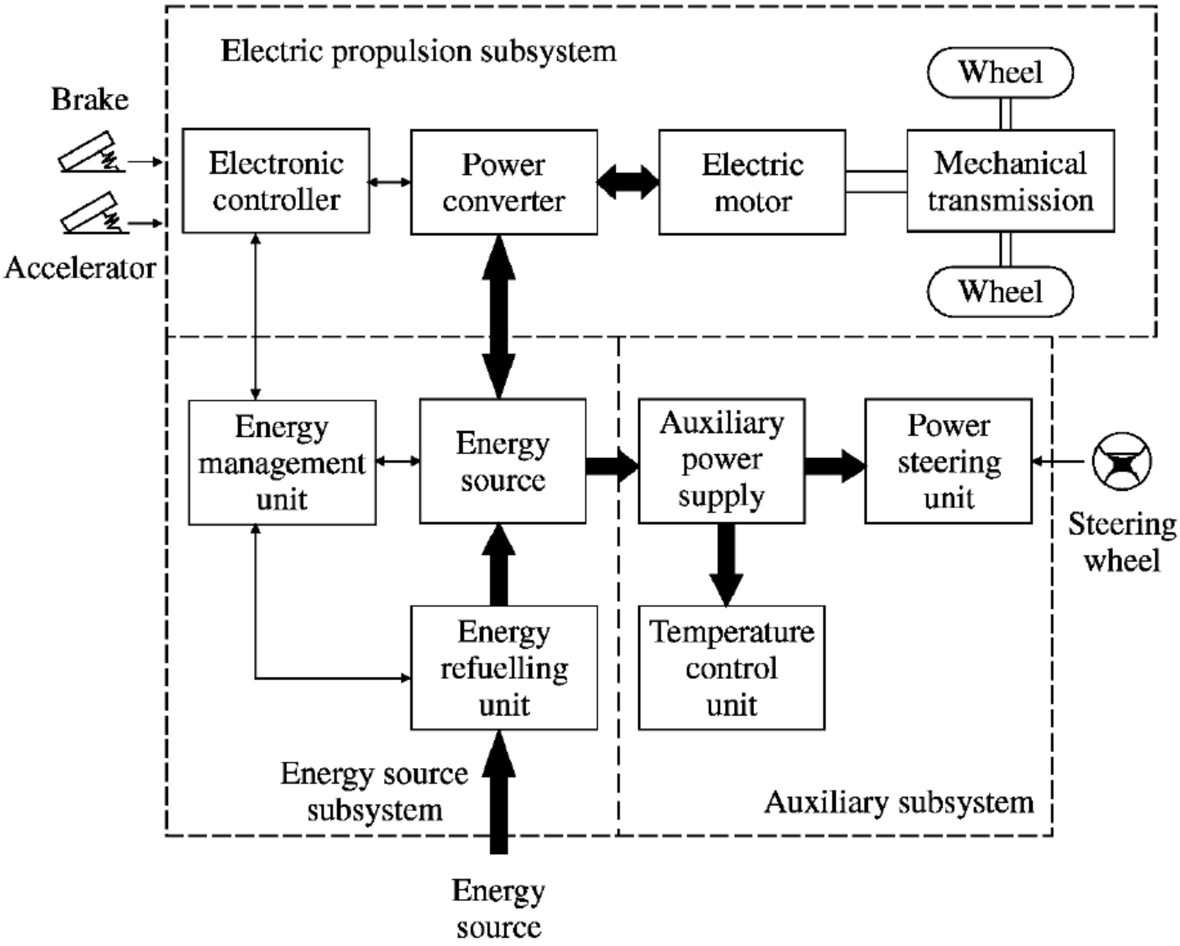
- As the interactions among various subsystems greatly affect the performance of EVs, the significance of those interactions should be analysed and taken into account.
- As the model accuracy is usually coherent with the model complexity but may be contradictory to the model usability, trade-offs among the accuracy, com-plexity and usability as well as simulation time should be considered.
- As the system voltage generally causes contradictory issues for EV design, including the battery weight, motor drive voltage and current ratings, accelera-tion performance, driving range and safety, it should be optimized on the system level.
- In order to increase the driving range, multiple energy sources may be adopted for modern EVs. The corresponding combination and hybridization ratio should be optimized on the basis of the vehicle performance and cost.
- Since EVs generally adopt fixed gearing, the gear ratio can greatly affect the vehicle performance and driveability. An optimal ratio should be determined through iterative optimization under different driving profiles.

1.4 EV configurations

Previously, the EV was mainly converted from the ICEV, simply replacing the combustion engine by the electric motor while retaining all the other components. This converted EV has been fading out because of the drawback of heavy weight, loss of flexibility and degradation of performance. At present, the modern EV is purposely built. This purpose-built EV is based on original body and frame designs to satisfy the structural requirements unique to EVs and to make use of the greater flexibility of electric propulsion.

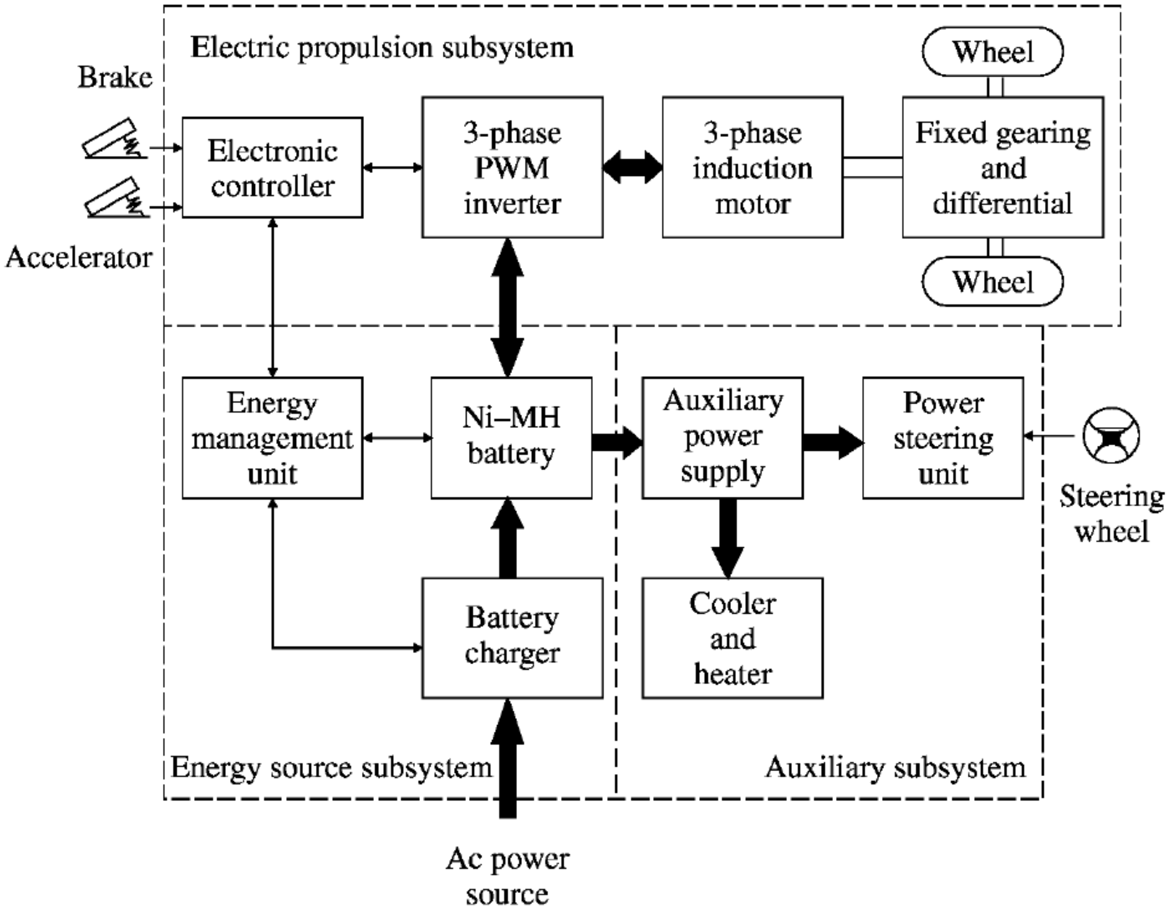
Compared with the ICEV, the configuration of the EV is particularly flexible. This flexibility is due to several factors unique to the EV. Firstly, the energy flow in the EV is mainly via flexible electrical wires rather than bolted flanges or rigid shafts. Thus, the concept of distributed subsystems in the EV is really achievable. Secondly, different EV propulsion arrangements (such as independent four-wheel and in-wheel drives) involve a significant difference in the system configuration. To a lesser degree, different EV propulsion devices (such as de and induction motor drives) also have different weights, sizes and shapes. Thirdly, different EV energy sources (such as batteries and fuel cells) have different weights, sizes and shapes. The corresponding refuelling systems also involve different hardware and mechanism. For example, the batteries can be electrically recharged via conductive or inductive means, or can also be mechanically exchanged (so-called mechanic-ally recharged) and then recharged centrally.

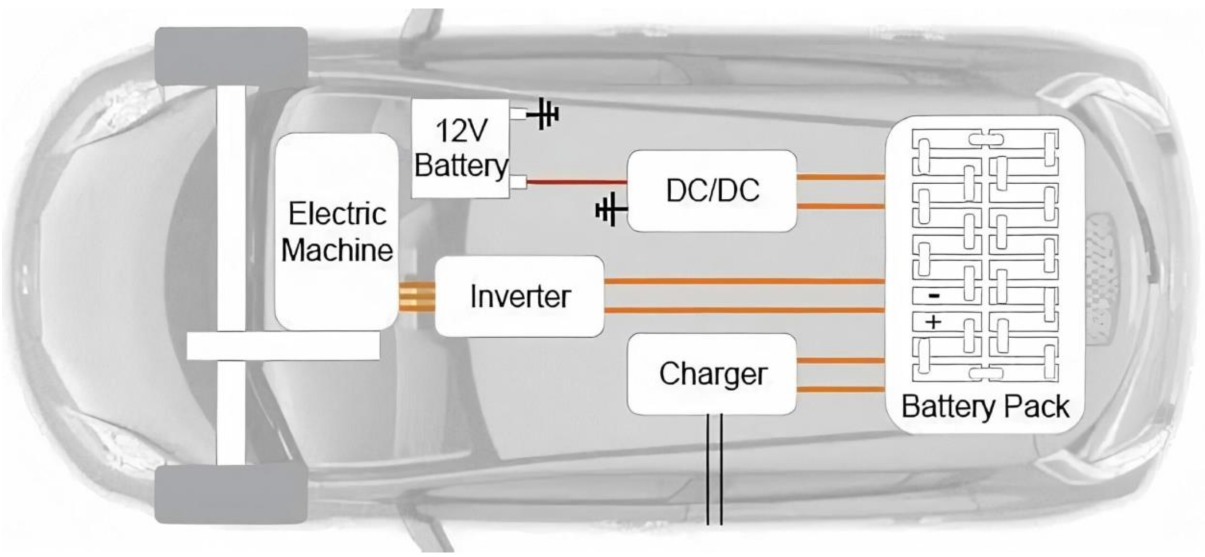
Figure 7.3 shows the general configuration of the EV, consisting of three major subsystems-electric propulsion, energy source and auxiliary. The electric propul-sion subsystem comprises the electronic controller, power converter, electric motor, mechanical transmission and driving wheels. The energy source subsystem involves the energy source, energy management unit and energy refuelling unit.



The auxiliary subsystem consists of the power steering unit, temperature control unit and auxiliary power supply. In the figure, a mechanical link is represented by a double line, an electrical link by a thick line and a control link by a thin line. The arrow on each line denotes the direction of electrical power flow or control information communication. Based on the control inputs from the brake and accelerator pedals, the electronic controller provides proper control signals to switch on or off the power devices of the power converter which functions to regulate power flow between the electric motor and energy source. The backward power flow is due to regenerative braking of the EV and this regenerative energy can be stored provided the energy source is receptive. Notice that most available EV batteries (except some metal/air batteries) as well as capacitors and flywheels readily accept regenerative energy. The energy management unit cooperates with the electronic controller to control regenerative braking and its energy recovery. It also works with the energy refuelling unit to control refuelling and to monitor usability of the energy source. The auxiliary power supply provides the necessary power with different voltage levels for all EV auxiliaries, especially the temperature control and power steering units. Besides the brake and accelerator, the steering wheel is another key control input of the EV. Based on its angular position, the power steering unit can determine how sharply the vehicle should turn.

For a modern EV, a three-phase induction motor is typically selected. The corresponding power converter is a three-phase PWM inverter. In general, the mechanical transmission is based on fixed gearing and a differential. Also, a nickel-metal hydride (Ni-MH) battery is also typically selected as the energy source. The corresponding refuelling unit becomes a battery charger. The temperature control unit generally consists of a cooler and/or a heater, depending on the climate of a particular country. This typical set-up is shown in Fig. 7.5.



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