21

More-Electric Vehicles

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21.1 Aircraft

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Mechanical, electrical, and centralized hydraulic and pneumatic systems are conventional power transfer systems in an aircraft. The More-Electric Aircraft (MEA) concept emphasizes utilizing electrical systems to replace more aircraft conventional power transfer systems and to facilitate new introduced electrical loads. Improving reliability, maintainability, supportability, survivability, performance, safety, emissions, and operating costs are the main motivations behind the MEA concept.

Conventional Electrical Loads

The power needed for the subsystems in an aircraft is currently derived from mechanical, electrical, hydraulic, and pneumatic sources or a combination of them [1–3]. Generally, hydraulic power transfer systems are used for most of the actuators. On the other hand, pneumatic power transfer systems are mainly employed for air-conditioning, pressurization, and ice protection systems.

Electrical and electronic systems are usually used for avionics and utility functions, such as air data instruments, communications, landing gear, lighting, navigation, and comfort of the passengers. Other conventional subsystems that are driven by the electrical sources include energy storage, engine starting, ignition, anti-skid control, and deicing and anti-icing systems [3].

Power Generation Systems

The wound-field synchronous machine has traditionally been used to generate AC electrical power with constant frequency of 400 Hz. This machine/drive system is known as a constant-speed drive (CSD) system [3–5]. Figure 21.1 shows a typical constant-speed drive system. In Fig. 21.1, synchronous generators supply AC constant-frequency voltage to the AC loads in the aircraft. Then, AC-DC rectifiers are used to convert the AC voltage with fixed frequency at the main AC bus to multilevel DC voltages at the

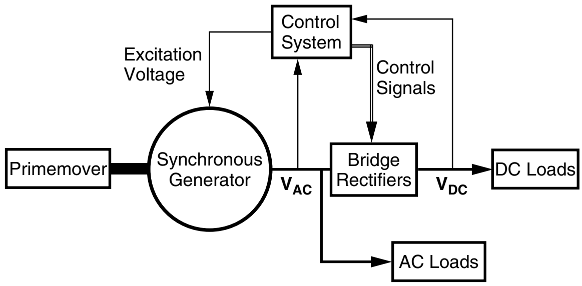

FIGURE 21.1 Typical CSD system.

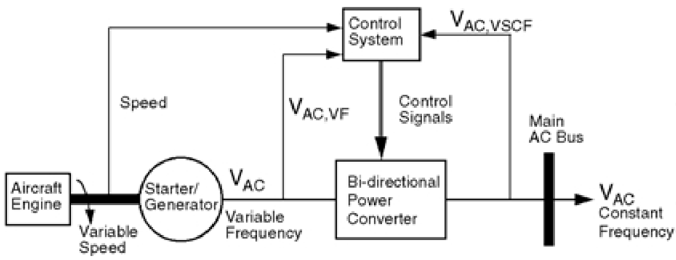

FIGURE 21.2 Typical VSCF starter/generator system.

secondary buses, which supply electrical power to the DC loads. Excitation voltage of the synchronous generator and firing angles of the bridge rectifiers are controlled via the control system of the CSD system.

Recent advances in the areas of power electronics, control electronics, electric motor drives, and electric machines have introduced a new technology of variable-speed constant-frequency (VSCF) systems. The main advantage of VSCF is that it provides better starter/generator systems. Other advantages are higher reliability, lower recurring costs, and shorter mission cycle times [5]. Figure 21.2 shows the block diagram of a typical VSCF starter/generator system. In the generating mode, an aircraft engine, which has variable speed, provides mechanical input power to the electric generator. Then, the electric generator supplies variable-frequency AC power to the bidirectional power converter, which provides AC constant-frequency voltage to the main bus. In the motoring mode, the constant-frequency AC system via the bidirectional power converter provides input electric power to the electric machine, which is a starter to the aircraft engine. Synchronous, induction, and switched reluctance machines are three candidates for VSCF starter/generator systems [3–6].

The bidirectional power electronic converter of the VSCF system is a multilevel converter, as depicted in Fig. 21.3. The input voltage is variable AC whose amplitude is not regulated. Moreover, the frequency is not constant. At the input stage of the bidirectional converter, there is an uncontrolled rectifier converting the variable AC to an unregulated DC voltage. Then, a DC voltage regulator is used to provide power for the regulated high-voltage 270-V DC system. A DC-DC converter and a DC-AC inverter connected to this system provide power for the low-voltage 28-V DC and 115/200-V, 400-Hz, three-phase AC loads, respectively. Batteries are also connected to the system via the battery charge/discharge unit.

Aircraft Electrical Distribution Systems

Because of the expansion of electrical loads and the replacement of conventional aircraft systems with the electrical counterparts, aircraft power systems are becoming more electric. As a result, in advanced aircraft, electrical distribution systems with larger capacity and more complex configuration are necessary.

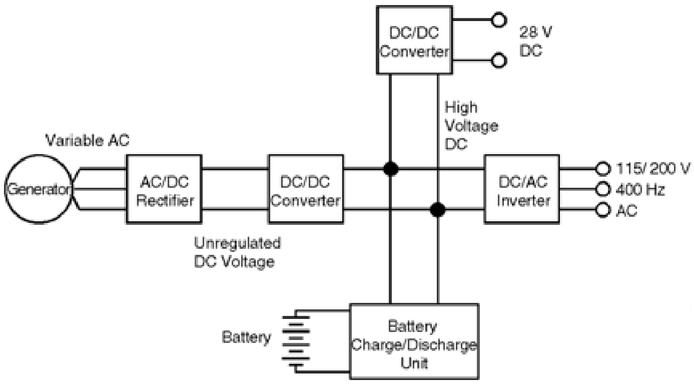

FIGURE 21.3 Multilevel conversion of the unregulated AC voltage to regulated DC and AC voltages.

Systems with constant-frequency (CF) and VSCF have 115-V AC, 400-Hz, three-phase electrical systems. They may also have a 270-V DC or higher primary power bus. The electrical system of an aircraft may have wild frequency with a variable-frequency VF generator of 115 V AC, three-phase power [7].

In the MEA electrical power systems, a number of different types of loads are used, which require power supplies different from the standard supplies provided by the main generator. Therefore, the future aircraft electrical power systems will employ multivoltage-level hybrid DC and AC systems. For example, in an advanced aircraft power system having a 270-V DC primary power supply, certain instruments and electronic equipment are employed that require 28-V DC and 115-V AC supplies for their operation. In fact, DC cannot be entirely eliminated even in aircraft that is primarily AC in concept. Furthermore, even within the items of consumer equipment themselves, certain sections of their circuits require different types of power supply and/or different levels of the same kind of the supply. It therefore becomes necessary to employ not only equipment converting electrical power from one form to another, but also equipment converting one form of supply to a higher or lower value. As a result, in a modern aircraft, different kinds of power electronic converters such as AC-DC rectifiers, DC-AC inverters, and DC-DC choppers are required. In addition, in the VSCF systems, solid-state bidirectional converters are used to condition VF power into a fixed frequency and voltage. Moreover, bidirectional DC-DC converters are used in the battery charge/discharge units.

As the AC-DC converters, conventional transformer rectifier units (TRU) are used. Each unit consists of a 12-pulse transformer and a controlled or uncontrolled rectifier. Power diodes and thyristors are used in uncontrolled and controlled rectifiers, respectively. If a constant voltage is needed, controlled rectifiers are used to regulate output voltage. And, if it is not necessary to regulate the output voltage or if there is a voltage regulator at the output side of TRU, uncontrolled rectifiers are used. However, in an advanced MEA, recent advances in the area of power electronics, such as resonant and soft switching techniques, can be used to increase the power density and improve the performance of all the power conditioning systems [8].

Advanced Electrical Loads

Performance improvements in electric actuation systems and electric motor drives are providing the impetus for the MEA concept. In fact, there is a trend toward replacement of more engine-driven mechanical, hydraulic, and pneumatic loads with electrical loads as a result of performance and reliability issues.

In an advanced aircraft, electromechanical actuators are used instead of the conventional hydraulic actuators. The expansion of this concept to braking systems results in electrically actuated braking systems [9]. Improved safety, reliability, and maintainability are the benefits that accrue through the removal of the hydraulic fluid. In addition, the efficiency is improved through better control of braking torque [9].

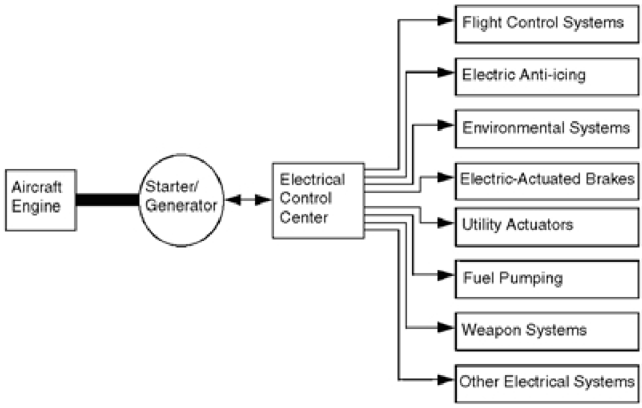

FIGURE 21.4 MEA electrical power subsystems.

Furthermore, conventional aeroengine actuators use fluid power in the form of pneumatic, hydraulic, or fueldraulics to provide the motive effort. There is also a trend toward replacing these traditional hydraulic/pneumatic/fueldraulic engine actuation systems with electromechanical actuators. The main advantages are easier interfacing, reduced maintenance costs, lighter systems, and improved reliability. The electric motor type selected is a three-phase brushless DC motor [10].

Some of the other loads considered are electromechanical and electrohydraulic flight control actuators, 270-V DC switched reluctance starter/generators, electric anti-icing systems, environmental systems, electromechanical valve controllers, air-conditioning systems, utility actuators, weapon systems, and different electric motor drives for pumps and other applications. In fact, electrical subsystems may require a lower engine power with higher efficiency. Also, they can be used only when needed. Therefore, MEA can have better fuel economy and performance. Figure 21.4 shows the main electrical power subsystems in the MEA power systems.

Advanced Electrical Distribution System Architectures

A conventional distribution network is a point-to-point topology in which all the electrical wires are distributed from the main bus to different loads through relays and switches. This kind of distribution network leads to expensive, complicated, and heavy wiring circuits. However, in an advanced aircraft, loads are controlled by intelligent remote modules. Therefore, the number and length of wires in the harness are reduced. Furthermore, by interconnection between remote modules via communication/control buses, it is possible to have a power management system (PMS). The primary function of the PMS is time-phasing of the duty cycle of loads to reduce the peak power demand [11]. Other functions of the PMS are battery management and charging strategy in a multiple-battery system, load management, management of the starter/generator system including the regulator, and provision and control of a high-integrity supply system. In addition, power management strategy can help optimize the size of the generators and batteries [11].

Figure 21.5 shows an advanced aircraft power system architecture in which there are several power electronic converters. The distribution control network of Fig. 21.5 simplifies vehicle physical design and assembly and offers additional benefits from the integration with intelligent power management control. Other advantages of this MEA technology are reduced design complexity, fewer flight test hours, reduced ground support equipment, and easier aircraft modification [7].

To power important systems in the case of an emergency, permanent magnet (PM) generators are used to generate 28-V DC voltage. Furthermore, the main distribution system can also be changed from DC to AC. The main advantage of AC distribution systems is easy conversion to different voltage levels by transformers. Also, AC machines are easy to use.

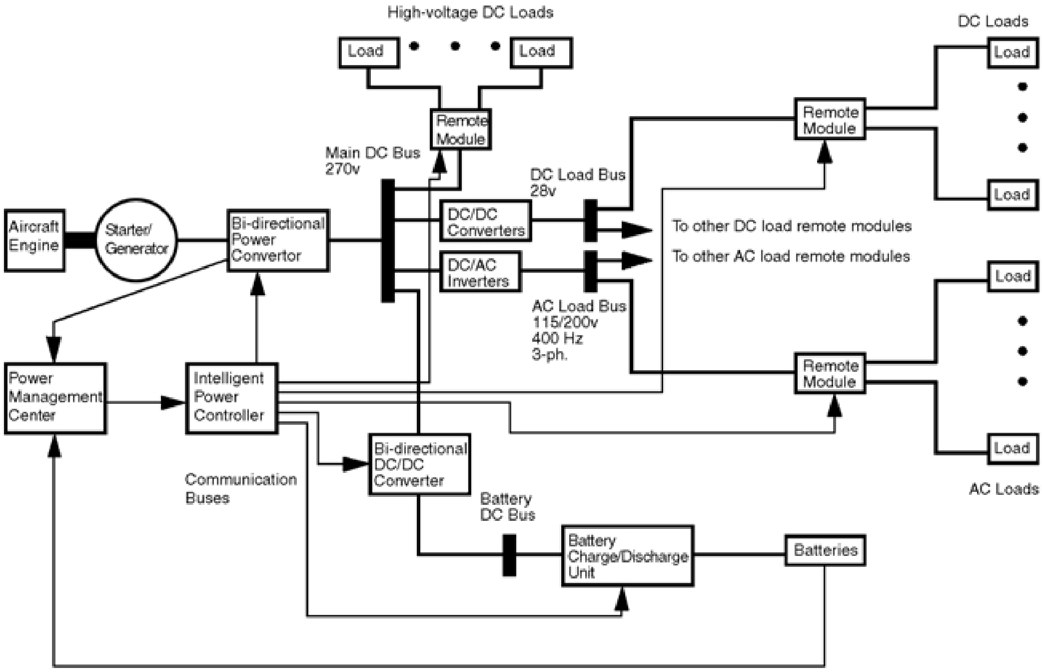

FIGURE 21.5 The concept of an advanced aircraft power system architecture of the future.

Specifications of the DC-DC converters and DC-AC inverters for MEA applications are given in Ref. 12. Two power electronic converters, which are highly compact with input nominal voltage of 270 V DC, are presented in Ref. 12. The DC-DC converter provides 5.6 kW at 29 ± 0.5 V DC with an efficiency of 90%. The DC-AC inverter provides 8 kVA of three-phase power at (115 ± 1.5)/200 V AC and 400 Hz with an efficiency of 87%. Both of these converters have high-frequency (120-kHz) resonant circuits. The reason for using the resonant circuits is that the power electronic devices are switched at zero current. This reduces the switching power losses and, in turn, increases the efficiency and switching frequency to 120 kHz [12].

Conclusions

To improve aircraft reliability, maintainability, emissions, and performance, the MEA concept emphasizes the utilization of electrical systems instead of the conventional mechanical, hydraulic, and pneumatic power transfer systems. The MEA concept facilitates high-power electric loads and requires power electronics in a solid-state rich electric environment. In fact, advanced aircraft and aerospace power systems are multiconverter power electronics–based systems. In these systems, different converters, such as AC-DC rectifiers, DC-DC choppers, and DC-AC inverters, are used to provide power at different voltage levels in both DC and AC forms. The AC system may be constant frequency, multifrequency, or wild frequency. In addition, advanced aircraft power systems employ separate buses for power and control as well as an intelligent power management center.

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21.2 Terrestrial Vehicles

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The More-Electric Vehicle (MEV) concept emphasizes the utilization of electrical systems instead of mechanical and hydraulic systems to optimize vehicle fuel economy, emissions, performance, and reliability. In addition, the need for improvement in comfort, convenience, entertainment, safety, security, and communications necessitates more electric automotive systems. As a result, an electric power distribution system with larger capacity and more complex configuration is required to facilitate increasing electrical loads.

Electrical Power Systems of Conventional Cars

The conventional electrical system in an automobile can be divided into the energy storage, charging, cranking ignition, lighting, electric motors, and instrumentation subsystems. In order for the power available at the sources to be made available at the terminals of the loads, some organized form of distribution throughout an automobile is essential. At present, most automobiles use a 14-V DC electrical system. Figure 21.6 shows the conventional electrical distribution system for automobiles. This has a single voltage level, i.e., 14-V DC, with the loads controlled by manual switches and relays [1–8]. Because of the point-to-point wiring, the wiring harness is heavy and complex.

The present average power demand in an automobile is approximately 1 kW. The voltage in a 14-V system actually varies between 9 and 16 V, depending on the alternator output current, battery age, state of charge, and other factors. This results in overrating the loads at nominal system voltage. There are several other disadvantages, which have been addressed in Refs. 1 through 4.

In addition to all the disadvantages, the present 14-V system cannot handle the future electrical loads to be introduced in the more electric environment of future cars, as it will be expensive and inefficient.

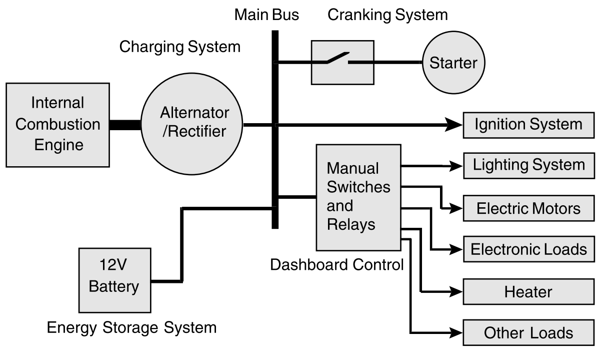

FIGURE 21.6 Conventional 14-V DC distribution system architecture.

Advanced Electrical Loads

In More-Electric Cars (MEC), there is a trend toward expanding electrical loads and replacement of more engine-driven mechanical and hydraulic systems with electrical systems. These loads include the well-known lights, pumps, fans, and electric motors for various functions. They will also include some less well known loads, such as electrically assisted power steering, electrically driven air-conditioner compressor, electromechanical valve control, electrically controlled suspension and vehicle dynamics, and electrically heated catalytic converter. In fact, electrical subsystems may require a lower engine power with higher efficiency. Furthermore, they can be used only when needed. Therefore, MEC can have optimum fuel economy and performance. There are also other loads such as antilock braking, throttle actuation, ride-height adjustment, and rear-wheel steering, which will be driven electrically in the future.

Figure 21.7 shows electrical loads in the MEC power systems. As is described in Refs. 5 through 8, most of the future electic loads require power electronic controls. In future automobiles, power electronics will be used to perform three different tasks. The first task is simple on/off switching of loads, which is performed by mechanical switches and relays in conventional cars. The second task is the control of electric machines. The third task is not only changing the system voltage to a higher or lower level, but also converting electrical power from one form to another using DC-DC, DC-AC, and AC-DC converters.

Increasing the System Voltage

Because of the increasing electrical loads, automotive systems are becoming more electric. Therefore, MEC will need highly reliable, fault-tolerant, autonomously controlled electrical power systems to deliver high-quality power from the sources to the loads. The voltage level and form in which power is distributed are important. A higher voltage such as the proposed 42 V will reduce the weight and volume of the wiring harness, among several other advantages [4, 5]. In fact, increasing the voltage of the system, which is 14 V in conventional cars, is necessary to cope with the greater loads associated with the more electric environments in future cars. The near-future average power demand is anticipated to be 3 kW and higher.

Figure 21.8 shows the concept of a dual-voltage automotive power system architecture of the future MEC. Indeed, it is a transitional two-voltage system, which can be introduced until all automotive components evolve to 42 V. Finally, the future MEC power system will most likely be a single-voltage bus (42 V DC) with provision for hybrid (DC and AC), multivoltage level distribution, and intelligent energy and load management.

Advanced Distribution Systems

The conventional automotive electrical power system is a point-to-point topology in which all the electrical wiring is distributed from the main bus to different loads through relays and switches of the dashboard control. As a result, the distribution network has expensive, complicated, and heavy wiring circuits.

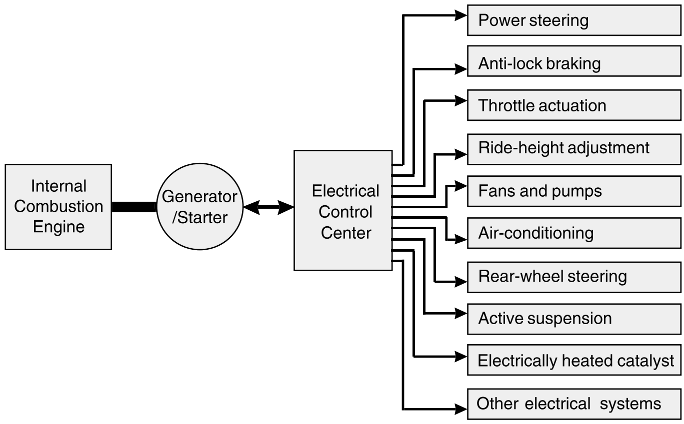

FIGURE 21.7 Electrical loads in MEC power systems.

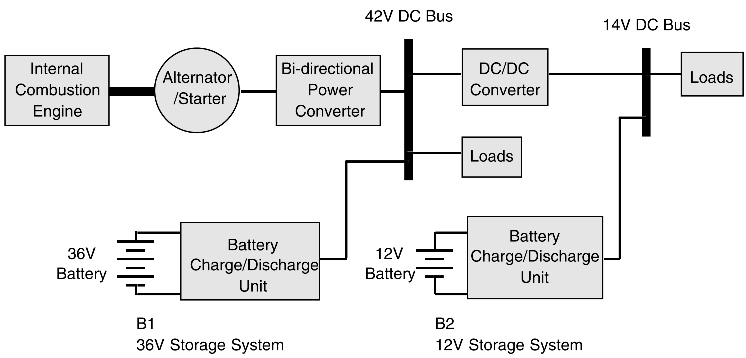

FIGURE 21.8 The concept of a dual-voltage automotive power system architecture of the future MEC.

However, in the advanced automotive electrical systems, multiplexed architectures with separate power and communication buses are used to improve the system. In a multiplexed network, loads are controlled by intelligent remote modules. Therefore, the number and length of wires in tthe harness are reduced. In addition, these systems have a power management system (PMS). The primary function of the PMS is time-phasing of the duty cycle of loads to reduce the peak power demand. Other functions of the PMS are battery management, load management, and management of the starter/generator system including the regulator. Figure 21.9 shows typical inputs and outputs of a power management center.

Figure 21.10 shows advanced multiplexed automotive power system architectures of the future with power and communication buses. The distribution control network of Fig. 21.10 simplifies vehicle physical design and assembly and offers additional benefits from the integration with intelligent power management control.

Electrical Power Systems of Electric and Hybrid Electric Vehicles

Because of environmental concerns, there is a significant impetus toward development of new propulsion systems for future cars in the form of electric and hybrid electric vehicles (EV and HEV). Electric vehicles are known as zero-emission vehicles. They use batteries as electrical energy storage devices and electric motors to propel the automobile. On the other hand, hybrid vehicles combine more than one energy source for propulsion. In heat engine/battery hybrid systems, the mechanical power available from the

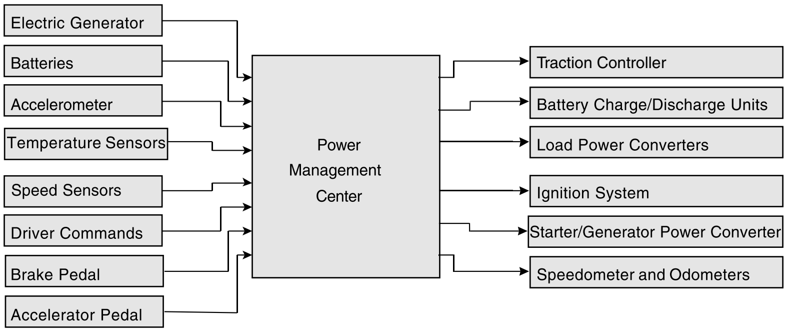

FIGURE 21.9 Power management system.

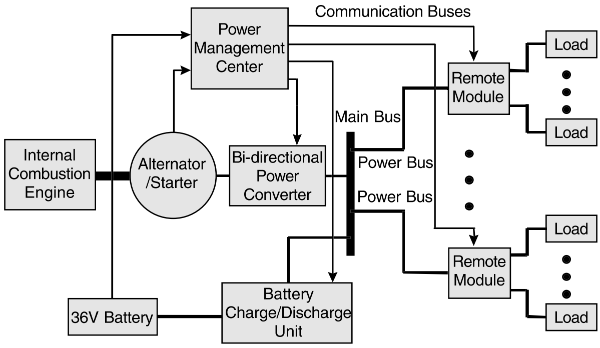

FIGURE 21.10 Advanced multiplexed automotive power system architectures of the future with power and communication buses.

heat engine is combined with the electrical energy stored in a battery to propel the vehicle. These systems also require an electric drive train to convert electrical energy into mechanical energy, as do electric vehicles.

Architectures of EV and HEV Drive Trains

Hybrid electric systems can be broadly classified as series or parallel hybrid systems [9–12]. The series and parallel hybrid architectures are shown in Figs. 21.11 and 21.12, respectively. In series hybrid systems, all the torque required to propel the vehicle is provided by an electric motor. On the other hand, in parallel hybrid systems, the torque obtained from the heat engine is mechanically coupled to the torque produced by an electric motor. In EV, the electric motor behaves exactly in the same manner as in a series hybrid. Therefore, the torque and power requirements of the electric motor are roughly equal for an EV and a series hybrid, whereas they are lower for a parallel hybrid.

Electrical Distribution System Architectures

Figure 21.13 depicts the conventional electrical power distribution system architecture for hybrid electric vehicles. It is a DC system with a main high-voltage bus, e.g., 300 or 140 V. The high-voltage storage system is connected to the main bus via the battery charge/discharge unit. This unit discharges and charges the batteries in motoring and generating modes of the electric machine operation, respectively. There are also two other charging systems, which are on-board and off-board. The off-board charger has three-phase or single-phase AC-DC rectifiers to charge the batteries when the vehicle is parked at a charging station. The on-board charger, as shown in Fig. 21.13 consists of a starter/generator and a bidirectional power converter. In the generating mode, the internal combustion engine provides mechanical input power to the electric generator. Then, the electric generator supplies electric power to the

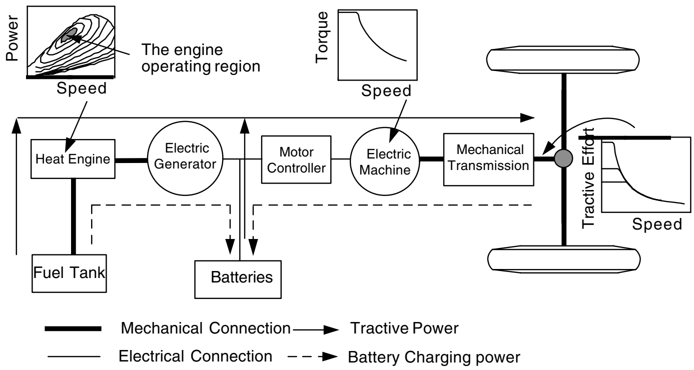

FIGURE 21.11 Series HEV architecture.

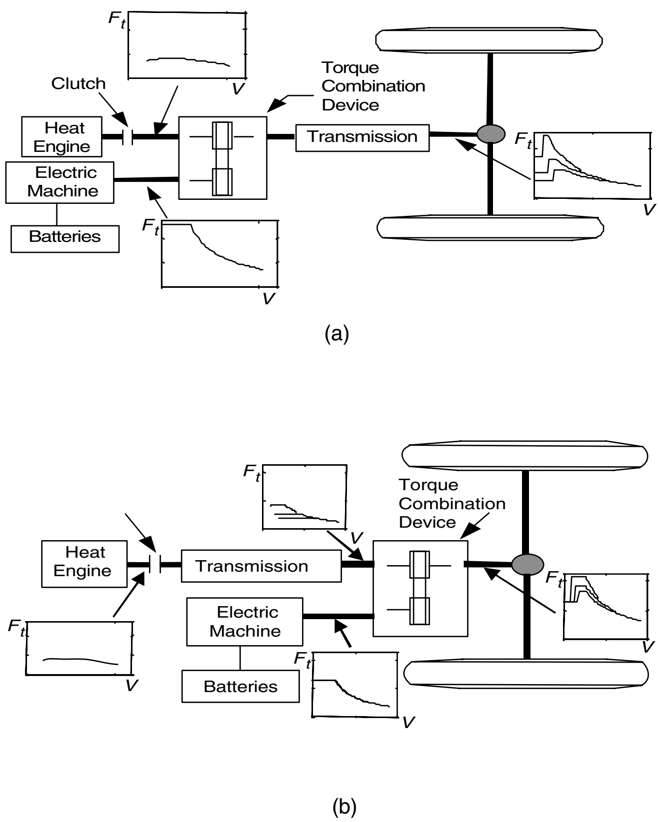

FIGURE 21.12 Parallel HEV architectures: (a) engine–motor–transmission configuration; (b) engine–transmission–motor configuration.

bidirectional power converter providing high-voltage DC to the main bus. Moreover, in the motoring mode, i.e., cranking the engine, the high-voltage DC system via the bidirectional power converter provides input electric power to the electric machine, which is a starter to the vehicle enigine.

In Fig. 21.13, the electric propulsion system feeds from the main high-voltage bus. Furthermore, conventional low-power 14 and 5 V DC loads are connected to the 14-V bus. The low-voltage 14-V bus is connected to the main bus with a step-down DC-DC converter. A 12-V storage system via the battery

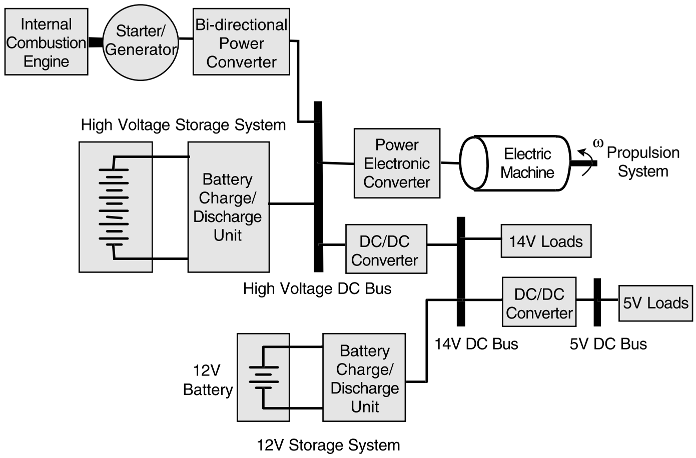

FIGURE 21.13 Conventional electrical power distribution system architecture for hybrid electric vehicles.

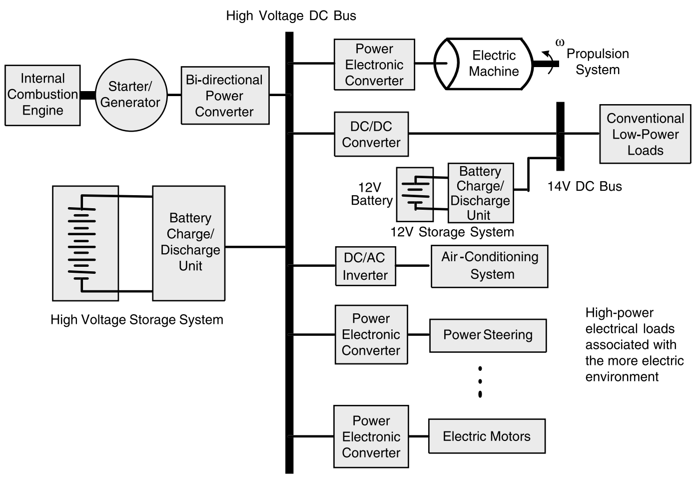

FIGURE 21.14 MEHV electrical power system architecture.

charge/discharge unit is also connected to the low-voltage bus. It should be mentioned that Fig. 21.13 without internal combustion engine, starter/generator, and bidirectional power converter shows the electrical power distribution system architecture of electric vehicles.

More-Electric Hybrid Vehicles

As described, demand for higher fuel economy, performance, and reliablility as well as reduced emissions will push the automotive industry to seek electrification of ancillaries and engine augmentations. This is the concept of MEV. Expansion of the MEV concept to HEV leads to More-Electric Hybrid Vehicles (MEHV). In the future MEV and MEHV, throttle actuation, power steering, antilock braking, rear-wheel steering, air-conditioning, ride-height adjustment, active suspension, and electrically heated catalyst will all benefit from electrical power systems.

Figure 21.14 shows the architecture of the MEHV electrical power system. It is a multivoltage hybrid (DC and AC) electrical power distribution system with a main high-voltage, e.g., 300 or 140 V, DC bus providing power for all loads. Conventional loads as well as new electrical ancillary and luxury loads associated with the more electric environment feed from the main bus via different DC-DC and DC-AC power electronic converters.

Automotive Electric Motor Drives

In a more electric car, most of the electrical loads, such as power steering and air-conditioning, require efficient, fault-tolerant, robust, simple, and compact electric motors. Different electric machines and power electronic converters will be used to facilitate conventional as well as advanced functions in future automotive systems.

DC motors with or without brushes are used for applications such as fans and pumps because of their high efficiency in addition to reduced cost, flexible control, high quality, and reliablity. Induction and variable reluctance machines are candidates for starter/generator systems. The comparison of these two machines for automotive applications is based on the electromagnetic weight, power density, efficiency, control complexity and features, complexity of design and fabrication, reliability, and thermal robustness [13, 14].

In EV and HEV, AC induction, DC commutator, and permanent magnet (PM) brushless DC motors are commonly used for propulsion systems. Recently, there has also been interest in switched reluctance motors (SRM) and synchronous reluctance motors [12, 15]. It is widely accepted that a suitable motor drive for traction applications in a vehicle should offer high efficiency, compactness, and low-cost manufacturing among other attributes. It is also important to remember that a successful candidate must provide a fault-tolerant and hazard-free operation.

A review of past works shows that considerable attention has been paid to the development of high-efficiency motor drives whereas the impact of vehicle dynamics is neglected. A field-oriented PM motor drive can have a high effciency because of the free excitation. However, a limited extended-speed constant-power region along with poor performance in the presence of short circuits and high temperature may prohibit effective use of these motor drives. Singly excited motor drives such as induction and switched reluctance machines, on the other hand, seem to have an excellent performance in the presence of partial failure and in harsh environments.

Conclusions

Advances in the areas of power electronics and electric motor drives along with fault-tolerant electrical distribution systems and control electronics enable the transforming of present automotive power systems into MEV systems. The future electrical power system for conventional cars will most likely be a single-voltage bus (42 V DC) with provision for hybrid and multivoltage-level distribution. On the other hand, the clearest direction for future HEV electrical power systems is a multivoltage system providing power for traction load and other automotive loads via high-voltage, e.g., 300 or 140 V DC, and low-voltage, e.g., 42 and/or 14 V DC, buses, respectively. The extent of these changes will certainly depend on cost-effective production of power electronics and other automotive electric and electronic components.

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