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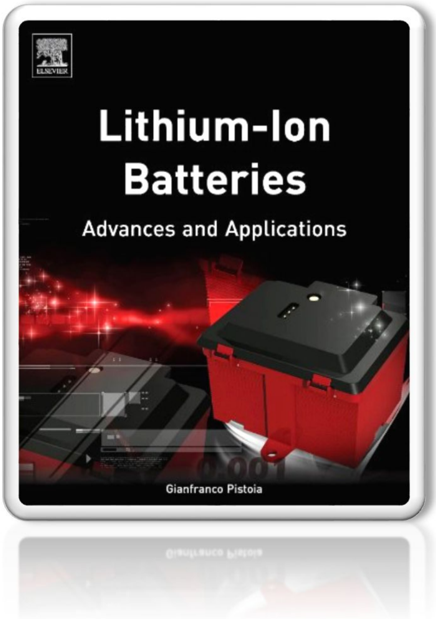

The Voltec System: Energy Storage and Electric Propulsion

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Abstract: Vehicle electrification is progressing significantly and is changing the architecture of future cars. This trend is a result of the need for higher vehicle efficiency and the desire to diversify the energy sources used for transportation. Voltec vehicles such as Chevrolet Volt and Opel Ampera are electric vehicles (EVs) with extended driving range. They operate as an EV as long as there is useful energy in the battery. However, unlike a pure battery EV, they do not suffer from lost vehicle utility when the battery is depleted. Volt and Ampera can continue operation by using an internal combustion engine as energy converter.

Within the framework of this chapter, in addition to the focus on the current Voltec battery and propulsion system technologies, a brief history of the General Motors EV activities is also provided.

Keywords: Battery, Chevrolet Volt, Opel Ampera, Propulsion system, Voltec.

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The Voltec System—Energy Storage and Electric Propulsion

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CHAPTER OUTLINE

1. Introduction

Today, the demand for individual mobility is still growing in many parts of the world, particularly in China and India. Temporarily, crude oil prices have already reached values substantially greater than US $100 per barrel, depending on the global market condition and the considered oil grade. In addition, the efforts to reduce greenhouse gas emissions to meet regulatory targets initiated the search for low-carbon fuels and fuels from non-fossil-fuel-based sources. This process accelerated the development of vehicles using electrified

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propulsion systems. After having fallen into oblivion during the first decades of the twentieth century, these technology programs had been restarted in the 1960s, when the development of originally aerospace-related technologies enabled the creation of the world's first fuel cell electric vehicles (FCEV) and battery electric vehicles (BEV) equipped with high-power batteries. During the 1990s, the aim of zero-emission transportation drove the development of electric vehicles (EVs) like the GM EV1 or FCEVs like the various generations of GM HydroGen1 to HydroGen4, as well as the purpose-built GM Sequel. Progress in power electronics, electric motors and the lithium-ion batteries led eventually to cars based on the Voltec system such as the Chevrolet Volt and the Opel Ampera, the first EVs with extended-range (ER) capability in the North American (2010) and European (2011) markets. These vehicles are utilizing a lithium-ion battery allowing 40–80 km of electric range where the electric motors exclusively provide the full power and top speed capability. If the battery reaches a well-defined low state of charge (SOC), a generator driven by an internal combustion engine (ICE) starts to provide the required power for long-distance driving.

The Voltec vehicles are utilizing an electric air-conditioning and electric cabin heating system. To optimize regenerative braking, the electric drive system can decelerate the vehicle and blend this process with the hydraulic brake system when higher deceleration is demanded.

Furthermore, test vehicles equipped with data loggers deliver important data for development, verification and validation on public roads in the United States, Europe and Dubai. Available real-world data confirms how significantly the Voltec propulsion concept can replace gasoline as an energy carrier by electricity. Application of electric energy from renewable sources is reducing the tank-to-wheels (TTW) greenhouse gas emissions further substantially.

2. A Brief History of Electric Vehicles

In the late nineteenth and the early twentieth centuries, EVs (see Figure 8.1) played a significant role in the emerging automotive market. The first vehicle that set a speed record exceeding 100 km/h was the "La Jamais Contente," an EV driven by Camille Jenatzy, a Belgian race driver and vehicle constructor. At the time, Oldsmobile, since 1908 part of General Motors, also manufactured EVs. EVs were easier to start and more comfortable, therefore being the early luxury vehicles: inter alia, Thomas A. Edison and Clara Ford owned EVs. In 1911, Charles F. Kettering, the founder and head of the GM R&D organization from 1920 to 1947, invented the electric starter for ICEs. Because of this seminal breakthrough, which had first been applied in a Cadillac vehicle, the ICE-driven vehicles (fueled by the more easily available gasoline, as well as providing greater range) started to dominate the automotive markets globally.

In the 1930s, the last American company building electric road vehicles stopped production. It took until 1964 when General Motors Research & Development integrated a silver–zinc battery originating from the US space program and electric motors in a Corvair-based EV, the Electrovair (see Figure 8.2(a)). In 1966, GM R&D developed the GM Electrovan (Figure 8.2(b)), the world's first fuel cell vehicle, with an alkaline fuel cell

(a)

(b)

FIGURE 8.1 (a) Oldsmobile electric vehicle; (b) GMC electric truck.

converting liquid oxygen and liquid hydrogen into electric energy. To drive the wheels, an AC induction motor was used. In 1969, General Motors presented a further experimental car, the XP-883. This concept vehicle combined a two-door hatchback body style with a two-cylinder opposed water-cooled engine, lead–acid batteries, a flywheel alternator and a DC series-wound electric motor. The XP-883 became an ancestor of a vehicle concept today known as plug-in hybrid EV. GM was also involved via its subsidiary Delco Electronics (cofounded by Kettering) into the design, development and testing of the Lunar Roving Vehicle which featured electric wheel hub motors and two 36-volt silver-zinc batteries. Three of these vehicles were operated on the moon by NASA astronauts within the framework of Apollo missions 15, 16 and 17.

(a)

(b)

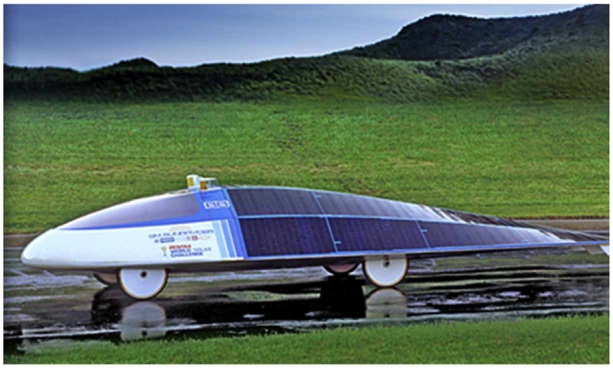
FIGURE 8.2 (a) Electrovair (1964); (b) GM Electrovan (1966). (For color version of this figure, the reader is referred to the online version of this book.)

But since all these technology strains were not mature enough for commercial application at that time, they fell into oblivion.

In 1987, the first "World Solar Challenge", a solar-powered car race through Australia, inspired General Motors, which at the time had just acquired Hughes Aircraft, to jointly develop a competition entry with the technology company AeroVironment [1]. The "Sunraycer" (see Figure 8.3(a)) won the race with an average speed of about 67 km/h.

Eventually, the success of "Sunraycer" convinced the GM engineers to develop the two-seater concept EV "Impact" [1]. In 1990, the Impact was designed to feature a low drag coefficient (c_W value: 0.19), low vehicle mass and low rolling resistance tires. The efficient propulsion system consisted of two AC induction motors (total rated power of 85 kW; reduction gear ratio of 10.5:1) and a power inverter with 228 MOSFET transistors. The battery system consisting of 32 lead–acid batteries had a voltage of 320 V and a capacity of 42.5 Ah, thus storing 13.6 kWh of energy. An acceleration time from 0 to 100 km/h in less than 9 s and a top speed of up to 128 km/h convinced all test drivers that EVs do not need to be slow-moving "traffic obstructions", but can accelerate easily on a

(a)



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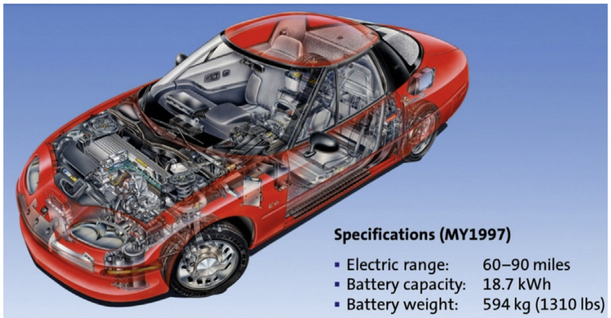

FIGURE 8.3 (a) GM Sunraycer; (b) GM EV1. (For color version of this figure, the reader is referred to the online version of this book.)

freeway ramp and provide the required performance in order to commute on highways. The electric range of the Impact, although significantly depending on driving style and weather conditions, exceeded 100 km.

The excellent impression on the public left by the GM Impact was one of the aspects that influenced the US state of California to establish the zero-emission vehicle (ZEV) mandate, requiring large manufacturers to sell a certain share of all vehicles as ZEVs. Based on this concept car, the GM EV1 [1] (see Figure 8.3(b)) had been designed, matching the original aerodynamic performance, but now using a production-optimized AC induction motor with a side-mounted reduction gear set and differential. The newly developed "insulated gate bipolar transistors" (IGBT) switched the DC current to generate three-phase AC current for the induction motor. Integrated in the power inverter housing were the inverter for the air-conditioning heat pump and the high-voltage heated windshield. For charging, a high-frequency inductive coupler (the so-called "blade" of Delco's "Magne Charge" system; standardized at the time as SAE J1773) was inserted in a slot in the car front. EV1 production started in 1996. More than 1000 vehicles have been built and leased to customers in California, Arizona and New York for several years. The second-generation GM EV1 eventually offered an optional nickel–metal hydride battery pack with a total energy of 26 kWh.

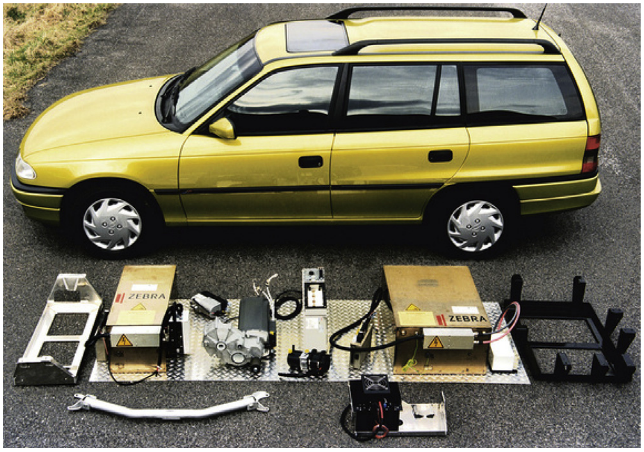

FIGURE 8.4 Opel Impuls. (For color version of this figure, the reader is referred to the online version of this book.)

In Europe, the drive system of the Impact propelled the Opel Impuls2, a conversion vehicle based on the Opel Astra Caravan in 1991. A new, specifically developed AC induction drive unit with IGBT inverter technology was used to build a small fleet of Impuls vehicles (see Figure 8.4). The fleet served as an automotive test bed for the integration of various advanced battery systems such as nickel–cadmium, nickel–metal hydride, sodium–nickel chloride, sodium–sulfur, and sealed lead–acid.

Those battery systems allowed typically a range of up to 160 km under specific driving conditions; but long charge times of 8–10 h, due the 3.3 kW restricted power level of typical German 230 V single-phase outlets, demonstrated that BEVs at the time were not a full replacement for vehicles with ICEs which can be refueled within minutes.

The fuel cell systems developed within the General Motors Fuel Cell Activities allowed both the extension of the EV range and refueling within minutes. In the year 2000, the Opel HydroGen1, based on the Opel Zafira, had been demonstrated to the public. Later, a small fleet of again Opel Zafira-based HydroGen3 vehicles had been used in demonstration programs in Germany, United States, Korea and Japan. Starting in 2007, a fleet of 119 Chevrolet Equinox FCEV, equipped with nickel–metal hydride power batteries, has been handed over to various private and commercial customers in the United States and Germany in order to gather experience for the next-generation fuel cell drive systems. As of mid-2012, this fleet has accumulated more than 4 million km on public roads within the framework of GM's "Project Driveway", with three cars counting each well over 110,000 km.

Progress in the technology of lithium-ion battery systems and the improvement of power densities of electric drives enabled the concept of the so-called "extended-range electric vehicles" (EREVs) [2,3]. A vehicle using a powertrain system of this type, such as Voltec, operates as a high-performance EV for most trips and uses a generator in connection with an ICE to provide energy for long-distance driving. Due to the smaller battery capacity compared to a hypothetical BEV of the same total range, reasonable charging times of less than 4 to 6 h, when using existing European 230 V infrastructure, are feasible.

The "Chevrolet Volt" concept car [2] was presented to the public at the North American International Auto Show 2007 in Detroit. Eventually, in 2010, the Chevrolet Volt (see Figure 8.5) was introduced to the US market. About 1 year later, the sale of Opel Ampera (also a Voltec-based vehicle [3]) started in Europe. In early 2013, the Cadillac ELR, a two-door coupe using a modified and performance-optimized Voltec powertrain, was unveiled as a 2014 production model to the general audience at the Detroit and Geneva motor shows.

Partial electrification improves automotive fuel economy and is introduced step by step in various vehicle classes. In 2008, the GM two-mode hybrid system had been introduced in large vehicles such as the Chevrolet Tahoe or trucks like the Chevrolet Silverado.

The "eAssist" mild hybrid system powered by a 115-V lithium-ion battery system is available since the sales start of the 2012 Buick Regal and Buick LaCrosse midsize vehicles.

The overall GM electrification strategy ranges from lower levels of vehicle electrification like stop-start systems over mild and full hybrid systems to plug-in vehicles [3,4]. This class includes EREVs based on Voltec systems, as well as mass production BEVs like the Chevrolet Spark, and EV prototypes such as the GM EN-V two-wheeler or the Opel Meriva MeRegioMobil (enabling bidirectional power flow [3]). Finally, FCEVs utilize the

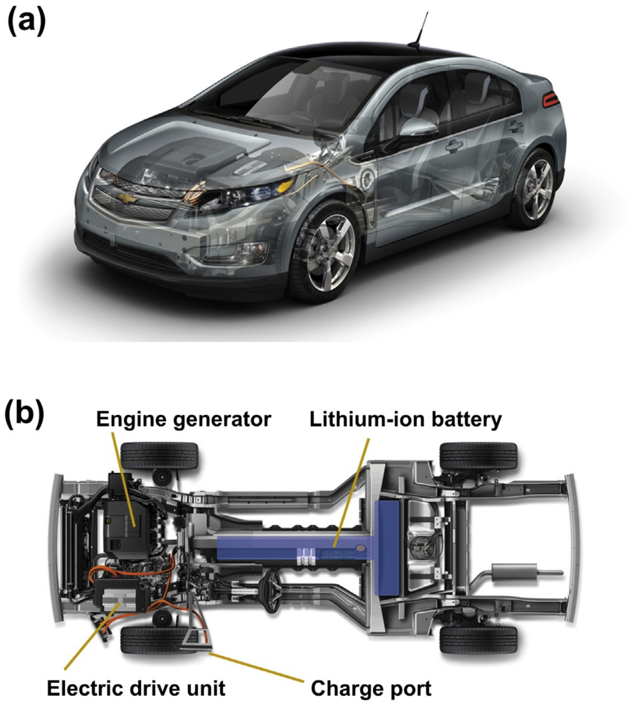

FIGURE 8.5 (a) Chevrolet Volt; (b) the Voltec system. (For color version of this figure, the reader is referred to the online version of this book.)

high energy density of a chemical energy carrier, namely hydrogen, to power their electric motor via a fuel cell as converter [5]. All these plug-in and fuel cell electric vehicle concepts replace at least partially gasoline- or diesel-based fuels by potentially “renewable” electricity or hydrogen. For both detailed and comprehensive information on energy sources, tank-to-wheels and well-to-wheels efficiencies regarding various types of powertrain concepts, the authors recommend Refs [3,4].

3. Extended-Range Electric Vehicles

Voltec vehicles, such as the Chevrolet Volt and the Opel Ampera, are extended-range electric vehicles (EREV). In the “charge-depletion” (CD) mode, these cars use electrical energy from the battery system until the SOC reaches a certain defined level (Figure 8.6); then the system passes on to the “extended-range” (ER) or “charge-sustaining” (CS) mode: the ICE kicks in and drives the electrical generator to deliver electrical energy in order to keep the SOC constant within a defined range. First-generation Voltec vehicles such as the Chevrolet Volt vehicles (model year 2011) have a 54-kW electric generator installed, driven by a 1.4-liter four-cylinder ICE. The combustion engine is switched off when no electric power is required by the system, e.g. in case of deceleration, downhill driving, stops or low load requirements. The Voltec system allows the selection of the most efficient engine operation areas.

In pure EV mode (also known as CD mode), the Voltec battery system provides power for acceleration and driving up to a speed of 161 km/h. This top speed is electronically limited. In the ER mode (also known as CS mode), the gasoline engine-powered generator delivers up to 54 kW of electric power. If needed, the battery system provides the additional power to maintain the full acceleration capability of the 111-kW drive system.

The EV range (see Table 8.1 and Figure 8.6) based on Voltec battery energy is 40–80 km, depending on the driving style, ambient temperature conditions and climate comfort settings. Determining the range of the Opel Ampera using the New European Driving Cycle (NEDC) (see Figure 8.6(b)), a value of 83 km is obtained. In combination with the ER mode, the vehicle is able to travel up to more than 500 km before a gasoline refill or recharge of the battery is required.

For electric recharging, a Voltec vehicle such as the Opel Ampera provides an onboard charger module (OBCM) which can be connected to a 230-V source in Europe, either using a wall-mounted charge cord with 16 A or to a household outlet via a transportable cord set with 10 A (part of the vehicle standard equipment). With a level of 16 A, the charging takes less than 4 h. Using the transportable cord set, the time will be less than 6 h or 8 h at a user-selected reduced amperage.

The controls system of a Voltec vehicle has the purpose to efficiently manage the energy distribution for propulsion, heating ventilation and air-conditioning, and the 12-V system (see Figure 8.7). When driving in pure EV mode, energy from the battery system (rechargeable energy storage system) or, on ER drives, energy from the fuel tank, has to be

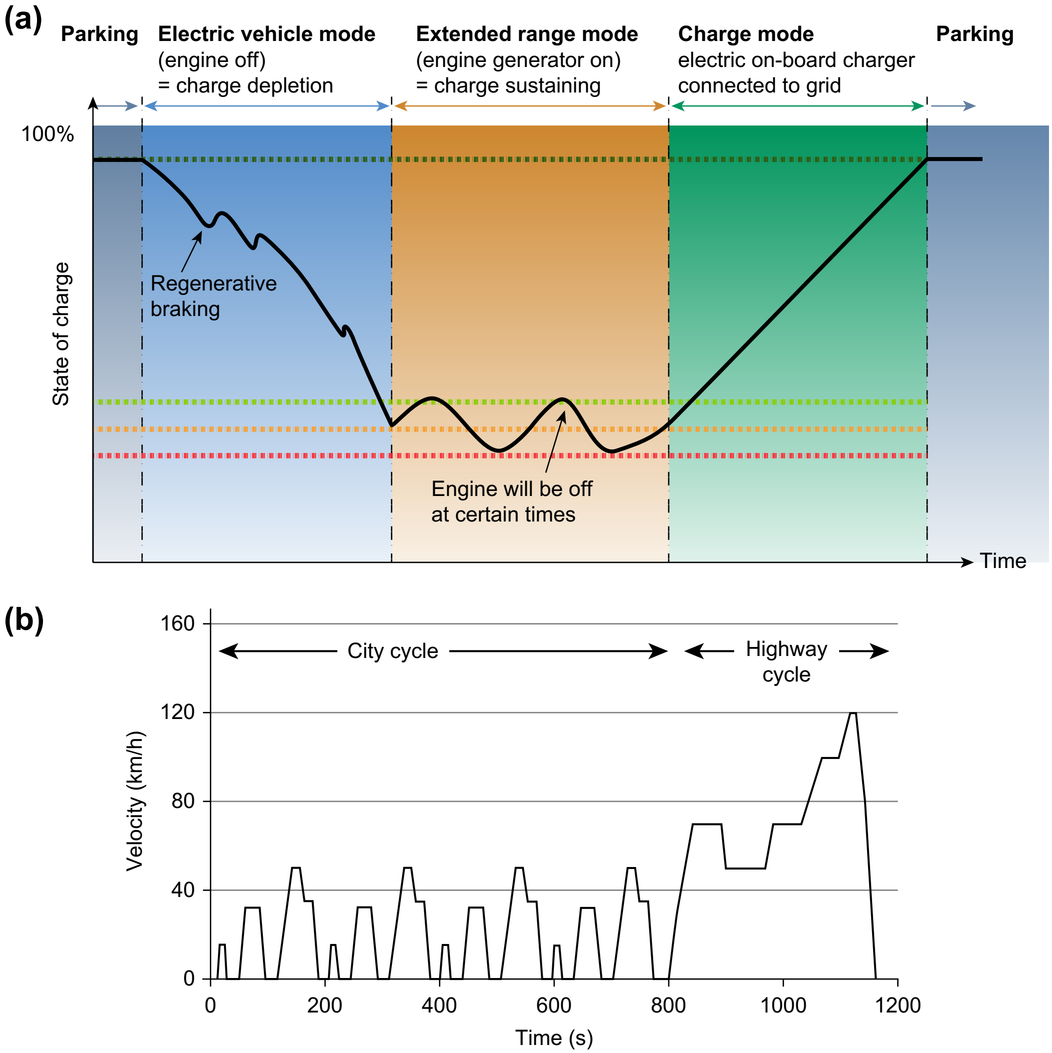

FIGURE 8.6 (a) Operation modes of extended-range electric vehicles, from Ref. [5]. (b) New European Driving Cycle. (For color version of this figure, the reader is referred to the online version of this book.)

managed to keep the electric energy storage systems within the allowed SOC range, depending on the drive mode. The overall objective is the optimization of vehicle efficiency. When the vehicle is plugged in via the charge cord to a power outlet, power is used to recharge the battery and on request to heat up or cool down, respectively, the cabin by operation of electric heater or electric air-condition system. The driver can select to precondition the vehicle in certain cold or hot climates. By doing so, the amount of usable energy stored in the battery can be optimized and therefore more energy is available for propulsion purposes; consequently, the effective EV range is increased.

Table 8.1 Opel Ampera Powertrain Specifications (Based on Voltec)

Traction motor	PM synchronous motor
Maximum power	111 kW
Maximum torque	370 Nm
Internal combustion engine	1.4-l DOHC I-4 engine (63 kW)
Generator	PM synchronous motor (54 kW)
Top speed	161 km/h
Acceleration time (0–100 km/h)	9 s
Energy content (battery)	16 kWh
Charging time	<4 h @ 230 V, 16 A (wall box) <6 h @ 230 V, 10 A (cord set)
Range	
EV mode, real-world	40–80 km
EV mode, NEDC value	83 km
Total	>500 km
Combined CO_2 emissions (CS/CD) based on NEDC and European ECE R101 regulation	27 g CO_2/100 km
Combined fuel economy (CS/CD) based on NEDC and European ECE R101 regulation	1.2-l gasoline (premium)/100 km

DOHC, double overhead camshaft; PM, permanent magnet.

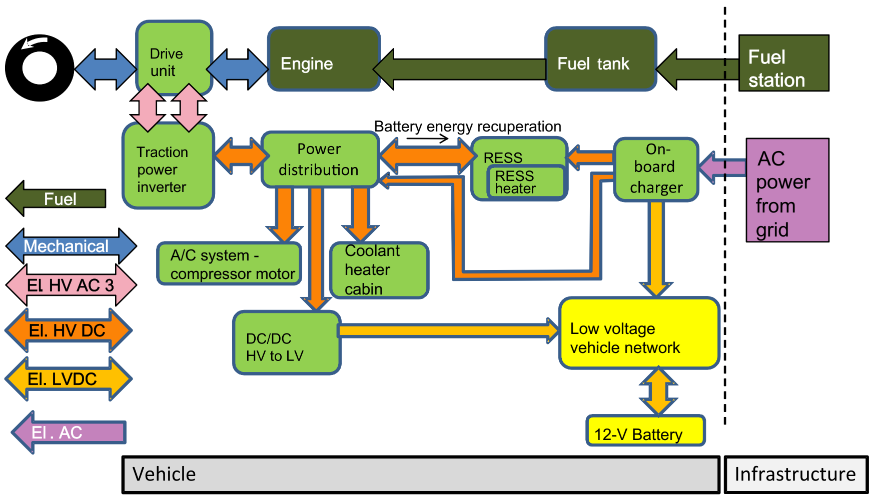

FIGURE 8.7 Schematic energy flow diagram. (For color version of this figure, the reader is referred to the online version of this book.)

4. The Voltec Propulsion System

The main subsystems of the propulsion system are the electric drive unit, the Voltec battery, the 1.4-l ICE, the OBCM, the auxiliary power module (APM) (HV-12-V DC/DC converter), and the electrically driven air-conditioning and cabin heating system.

The electric drive unit (see Figure 8.8) comprises two electric motors, one planetary gear set, the gear reduction final drive and three clutches. The traction motor is rated at 111 kW and 370 Nm and the electric generator can deliver up to 54 kW of high-voltage DC power through the power inverter. In both cases, permanent-magnet synchronous motors are used; a Voltec vehicle requires circa 3 kg of rare-earth material.

The Voltec battery system [2] contains 288 lithium-ion pouch cells, each with a 15 Ah capacity and a 3.8 V nominal voltage. Three Li-ion cells are connected in parallel to create cell groups of 45 Ah. A total of 96 cell groups are connected in series and the resulting battery's nominal system voltage is 360 V (see Figure 8.9(a)) [2]. The cell groups are integrated in nine modules assembled to three sections (see Figures 8.9 and 8.10). The pouch cells were developed and are manufactured by LG Chem, using a manganese-based cathode material [2]. Each cell is pressed on one side to a heat exchanger plate which contains channels for the thermal fluid (see Figure 8.9(b)). Heat exchanger plates and cells are stacked with plastic frames containing the fluid manifold. The thermal fluid is pumped by an electric pump and distributed through a valve to the radiator or the chiller connection to the air-conditioning fluid system. The battery system contains a fluid heater to keep the battery temperature above the outside temperatures in cold climates. This heating function, also provided during plug-in charging of the battery, keeps the discharge and charge power level of the battery system sufficiently high to improve vehicle acceleration and enable regenerative breaking. By doing so, a vehicle start-up at very low ambient temperatures, down to −40 °C, is possible.

The liquid-based thermal management system of the Voltec battery system is fully integrated into the vehicle's heating, ventilation, and air conditioning system (HVAC) via its thermal interface, a coolant-in and coolant-out hose [2]. The coolant is normally

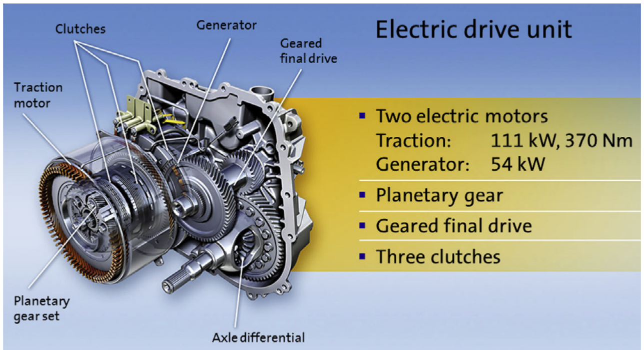

FIGURE 8.8 Voltec electric drive unit. (For color version of this figure, the reader is referred to the online version of this book.)

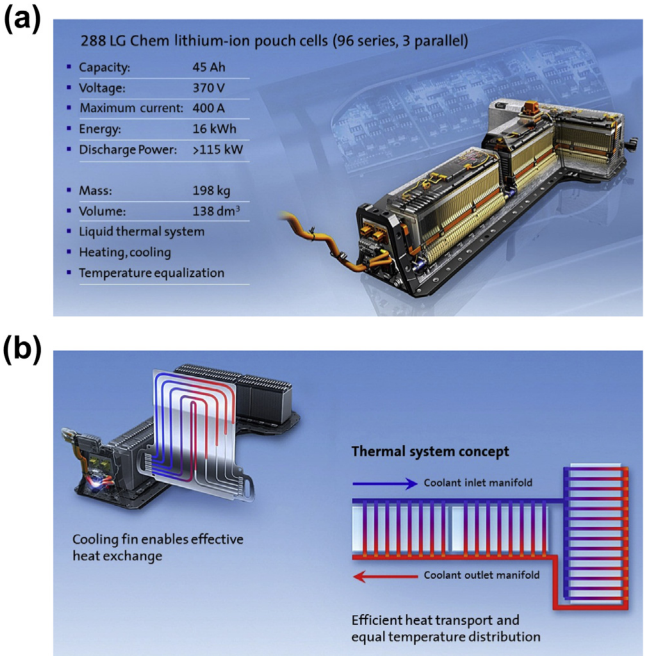

FIGURE 8.9 (a) Voltec battery pack; (b) active thermal system. (For color version of this figure, the reader is referred to the online version of this book.)

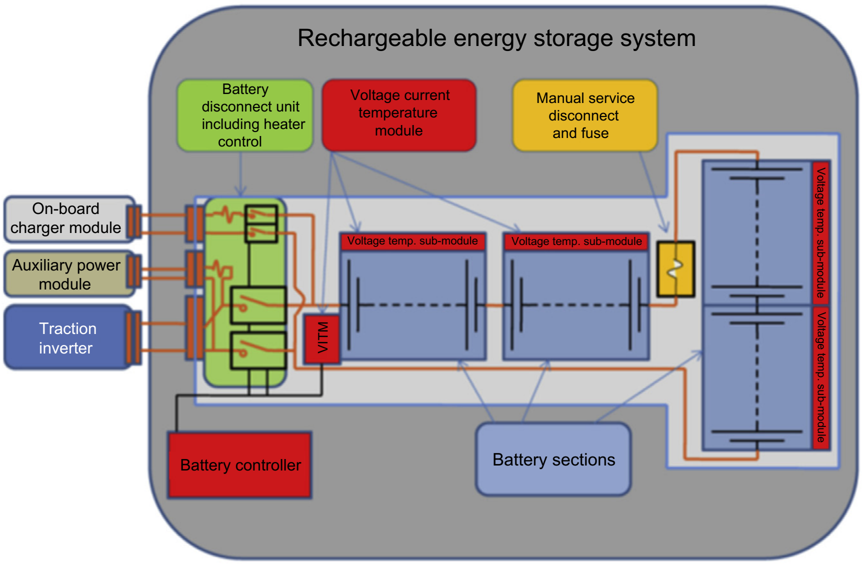

FIGURE 8.10 High-voltage architecture and details of the battery system. (For color version of this figure, the reader is referred to the online version of this book.)

cooled by a low-temperature radiator that is especially dedicated to the battery. This method ensures a good efficiency and minimum energy use for the thermal management which is subsequently important for an excellent range in pure EV mode. At high ambient temperatures, the coolant heated up in the battery system is cooled down in a two-step process: (1) in the radiator to an intermediate temperature level and (2) further down to a final temperature level via a chiller that is connected to the vehicle's AC system. Thus, the Voltec battery system can be cooled adequately at nearly all ambient temperatures and the vehicle's overall efficiency is optimized. In addition, at low temperatures, it is possible to make use of the vehicle's HVAC system for slightly heating up the battery system. This increases the battery performance at the beginning of the trip and allows the battery system to reach its optimum temperature earlier.

The front part of the battery system contains two main contactors, rated for maximum operation current, which are used during drive operation. They connect the traction power inverter module (TPIM) and the APM to the DC/DC converter providing 12 V power. Through the TPIM, power is distributed to the electrically driven air-conditioning system and the electric coolant cabin heater (see Figures 8.7 and 8.10). Two smaller, power-saving contactors are used during longer battery charging periods, connecting the OBCM. The contactors are integrated within the battery disconnect unit (BDU) which also contains the electric heater for the battery thermal fluid and the heater control device.

The front plate contains connectors for the TPIM, OBCM and APM modules, additionally two signal connectors for the controller area network bus (CAN bus) and the 12-V power supply. On top of the battery housing, a socket for the manual service disconnect (MSD) is positioned. The MSD plug contains the main fuse of the system. All external connections of the battery system are equipped with contacts for the high-voltage interlock loop. Pulling a connector or the MSD will cause the contactors to open in order to prevent arcing.

The battery system's total nominal energy is 16 kWh; approximately 10 kWh of the stored energy is usable. The maximum discharge power (10 s) within the SOC operating window exceeds 115 kW at standard temperature conditions. The total mass of the battery system amounts to 198 kg, including cables to the traction inverter and the rear bracket.

In order to monitor the battery system voltage, all cell group voltages, the battery current, selected cell temperatures and the battery thermal fluid temperature of the "voltage current temperature module" (VITM) are used. The VITM is located between the BDU and the first section. This module is connected by data bus with several "voltage temperature sub-modules" (VTSM), placed on top of each section (see Figure 8.10). The VTSM modules measure cell voltages: they contain a transistor and a resistor per each cell to control the cell discharge. Cell groups with a higher voltage can be discharged to equalize the voltages of all cell groups within the battery system. This equalization or cell balancing is required to enable the successful long-term operation of the system. Furthermore, every module contains cell temperature sensors connected to a VTSM. The battery current is measured with a Hall effect sensor. The VITM signals are processed and analyzed by a battery-state-estimation algorithm in order to obtain the SOC value.

Additionally, the VITM signals are used to determine the insulation resistance between high-voltage conductors and the vehicle ground potential.

5. Voltec Drive Unit and Vehicle Operation Modes

5.1. Drive Unit Operation

The electric drive unit (see Figures 8.8 and 8.11) of Voltec vehicles can be operated in four different modes [3], the two pure EV (or "charge depletion", CS) modes with one-motor (1) and two-motor operation (2) and the two ER (or "charge sustaining", CS) modes in series (3), respectively, combined operation (4).

(1) In EV operation at lower speed, with clutches C3 and C2 open and clutch C1 closed, the drive operates in "one-motor EV mode" and the traction motor exclusively propels the vehicle. (2) In battery-only operation at higher speeds, the "two-motor EV mode" is more efficient: clutch C2 is closed and clutches C1 and C3 are open. The two electric motors (i.e. traction motor and generator) operate on the planetary gear, where the second motor is now counteracting the torque on the ring gear. The torque and the speed of the two electric motors is determined by the linear relationship defined by the planetary gearset and can be adjusted continuously. The two-motor EV mode reduces the speed of the electric motors. When using this mode at higher speeds, the vehicle efficiency and consequently the mileage is improved. Considering the U.S. Highway cycle (US06), the EV range is extended by additional 1 - 2 miles.

(3) In ER mode at lower speeds, the so-called "one-motor series ER" mode is used: clutches C1 and C3 are closed, while clutch C2 is open (see Figure 8.11). The generator driven by the ICE is generating electric power for the traction motor, the APM, the electric air-conditioning system and for sustaining the battery SOC. Using the series-drive

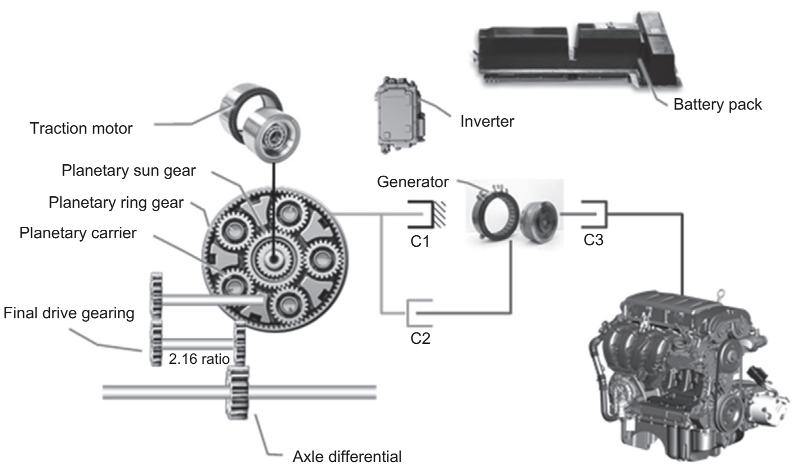

FIGURE 8.11 Voltec drive architecture with clutches and planetary gear set.

configuration, there is no mechanical power flow from the engine to the wheels; the vehicle is exclusively driven by the electric traction motor. (4) At higher speeds in ER operation, the “two-motor combined mode” is applied: clutches C3 and C2 are closed and clutch C1 is open. During highway driving, efficiency is improved by 10 to 15 percent compared to (3) since the efficiency loss of the electric motor operated at high speed and the dual energy conversion of the series path from mechanical energy to electrical energy and back can be avoided. Engine power and traction motor power are combined in the planetary gear set and drive the vehicle in this output power-split configuration jointly (see Figures 8.11 and 8.12).

5.2. Driver Selectable Modes

The driver of a Voltec vehicle such as the Opel Ampera can select one of four driving modes. After starting up the vehicle, “normal mode” is the default setting. In this mode, the vehicle is operating as pure EV until the standard SOC level for the transition into “charge-sustaining” operation is reached: the engine will turn on, depending on the amount of energy required by the generator. In case the vehicle is switched into “sport mode” by the driver, the accelerator pedal characteristics are changed. “Sport mode” should be selected when driving at higher speeds, e.g. on a German “autobahn”, in order to ensure “maximum power availability”. By contrast, “mountain mode” will increase the SOC level for the transition into “charge-sustaining” operation (see Figure 8.6). “Mountain mode” should be selected before reaching mountain pass roads or long, steep grades at higher speeds: the extra energy reserve eventually allows combining the power of the generator (54 kW) and battery over an extended time period to the maximum propulsion power of 111 kW. Finally, the “hold mode” should be selected during a long-distance trip if the driver wants to preserve some energy to enable EV mode operation at the destination. By starting the ICE, “hold” mode will keep the SOC level fixed at the value of the point of time when the mode was selected. The vehicle is “artificially” forced to enter the “CS mode”.

6. Battery Operation Strategy

Operation of a lithium-ion battery requires preventing overvoltage, overcurrent and undervoltage conditions in order to avoid cell damage or degradation of battery life. Based on the internal resistance, the open-circuit voltage, the upper/lower voltage limit and the current limit, the charge and discharge power will change as a function of the SOC level.

Typically, the discharge power is maximal at high SOC and decreases toward low SOC [2]. The charge power behaves more or less vice versa. At low and medium SOC, a good charge power capability is observed. Details can be seen in Figure 8.13.

Similar to the charge power at low temperature, the charge power at high SOC needs to be controlled quite precisely. As a consequence, the battery cannot be operated over the

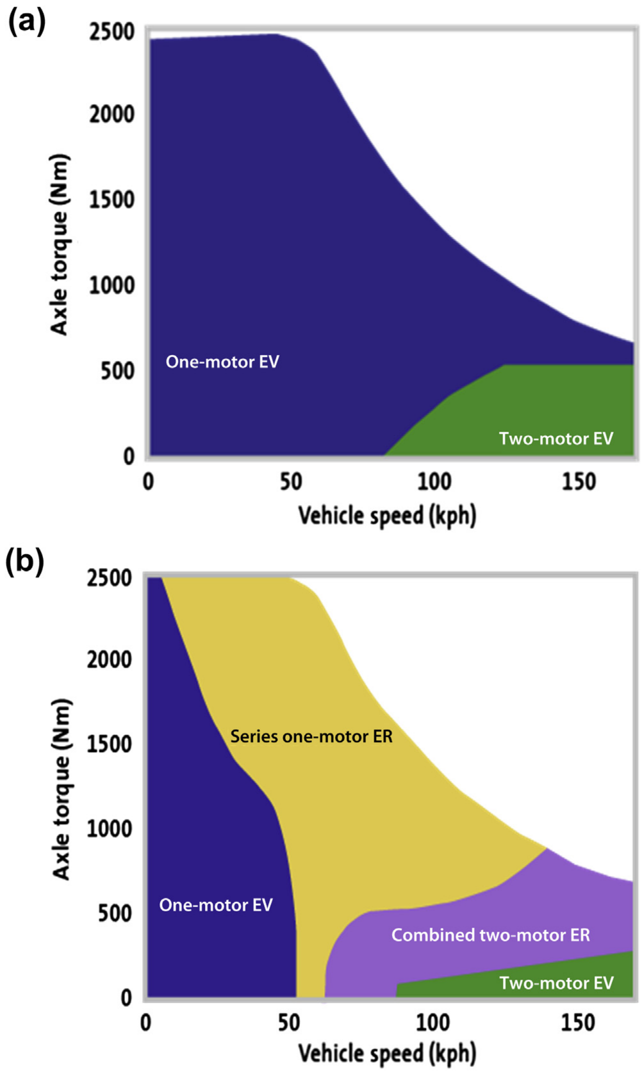

FIGURE 8.12 (a) Pure EV; (b) extended-range drive operation. (For color version of this figure, the reader is referred to the online version of this book.)

complete SOC range. Low SOC values have to be excluded due to insufficient discharge power; at high SOC, the traction battery cannot be used for regenerative braking any more. Therefore, the usable energy window is only a part of the total energy [2].

At a high SOC level, the charging power has to be reduced to avoid cell overvoltage (see Figure 8.13). To optimize regenerative braking, the electric power of the motor and the hydraulic power have to be managed by a process called brake blending.

At very low battery SOC, the discharge power has to be reduced to avoid "cell undervoltage". The low-end SOC level is defined in such a way that the discharge power is

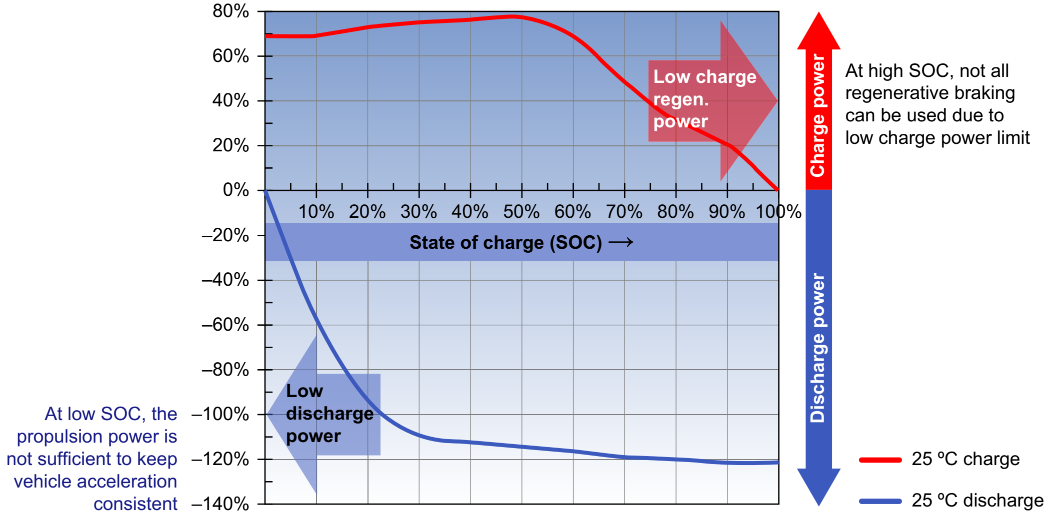

FIGURE 8.13 Lithium-ion battery charge and discharge power. (For color version of this figure, the reader is referred to the online version of this book.)

sufficient to enable transient power values of 115 kW in order to allow consistent acceleration and provide sufficient energy for extended overtakings (see Figure 8.13).

The total energy throughput of lithium-ion batteries is greater when many “small” charge–discharge cycles are performed compared to a few “large” charge–discharge cycles (see Figure 8.14). “Small” cycles could be, inter alia, cycles from 20% to 25% SOC. An example of a “large cycle” would be one from 100% SOC to 5% SOC.

Stress within the cathode or anode materials can be caused when the cathode or anode is fully “lithiated” or “delithiated”. This effect, leading to battery durability issues, has to be understood and carefully assessed when deciding on the SOC operating strategy.

At lower temperatures, the internal resistance of the cells increases. This effect is leading to a reduced battery power. For a consistent vehicle operation close to the rated power, battery temperatures above 0 °C are needed (see Figure 8.15). Down to −30 °C, the battery should have at least sufficient power to crank the engine. By ensuring this feature, the EREV concept allows complementing battery power with generator power at subzero temperatures and at low SOC levels for an improved vehicle performance.

Lithium-ion batteries are electrochemical systems whose processes are related to temperature: higher temperatures accelerate side reactions which cause a reduction of battery capacity or an increase in battery resistance. Long-term exposure to temperature values above 32 °C should be minimized to meet a 10-year durability target (see Figure 8.16). Each specific battery chemistry has a different sensitivity, but the general rule applies to all systems.

The battery operation strategy needs to balance power, energy and temperature. Therefore, voltage, current and temperature need to be carefully monitored and

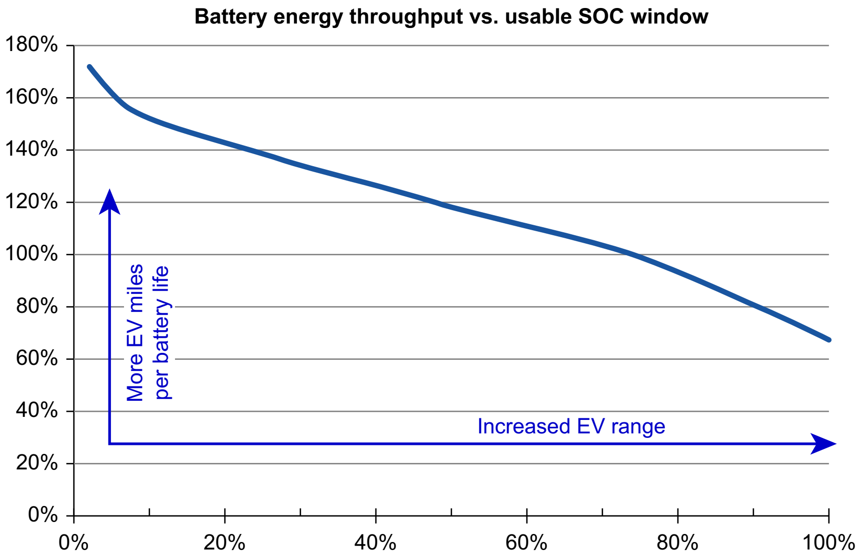

FIGURE 8.14 Total battery energy throughput as function of the state-of-charge window size. (For color version of this figure, the reader is referred to the online version of this book.)

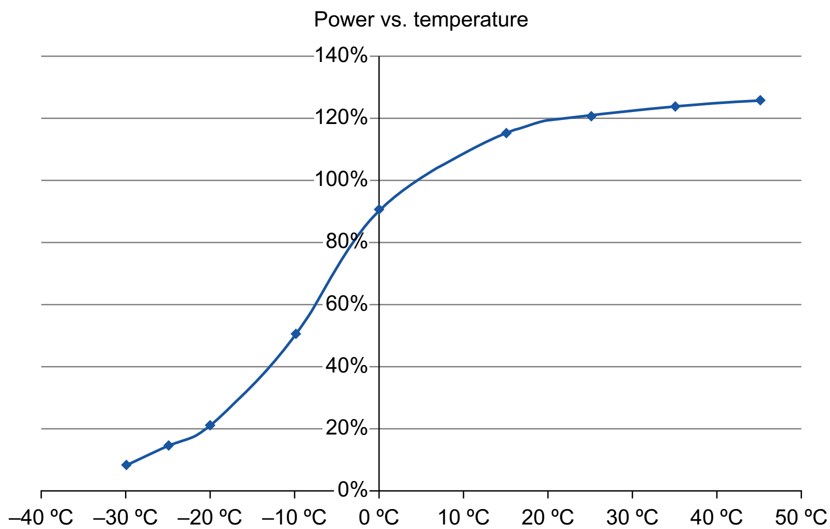

FIGURE 8.15 Power as function of the lithium-ion battery temperature. (For color version of this figure, the reader is referred to the online version of this book.)

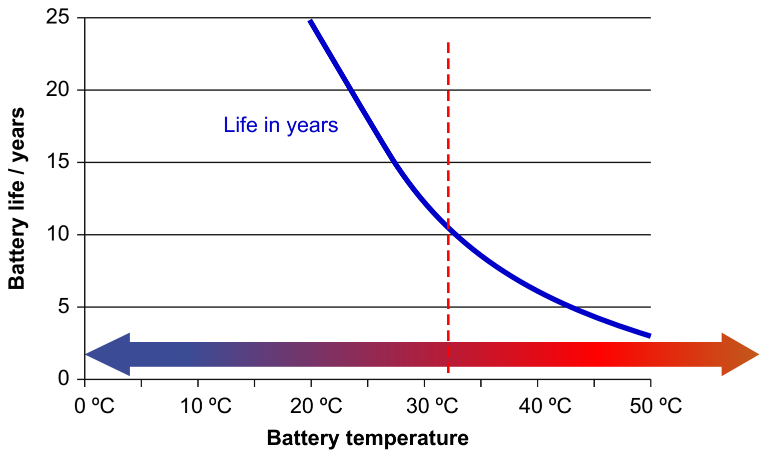

FIGURE 8.16 Battery life is shorter at higher temperatures. (For color version of this figure, the reader is referred to the online version of this book.)

controlled. A thermal system which enables heating and cooling makes an electric propulsion system viable for real-world operation in different geographic regions and climate zones. The power management system allows implementing operating strategies for slow degradation and long battery lifetimes, but the basis of any such strategy remains the selection of a robust and safe lithium-ion cell chemistry.

7. Development and Validation Processes

Modeling and experimental testing are the starting points of the development and validation chain of modern automotive products (see Figure 8.17). Therefore, standardized tests and modeling methods are applied and the modeling results have to be verified experimentally and the respective procedures and methods validated. The Voltec powertrain and battery systems are composed of various novel technologies and designs which required in many cases the development of completely new test procedures. Where applicable, e.g. for electronic controllers, existing procedures were applied or used after modifications. This section will focus on the development and validation processes of the battery system.

The battery development process included a large number of cell tests. For instance, in order to characterize the cells, the usable power was measured over SOC and temperature. Furthermore, early in the process, cell abuse tests were performed to qualify their usage in a vehicle production program. Such abuse tests included overcharge, overdischarge, short-circuit, nail-penetration, hot-box and crush procedures.

To determine the best operation range, a large number of different cycle tests with variations of depth of discharge, power and temperature were performed. For cell tests, hundreds of test channels had been operated over several years. A test channel is a bidirectional DC power supply which can be programmed to charge and discharge the

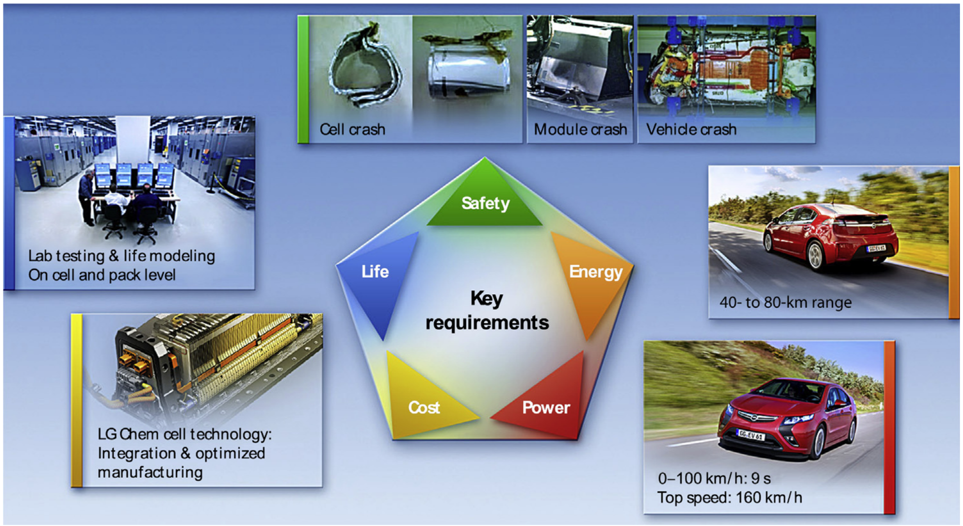

FIGURE 8.17 Development and validation processes of key requirements. (For color version of this figure, the reader is referred to the online version of this book.)

battery cell according to power-over-time profile; the device measures the actual voltage and current data. The cells are placed in environmental chambers, controllable from −40 °C up to 70 °C. The results of the numerous cell cycle tests are the basis for the mathematical battery life model. The battery life model allows anticipating with sufficient precision how different styles of vehicle usage in different climatic conditions would affect battery capacity and resistance variations over time.

On a statistically relevant scale, the cell tests are complemented by tests at the module and pack level, using larger battery cyclers. Within the framework of a battery pack lifecycle test, a full charge-depletion profile is applied, followed by a simulated charge-sustaining profile and eventually an accelerated recharge profile. The resulting complete test profile is then rerun continuously as an accelerated lifetime test. Applying these profiles under the simulated conditions of the climate zones of Detroit, Los Angeles or Phoenix in environmental chambers, a number of battery packs have already reached durability values of about 320,000 km without failing to meet the respective capacity or power requirements.

To validate the robustness of a Voltec battery system against vibration and shock, on proving-ground road conditions, test profiles were recorded using a comparable conventional vehicle. The profile was simulated on a full-size battery shaker combined with temperature variations from minimum to maximum values, as required by automotive specifications. During the vibration and thermal cycles, an electric power profile (including the maximum charge and discharge levels) was applied to identify potential issues as early as possible in the vehicle development process.

The Voltec battery system is designed according to the International Protection Code (or briefly IP Code) classification IP6k9k. Dunk tests confirmed the protection against water intrusion. Modules were tested according to the procedures of UN38-03, including vibration, shock and short-circuit tests. These tests are required to obtain the approval for battery system transports by air, road or sea.

On a vehicle level, functionality, electromagnetic compatibility and the water drive-through tests were performed. An NCAP vehicle crash performance rating of 5 stars (both in the US and Europe) was obtained through a careful development process using, inter alia, computer-aided engineering tools; simulation results were validated by vehicle crash tests. Road tests were important to refine noise and vibration quality and vehicle handling and to verify the controls functions of all systems under real-world conditions. Series production of Voltec vehicles started at the end of 2010. Using LG Chem cells, the battery packs are manufactured at a GM facility in Brownstown Township, Michigan. The ICE range-extender has been originally produced at the GM/Opel powertrain plant in Vienna-Aspern, Austria. Finally, at the GM plant in Hamtramck, Michigan, the Voltec car assembly takes place.

8. Vehicle Field Experience

In 2008, battery packs were mounted on mule vehicles for early testing of the production-intent Voltec system. After these successful initial tests, the first Chevrolet Volt preproduction vehicles (“integration vehicles”) were built in the GM prototype workshop in summer 2009 and were used for finishing the calibration of the control systems. Most of those vehicles had been equipped with data loggers to allow root cause analysis and monitoring of the battery systems over extended periods. In 2010, the captured-test fleet vehicles had been produced and were added to the test programs. Data recorders were also installed in these cars. Enabled by the use of data loggers, one decisive result was the successful experimental verification of the required cell-balancing quality over the course of extended vehicle usage periods.

Vehicles in North America, Europe and the United Arab Emirates were operated and tested on public roads by various drivers in order to gather data on battery power and the energy flow within subsystems. The thermal system demonstrated the capability to keep the battery temperatures below 30 °C during the summer in Dubai and above 0 °C during the wintertime in Michigan. In Europe, the vehicles were driven in the stop-and-go traffic conditions of large urban agglomerations (e.g. the Rhein-Main area around Frankfurt) and on German autobahn sections with high average vehicle speeds on long grades (e.g. “Albaufstieg” near Stuttgart). Real-world driving profiles from the German town of Wiesbaden to Koblenz and vice versa are given in Figures 8.18 and 8.19. For a comparison with the official NEDC profile and values, see Figure 8.6(b) and Table 8.1.

Real-world data recorded from the Chevrolet Volt customers in the United States via GM’s OnStar system show that about 65% of the fleet miles are driven completely in EV mode; for exact numbers see Figure 8.20(a). The measured clear prevalence of the EV mode in real-world Chevrolet Volt operation is in very good agreement with the results of the US Department of Transport 2003 BTS Omnibus Household Survey which show that 68% of US households have an average daily commute of less than 30 miles and 78% have commute of less than 40 miles (see Figure 8.20(b)).

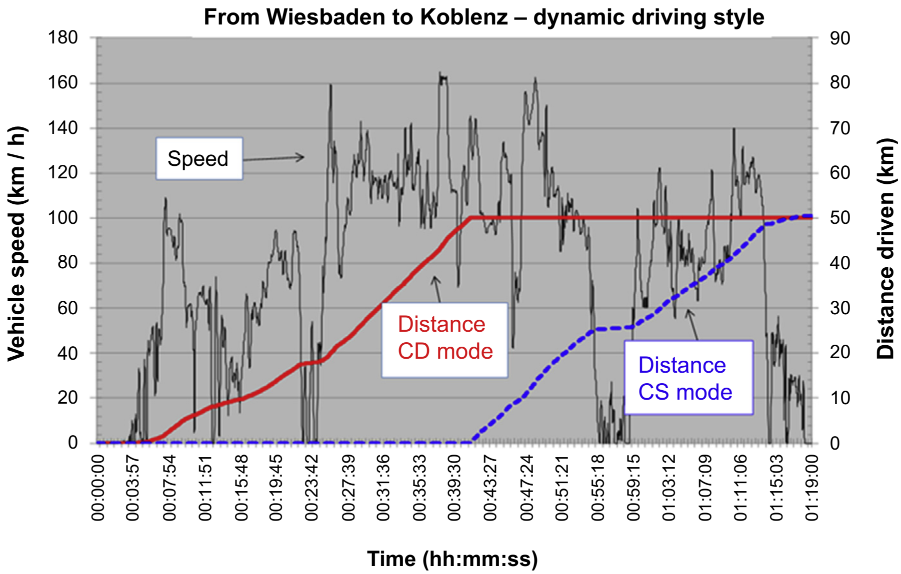

FIGURE 8.18 Recording of a 50-km range in charge-depletion mode, real-world data (from Wiesbaden to Koblenz); dynamic driving style. (For color version of this figure, the reader is referred to the online version of this book.)

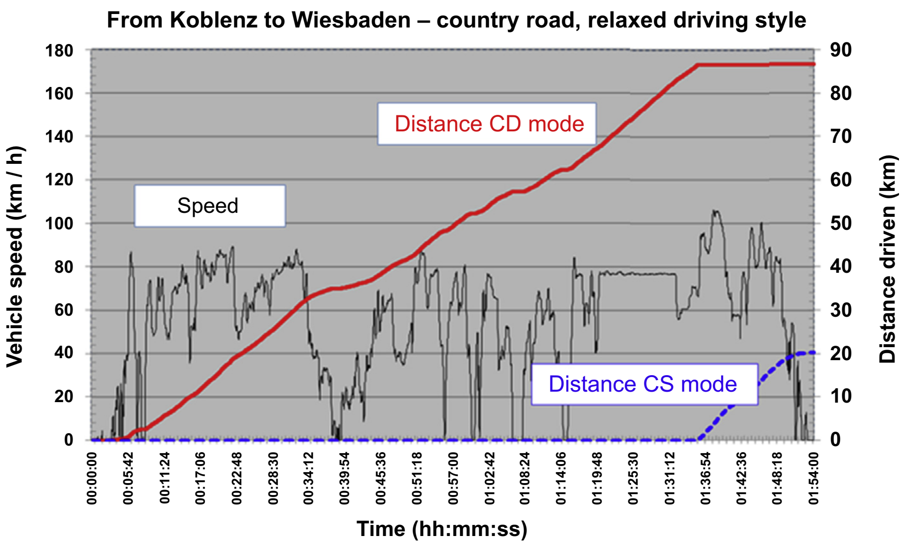

FIGURE 8.19 Recording of a 86-km range in charge-depletion mode, real-world data (from Koblenz to Wiesbaden); relaxed driving style. (For color version of this figure, the reader is referred to the online version of this book.)

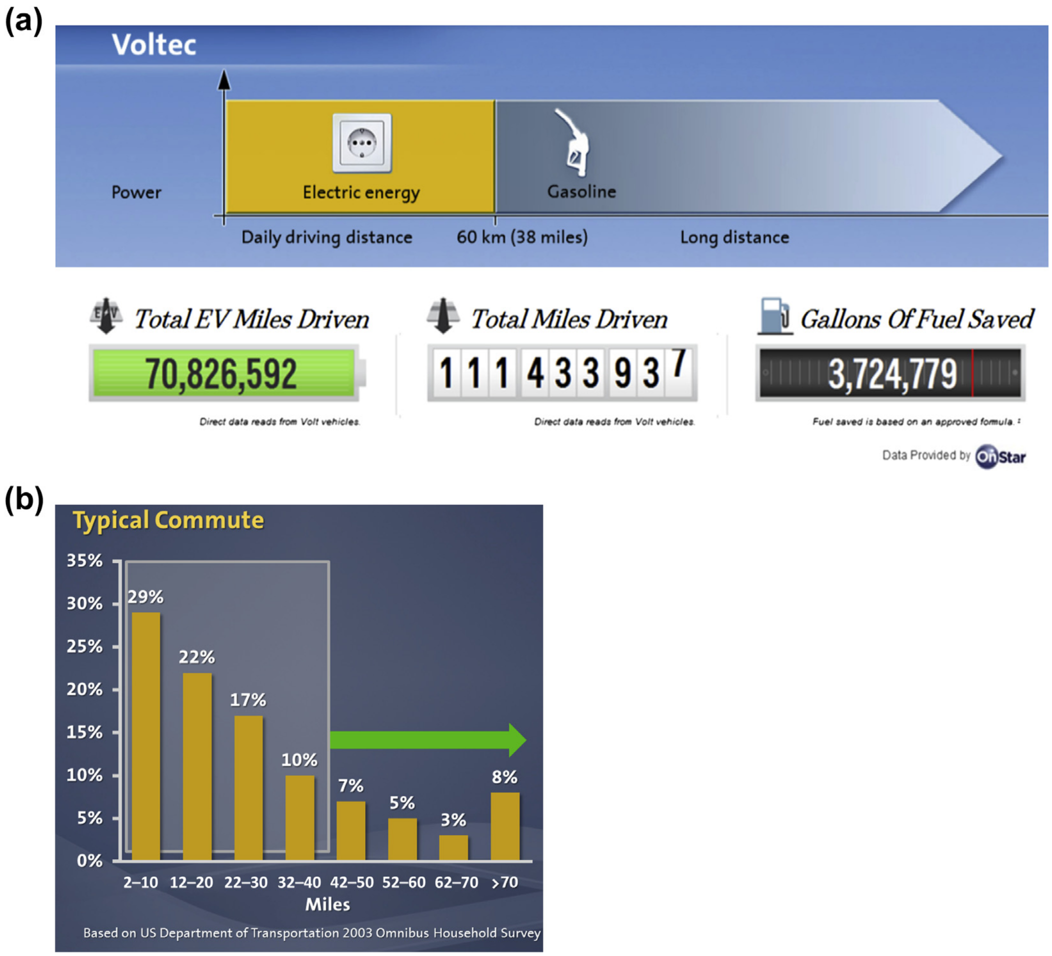

FIGURE 8.20 (a,b) Share of driving in EV mode (Chevrolet Volt fleet in the United States, status as of July 31, 2012). (For color version of this figure, the reader is referred to the online version of this book.)

9. Summary

The Chevrolet Volt and the Opel Ampera are the first extended-range electric vehicles available in the North American and European markets. These cars allow a daily commuter to drive ~40–80 km using electric energy. Since, as an example, about 80% of all German commuters [5] and circa. 70% of US commuters drive less than 50 km/day, the Voltec technology offers great potential for a reduction in crude oil consumption and CO_2 emissions. Without requiring heavy infrastructure investment, the vehicles can be either recharged from standard 230-V outlets or through a wall box connected to 230-V AC grid.

The Voltec battery and drive system is designed, developed and validated to be operated under all climatic and traffic conditions. Data from real-world vehicle operation confirm that these cars perform as expected under all relevant conditions. A large majority of customers (about 65%) use it predominantly as an EV, suitable for daily use, replacing their conventional vehicles. Customer feedback shows that drivers highly appreciate the driving quality of fully electrified vehicles such as Volt and Ampera.

Beside compact cars, the recent progress of automotive electrification technologies allows opportunities to electrify other vehicle segments, as well [3,5]. Although many of the remaining physical limitations of the various electrified propulsion systems need to be addressed over the coming years, BEV, FCEV, and EREV powertrains (e.g. Voltec) provide the highest potential to reduce CO_2 emissions, especially if renewable energy sources are used to produce the required electricity and/or hydrogen.

Concurrent with these advanced propulsion technologies, the electrification of more conventional ICE powertrains will also increase as these engines will be complemented by integrated mild hybrid or strong hybrid systems across all vehicles classes [3]. In addition, applications that are highly sensitive to running costs, such as long-haul trucks, could also benefit significantly from hybridization.

At the current state of technology, the BEV has range and vehicle mass limitations due to the low energy storage density of batteries, but it shows potential for commercial success in such applications as city buses and small urban vehicles. Nowadays, EREV technology allows the end customers to drive an average distance of 40–80 km/day on electricity without the need for a second vehicle or restrictions to vehicle use. The Voltec technology is therefore a substantial enabler for the widespread use of EVs.

Both EREVs and BEVs provide opportunities for load leveling through smart charging. This makes them a complementary technology to solar and wind power generation. In the longer term, however, load leveling by large-scale storage of hydrogen offers the greatest potential [3,5]. Unfortunately, the deployment of a sufficient infrastructure remains a challenge since high infrastructure and product development investment is required for all future energy carrier options.

Ultimately, the degree of electrification across the different application areas is a function of energy prices, technology progress, infrastructure availability, the regulatory framework, vehicle performance and fun-to-drive characteristics, and, finally, the overall customer value proposition.

Acknowledgments

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Nomenclature

AC	Alternating current
ACEA	Association of the European Automotive Industry
APM	Auxiliary power module
BEV	Battery electric vehicle
CAFE	Corporate average fuel economy
CAN	Controller area network, an automotive data bus standard
CD	Charge-depletion mode (SOC is decreasing)
CNG	Compressed natural gas
CNGV	Compressed natural gas vehicle
CONCAWE	The oil companies' European association for environment, health and safety in refining and distribution
CS	Charge-sustaining mode (SOC is constant over a period)
DFMEA	Design failure mode effect analysis
DC	Direct current
DOHC	Double overhead camshaft
ECE	United Nations Economic Commission for Europe
EMC	Electromagnetic compatibility
EPA	Environmental Protection Agency
ER	Extended-range
EREV	Extended-range electric vehicle
EU	European Union
EUCAR	European Council for Automotive R&D
FTP	Federal test procedure
FCEV	Fuel cell electric vehicle
GM	General Motors
GHG	Greenhouse gas emissions
HV	High voltage (above 60 V in automotive applications)
HVIL	High-voltage interlock loop
HVAC	Heating, ventilation and air-conditioning
HV AC	High-voltage alternating current
HV DC	High-voltage direct current
ICE	Internal combustion engine
IGBT	Insulated gate bipolar transistor
JRC	Joint Research Center of the European Commission
LV	Low voltage (here: less than 60 V)
NEDC	New European Driving Cycle
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MSD	Manual service disconnect
NCAP	New Car Assessment Program
OBCM	Onboard charger module
PHEV	Plug-in hybrid electric vehicle
PM	Permanent magnet
R&D	Research and Development

RESS	Rechargeable energy storage system
SOC	State of charge
TPIM	Traction power inverter module
TTW	Tank-to-wheels
USABC	United States Advanced Battery Consortium
VITM	Voltage current temperature module
VOLTEC	GM propulsion system for extended-range vehicles
VTSM	Voltage temperature sub-modules
WTW	Well-to-wheels
ZEV	Zero-emission vehicle

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