11

Batteries, Ultracapacitors, Fuel Cells, and Controls

11.1 Introduction

In this chapter, the requisite energy storage systems for EVs and HEVs are discussed. In a HEV or PHEV, onboard batteries or ultracapacitors are charged from the internal combustion engine/generator set or from the electric power grid. The chemical energy stored in batteries is converted to electrical energy for traction motor and vehicle propulsion. Also, energy storage systems are responsible for recuperating regenerative braking energy to further increase vehicle efficiency. Thus, the performance of EVs and HEVs depends on energy storage systems to a large extent. Therefore, this chapter is devoted to a discussion of battery, ultracapacitor, and fuel cell technology. Here, we will focus on the techniques of modeling, hybridization, equalization, charging control for batteries and ultracapacitors.

Batteries are made of cells where chemical energy is converted to electrical energy and vice versa. The battery energy storage system (BESS) comprises mainly batteries, the power electronics-based conditioning system, and a control system. In HEVs, batteries provide energy for the traction motor and store regenerative energy; a power electronics converter, typically of bidirectional capability, provides an interface between the batteries and power produced by the onboard internal combustion engine or utility power in the case of a PHEV; the control system is responsible for power and energy management including charging/discharging and equalization control. The above description applies as well for the ultracapacitor energy storage system (UESS). The main difference is that the battery is an electrochemical energy conversion device while the ultracapacitor does not involve any chemical reactions. The BESS or UESS topology is illustrated in Figure 11.1.

In order to have the desired voltage rating and current rating for application in HEVs, many cells must be connected in series and/or in parallel in the BESS or UESS. Voltage balancing or equalization is required if more than three cells are connected in series.

Generally speaking, a battery has the characteristics of high energy density and relatively low power density. The internal resistance is the major factor for its limited discharging and charging current capability. The internal equivalent series resistance

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Hybrid Electric Vehicles: Principles and Applications with Practical Perspectives, First Edition.
Chris Mi, M. Abul Masrur and David Wenzhong Gao.

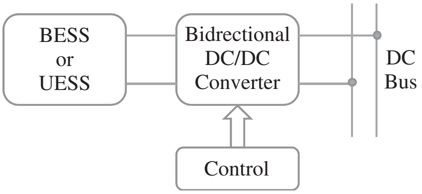


Figure 11.1 HEV BESS/UESS topology

(ESR) has different values under charging and discharging operating conditions. The values are also dependent on the frequency of the discharging current [1]. For lithium-ion batteries, the internal resistance could increase by 50% from 1000 Hz to 100 Hz. The ampere-hour capacity is affected by the discharging current rate and is modeled by Peukert's equation [2], $C_p = I^k t$, where k is the Peukert constant; $k = 1$ for an ideal battery. The charging and discharging efficiencies are nonlinear functions of current and the state of charge (SOC).

The battery can be modeled as an equivalent circuit such as an internal resistance model or a resistance–capacitance (RC) model in ADVISOR [3]. In an internal resistance model, a battery is modeled as a voltage source and an internal resistor. Both the voltage source and the internal resistor are functions of the SOC and temperature, which can be implemented as lookup tables. In a RC model, a battery is represented as a parallel combination of two RC branches. The very large capacitor models the battery's charge capacity while the smaller capacitor models the time constant due to surface effects that limit the current. The model can be implemented as an S function in MATLAB/Simulink.

On the other hand, when compared to common capacitors, the ultracapacitor (electric double-layer capacitor) has a very high energy density, which could be thousands of times greater than a high-capacity electrolytic capacitor. Larger double-layer capacitors can have capacitances up to 5000 F as of 2010. Compared to batteries, an ultracapacitor has the characteristics of high power density and relatively lower energy density. Its equivalent internal resistance is decades lower than that of a battery, thus allowing decades of higher discharging/charging current. Its overall round-trip efficiency is higher than that of a battery. Its capacitance is huge compared to an ordinary electrolyte capacitor, allowing enough energy storage for HEV acceleration power requirements. Note that the internal resistance and capacitance are highly dependent on the frequency because of the porous nature of the electrodes. One big advantage of the ultracapacitor is that its SOC is allowed to vary more widely and thus has longer life cycles. Its capability to provide high power bursts is ideal for hybrid vehicle applications.

An ultracapacitor can also be modeled as an internal resistance model or RC model in the same way as for a battery. The difference is that the ultracapacitor's internal resistance for charging is typically the same as for discharging.

To predict the behavior of battery/ultracapacitor voltage and current during transient operation such as acceleration and deceleration, physics-based dynamic models are needed to account for the time constants due to the electrochemical reactions in batteries or double-layer effects in ultracapacitors.

11.2 Battery Characterization

Capacity (C)

The battery capacity specifies the amount of electric charge a battery can supply before it is fully discharged. The SI unit of battery capacity is the coulomb. A more general unit for battery capacity is *ampere-hour (Ah)*, with 1 Ah = 3600 C. For example, a battery of 20 Ah can supply 1 A current for 20 hours or 2 A for 10 hours, or in theory 20 A for 1 hour. But in general, the battery capacity is dependent on discharge rate.

There are two ways of indicating battery discharge rate: C rate is the rate in amperes, while nC rate will discharge a battery in $1/n$ hours. For example, a rate of $C/2$ will discharge a battery in 2 hours, and a rate of $5C$ will discharge a battery in 0.2 hours. For a 2 Ah battery, the $C/5$ rate is 400 mA, while its $5C$ rate is 10 A.

As mentioned before, C depends on battery discharge current rate according to Peukert's equation. For a lead acid battery, the Peukert constant can range from 2.0 to 1.05 depending on manufacturing technology.

Energy Stored (E)

The energy stored in a battery is dependent on battery voltage and the amount of charge stored within. The watt hour or Wh is the SI unit for energy stored. Assume a constant voltage (CV) for the battery. Then

$$E\ (\mathrm{Wh}) = V \times C \tag{11.1}$$

where V is the voltage and C is the capacity in Ah. The capacity of the battery changes with the discharge rate, and the associated discharging current affects the voltage value. The energy stored is thus not a constant quantity and is a function of two variables, namely, the voltage and capacity of the battery.

State of Charge (SOC)

A key parameter in the electric vehicle is the SOC of the battery. The SOC is a measure of the residual capacity of a battery. To define it mathematically, consider a completely discharged battery. The battery is charged with a charging current of $I_b(t)$; thus from time t_0 to t, a battery will hold an electric charge of

$$\int_{t_0}^{t} I_b(\tau)\, d\tau$$

The total charge that the battery can hold is given by

$$Q_o = \int_{t_0}^{t_2} I_b(\tau)\, d\tau \tag{11.2}$$

where t_2 is the cutoff time when the battery no longer takes any further charge. Then, the SOC can be expressed as

$$\mathrm{SOC}(t) = \frac{\int_{t_0}^{t} I_b(\tau)\, d\tau}{Q_o} \times 100\% \tag{11.3}$$

Typically, the battery SOC is maintained between 20 and 95%.

A common mistake that people may make about a battery's charge is that when a battery "goes dead," the voltage goes from 12 to 0 V (for a 12 V battery). In reality a battery's voltage varies between 12.6 V with a SOC of 100% to approximately 10.5 V with a SOC of near 0%. It is advised that the SOC should not fall below 40%, which corresponds to a voltage of 11.9 V. All batteries have a SOC vs. voltage curve which can be either looked up from the manufacturer's data or determined experimentally. An example of an SOC vs. voltage curve of a lead acid battery is shown in Figure 11.2. Note that for a lithium-ion battery, the curve may be much flatter, especially for the mid-SOC range of 40–80%.

Depth of Discharge (DOD)

The depth of discharge (DOD) is the percentage of battery capacity to which the battery is discharged. The DOD is given by

$$\mathrm{DOD}(t) = \frac{Q_o - \int_{t_0}^{t} I_b(\tau)\, d\tau}{Q_o} \times 100\% \tag{11.4}$$

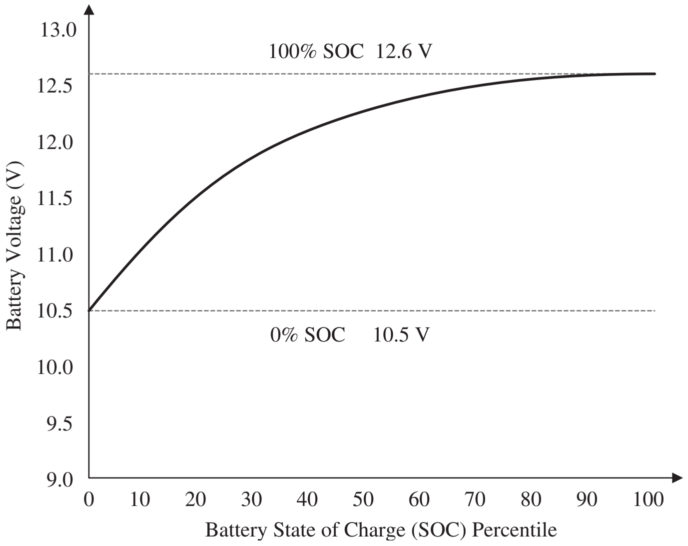


Figure 11.2 Example SOC vs. voltage curve for a 12 V battery

Generally, a battery is prevented from having a low DOD. The withdrawal of at least 80% of battery capacity is regarded as a deep discharge.

One important precaution is that the charge in a battery should never be discharged down to zero voltage, otherwise the battery may be permanently damaged. So, in this case, a cutoff voltage is defined for the battery voltage so that the voltage at the battery terminals will never drop below this cutoff voltage. This point is referenced as 100% DOD.

Specific Energy

Specific energy means how much electrical energy can be stored per unit mass of battery. The SI unit for this quantity is watt hour per kilogram. Knowing the energy stored and specific energy of the battery, the mass of the battery can be easily obtained by dividing the energy by specific energy. Again, the specific energy is not a constant parameter since the energy stored varies with discharge rate. A comparison of the specific energy of various energy sources (typical numbers) is given in Table 11.1.

Energy Density

Energy density means how much electrical energy can be stored per cubic meter of battery volume. It is computed by dividing the energy stored in the battery by the battery volume. The SI unit for energy density is watt hour per cubic meter.

Specific Power and Power Density

Specific power means how much power can be supplied per kilogram of battery. Note that this quantity is dependent on the load served by the battery and is thus highly variable and anomalous. The SI unit of specific power is watt per kilogram. Specific power is the ability of the battery to supply energy. Higher specific power indicates that it can give and take energy quickly. Volume specific power is also called power density or volume power density, indicating the amount of power (time rate of energy transfer) per unit volume of

Table 11.1 Specific energy of different energy sources

Energy source	Specific energy (Wh/kg)
Gasoline	12 500
Natural gas	9350
Methanol	6050
Hydrogen	33 000
Coal	8200
Lead acid battery	35
Nickel metal hydride battery	50
Lithium-polymer battery	200
Lithium-ion battery	120
Flywheel (carbon fiber)	30
Ultracapacitor	3.3

battery. If a battery has high specific energy but low specific power, this means that the battery stores a lot of energy, but gives it out slowly. A Ragone plot is used to depict the relationship between specific power and specific energy of a certain battery.

Ampere-Hour (or Charge) Efficiency

Ampere-hour efficiency is the ratio between the electric charge given out during discharging a battery and the electric charge needed for the battery to return to the previous charge level. In practice, these two values will never be equal, limiting the efficiency to 100%. In fact the typical values of charge efficiency range from 65 to 90%. The efficiency depends on various factors such as the battery type, temperature, and rate of charge.

Energy Efficiency

This important quantity indicates the energy conversion efficiency of the battery, which depends a great deal on the internal resistance of the battery. It can be computed as the ratio of electrical energy supplied by a battery to the amount of charging energy required for the battery to return to its previous SOC before discharging. The efficiency decreases considerably if a battery is discharged and charged very quickly. Typically, the energy efficiency of a battery is in the range of 55–95%.

Number of Deep Cycles and Battery Life

EV/HEV batteries can undergo a few hundred deep cycles to as low as 80% DOD of the battery. Different battery types and design result in different numbers of deep cycles. Also, the usage pattern will affect the number of deep cycles a battery can sustain before malfunction. The United States Advanced Battery Consortium (USABC) has a mid-term target of 600 deep cycles for EV batteries. This specification is very important since it affects battery life time in terms of deep-cycle number. So, generally, we should reduce the chances of DOD in the control strategy for EVs and HEVs in order to limit the operating cost of the vehicles.

Example: The NiMH traction battery of the Toyota Prius 2004 model has the following specifications:

- 168 cells (28 modules)
- 201.6 V nominal voltage
- 6.5 Ah nominal capacity
- 28 hp (21 kW) output power
- 1300 W/kg specific power
- 46 Wh/kg specific energy.

Assume that the voltage is relatively constant.

1. What is the energy rating of the battery in kilowatt hours?

   Solution: $201.6\,\mathrm{V} \times 6.5\,\mathrm{Ah} = 1310\,\mathrm{Wh} = 1.31\,\mathrm{kWh}$

2. If the battery can be discharged at a maximum rate of 100 A, and only 40% can be discharged, for how many seconds can the battery be used when fully charged?

   Solution: $\frac{(40\%)6.5\,\mathrm{Ah}}{100\,\mathrm{A}} = 0.026\,\mathrm{h} = 93.6$ seconds

3. If the battery can be charged at a maximum rate of 90 A, and the current SOC is 40%, how long does it take to charge the battery to 80% SOC?

   Solution: $\frac{(80\% - 40\%)6.5\,\mathrm{Ah}}{90\,\mathrm{A}} = 0.0289$ hours $= 1.73$ minutes

4. The battery has an internal resistance of 0.15 Ω. What is the efficiency at maximum charge rate?

   Solution: $\eta = 1 - \frac{\left(90^2\right)(0.15)}{(90)\,(201.6)} = 93.6\%$

5. The battery has an internal resistance of 0.1 Ω. What is the efficiency at maximum discharge rate?

   Solution: $\eta = 1 - \frac{\left(100^2\right)(0.1)}{(100)\,(201.6)} = 95\%$

6. How much voltage drop is caused by this internal resistance at maximum charge/discharge?

   Solution: At maximum charge, the voltage drop is $90 \times 0.15 = 13.5\,\mathrm{V}$; at maximum discharge, the voltage drop is $100 \times 0.1 = 10\,\mathrm{V}$.

7. Does the efficiency change with maximum charge/discharge current?

   Solution: Yes, the battery efficiency depends on the maximum charge/discharge current and internal resistance.

8. If the leakage current is 20 mA, how many days does it take for the battery to self-discharge from 80% SOC to 40% SOC?

   Solution: $\frac{(80 - 40\%)6.5\,\mathrm{Ah}}{20 \times 10^{-3}\,\mathrm{A}} = 130$ hours $= 5.4$ days.

11.3 Comparison of Different Energy Storage Technologies for HEVs

Different energy storage technologies, including but not limited to those shown in Table 11.2, are available for HEV applications: Li-ion battery, nickel metal hydride battery, lead acid battery, and ultracapacitors. In the table, the typical range of

Table 11.2 Comparison of energy storage technologies suitable for HEVs

Storage technology	Cycle life	Efficiency (%)	Specific power (W/kg)	Specific energy (Wh/kg)
Lead acid battery	500–800	50–92	150–400	30–40
Li-ion battery	400–1200	80–90	300–1500	150–250
Nickel metal hydride battery	500–1000	66	250–1000	30–80
Ultracapacitor	1 000 000	90	1000–9000	0.5–30
USABC long-term goals	1000	80	400	200

specification is given for each type of storage device along with the long-term goal set by the USABC (http://www.uscar.org/, http://en.wikipedia.org/wiki/United_States_Council_for_Automotive_Research). The advanced lead acid and Li-ion batteries are the most promising for application in HEVs. While battery and ultracapacitor technologies have their respective advantages and disadvantages, hybridization could result in better vehicle performance and longer battery life. The vehicle road load transients can be handled by ultracapacitors during acceleration and deceleration.

A battery is an electrochemical cell that can convert chemical energy into electrical energy (redox reaction). There are three main parts in a battery: electrolyte, anode, and cathode. At the anode, the "negative" terminal, an oxidation reaction takes place and the electrode loses electrons. At the cathode, the "positive" terminal, a reduction reaction takes place and the electrode gains electrons. There is also a porous separator between the two electrodes.

Lead Acid Battery

This type of battery is the earliest and the most widely used in automotive applications. For example, it is extensively used as the starting battery to provide "cranking amps" for an automobile's starter motor. One of the plates is made of lead while the other plate is made of lead dioxide. The electrolyte is composed of sulfuric acid. These batteries can last a long time if they are charged and discharged properly.

The energy-to-volume ratio is low for a lead acid battery. This ratio can be used to measure the drive range of an EV. How to treat used lead acid batteries is another serious problem. As a result, this type of battery cannot satisfy the requirements for future environmentally-friendly vehicles. Fortunately, lead acid batteries have very high recyclability with good recycling infrastructure.

The chemical equation for a lead acid battery during discharge is

$$\mathrm{PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O} \tag{11.5}$$

The chemical equation for a lead acid battery during charge is

$$\mathrm{2PbSO_4 + 2H_2O \rightarrow PbO_2 + Pb + 2H_2SO_4} \tag{11.6}$$

According to the chemical equation, electrolyte and the active material on the battery plates are consumed and water and lead sulfate are produced when a lead acid battery is discharged. On the other hand, during the charging process, electrical energy is absorbed by the battery, water and lead sulfate are consumed, and electrolyte and the active material at the plates are produced.

Nickel Metal Hydride Battery

The NiMH battery is a new type of high-capacity battery. Its technology has grown rapidly in the past five years. It has many advantages such as environmental friendliness, high specific energy and energy density, and a long cycle life. The NiMH battery has already occupied a good market share as energy storage in HEVs.

The overall reversible chemical reaction occurring in a NiMH cell is:

$$\mathrm{MH} + \mathrm{NiOOH} \Leftrightarrow \mathrm{M} + \mathrm{Ni(OH)_2} \tag{11.7}$$

Lithium-Ion Battery

In Li-ion batteries, Li ions alternatively move into and out of host lattices during charging and discharging cycles. This fundamental mechanism has led to the Li-ion battery's nick-name of "rocking-chair" battery. In its physical composition, a Li-ion battery has anode and cathode plates like a lead acid battery, except that these are made of lithium cobalt oxide (or other lithium composites) and carbon. These plates and the separator are immersed in a solvent which is most commonly ether [4]. This type of battery can be made with very high energy density. The overall reversible chemical reaction occurring in a Li-ion cell is

$$\mathrm{Li}_x\mathrm{C} + \mathrm{Li}_{1-x}\mathrm{M}_y\mathrm{O}_z \Leftrightarrow \mathrm{C} + \mathrm{LiM}_y\mathrm{O}_z \tag{11.8}$$

Li-ion batteries do not have the "memory effect" that causes other rechargeable batteries to lose their maximum charge level when repeatedly recharged or not charged to full capacity. Li-ion batteries also impact the environment less due to their composition. Unlike lead acid batteries, they have a much lower self-discharge rate, thus greatly increasing idle period capabilities. These batteries also have a higher power-to-volume ratio which also makes them ideal for automotive applications [5]. Two of the latest EVs, the Nissan Leaf and Chevy Volt, both use lithium batteries. Different materials can be used for anode. The Mn series Li-ion battery has been used in the Nissan Leaf, Mitsubishi i-MiEV, GM Volt, Chrysler S400 Hybrid, BMW 7 series ActiveHybrid, THINK TH!NK City, and Hyundai Sonata Hybrid Blue Drive.

However, lead acid batteries have remained the favored ones due to cost and the fact that Li-ion batteries require a lot more safety attention. These batteries are much more susceptible to overcharging and overdischarging and the associated safety hazards. Overcharging or overdischarging the battery can severely damage the plates inside the case. Overcharging can also cause gassing of the electrolyte and buildup of pressure in the case, which can lead to an explosion, therefore a precise regulatory system is necessary. The reduction in life due to this effect is much greater than in lead acid batteries. The same reaction occurs when they are used improperly, leading to overheating and the risk of an explosion. In the event of charging or discharging a Li-ion battery, the voltage must be monitored carefully because the absolute limits are so close to the required 100% SOC voltage [6].

Ultracapacitors

Ultracapacitors have a very long shelf life, with much lower maintenance requirements, enhanced performance at low temperature, and environmental friendliness. The only downside to ultracapacitors is their initial cost and relatively low energy density when compared to batteries [7]. Unlike batteries, no chemical reactions are needed for storing and retrieving electrical energy with ultracapacitors and thus the energy efficiency is higher. The ultracapacitor's SOC is easier to estimate than that of a battery because the voltage is the only measurement needed (SOC is proportional to V^2). Also, ultracapacitors can be charged to a specific value and, due to their shelf life and charging mechanism, they can hold that charge with virtually no loss. Batteries are incapable of achieving this. Repeated depletion cycles of a lead acid or Li-ion battery can be detrimental to its lifespan; however, this is not the case with an ultracapacitor.

Ultracapacitors provide more freedom in the DC link voltage or wherever else they are used because their charge does not depend on a certain voltage. Whatever voltage they are charged to is what they retain [8]. As a result, a hybrid topology consisting of ultracapacitors is desired when variable voltages are required. This would be beneficial in portable fuel cell/ultracapacitor power supplies that could be used in emergencies or general use. A vast array of loads or devices could be powered by this system.

Ultracapacitors allow rapid charging and discharging. This is especially useful for faster and efficient regenerative energy recovery in HEVs as well as for rapid charging of PHEVs. Simple charging methods can be used without needing a sophisticated SOC detection algorithm, and there is little danger of overcharging so long as the voltage is below the maximum allowable value. Ultracapacitors have a long cycle life (on the order of a million cycles), with little degradation over hundreds of thousands of discharge/charge cycles. In comparison, rechargeable batteries last for only a few hundred deep cycles.

The ultracapacitor's energy density is much lower than that of an electrochemical battery (3–5 Wh/kg for an ultracapacitor compared to 30–40 Wh/kg for a lead acid battery, and 120 Wh/kg or more for a Li-ion battery), and its volumetric energy density is only about 1/1000th of that of gasoline. As in any capacitor, the energy stored is a function of voltage squared. Effective storage and retrieval of energy requires complex electronic control and balancing circuits involving power electronics switches. The self-discharge rate is much higher than that of an electrochemical battery and thus it is only suitable for short-term energy storage. An enormous amount of energy could be released in a fraction of a second from an ultracapacitor and this could be life threatening if precautions were not taken. The internal resistance of ultracapacitors is very low, resulting in high cycle efficiency (95% or more). Environmentally, ultracapacitors are safer since they do not contain corrosive electrolytes or other highly toxic materials. In comparison, the reactive chemical electrolytes of rechargeable batteries present a disposal and safety hazard.

A comparison of the power density and energy density of different energy storage systems (ESSs) is illustrated in Figure 11.3 (Ragone plot or chart).

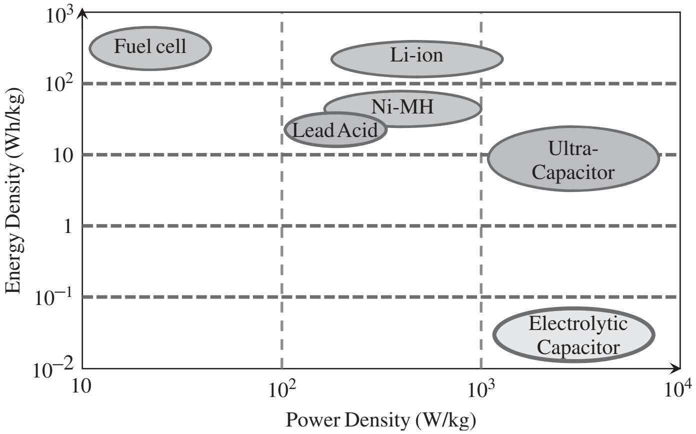


Figure 11.3 Comparison of power density and energy density for ESS in HEVs

11.4 Modeling Based on Equivalent Electric Circuits

11.4.1 Battery Modeling

A commonly used simple battery model is shown in Figure 11.4. It consists of an ideal battery with open-circuit voltage V_{oc} and a constant equivalent internal resistance R_{int}. The battery terminal voltage is V_t. V_{oc} can be obtained from the open-circuit measurement, and R_{int} can be measured by connecting a load and measuring both the terminal voltage and current, at fully charged condition. The terminal voltage V_t can be written as

$$V_t = V_{oc} - I_b R_{int} \tag{11.9}$$

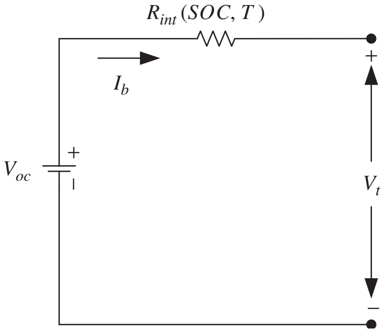


Figure 11.4 Simple battery model

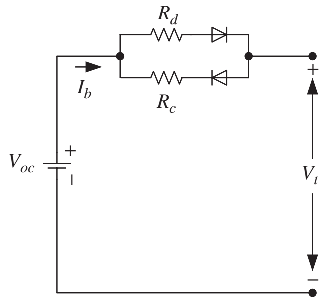


Figure 11.5 Battery model accounting for the different charging and discharging resistances

V_{oc}, the equilibrium potential of the battery, is a nonlinear function of the SOC and temperature T given by Larminie and Lowry [9]:

$$V_{oc} = E_o + (RT/F) \times \ln(\mathrm{SOC}/(1 - \mathrm{SOC})) \tag{11.10}$$

where E_o is the standard potential of the battery, R the ideal gas constant, T the absolute temperature, and F the Faraday constant

This is a fairly good way of predicting the battery voltage. However, the battery open-circuit voltage does not remain constant. As discussed above, the voltage is affected by the SOC/DOD of the battery and temperature. The variation in the open-circuit voltage due to DOD, for a lead acid battery cell, as given by Larminie and Lowry [9] is

$$V_{oc} = (2.15 - \mathrm{DOD} \times (2.15 - 2.0)) \tag{11.11}$$

The main drawback of this model is that it cannot capture the response to dynamic events in a battery. For example, if a load is connected to the battery, the terminal voltage will immediately change to a new, lower value according to this simplified model. In fact this is not true; rather it will take some time for the voltage to settle to a new value.

The internal resistance of the battery has different values on charging and discharging. To account for the different resistance values under charge and discharge conditions, the circuit model in Figure 11.4 can be modified as shown in Figure 11.5. An improved model can be obtained by incorporating a self-discharge resistance R_p in parallel with V_{oc}.

In this model, the internal resistance takes different values during the charging and discharging process: R_c for charging and R_d for discharging. The internal resistance is used to model all energy losses within the battery during charging and discharging, including electrical and non-electrical losses. The ideal diodes are present only for modeling purposes of selecting either R_d or R_c as the internal resistance based on the current direction and have no physical significance in the battery. For a given required power, the battery current I_b is expressed as

$$I_b = \frac{V_{oc} - \sqrt{V_{oc}^2 - 4 \times R \times P_{req}}}{2R} \tag{11.12}$$

where

$$R = \begin{cases} R_{discharge}(\mathrm{SOC}, T) & \text{for } I_b \geq 0,\ P_{req} \geq 0 \\ R_{charge}(\mathrm{SOC}, T) & \text{for } I_b < 0,\ P_{req} \leq 0 \end{cases}$$

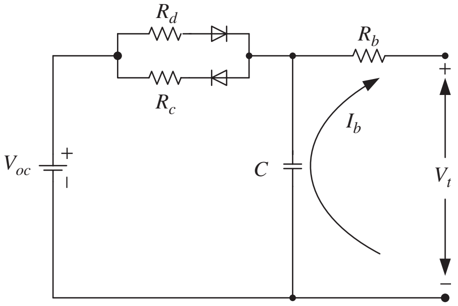


Figure 11.6 Dynamic battery model

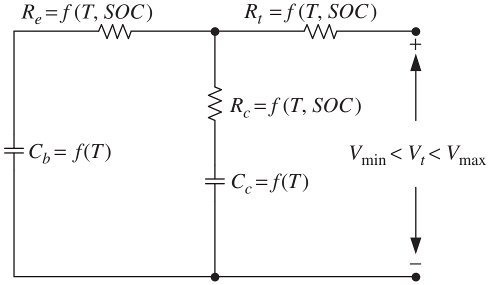


Figure 11.7 RC model of a battery

The sign of the battery current, I_b, appears to be positive in discharging mode and negative in charging mode.

The models in Figures 11.4 and 11.5 have the disadvantage of not being sensitive to dynamic events in the battery. In order to model such dynamic or transient effects in a battery, a capacitor is added to the model as a parallel branch, as shown in Figure 11.6.

The model in ADVISOR [3], given in Figure 11.7, is called the “RC model”; it takes power as an input and maintains the battery output voltage within the high- and low-voltage limits. The “RC model” can predict the average internal battery temperature as a function of time while driving and during soak periods. In this model, the capacitor C_b is large enough to hold the capacity of the battery and the smaller capacitor C_c is used to reflect the dynamic changes in the battery.

11.4.2 Battery Modeling Example

Here, the model in Figure 11.5 is implemented in MATLAB as an example. The SOC is obtained by the following equation:

$$\text{SOC} = 1 - \frac{\text{used Ah capacity}}{\text{max Ah capacity}} \tag{11.13}$$

where the used Ah capacity is calculated from

$$\text{Used Ah capacity} = \begin{cases} \int_0^t i_b(t)dt & \text{for } i_b(t) \geq 0 \text{ discharge} \\ \int_0^t \eta_{coulomb} i_b(t)dt & \text{for } i_b(t) < 0 \text{ charge} \end{cases} \tag{11.14}$$

where $I_b(t)$ is the charge/discharge current for the battery and $\eta_{coulomb}$ is the coulombic efficiency for charging.

In this example, V_{oc} is a function of the SOC; the data is obtained from the experimental tests of a Hawker Genesis 12 V, 26 Ah, 10EP sealed valve-regulated lead acid (VRLA) battery and implemented as a lookup table in MATLAB [3]. The open-circuit voltage of each cell takes values ranging from 11.7 to 12.89 V corresponding to the SOC from 0 to 1. The internal resistors R_d and R_c are also indexed by the SOC and T from two different lookup tables corresponding to discharging and charging respectively. The coulombic efficiency is assumed to be 90%. V_{oc}, R_d, and R_c of this battery model are plotted in Figure 11.8.

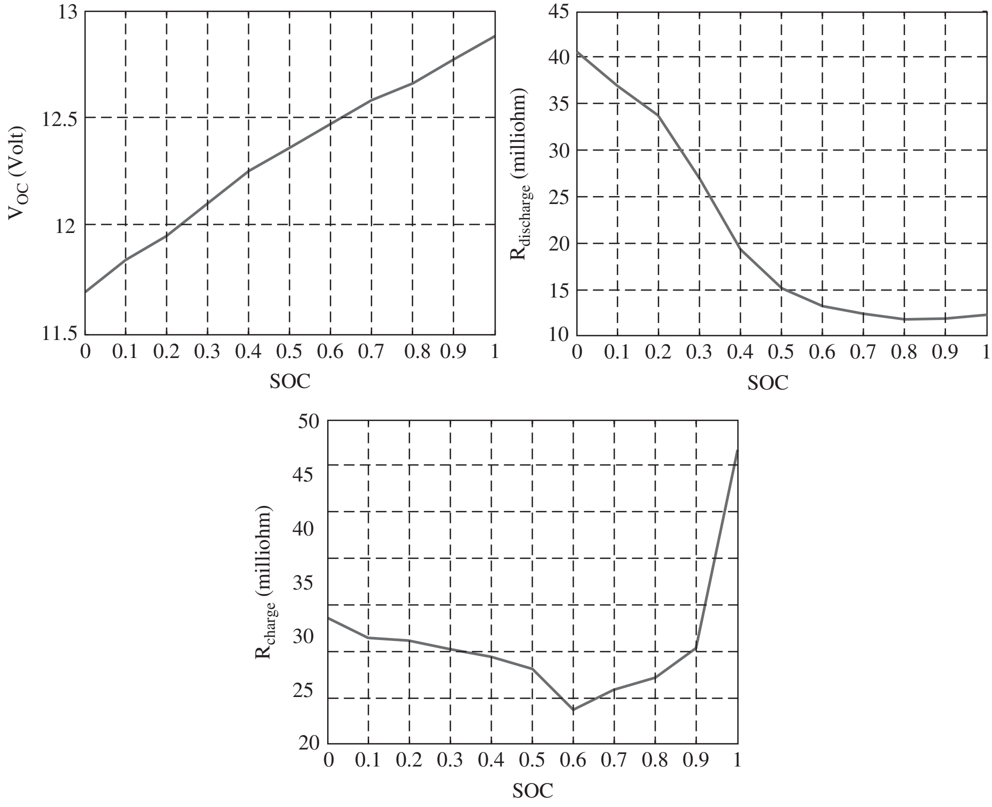


Figure 11.8 V_{oc}, R_d, and R_c of the battery model

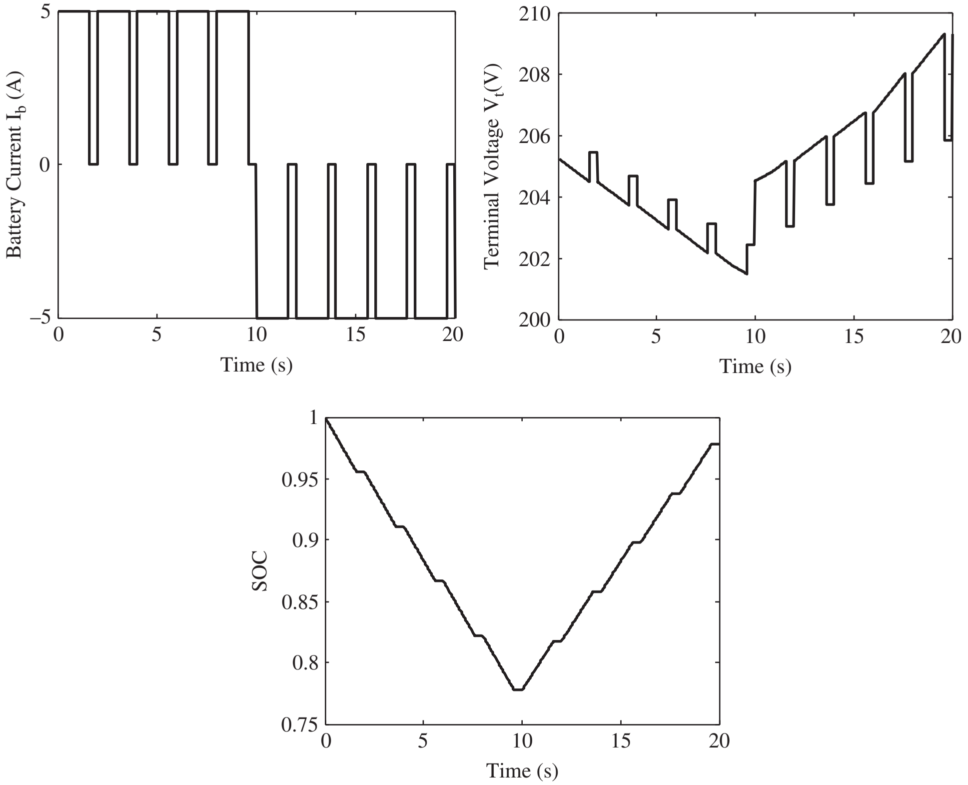


Figure 11.9 Simulation results of the battery model

A battery pack consisting of 16 battery cells in series is simulated to test the developed battery model. The magnitude of battery current pulse is 5 A with a frequency of 0.5 Hz and pulse width of 1.6 seconds. The battery temperature is assumed constant at 34.7 °C. Simulation results are shown in Figure 11.9. From the discharge and charge current pulse profiles, in the first 10 seconds discharge current pulses are applied to the battery model, while in the last 10 seconds charge current pulses of the same magnitude are applied. The battery pack terminal voltage decreases from around 206 V over the first discharging duration in the first 10 seconds. In the last 10 seconds, however, the terminal voltage gains almost linearly over the charging intervals. From the SOC plot, it can be seen that in the first 10 seconds, the SOC is reduced from 1.0 to 0.78 during discharging but increases to 0.975 after the pulsed charge currents are applied.

11.4.3 Modeling of Ultracapacitors

In any capacitor, the electrical energy is stored by using a positively charged electrode surface and a negatively charged electrode surface with a dielectric separator between them. In supercapacitors or ultracapacitors, special carbon-based electrodes are made to provide an extremely large internal active surface area. The charge and energy stored in a capacitor are given by

$$Q = C \times V \tag{11.15}$$

$$E = \frac{1}{2}CV^2 \tag{11.16}$$

where

Q is the charge in the capacitor,
C is the capacitance in farads,
V is the voltage across the capacitor,
E is the energy of the capacitor.

For ultracapacitors, the SOC can be computed with high accuracy:

$$\text{SOC} = \frac{C\,(V - V_{\min})}{C\,(V_{\max} - V_{\min})} = \frac{(V - V_{\min})}{(V_{\max} - V_{\min})} \tag{11.17}$$

where $V_{\max}$ and $V_{\min}$ denote maximum and minimum allowable voltage for the ultracapacitor.

The capacitance C of a capacitor is given by

$$C = \varepsilon\frac{A}{d} \tag{11.18}$$

where ε is the permittivity of the dielectric medium, A is the plate area, and d is the distance between the plates.

Supercapacitors get their name from their ability to store high energy. This can be done by increasing the area of parallel plates in a capacitor. The capacitance is increased by decreasing the separation distance between the parallel plates. This is the key to modern capacitors, but the voltage across the capacitor must be small otherwise the capacitor may be damaged and act like a short circuit. This puts a limit on the maximum energy a capacitor can store. Connecting capacitors in series decreases the effective capacitance and increases the voltage across them. The energy stored now increases, but not as the voltage squared because of the problem of voltage imbalance among the cells. The fundamental reason for the voltage mismatch between the series-connected cells is due to the variation of capacitance between the cells. The problem can be avoided by charge-equalizing circuits. These circuits balance the charge on the adjacent capacitors keeping the cell voltage the same.

The simplest equivalent electric circuit model for an ultracapacitor consists of a capacitance in series with an internal resistance, which models all the energy losses in the ultracapacitor. This model can capture to a large extent the essential behavior and dynamics of the ultracapacitor for most modeling and analysis needs. However, more detailed and complex models can be developed as outlined in the following.

A slightly more complex model is shown in Figure 11.10. The equivalent circuit of the ultracapacitor unit consists of a capacitor (C), an ESR to model the internal resistance during discharging and charging, and an equivalent parallel resistance (EPR), R_p, which

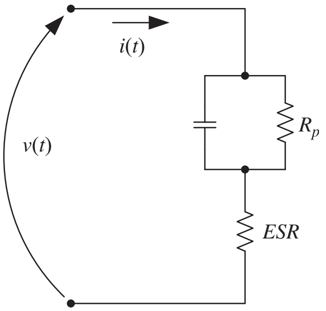


Figure 11.10 Simple electrical equivalent circuit of a supercapacitor

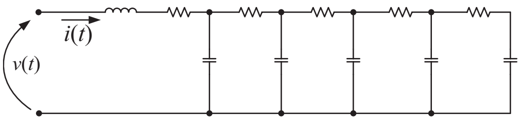


Figure 11.11 The fifth-order ultracapacitor model

is much higher than the ESR, to account for any self-discharging losses. These parameters can be obtained from ultracapacitor data sheets provided by manufacturers.

For an accurate representation of an ultracapacitor, a fifth-order model is needed [10]. The ultracapacitor is represented by a series–parallel connection of resistors and capacitors, and the values of each can be varied to achieve the desired modeling accuracy over a wide range of operating frequency. Figure 11.11 shows the representation of an ultracapacitor by a fifth-order model. For electric vehicle modeling and simulation, the model order can be reduced to third order to account for a frequency range of interest between 0.0034 and 1.44 Hz [10].

11.4.4 Battery Modeling Example for Hybrid Battery and Ultracapacitor

As mentioned previously, hybridization of battery and ultracapacitor could yield a better energy storage system to supply transient loads with the benefit of longer battery life. Based on the battery model described in Section 11.4.2, an electrical model for a hybrid energy storage system (HESS) consisting of a battery and supercapacitor systems is developed and implemented in MATLAB/Simulink to demonstrate the concept of passive HESS. The equivalent circuit of the HESS is shown in Figure 11.12.

In Figure 11.12, the lead acid battery is modeled by the internal emf, E_m, and the internal resistor R_2. The values of the internal series resistance R_2 are dependent on the charge/discharge current. $R_{2,c}$ and $R_{2,d}$ correspond to charging resistance and discharging resistance respectively. In this HESS model, the internal parameters, including E_m and R_2, are SOC and temperature, T dependent.

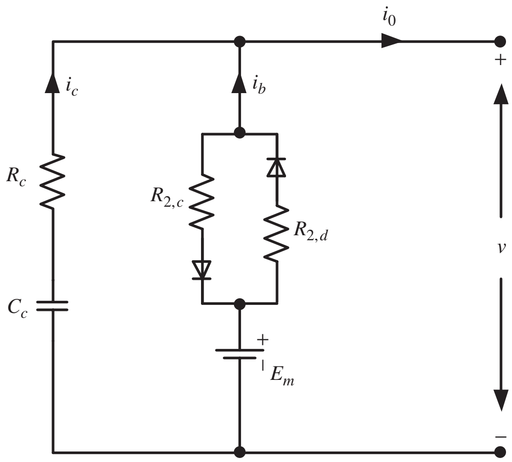


Figure 11.12 Equivalent circuit model for HESS consisting of lead acid battery and ultracapacitor

Though the charge/discharge characteristic of the ultracapacitor can be modeled in more complex forms as shown in previous section, the ultracapacitor model used in this example is represented by a single lumped capacitance, C_c, and a single lumped resistance, R_c. In this model, C_c is the capacitance between the double layers of the ultracapacitor and R_c models the internal loss inside the supercapacitor.

For a given discharge current i_0, one can assume it is distributed between the battery and ultracapacitor branches based on the impedances of the two branches, as denoted by i_b and i_c respectively in Figure 11.12. The calculation of i_b and i_c for a given i_0 will be detailed in the following.

The Thévenin equivalent circuit of the HESS as shown in Figure 11.12 can be depicted as in Figure 11.13, where the Thévenin equivalent voltage and impedance of the HESS

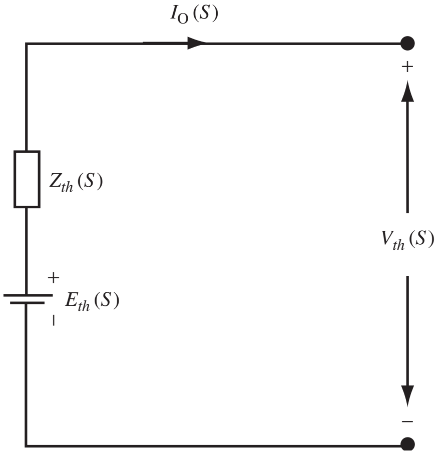


Figure 11.13 Thévenin equivalent circuit of the HESS

circuit are denoted by $E_{th}(s)$ and $Z_{th}(s)$ respectively. Note that Figure 11.13 is derived in the frequency domain and $E_{th}(s)$ and $Z_{th}(s)$ are obtained by

$$E_{th}(s) = \frac{R_c}{R_2 + R_c} E_m \frac{s+\alpha}{s(s+\beta)} + \frac{R_2}{R_2 + R_c} V_{c0} \frac{1}{s+\beta} \tag{11.19}$$

$$Z_{th}(s) = \frac{R_2 R_c}{R_2 + R_c} \frac{s+\alpha}{s+\beta} \tag{11.20}$$

where s is the complex frequency, V_{c0} is the initial voltage across the ultracapacitor, and

$$\alpha = \frac{1}{R_c C_c} \tag{11.21}$$

$$\beta = \frac{1}{(R_2 + R_c) C_c} \tag{11.22}$$

By assuming the charge/discharge current is a pulsed signal with period T_1 and duty ratio D, the current for the first N pulses can be expressed as

$$i_0(t) = I_0 \sum_{k=0}^{N-1} [\Phi(t - kT_1) - \Phi(t - (k+D)T_1)] \tag{11.23}$$

where I_0 is the magnitude of the current and $\Phi(t)$ is a unit step change function at $t = 0$. By applying the Laplace transform operation to this equation, one can readily obtain the current in the frequency domain as

$$I_0(s) = I_0 \sum_{k=0}^{N-1} \left[\frac{e^{-kT_1 s}}{s} - \frac{e^{-(k+D)T_1 s}}{s} \right] \tag{11.24}$$

Based on this, the internal voltage drop due to internal equivalent impedance inside the HESS, $V_i(s)$, is given by

$$V_i(s) = I_0(s) \cdot Z_{th}(s) = \frac{R_2 R_c}{R_2 + R_c} I_0 \left[\left(\frac{\alpha}{\beta} \frac{1}{s} + \frac{\beta - \alpha}{\beta} \frac{1}{s+\beta} \right) \times \left(e^{-kT_1 s} - e^{-(k+D)T_1 s} \right) \right]. \tag{11.25}$$

Thus, the terminal voltage of the HESS, $V_{th}(s)$, can be calculated by

$$V_{th}(s) = E_{th}(s) - V_i(s) \tag{11.26}$$

Performing the inverse Laplace transform, we get

$$\begin{aligned} v(t) = E_{th}(t) - v_i(t) &= E_m + \frac{R_2}{R_2 + R_c} (V_{c0} - E_m) e^{-\beta t} \\ &- R_2 I_0 \sum_{k=0}^{N-1} \left[\left(1 - \frac{R_2}{R_2 + R_c} e^{-\beta(t - kT_1)} \right) \Phi(t - kT_1) \right. \\ &\left. - \left(1 - \frac{R_2}{R_2 + R_c} e^{-\beta[t - (k+D)T_1]} \right) \Phi[t - (k+D)T_1] \right] \end{aligned} \tag{11.27}$$

Note that the second term in this equation is caused by the energy redistribution between the battery and supercapacitor at the beginning of the discharge. This item decays as time lapses. The Thévenin voltage of the HESS finally approaches E_m.

After obtaining the HESS terminal voltage, the charge/discharge currents flowing through the battery and the ultracapacitor can be calculated by the following two equations respectively:

$$i_b(t) = \frac{1}{R_2}\left[E_m(t) - v(t)\right] \tag{11.28}$$

$$i_c(t) = i_0(t) - i_b(t) \tag{11.29}$$

The above HESS model equations are implemented in MATLAB/Simulink. To verify the validity of this HESS model, a pulsed signal with a magnitude of 8 A, period $T_1 = 2$ seconds, and duty ratio $D = 0.8$ is applied in the model. Note that positive values of i_0 correspond to discharge currents, while negative values correspond to charge currents. The battery pack consists of 16 Hawker Genesis 12 V, 26 Ah, 10EP sealed VRLA batteries connected in series to obtain 206.24 V at the original state. The ultracapacitor system consists of 77 modules of Nesscap 2.7 V/600 F capacitors connected in series to match the BESS terminal voltage. We assume that the ultracapacitors are fully charged at the initial stage having an initial voltage of 207.9 V. The internal resistance of the ultracapacitor is 1mΩ. The simulation results are shown in Figure 11.14.

The discharge/charge current applied to the HESS is given in Figure 11.14a. The battery (BESS) current is shown in Figure 11.14b, from which one can find that the BESS current increases gradually to approach the pulse magnitude, 8 A, after five periods or 10 seconds. The current balance between the applied current and that taken by the BESS is compensated by the parallel-connected supercapacitor, which can be found from Figure 11.14c. This contribution of the supercapacitor will reduce the negative effect of the high discharge/charge current on the battery and hence effectively extends the lifetime of the BESS. The terminal voltage and SOC of the battery over the simulated interval are depicted in Figure 11.14d,e respectively. The exchange current between the BESS and supercapacitor is shown in Figure 11.14f. The exchange current originates from the second term in the equation for $v(t)$, which is due to the difference between the initial voltage of the ultracapacitor V_{c0} and E_m. The negative exchange current indicates that the ultracapacitor provides a decaying charging current to the battery. It can be observed that the exchange current decays to 0 after about 25 seconds, which verifies the analysis regarding $v(t)$.

11.5 Battery Charging Control

Charging technology plays a key role in maximizing battery performance. A proper battery charging technique ensures battery safety and increases system reliability. The primary requirement of the charging process is to provide a fast and efficient way of charging without degrading the battery. Some of the factors to be taken into account while charging the battery are:

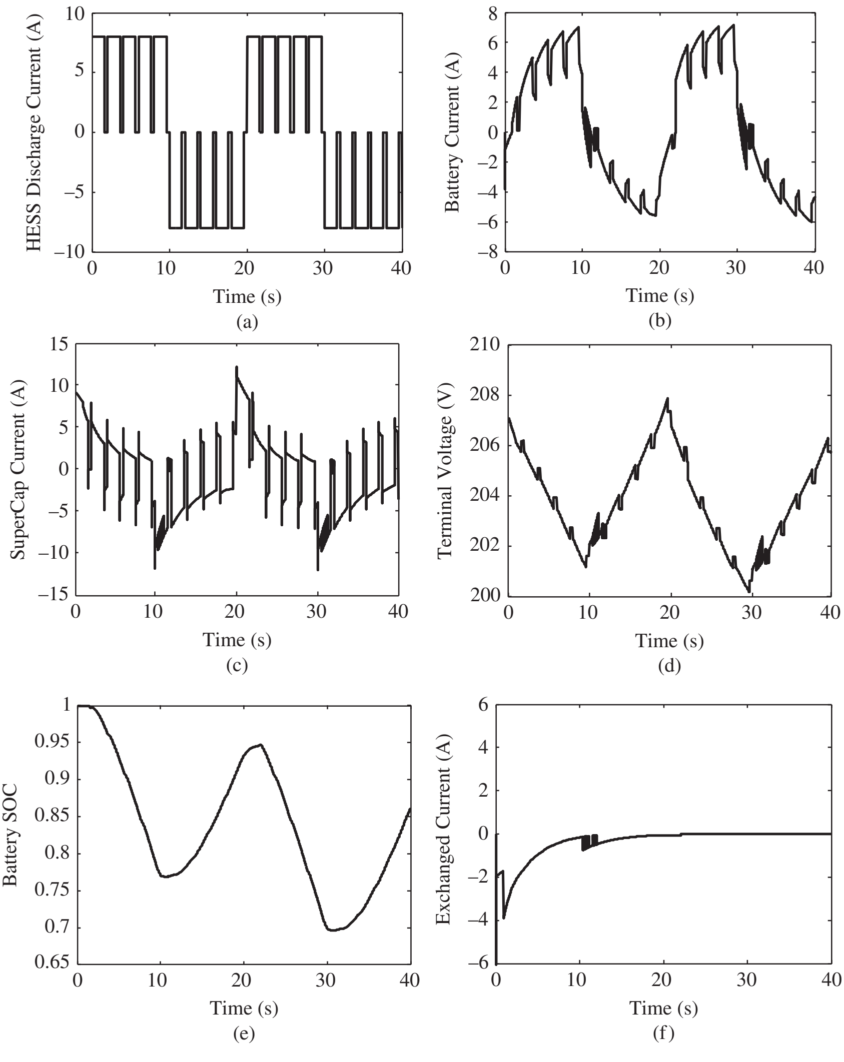


Figure 11.14 Simulation results of the HESS model: (a) applied discharge/charge current; (b) BESS current; (c) ultracapacitor current; (d) BESS terminal voltage; (e) SOC of the BESS; and (f) the exchange current between the BESS and the ultracapacitor

- Avoiding overcharging and undercharging.
- Fast charging without affecting the battery life.
- Maintaining a good quality of charging current.

Conventional charging methods include passive charging, constant current (CC) charging, CV charging, and CC–CV charging. The pulse charging method is gaining popularity because of its advantages over CC and CV charging. In this section, different charging techniques will be reviewed and discussed.

The simplest method is passive charging. This method is also the worst method for the health of a battery. In passive charging, the battery is connected to a DC link which has a fixed voltage higher (hopefully by only a small percentage) than the rated voltage of the battery. The charging current is unregulated in this method and can spike greatly and possibly stay at a charging current above the safe value. As a result, there is the risk of overcurrent and definitely overvoltage. This method is not recommended for critical systems.

The second method is CV charging. For example, for a 12 V battery, the charging voltage would be maintained at a value of about 12.1 V regardless of the SOC. As a result of CV charging, the current supplied to the battery is unregulated. In turn, with a low initial SOC there is a high current spike of unknown duration that could exceed the safe charging current for the battery. This is a very fast method of charging with an exponential profile; however, the initial current spike can be damaging.

In the CC scheme, the charging voltage is varied and tracks the SOC of the battery to maintain a CC at the battery's DC link. As a result, the charging current profile of the battery stays well below the safe charging rate. A great advantage of this method is that it prevents heat from building up during the charging process and thus increases the life of the battery. The disadvantage of this method is that the constant higher current, even at the end of the charging cycle, could lead to the growth of deposits which could short the plates in the batteries. As a result, the method is harmful at the end of the charging cycle. This method also requires monitoring of both voltage and current measurements. It is slower than CV charging and has a linear charging profile.

In the CC–CV charging method, in the first stage a CC is maintained for charging the battery. This current level is regulated at the safe charge limit by increasing or decreasing the terminal voltage level of the charging source. Once the battery reaches a certain SOC or voltage value, the current is decreased (voltage decreased) to prevent damaging currents at the end stage. This particular charging stage is usually called the floating charge. This method combines the best attributes of both the CV and CC methods and eliminates their disadvantages. It is slower than the previously mentioned methods; however, it is the safest for the battery [11].

The final charging method to mention is the pulsed current method. This method is similar to pulse width modulation in that the pulse duration is proportional to the SOC. When the SOC is low, the pulses have a longer duration; when the SOC approaches 100%, the pulse duration is reduced to near zero. At any pulse duration, there will be a rest period in which the charging current is low. The relaxation period between pulses equalizes the chemical reaction in the battery as the ions diffuse and distribute evenly throughout the battery. This process normalizes the ion concentration in the battery and thus prevents the negative effect experienced in CC charging. Because of the equal charge distribution, battery performance as well as battery life are enhanced. The charging rate can be controlled by varying the width of the pulses. This type of charging is advantageous over CC charging in that the charging rate is higher and battery internal impedance is kept lower [12]. This is the fastest method of the above-mentioned

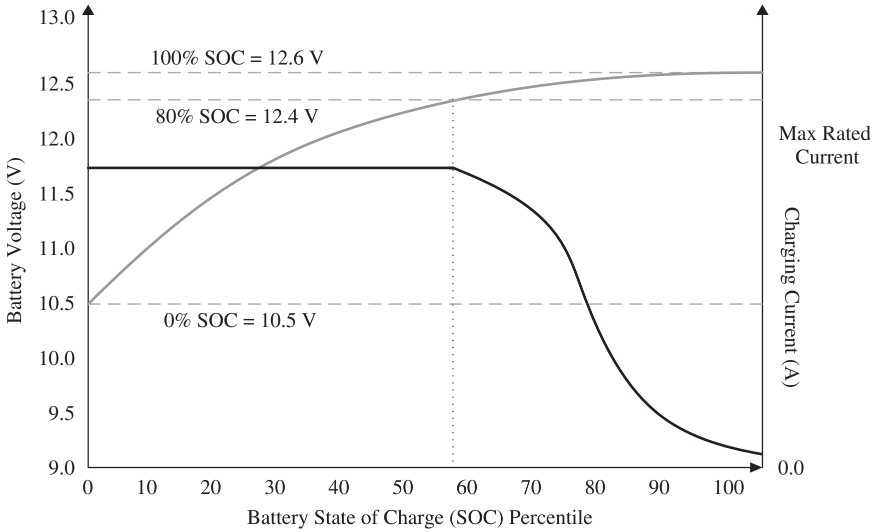


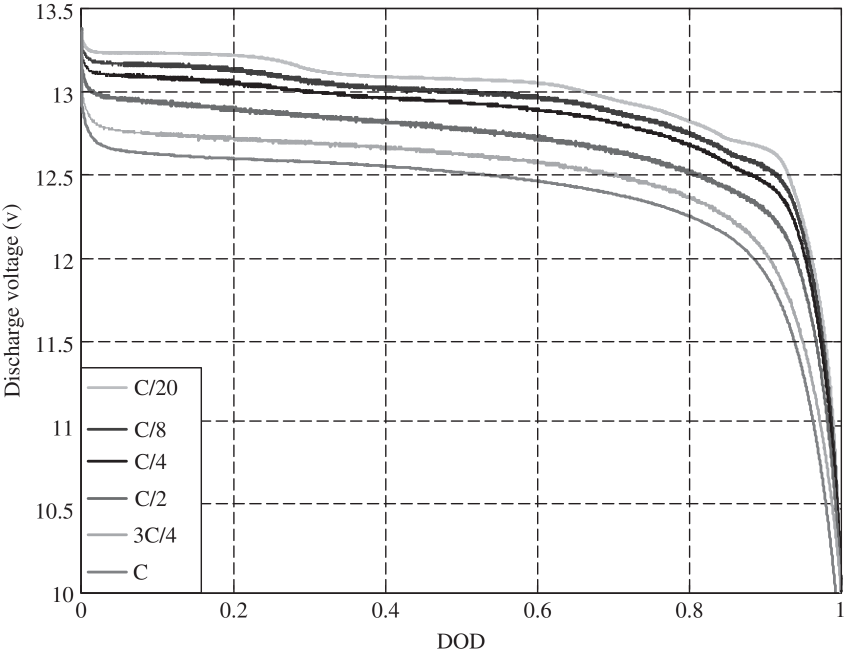
Figure 11.15 Plot of the battery voltage and charging current vs. SOC for a three-stage charger

methods and is becoming more popular with charging protocols. However, it would require a power electronics converter with a dedicated control algorithm.

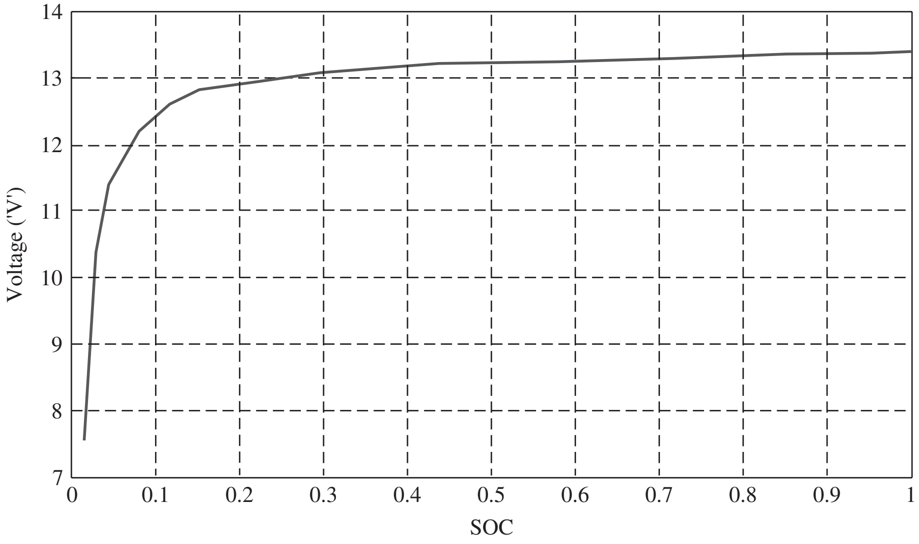
The three-stage charger is an example of a controlled charging method on the market today and is mainly used for 12 V lead acid batteries. The CC–CV scheme is used. The first stage is called the bulk charge stage. In this stage, the maximum current that the batteries are rated for is delivered until the SOC reaches about 80–90%. The charging voltage at this stage exists between 10.5 and 15 V. The second stage, called the absorption stage, delivers reduced current and maximum voltage in the range of 14.2–15.5 V. The third stage, the float charge stage, occurs when the batteries have reached nearly 100% SOC and all that is needed is to keep them at full charge. In this stage the voltage can vary between 12.8 and 13.2 V [13]. A sketch of a three-stage charger for a 12 V lead acid battery is shown in Figure 11.15. An example of battery charge and discharge versus the SOC of a Li-ion battery is shown in Figure 11.16.

11.6 Charge Management of Storage Devices

The voltage of energy storage devices in electric vehicles is designed to be in the range of 300–400 V in order to provide adequate power for traction motors. As a result, many cells must be connected in series. When dealing with long battery or ultracapacitor strings, charge distribution must be equalized between the individual cells in order to prevent under- or overcharging and extend energy storage life. For HEV batteries, the cells will undergo many charge/discharge cycles, where major amounts of power are consumed from and injected into them [14]. In HEVs, the battery bank is charged with power from the IC engine or via regenerative braking. The charge/discharge lapses can cause

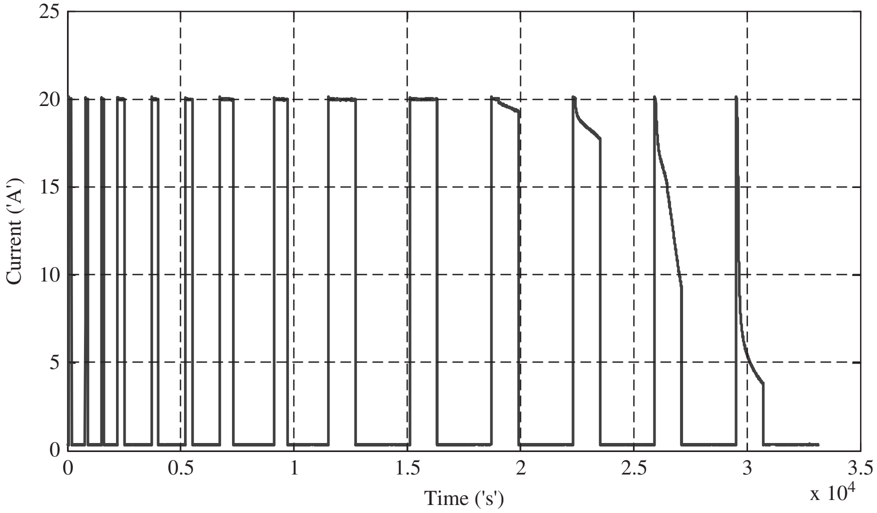


(a)

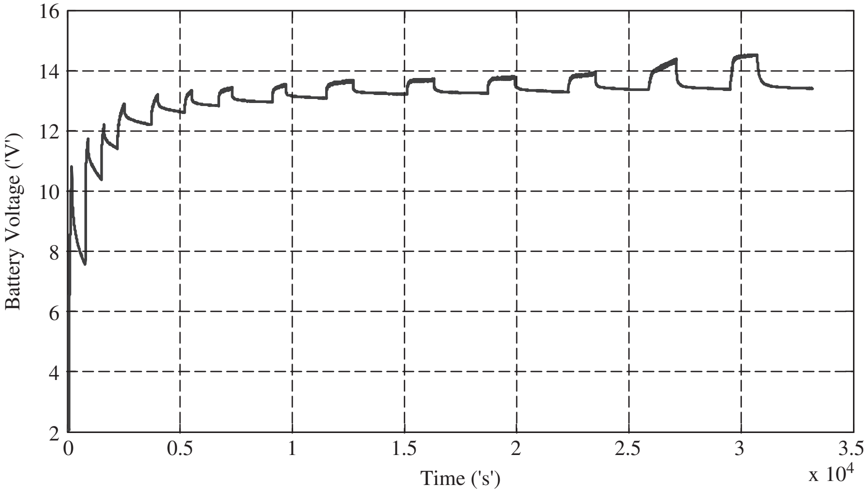


(b)

Figure 11.16 Lithium-ion battery discharge and charge characteristics. (a) Voltage versus depth of discharge (DOD) during the discharge of lithium ion battery at different discharge rates, at room temperature. (b) Battery voltage versus state of charge of a lithium ion battery, calibrated through testing data. (c) Charge current during pulsed charge of lithium ion battery. (d) Terminal voltage during pulsed charge using the charging current shown in (c)



(c)



(d)

Figure 11.16 (*continued*)

lasting damage to an unprotected battery string. A battery cell usually can act differently from other cells in a string. Some may charge or discharge faster than others due to differences in internal impedance, temperature, and so on. This can cause an imbalance in charges among individual cells. If left unchecked, some can become over/undercharged or over/underdischarged. As a result, battery longevity is severely shortened and the overcharged batteries in an unprotected string could overheat, build up gas pressures, and explode. The battery string presents a safety hazard and must be carefully maintained [6, 15–17]. Thus, a carefully controlled charge equalization system is needed. Our discussion is focused on the battery system; a good discussion on cell balancing for an ultracapacitor system can be found in [18].

The general principle behind the charge equalization circuit is to distribute an equal amount of energy or voltage to every cell in the series-connected string. In order to do this, the circuit must remove the energy from the more strongly charged cells and redistribute it to the weaker cells in order to obtain a uniform voltage or uniform energy distribution. This process is not instantaneous, it will happen over time, the length of which is determined by the method used. Of course, this can be done in many different ways. Charge equalization methods fall into several different categories. The two top categories are dissipative and non-dissipative equalizers. In the dissipative charge equalizing method, resistive shunts are used. An active version of the resistive shunt method utilizes a PWM control switch in line with the resistive shunt. This method is the simplest but very inefficient.

Moving on to non-dissipative equalizers, there exist three more tiers in classification. First of all, there is the charge type, discharge type, and the charge–discharge (bidirectional) type. With respect to the charge–discharge type, the classification splits again into current-fed equalizers and voltage-fed equalizers. For the former case, the equalizers contain bidirectional converters; and for the latter case, the circuit contains switched capacitors. An equalization scheme using switched capacitors is shown in Figure 11.17.

The circuit in the figure is the double-tiered method. In this method, as in the single-tiered method, no dedicated control system is necessary. The switches are set to a fixed frequency and are all switched at the same time. As a result, only one switching signal is necessary for this configuration. Even as the batteries reach an equalized state, the switching action remains; however, this consumes negligible energy. The addition of the second tier allows batteries 1 and 3 to also exchange charge between each other. This allows for faster equalization. Another advantage is that sensors are not necessary, resulting in cost savings [19].

As for the current-fed bidirectional converter type, the system presented by Lee and Cheng [5] utilizes two bidirectional converters sharing one capacitor shown in Figure 11.18.

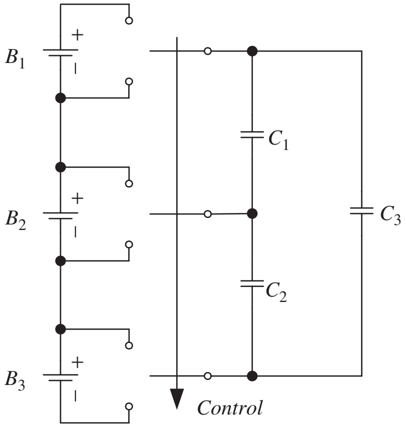


Figure 11.17 Circuit diagram of non-dissipative equalization with switched capacitors

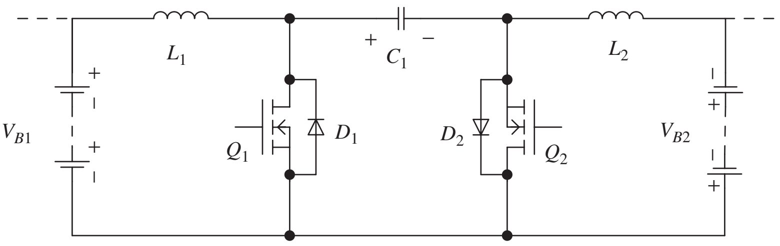


Figure 11.18 Circuit diagram of the current-fed bidirectional converter method

In the process of equalization, if battery 1 has a higher voltage than battery 2, then the first switch turns on at the duty cycle specified by the control system depending on the system's current state and measured values. This action charges the first inductor and then releases that energy through the capacitor and into the second battery, charging it. Hence the method is named a current-fed charge–discharge type. When the second battery has a greater voltage than the first battery, the same process happens, just with reversed currents, with the first battery being charged. PWM signals for controlling the converters' switches regulate the amount of current going into and out of each battery cell. This would be dependent on the SOC of the batteries. Different methods can be designed to control the PWM signals.

With respect to the discharge type, there exist two more tiers, namely, direct transfer and indirect transfer. With direct transfer, a serial recovery method uses step-up converters and a parallel recovery method uses primary multiple windings. With indirect transfer, a two-step method uses buck–boost converters and a multi-step method uses unidirectional converters. As with the charge type, there also exist two more tiers. The first is an automatic method which uses secondary multiple windings. The second is a selective method which uses secondary multiple windings plus switches [14].

11.7 Flywheel Energy Storage System

Flywheels are becoming of increasing interest in hybrid vehicle design, particularly for larger passenger transit vehicles. This is because of the following reasons. First, the requirements on specific power and specific energy of the battery can be decoupled, affording optimization of the battery's specific energy density and hence cycle life. Second, as the high-rate power demand and high-current discharge are greatly reduced by the load leveling effect of the flywheel, the usable energy, endurance, and battery cycle life can be increased. Third, the flywheel can allow rapid interim recharges with high efficiency during periods of low power demand or regenerative braking. Due to the combined effect of load leveling of the main energy source and improved energy recovery during regenerative braking, the range of the vehicle can be remarkably extended. The energy density is primarily related to the flywheel's speed of rotation. Increasing the speed of rotation produces improved specific energy, but increases the potential safety hazard, and also the cost, since special bearings and high-strength materials are required. Instead of using a battery or fuel cell, an EV can potentially be powered solely by an ultrahigh-speed flywheel. The corresponding long-term potential benefits for EV applications are possible,