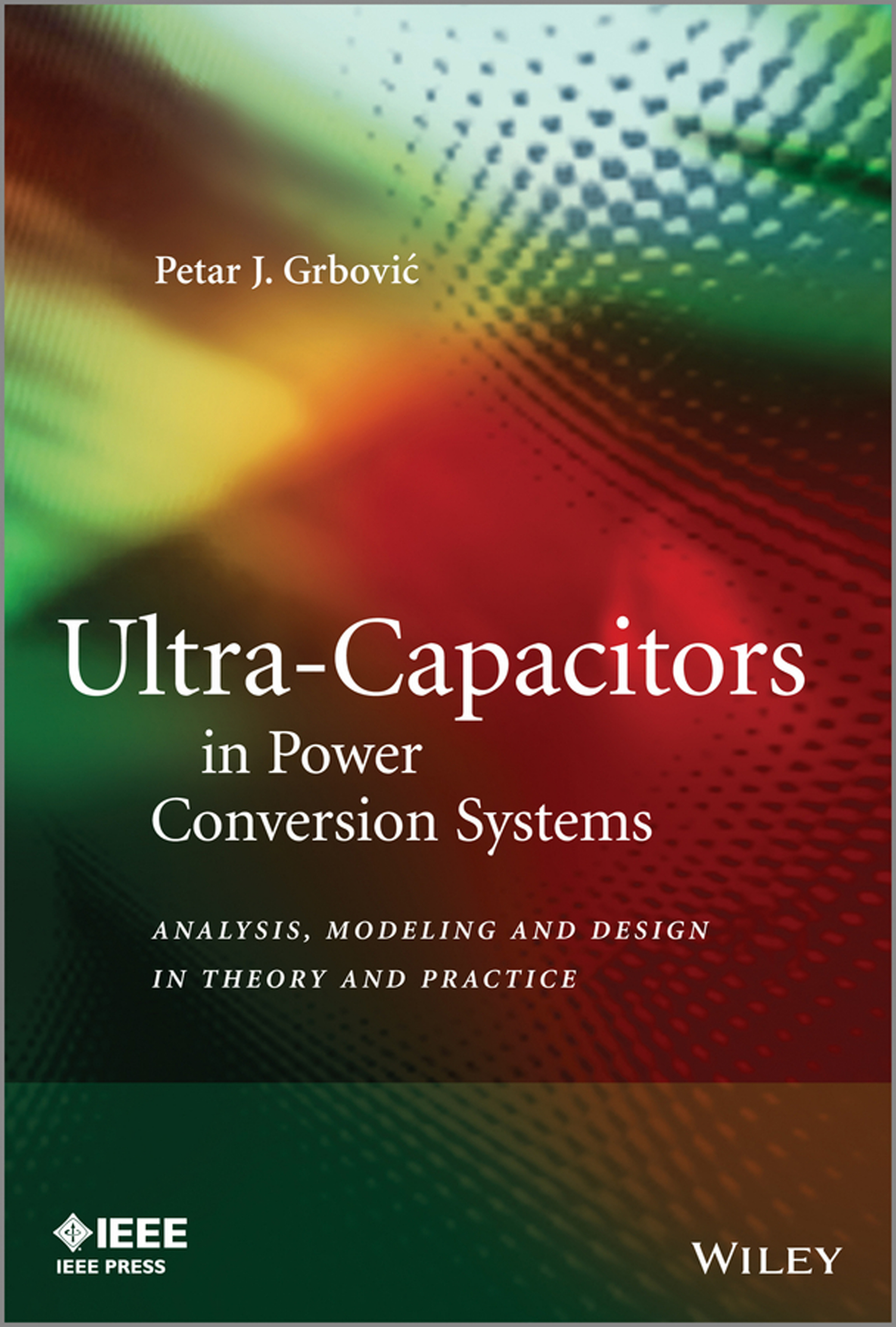

Petar J. Grbović

Ultra-Capacitors in Power Conversion Systems

ANALYSIS, MODELING AND DESIGN IN THEORY AND PRACTICE

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ULTRA-CAPACITORS IN POWER CONVERSION SYSTEMS

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APPLICATIONS, ANALYSIS AND DESIGN FROM THEORY TO PRACTICE

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Preface

What this Book is About

This book is about ultra-capacitors and their application in power conversion systems. It is particularly focused on the analysis, modeling, and design of ultra-capacitor modules and interface dc–dc power converters.

Power conversion systems and power electronics play a significant role in our everyday life. It would be difficult to imagine a power conversion application, such as industrial controlled electric drives, renewable sources, power generation and transmission devices, home appliances, mobile diesel electric gen-sets, earth moving machines and equipment, transportation, and so on, without power electronics and static power converters. In most of these applications, we are facing growing demands for a device that is able to store and re-store certain amounts of energy during a short period. Controlled electric drives may require energy storage to save energy during braking or provide energy in case of power supply interruption. Wind renewable "generators" may need energy storage to smooth power fluctuations caused by wind fluctuation. Power transmission devices such as static synchronous compensators (STATCOMs) need energy storage to support the power system with active power during faults and unstable operation. Mobile diesel electric gen-sets need energy storage to reduce fuel consumption and CO_2 pollution. There is a strong requirement for energy storage in transportation systems in order to improve the system's efficiency and reliability.

The energy storage device should be able to quickly store and re-store energy at very high power rates. The charge and discharge time should be a few seconds up to a few tens of seconds, while charging specific power is in the order of 5–10 kW/kg. Today, two energy storage technologies fit such requirements well: (i) flywheel energy storage and (ii) electrochemical double-layer capacitorss (EDLCs), best known as ultra-capacitors. In this book, ultra-capacitors are addressed alone.

What is Inside the Book

This book starts from a background of energy storage technologies and devices. Then, the detailed theory of ultra-capacitors follows. The fundamentals of power conversion systems and applications are also addressed. An important part of the book is the process of selection and design of ultra-capacitor modules. Finally, the book ends with a detailed analysis of interface dc–dc converters. In total, the book has five chapters.

The fundamentals of energy storage technologies and devices are given in the first chapter. All energy storage systems are classified into two categories: direct and indirect energy storage systems. Direct energy storage devices store electrical energy directly without conversion into another type of energy. Inductors and capacitors are direct energy storage devices. Particular devices with high energy density are super magnet energy storage devices (SMES) and ultra-capacitors. Indirect energy storage systems and devices convert electrical energy into another type of energy that is easier to handle and store. Typical systems are electromechanical energy storage systems, such as fly-wheel, hydro pumped, and compressed air energy storage systems. Electrochemical energy storage systems, such as electrochemical batteries and hydrogen fuel cells, are other well known energy storage systems.

The background theory of ultra-capacitors is presented in the second chapter. The ultra-capacitor model is given with particular attention to the application oriented model. The ultra-capacitor's energy and power are then defined and discussed. Different charging/discharging methods, such as voltage-resistance, current, and power control modes are analyzed. The ultra-capacitor's voltage and current characteristics are derived for different charge/discharge methods. Analysis and calculation of the ultra-capacitor's current stress and power losses under different conditions are discussed. An explanation is given of how ultra-capacitor losses depend on the charge/discharge frequency and how such losses are determined when the charge/discharge current frequency is in the range of megahertz (very low frequency) as well as in the range of a couple of hertz (low frequency). Some application examples, such as variable speed drives with braking and ride through capability, are given.

The fundamentals of power conversion are presented in the first part of the third chapter. Requirements for the use of a short-term energy storage device in power conversion systems are addressed and discussed. The structure of a typical power conversion system with ultra-capacitor energy storage is presented. The process of selection of an energy storage device for a particular application requirement is briefly described. Two main energy storage devices are compared: electrochemical batteries and ultra-capacitors. In the second part of the chapter we discuss different power conversion applications, such as controlled electric drives, renewable energy sources (wind, PV, and marine currents for example), autonomous diesel and natural liquid gas (NLG) gen-sets, STATCOM with short-term active power capability, UPS, and traction.

The selection of an ultra-capacitor module is intensively discussed in the fourth chapter. Design of an ultra-capacitor module is based on three main parameters, namely the module voltage, capacitance, and internal resistance. The module voltage is in fact a set of different operating voltages and the module rated voltage. The operating and rated voltages, the module capacitance and internal resistance are defined according to application requirements, such as energy storage capability, operation life span, efficiency, and so on. Ultra-capacitor losses and efficiency versus size and cost are discussed in the second part of the chapter. Some aspects of ultra-capacitor module design are presented. Series connection of elementary ultra-capacitor cells and voltage balancing issues are also discussed and the module's thermal design is considered too. The theoretical analysis is supported by several examples from some real power conversion applications.

Interface dc–dc converters are discussed in the fifth chapter. First, the background of bi-directional dc–dc power converters is given. The converters are classified in different categories, such as full power versus fractional power rated converters, isolated versus non-isolated converters, two-level versus multi-level and single-cell versus multi-cell interleaved converters. State-of-the-art topologies are compared according to the application's requirements. A detailed analysis of a multi-cell interleaved bi-directional dc–dc converter is given in the second part of the chapter where design guidelines are given too. The theoretical analysis is supported by a set of numerical examples from real applications, such as high power UPS and controlled electric drive applications.

Who Should Read this Book (and Why)

This book is mainly aimed at power electronics engineers and professionals who want to improve their knowledge and understanding of advanced ultra-capacitor energy storage devices and their application in power conversion, in the present as well as in the near future. The book could also be background material for graduate and PhD students who want to learn more about ultra-capacitors and power conversion application in general. The reader is expected to have basic knowledge in math, theory of electric circuits and systems, electromagnetics, and power electronics.

Acknowledgments

I started this story about ultra-capacitors some years ago, when I was with Schneider Electric, R&D of Schneider Toshiba Inverter (STI), in Pacy sur Eure, France. I would like to express my thanks to Dr. Philippe Baudesson and Dr. Fabrice Jadot for the support I received at that time when I first started thinking about the application of ultra-capacitors in controlled electric drives.

I would like to express my deep gratitude to Professor Philippe Delarue and Professor Philippe Le Moigne from Laboratoire d'Electrotechnique et d'Electronique de Puissance (L2EP), Lille, France, for all the creative and fruitful discussions we had and all his comments and suggestions.

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Last but not least, I offer my deepest gratitude to my family, my wife Jelena, son Pavle, and mother Stojka, for their love and support and for their confidence in me.

Finally, let me express my deepest gratitude to God for His blessing.

Dr Petar J. Grbović
Ismaning, Germany

1

Energy Storage Technologies and Devices

1.1 Introduction

1.1.1 Energy

By definition, energy is that property of a body by virtue of which work can be done. Energy cannot be created nor destroyed; it can only be transformed from one form into another. Energy can exist in many forms, such as electromagnetic field, gravity, chemical energy, nuclear energy, and so on [1, 2]. One form of energy that we use in everyday life is so-called electrical energy. In this chapter we will discuss electrical energy storage technologies and devices.

1.1.2 Electrical Energy and its Role in Everyday Life

Electrical energy can be defined as the ability to do work by means of electric devices. Electrical energy has been used in segments of everyday life since end of 1800s, the age of Tesla and Edison. Today, electrical energy is the dominant form of energy. Approximately 60% of primary energy is converted into electrical energy and then used in diverse applications such as industry, transportation, lighting, home appliances, telecommunication, computing, entertainment, and so on.

Figure 1.1 shows a simplified block diagram of electrical energy production–transmission–consumption flow. Electrical energy is usually "generated" by electromechanical generators. The generators are driven by steam turbines, NLG (natural liquid gas) turbines, hydro turbines, wind-turbines, and internal combustion diesel engines. Additionally, electrical energy can be "produced" by static generators, such as photovoltaic panels and hydrogen fuel cells.

Transmission of electrical energy from the "production" to the "consumption" location is also convenient. The "production" point can be a centralized, dislocated power station

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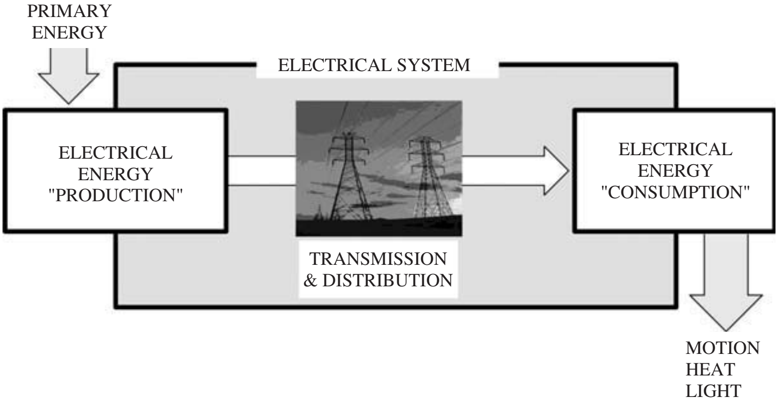

Figure 1.1 Electrical energy production–transmission–consumption process

far away from the "consumption" point, for example, a big city. The electrical energy is transferred and distributed via a high voltage transmission line and a medium/low voltage distribution network. Electrical energy is "consumed" by the end customer. In fact, electrical energy is converted to another form of energy, such as heat, light, chemical energy, linear or rotational movement, and so on.

In small-scale systems, such as diesel electric locomotives, hybrid tracks, earth moving equipment (excavators), and RTG (rubber tyred gantry) cranes, for example, electrical energy is produced by an on-board diesel–electric generator and transmitted to the on-board dislocate loads (electric motors).

It is very convenient to "produce" electrical energy from another form of energy such as mechanical or chemical. However, electrical energy cannot be easily stored. Hence, electrical energy must be "consumed" at same time that it is "produced." An imbalance between total production and consumption leads to problems of power quality, instability, and collapse of the electrical system. This makes it difficult to use electrical energy in systems with dynamic, fluctuating "production" and/or "consumption." An energy storage device is required to store or restore electrical energy and make the dynamic balance between "production" and "consumption." In this chapter we will briefly describe the major types of electrical energy storage technologies and devices.

1.1.3 Energy Storage

An energy storage device is a multi-physic device with the ability to store energy in different forms. Energy in electrical systems, so-called "electrical energy," can be stored directly or indirectly, depending on the means of the storage medium. Figure 1.2 illustrates direct and indirect energy storage processes and devices.

Devices that store the electrical energy, without conversion from electrical to another form, are called direct electrical energy storage devices. The energy storage medium is the electromagnetic field. The storage devices are electric capacitors and inductors. Devices that convert and store the electrical energy in another form of energy are called indirect

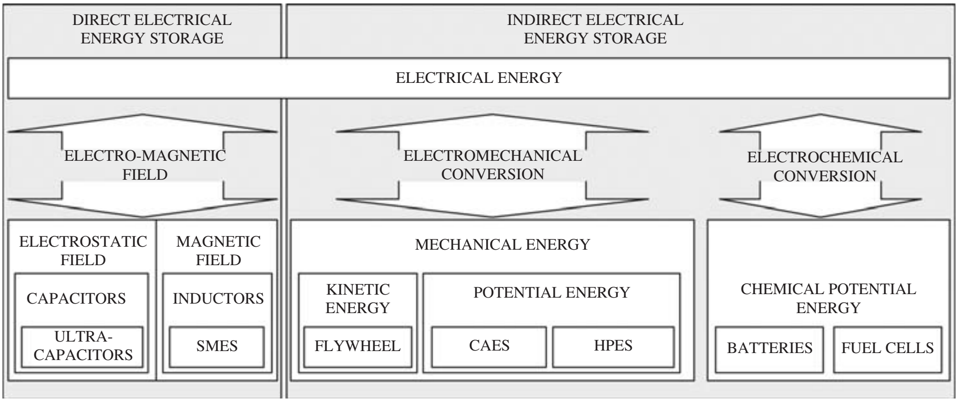

Figure 1.2 Energy storage technologies and devices

electrical energy storage devices. There are several forms of energy that can be converted from/to electrical energy. Some of the most appropriate forms of energy are mechanical and chemical. Mechanical energy can exist in two forms: energy of position, known best as potential energy and energy of motion, known as kinetic energy. The storage devices are flywheels, compressed air energy storage (CAES), and hydro pumped energy storage (HPES). Devices that use chemical energy as the form of energy to be stored are electrochemical batteries and fuel cells.

1.2 Direct Electrical Energy Storage Devices

Direct electrical energy storage devices store electrical energy directly, without conversion from electrical to another form of energy. Energy is stored in the form of an electromagnetic field in a defined Volume V. The field could be predominantly electrostatic (electric) field E and magnetic field H. Devices that predominantly use the electric field as the storage medium are known as electric capacitors. Devices that use predominantly magnetic fields to store energy are magnetic devices such as inductors. The energy storage capability of conventional capacitors and inductors is insufficient for most power conversion applications. To overcome this disadvantage, ultra-capacitor energy storage (UCES) [3–6] and super-conducting magnetic energy storage (SMES) [1, 2, 6] have been developed.

1.2.1 An Electric Capacitor as Energy Storage

Let’s consider an electrostatic system composed of two metallic bodies and a dielectric in volume V between the bodies. Charging the bodies of the electrical system illustrated above, electrical energy is directly stored in the form of an electric field. Energy stored in such a system is

$$W_E = \frac{1}{2}\oiiint_V \epsilon(E)E^2 dv, \tag{1.1}$$

where

V is the volume of the dielectric,

E is the electric field, and

$\epsilon(E)$ is the permeability of the dielectric material.

Let's now consider a parallel-plate capacitor as illustrated in Figure 1.3. The capacitor consists of two plates and a dielectric between the plates. The distance between the plates is d, while the plates surface is A. The plates are charged by charge $+Q$ and $-Q$ respectively.

Without losing the generality of the discussion, we can assume that the capacitor is a nonlinear capacitor with a voltage dependent charge and consequently capacitance. Charge and capacitance of a nonlinear capacitor are illustrated in Figure 1.4. The charge of a nonlinear capacitor saturates and capacitance decreases once the voltage reaches a certain level. However, there are some examples when capacitance increases with the voltage applied. As an example, electrochemical ultra-capacitors will be discussed in the following section.

The energy of a nonlinear capacitor charged to voltage U_0 is

$$W_E = \int_0^{Q_0} u(q)dq = \int_0^{U_0} \left(C\,(u) + \frac{\partial C(u)}{\partial u} u \right) udu, \tag{1.2}$$

where

$C(u)$ is the voltage dependent capacitance.

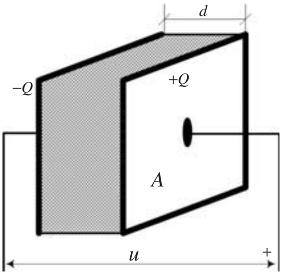

Figure 1.3 A parallel plate capacitor

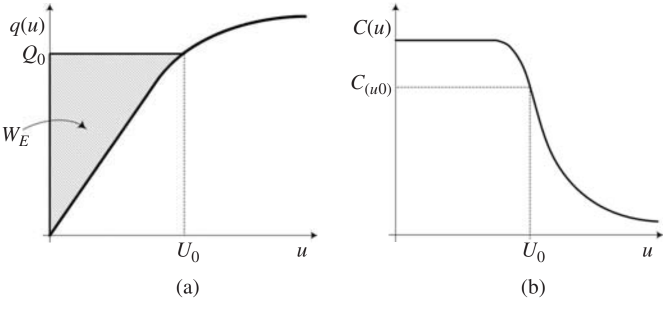

Figure 1.4 (a) The capacitor charge characteristic and (b) capacitance versus voltage

If the dielectric is linear, energy is computed from Equation 1.2 as

$$W_E = \frac{1}{2}Q_0U_0 = \frac{1}{2}C_0U_0^2, \tag{1.3}$$

where

C_0 is the capacitance of the capacitor and
Q_0 is the charge of the capacitor.

From Equations 1.3 and 1.2 we can see that the energy storage capability of an electric capacitor strongly depends on the capacitor voltage and the capacitance. It is obvious that the voltage rating and the capacitance have to be as high as possible in order to increase the capacitor's energy capability. The voltage rating and capacitance depend on capacitor technology. The most commonly used power capacitor technologies are electrolytic and polypropylene film capacitors.

1.2.1.1 Ultra-Capacitor Energy Storage

Ultra-capacitor energy storage (UCES) devices store electrical energy in the form of an electric field between two conducting plates [3, 4]. The energy storage system is composed of an ultra-capacitor and an interface power converter, as shown in Figure 1.5. The interface power converter is traditionally used for reasons of better controllability and flexibility of the UCES system. Depending on the application and nature of the electrical system, the interface power converter can be an ac–dc or a dc–dc bi-directional power converter. In some applications, the interface power converter is a cascade connected ac–dc and dc–dc power converter.

The ultra-capacitor is an electrochemical capacitor, which is composed of two porous conducting electrodes. To prevent direct contact between the electrodes, a separator is inserted between them. The electrodes are attached to metallic current collectors which are the capacitor terminals. A simplified cross-section is depicted in Figure 1.6. The electrodes and the separator are immersed in electrolyte. Each electrode forms a capacitor

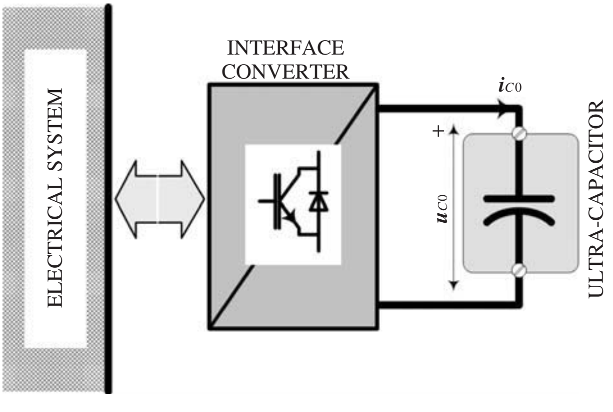

Figure 1.5 Ultra-capacitor energy storage system connected to an electrical system

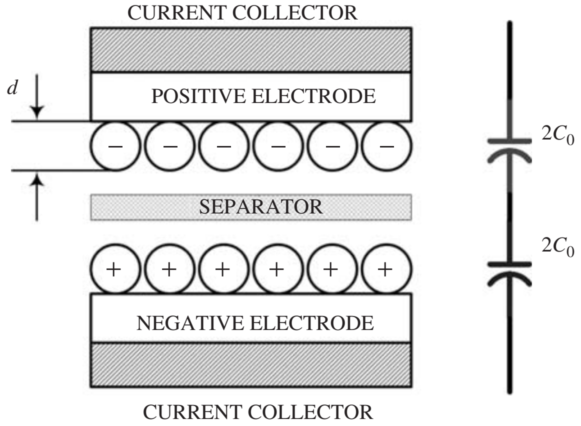

Figure 1.6 Simplified cross-section of an ultra-capacitor cell

with a layer of the electrolyte's ions. The capacitance depends on the size of the ions and the surface of the conducting electrode. Since the ion's diameter is in the range of angstroms, while the surface is in range of thousands of square meters, the capacitance is in the range of thousands of farads, which is significantly higher than that of standard electrolytic capacitors.

The ultra-capacitor is a nonlinear capacitor. The capacitance is voltage controlled capacitance defined as

$$C(u) = C_0 + k_C u, \tag{1.4}$$

where

C_0 is the initial capacitance, which represents electrostatic capacitance of the capacitor and

k_C is a coefficient, which represents the effects of the diffused layer of the ultra-capacitor.

Let the ultra-capacitor be charged on voltage U_0. The energy of the ultra-capacitor is

$$W_E = \frac{1}{2}\left(C_0 + \frac{4}{3}k_C U_0\right) U_0^2. \tag{1.5}$$

Since the capacitance C_0 is in the order of thousands of farads (F), the energy capability of the ultra-capacitor can be significantly higher than the capability of a "standard" electrolytic capacitor.

Ultra-capacitors are available as single cells from various manufacturers [5, 6]. The typical capacitance of available ultra-capacitor cells is in the range 100–6000 F, while the voltage rating is 2.5–2.8 V. Figures 1.7 and 1.8 show some of the commercially available ultra-capacitor cells from manufacturer LS Mtron [5].

Ultra-capacitors are used as short-term energy storage, mainly for applications requiring high power rather than high energy. A detailed discussion on possible application fields is given in Chapter 3 of the book.

(a)

(b) (c) (d)

Figure 1.7 LS Mtron ultra-capacitors. Copyright LS Mtron, with permission

1.2.1.2 Ultra-Capacitors versus Electrolytic and Film Capacitors

Performances of electrostatic, electrolytic, and ultra-capacitors are summarized and compared in Table 1.1.

Electrostatic capacitors have a high voltage rating, in the range of a hundred volts up to a thousand volts or more. Specific capacitance is below 1000 μF/dm^3, while energy density is in range of 270–350 J/dm^3.


(a) (b)

Figure 1.8 LS Mtron ultra-capacitor module. Copyright LS Mtron, with permission

Table 1.1 Properties of high power capacitors and ultra-capacitors

	Voltage rating (V)	Capacitance	Energy
Electrostatic film capacitors	880	700–900 μF/dm^3	270–350 J/dm^3
Electrolytic capacitors	450	5000–7500 μF/dm^3	500–750 J/dm^3
Ultra-capacitors	2.8	5000–7500 F/dm^3	19–30 kJ/dm^3

In contrast to this, electrolytic capacitors have a lower voltage rating, usually up to 550 V, which is roughly half of that of the electrostatic capacitors. The specific capacitance of electrolytic capacitors is in the range 5000–7500 μF/dm^3. The energy density is in range of 500–750 J/dm^3, which is double that of electrostatic capacitors.

As can be seen from Table 1.1, the parameters of ultra-capacitors are different from the parameters of electrostatic and electrolytic capacitors in order of magnitude. The voltage rating is in the range 2.5–2.8 V, which is more than 2 orders of magnitude lower than that of electrolytic capacitors. However, the capacitance density is in the range of 5000–7500 F/dm^3, which is 6 orders of magnitude more than that of electrolytic capacitors. Therefore, the energy density is 25–60 times higher than that of electrolytic capacitors.

1.2.2 An Inductor as Energy Storage

In the previous section we saw how the electric field can be used as a medium to store energy. In a similar way, we can use the magnetic field to store energy. In this section, we will briefly present a magnetic device, the so-called an inductor, as an energy storage device.

Let's consider a volume V. Let the flux density and strength of magnetic field be B and H. In this instance we do not consider the source of the magnetic field. It could be pre-magnetized material, a magnetic field in the vicinity of a wire carrying a current, or a combination of the two. Energy localized in the volume V is

$$W_M = \frac{1}{2}\oiiint_V \vec{H}\,\vec{B}\,dv. \tag{1.6}$$

Let's now consider an inductor, such as that shown in Figure 1.9a. The inductor consists of a ring-core and a winding with N turns wound around the core. The winding is carrying a current I_0. The magnetic field flux density and magnetic field in the core are B and H. A general B–H characteristic of a core with nonlinear characteristics is depicted in Figure 1.9b.

Energy localized in the core can be computed from the total flux and the inductor current,

$$W_E = \int_0^{\Psi_0} i(\psi)d\psi, \tag{1.7}$$

where

$i(\psi)$ is the inductor current versus the total flux ψ (Figure 1.10).

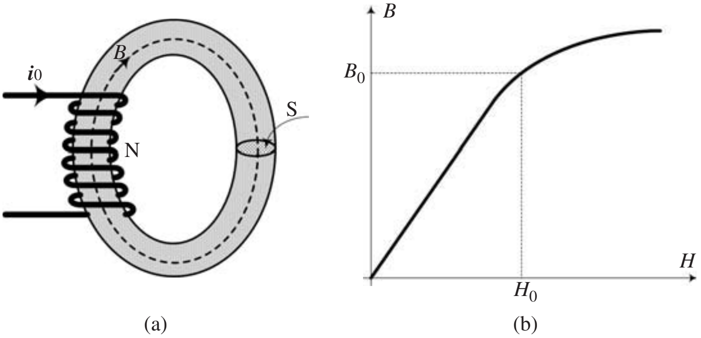

Figure 1.9 (a) A ring-core inductor and (b) H–B characteristic of the inductor core

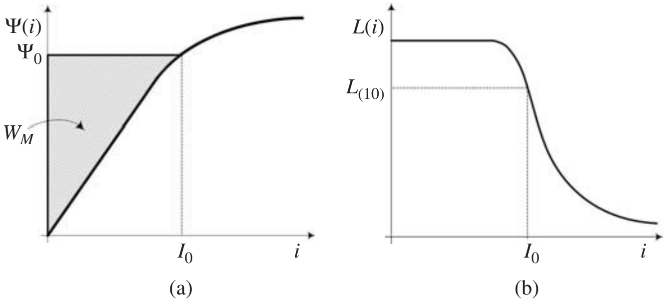

Figure 1.10 (a) Total flux versus the current and (b) inductance versus the current

The flux is defined by

$$\psi = N \iint_S \overrightarrow{B} d\overrightarrow{s}, \tag{1.8}$$

where

S is the core cross-section and
N is the number of turns.

The energy of a nonlinear inductor carrying (being charged with) current I_0 is

$$W_E = \int_0^{I_0} \left(L(i) + \frac{\partial L(i)}{\partial i} i \right) idi, \tag{1.9}$$

where

$L(i)$ is the current dependent inductance.

1.2.2.1 Super-Conducting Magnetic Energy Storage

An SMES device stores energy in the form of magnetic field that is created by a current in a super-conducting coil that is cryogenically cooled [1, 2, 10]. The SMES is composed of a super-conducting coil and a bi-directional interface converter, as illustrated in Figure 1.11. The interface power converter is traditionally used for reasons of better controllability and flexibility of the SMES system. Depending on the application and nature of the electrical system, the interface power converter can be an ac–dc or a dc–dc bi-directional power converter. In some applications, cascade connection of a voltage source ac–dc and dc–dc converter is used for the sake of flexibility.

A super conduction coil is a linear inductor with an inductance L_0. The energy of a SMES charged with the current I_0 is

$$W_{SMES} = \frac{1}{2} L_0 I_0^2. \tag{1.10}$$

From Equation 1.10, it is obvious that high energy requires large inductance and high current. The resistance of a super-conducting magnet is virtually zero. Because of this property of the super-conducting magnet, an inductance in the order of tens of henry can be easily achieved, while the current I_0 can be in the order of a thousand amperes. Therefore, an energy capability in the order of tens of megajoules can be achieved.

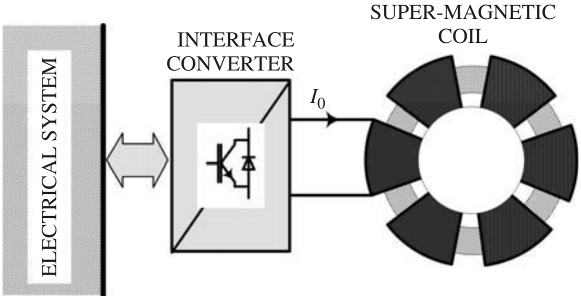

Figure 1.11 Super-conducting magnet energy storage connected to an electric system

The SMES is charged from the electric grid via an interface ac–dc or dc–dc power converter. Once the current I_0 is established in the SMES coil, the coil can be virtually disconnected from the grid. The current I_0 circulates via the SMES coil and the output terminal of the interface power converter. When the energy is required, the SMES coil current, and therefore the energy, is transferred to the grid via the interface power converter.

SMES are used in high power short-term applications. Their power level is in range of hundreds of megawatts while their charge/discharge time is less than a second. The main field of application is large-scale utility power quality restorers.

1.3 Indirect Electrical Energy Storage Technologies and Devices

Indirect electric energy storage devices are devices that use the energy conversion process to store and restore electrical energy. The energy storage device consists of an energy converter and an energy storage medium, as illustrated in Figure 1.12. Electrical energy is converted to another type of energy, such as mechanical or chemical energy. Then, the converted energy is stored using a proper storage medium. The energy conversion is performed via an energy converter, such as an electric motor/generator or an electrochemical reactor.

Mechanical energy can be stored as kinetic and potential energy. Energy storage that uses kinetic energy as storage medium is known as flywheel energy storage (FES). Energy storage devices that use potential energy as a storage medium can be divided into two groups: (i) hydro pumped energy storage (HPES) and (ii) compressed air energy storage (CAES). Energy storage devices that use chemical potential energy to store electrical energy are: (i) electrochemical batteries and (ii) hydrogen fuel cells.

1.3.1 Mechanical Energy Storage

The mechanical energy of a body can be defined by the following equation,

$$W_{MC} = \int_L \vec{F}\, d\vec{l}\,. \tag{1.11}$$

where

F is the mechanical force that acts on the body and
l is the linear distance.

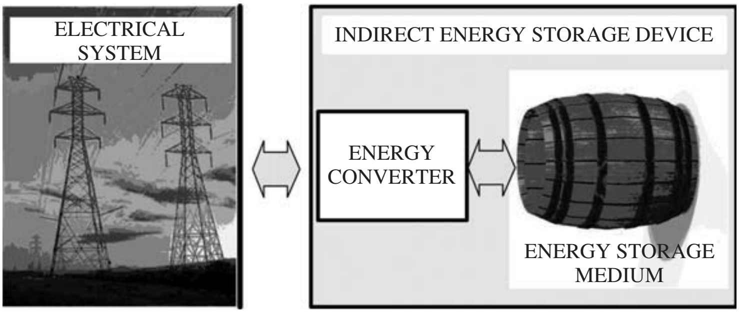

Figure 1.12 Illustration of an indirect electrical storage system

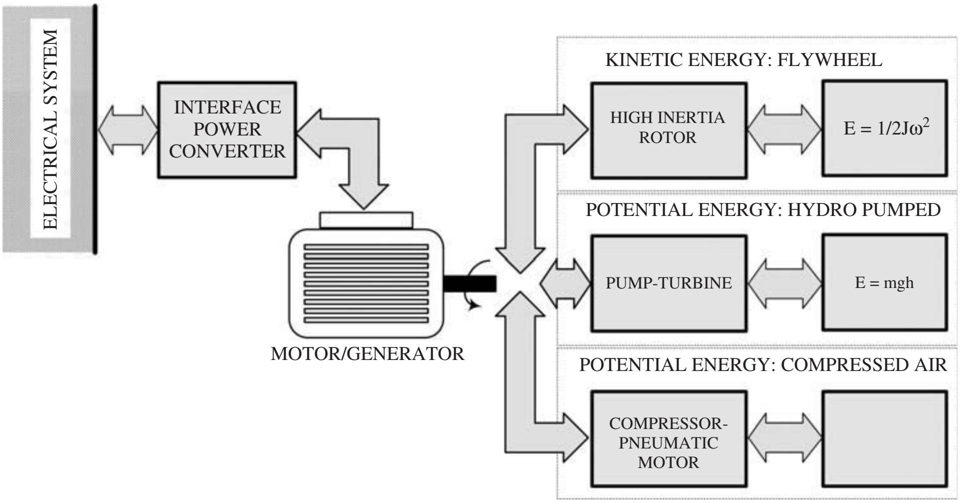

Figure 1.13 Indirect electromechanical energy storage

The force can be, for example: (i) gravity, (ii) inertia, and (iii) elastic force.

1. $F = mg$, where m is the mass of the body and $g = 9.81$ is the gravity acceleration.
2. $F = ma$, where a is the acceleration of the body in movement.
3. $F = k_c y$, where k_c is the coefficient of elasticity and y is deformation.

A structural block diagram of a mechanical energy storage system is depicted in Figure 1.13. Electrical energy is converted to mechanical energy via an electromechanical converter, such as a three-phase motor/generator. The mechanical energy can be stored directly as kinetic energy of a rotating mass or it can be converted and stored as the potential energy of elevated water or compressed air. The stored energy can be realized in the opposite way: kinetic or potential energy is converted to mechanical, which is further converted to electrical energy via a generator and fed back to the electric grid. For the sake of system flexibility and efficiency, the motor/generator is connected to the electrical system via an interface power converter. The converter is controlled to match the variable frequency and voltage of the motor/generator to constant frequency and voltage of the electrical system.

1.3.1.1 Flywheel Energy Storage

FES is a device that uses the kinetic energy of a rotating body as the storage medium [1, 2, 7]. As illustrated in Figure 1.14, basic FES consists of a high inertia rotor and a bi-directional electromechanical converter such as a three-phase motor/generator, which is attached to the same shaft as the high inertia rotor. The motor/generator is connected to an electrical system via an interface power converter.

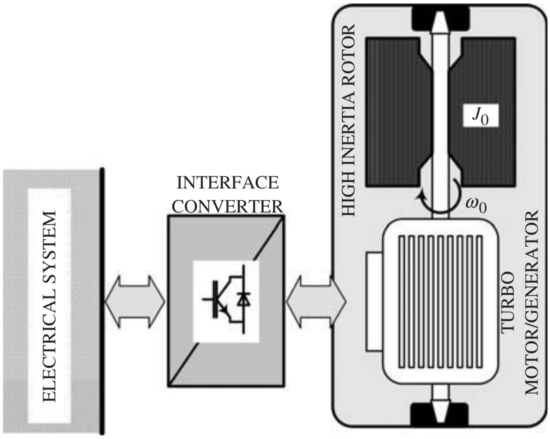

Figure 1.14 Flywheel energy storage connected to an electrical system

The kinetic energy of the flywheel is

$$W_{FW} = \frac{1}{2} J_0 \omega_0^2 \tag{1.12}$$

where

J_0 is the moment of inertia of entire rotating system that includes the motor/generator rotor and the flywheel rotor and

ω_0 is the angular velocity of the flywheel.

The energy is being stored in the flywheel when the rotor is accelerating, and the motor/generator operates as a motor. The energy is restored when the flywheel is decelerating and the motor/generator operates as a generator. As we can see from Equation 1.12, energy depends strongly on the flywheel speed. Therefore, the voltage and frequency of the motor/generator varies significantly with the flywheel energy. It makes it both difficult and inefficient to connect the motor/generator directly to the electrical subsystem. In practice, the motor/generator is connected to the electrical subsystem via a bi-directional power converter that matches the generator voltage/frequency (which corresponds to the flywheel velocity) to the constant voltage and frequency of the electrical subsystem.

1.3.1.2 Hydro Pumped Energy Storage

HPES store energy using the potential energy of water [2]. Figure 1.15 shows a simplified block diagram of an HPES. The HPES is composed of a motor/generator, a pump/turbine, an interconnection pipe, and large upper and lower reservoirs. When electrical energy is being stored, the motor converts electrical energy into mechanical energy and runs the pump that pumps water from the lower reservoir to the upper reservoir. When the energy is being restored, the water flows from the upper reservoir to the lower reservoir via a

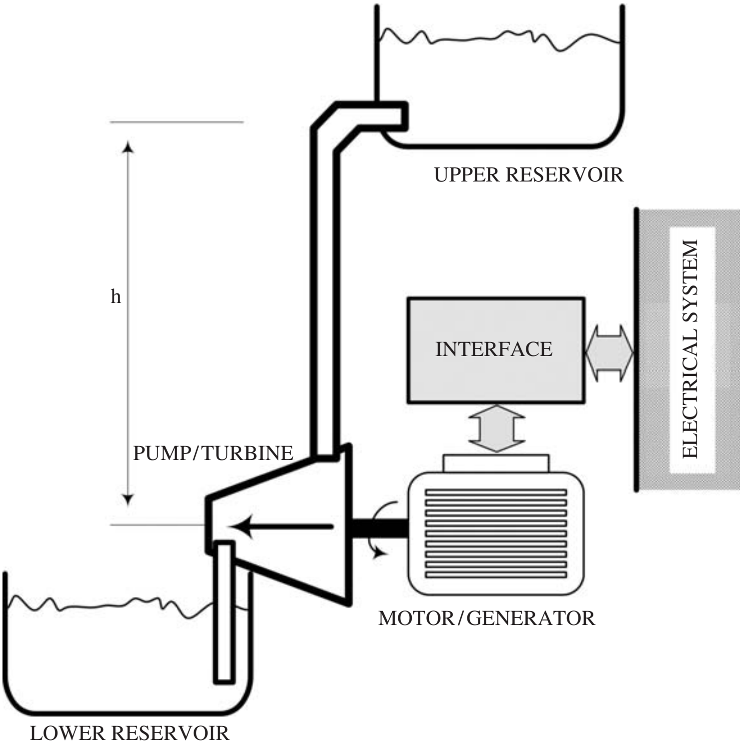

Figure 1.15 Hydro pumped energy storage system

pump that now works as a high-pressure turbine. The turbine runs the motor/generator that works as a generator and converts the mechanical energy into electrical energy. The motor/generator is directly connected to the electrical system.

The stored energy of an HPES system can be computed as

$$W_{HPES} = V_0 \rho g H, \tag{1.13}$$

where

V_0 (m^3)	is the volume of the upper reservoir,
ρ (kg/m^3)	is the water density,
g (m/s^2)	is the gravity acceleration ($\cong 9.81$), and
H (m)	is the vertical distance between the upper reservoir and the pump/turbine, the so-called hydraulic head.

HPES are used in large-scale systems that require large energy capacity and high power, such as power systems.

1.3.1.3 Compressed Air Energy Storage

CAES store energy in the form of compressed air [8]. A CAES is composed of a hermetic reservoir, a compressor, a turbine, and a motor/generator, as illustrated in Figure 1.16.

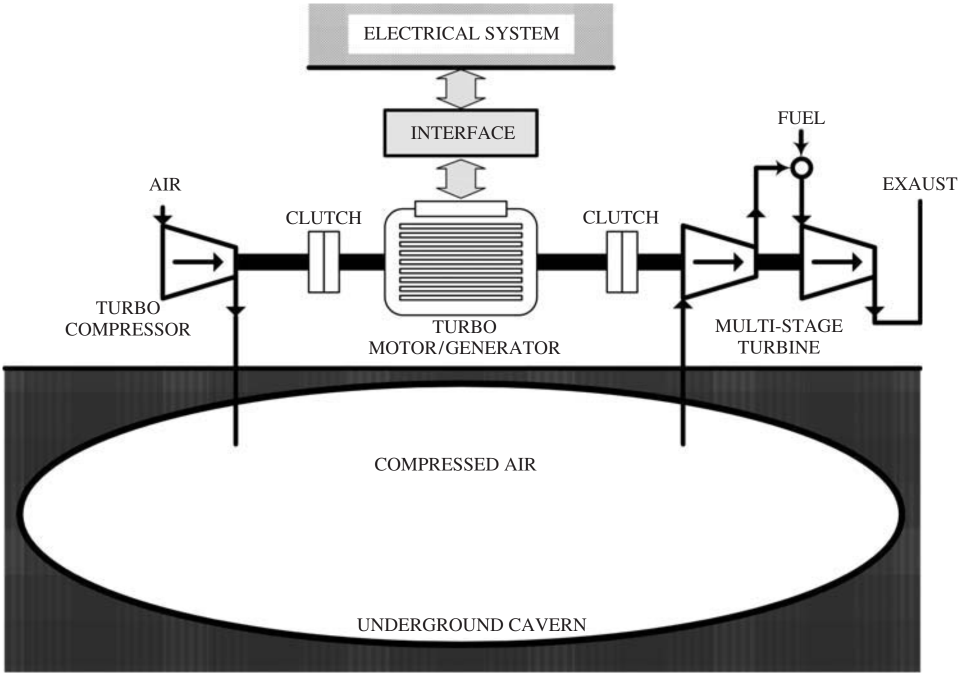

Figure 1.16 Compressed air energy storage system

The hermetic reservoir is usually an underground cavern. When the energy is being stored, the motor converts electrical energy into mechanical energy and runs the compressor that compresses air into the reservoir. When it is required, the energy can be realized by decompressing the air from the reservoir via a multi-stage gas turbine. The turbine drives the generator and converts the mechanical energy into the electrical energy that is fed back into the electrical system via an interface power converter.

The energy storage capacity depends on the deposit volume and maximum storage pressure of the compressed air. CAES are used in large-scale applications that require large energy capacity and high power, such as power systems and renewable sources.

1.3.2 Chemical Energy Storage

Chemical energy storage devices belong to the group of indirect electrical energy storage devices. Electrical energy is converted into chemical potential energy, which is further stored in a proper way. Two concepts of electrochemical energy are most often used: (i) electrochemical batteries [9] and (ii) hydrogen fuel cells [7].

1.3.2.1 Electrochemical Batteries

Battery Energy Storages (BESs), best known as electrochemical batteries, are the oldest and most established technology for storing electrical energy. Batteries are electrochemical

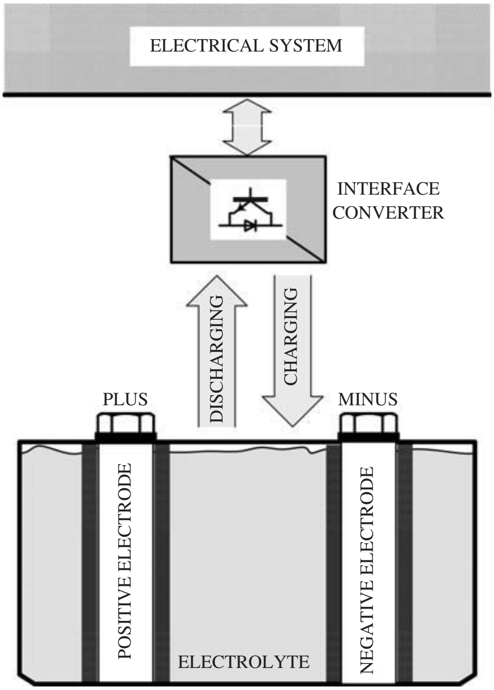

Figure 1.17 Simplified layout of an electrochemical battery cell

devices that convert electrical energy into potential chemical energy and store it during charging. When required, the stored chemical energy is realized and converted into electrical energy. An electrochemical battery as an energy storage device that is composed of one or more elementary cells connected into one unit. A battery cell consists of two electrodes, positive and negative, which are immersed in electrolyte. When the battery is being charged, an external voltage/current source is applied across the electrodes. A flow of ions is formed between the battery electrodes via the electrolyte and electrode material is transferred from one electrode to another. When required, an external load is applied between the battery electrodes. A flow of ions in the opposite direction is formed and the electrode material is transferred back from the second electrode to the first (Figure 1.17).

Depending on the electrode material and electrolyte, we can distinguish different types of electrochemical batteries. Characteristics of major state-of-the-art batteries are summarized in Table 1.2.

Lead–Acid Batteries

Lead–acid batteries are oldest and most mature battery technology. The lead-acid battery consists of a lead (Pb) negative electrode, a lead dioxide (PbO_2) positive electrode, and a separator that electrically separates the electrodes. The electrodes and separator are flooded in dilute sulfuric acid (H_2SO_4) acting as the electrolyte. Lead–acid batteries are basically