2 Energy Storage Systems

2.1 PHYSICAL SYSTEMS

Storing energy is usually a repetitive task with a very high number of expected cycles. In contrast with the classical electrochemical batteries, where the expected number of cycles is limited due to degradation phenomena, physical systems based on reversible mechanisms of various natures can be used with much longer life cycles. One good example can be found in the hydraulic sector with the classical pumped hydropower plants. Such systems can in addition be realized for very high power levels in the range of hundreds of megawatt [1,2].

Another principle is based on gas compression and expansion and is known as compressed air energy storage (CAES) [3,4].

Further, mechanical systems are also used based on rotational kinetic energy and are known as flywheels [5,6].

Electrical components such as capacitors or inductors are also candidates for energy storage, even if their specific energy capacity is limited. Such systems are generally used for their ability to provide a high level of instantaneous power [7–9].

2.1.1 GRAVITATIONAL HYDRO PUMPED STORAGE

Hydro pumped-storage facilities comprise water reservoirs placed at different altitudes and which are interfaced through a reversible pump/turbine set. The stored energy E can be described through the gravitation law

$$E = m \cdot g \cdot h \tag{2.1}$$

where

m is the displaced mass
g is the gravitational acceleration
h is the difference of the levels of both reservoirs

A simplified diagram of a hydro pumped storage facility is given in Figure 2.1. The main conversion components are hydraulic pumps and turbines, coupled directly to synchronous machines used as motors in the accumulation mode and as generators in the restitution mode. Modern pumped hydro plants use variable speed generators/motors offering many advantages like variable power in the pump mode.

The gravitational hydraulic pumped storage will be described more in detail in Chapter 7.

The gravitation force and variation of the altitude of a given mass can be used with means other than water, as proposed in Reference 10. In such a system, blocks of concrete are transported on rails from one altitude to another.

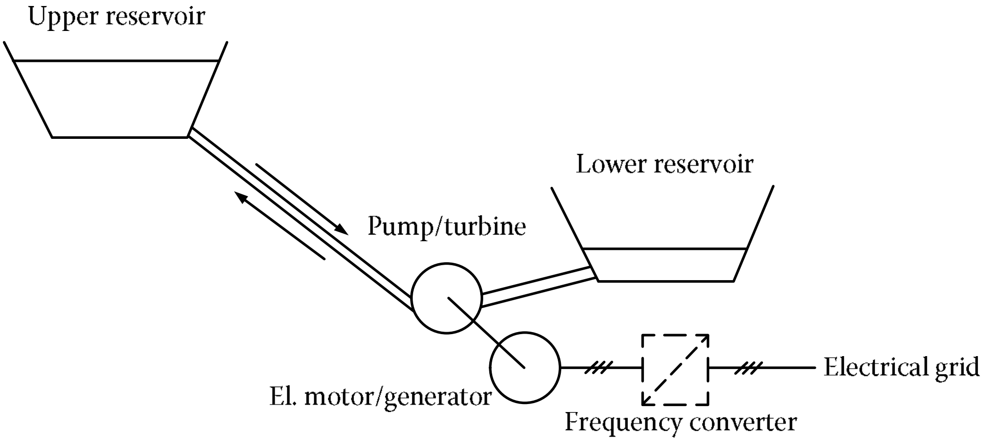

FIGURE 2.1 Principle of a hydro pumped-storage plant.

2.1.2 COMPRESSED AIR ENERGY STORAGE

CAES is based on the compression and expansion of air. Such systems use generally a compression stage comprising an electric motor driving a compression machine. Then, the compressed air is stored in a reservoir. For the recovery of the stored energy, an expansion system is also provided. This expansion machine is composed of a volumetric expander driving an electric generator. The general scheme of CAES is represented in Figure 2.2.

The amount of energy stored in a reservoir of volume V_1, pressurized at a pressure level P_1 and stabilized at the same temperature as its surroundings, can be calculated through the expression (2.2) [3]

$$E = P_1 \cdot V_1 \left[\ln\left(\frac{P_1}{P_a}\right) - 1 + \frac{P_a}{P_1} \right] \tag{2.2}$$

P_a is the pressure of the surrounding (atmosphere). The expression gives the value of the maximum amount of energy that can be recovered from the reservoir that corresponds to a full expansion under isothermal conditions.

System performances and the description of components dedicated to the principle of CAES will be presented in Chapter 6.

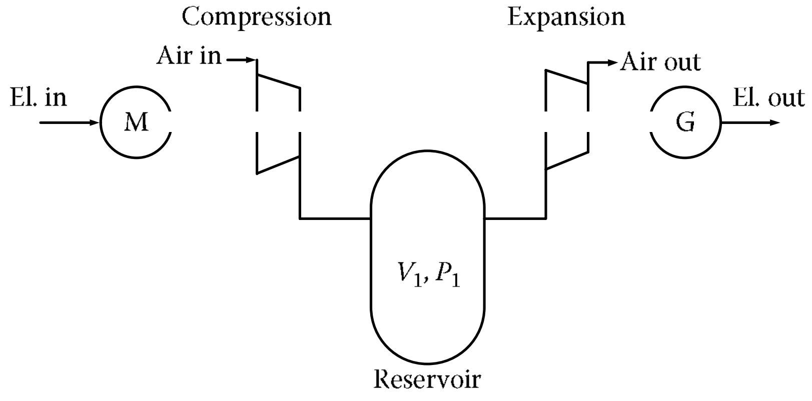

FIGURE 2.2 General scheme of CAES.

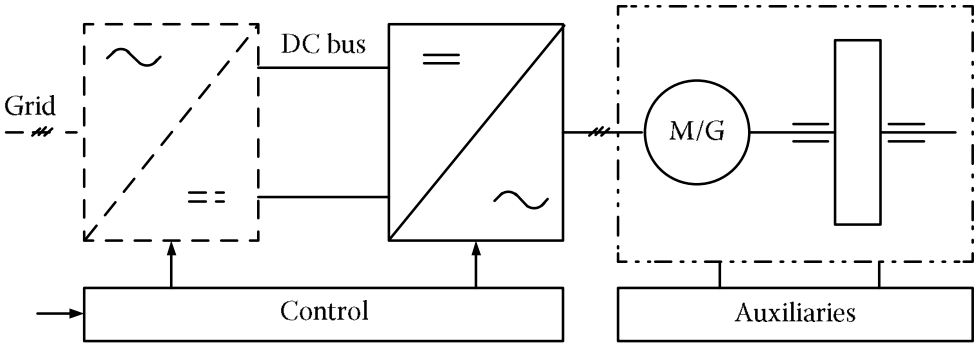

FIGURE 2.3 Flywheel system.

2.1.3 Rotational Kinetic Energy (Flywheels)

Another possibility to store energy is through rotational kinetic energy. Such systems belong also to the category of reversible physics phenomena. A flywheel system is generally composed of an electric machine coupled to a rotating mass. With the help of a power electronic converter, the driving torque of the variable speed machine (positive for charging and negative for discharging) can be imposed precisely and makes possible the control of the exchanged power level. Flywheels have been realized in the past based on normal steel and limited speed, but modern equipment benefits from advanced materials like carbon composites and fast-running permanent magnet motors that can rotate at several hundred thousand revolutions per minute. Partially evacuated encapsulations reduce the aerodynamic losses of the flywheel and motor. A schematic representation of a flywheel system is given in Figure 2.3.

The amount of energy stored in rotating mass running at a speed Ω is given by

$$E = \frac{1}{2} J\Omega^2 \tag{2.3}$$

where J is the moment of inertia.

The auxiliaries of a flywheel system provide the partial vacuum needed to reduce the aerodynamic losses, and they often include control of special bearings (magnetic, air).

The principle of the flywheel storage, together with the related performances, will be described more in detail in Chapter 8.

2.2 ELECTRICAL SYSTEMS

2.2.1 Superconductive Magnetic Energy Storage Systems (SMES)

On the base of a purely electric/magnetic component like the inductor, energy can also be stored. The energy stored in an inductor can generally be expressed by the following law:

$$E = \frac{1}{2} L \cdot I^2 \tag{2.4}$$

where

L is the value of the inductance

I is the circulating current

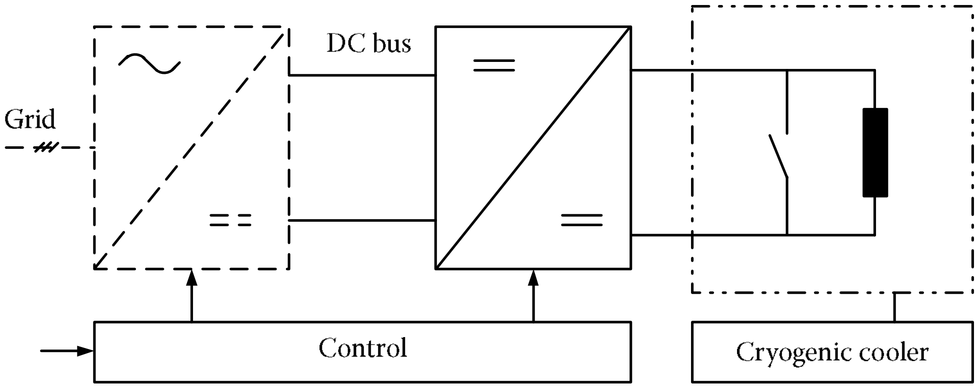

FIGURE 2.4 SMES (superconductive magnetic energy storage system).

The maximum power $P_{\max}$ during charging and discharging is given by the values of maximum current and voltage delivered by the power electronic converter:

$$P_{\max} = U_{\max} I_{\max} \tag{2.5}$$

A SMES system uses superconductivity in order to increase the energy density (higher current in the same support) and in order to reduce the ohmic losses to a minimum value [8].

A general scheme of a SMES system is given in Figure 2.4.

During the charged state of a SMES system, note that the inductor current must always flow. Even if there are no variations of this current, it causes conduction losses in the inductor itself and in the interconnections but also in the freewheeling paths of the converter. For a long-term idling mode, but also for security reasons, a bypass switch is generally provided.

2.2.2 CAPACITIVE (AND SUPERCAPACITIVE) SYSTEMS

The dual element of the inductor is the electric capacitor. It can be used for energy storage according to the relation giving its energy content:

$$E = \frac{1}{2} C \cdot U^2 \tag{2.6}$$

where

C is the value of the capacitance
U is the value of the voltage across the capacitor

The charging and discharging of a capacitor is realized by using a power electronic converter. The general scheme of a capacitive energy storage device is represented in Figure 2.5. Classical high-voltage capacitors can be used for energy storage [9], but also more recently developed supercapacitors, characterized by their high value of capacity.

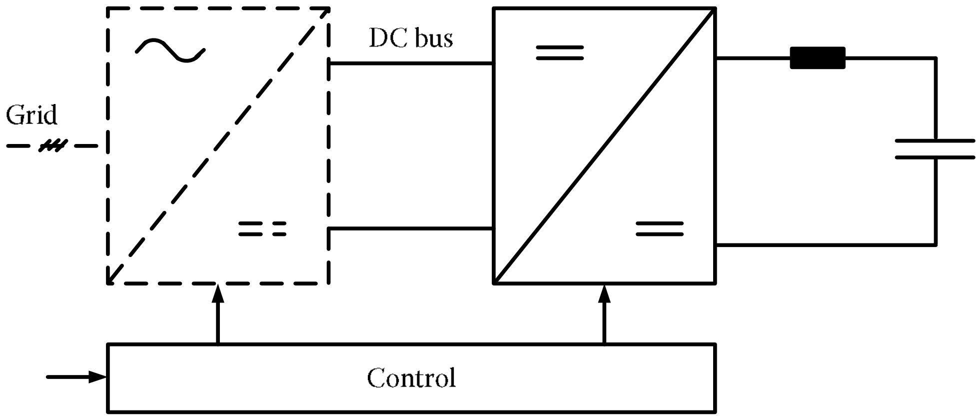

FIGURE 2.5 Capacitive energy storage system.

In the case of a capacitive storage system, the power electronic converter must be able to control the capacitor current. A positive current charges the capacitor, while a negative current causes its discharge. A steady-state idling mode is characterized through a zero current flowing. This is an interesting property regarding energy efficiency.

An example of an application of a high-power capacitive storage is described in Reference 9. This equipment is dedicated to the smoothing of the power demand of the supply of the magnets of a particle accelerator (CERN). The capacity is around 20 MJ, and the maximum power is at 60 MW.

From the beginning of the twenty-first century, the capacitive storage in general undergoes higher interest due to the appearance on the market of new components called supercapacitors or double-layer capacitors. Chapter 5 gives a detailed description of the components and describes several innovative application examples.

2.2.3 ELECTROCHEMICAL SYSTEMS

There is a high diversity of electrochemical technologies as potential solutions in the area of energy storage. Many of them are well established, especially in the domain of mobile applications. Larger systems are today developed for their utilization in connection with public grids [11–14].

Today, an increasing number of modern materials are emerging and appear often with promising characteristics. These progresses are seen in the direction of higher energy densities but also with regard to the power density. Additionally, more intensive studies on failure and aging mechanisms are aimed at reaching higher number of cycles or longer lifetimes of batteries. Many aspects of the electrochemical techniques and of the battery storage technology are presented in Chapter 4.

An electrochemical battery is composed of several elements (cells) connected in series, each consisting of two electrodes. In each cell, an electric current is assumed to flow thanks to ion transport. The positive electrode called the cathode and the negative one called the anode are generally placed in an electrolyte.

2.2.3.1 Oxidation and Reduction

At the level of the electrodes, the chemical reactions are called oxidation and reduction.

An oxidation is a reaction where one atom or one ion loses one or more electrons.

The "actor" of an oxidation is an electron donor, also called a reducer.

A reduction is a reaction where one atom or one ion receives one or several electrons.

The "actor" of the reduction is an electron acceptor called an oxidant.

A reaction of oxidoreduction (redox reaction) can be described in a generic form:

$$a\mathrm{Ox} + n\mathrm{e} \rightleftarrows b\mathrm{Re}d \tag{2.7}$$

where a, n, and b appear as coefficients for the balance of the two members of the equation. They depend on the species used. Numerous examples will be presented in Chapter 4.

The *anode* is the electrode where the oxidation takes place.

The *cathode* is the electrode where the reduction takes place.

For the system approach point of view, an electrochemical battery can be seen as a voltage source, the charging and discharging variable being the battery current. Figure 2.6 gives a simplified scheme of a BESS (battery energy storage system).

The principle scheme of a BESS is very similar to that of a capacitive storage device. Principally, the positive and negative DC current is provided by a DC–DC converter. The interface to the external world can be defined at the DC bus level or through a front-end converter to the AC grid.

On the lower right side of Figure 2.6, a so-called battery management system (BMS) is represented. This unit has the role of balancing the different elements of the series connection but has also the task to supervise and protect the overall system.

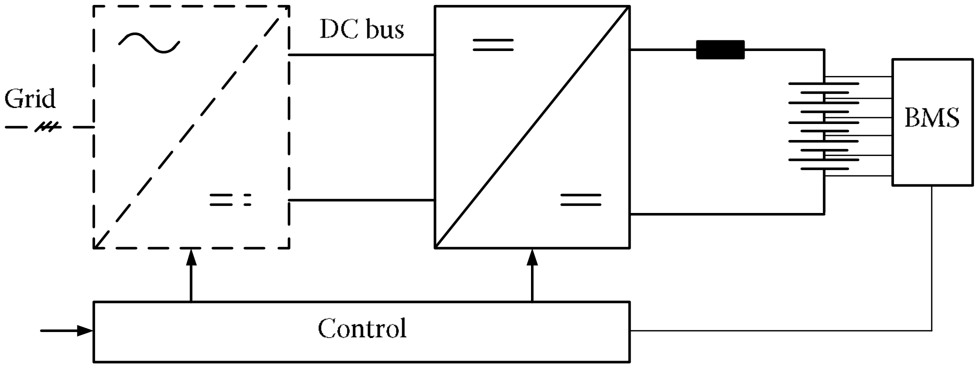

FIGURE 2.6 Battery energy storage system (BESS).

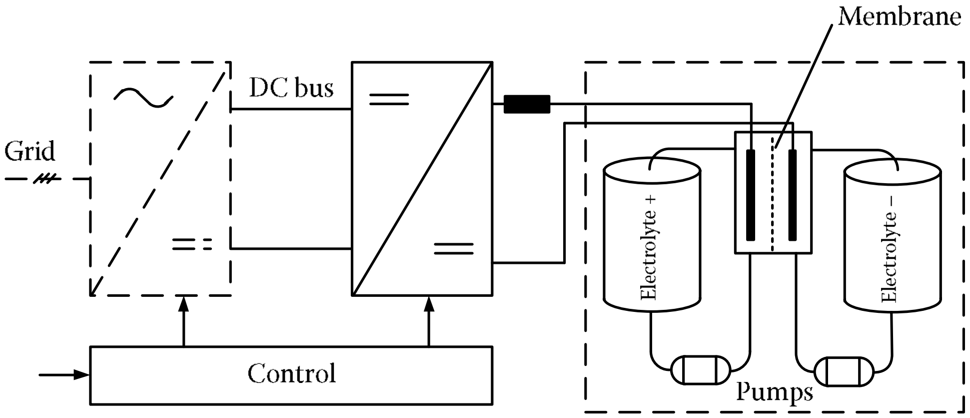

FIGURE 2.7 Redox flow battery storage system.

2.2.4 FLOW BATTERIES

Flow batteries are a new type of electrochemical accumulators composed of two electrodes separated by a proton exchange membrane, as can be found in fuel cells or in electrolyzers. The energy storage occurs in such flow batteries within the change of the concentration of ions at the level of two liquids, an anolyte and a catholyte, circulating from two separated reservoirs [15].

Flow batteries allow the skirting of some limitation of classical electrochemical batteries where the electrochemical reactions create solid composites accumulated on the electrodes where they are generated and where the mass that can be accumulated is perforce limited. The generation of internal stresses on the electrodes due to variations of the volumetric density of the active materials is another cause of aging phenomena in classical batteries. In flow batteries, the chemical compounds that represent the state of charge are in liquid form and are in solution in the two electrolytes.

These electrolytes are pumped from separated reservoirs to the "reactor," which is composed of the electrodes and the membrane.

One main characteristic of flow batteries is that the electrochemical converter (the reactor) is designed for the power level of the accumulator, while the energy capacity is only related to the volume (and mass) of the liquid electrolytes. In Figure 2.7, one example of a flow battery is represented. Because the circulation pumps for the electrolytes need a given amount of power, a more detailed calculation of the efficiency will be given in the dedicated Section 4.2.3 [16,17].

While the electrochemical batteries cover the largest area of today's energy storage applications, their principles and components will be described in further detail in Chapter 4.

2.2.5 FUEL CELLS AND HYDROGEN STORAGE

Another electrochemical energy converter is the fuel cell. Combined with a relatively complex chain of subcomponents such as electrolyzer, hydrogen conditioning, and storage, the fuel cell represents an interesting energy source for the future. The complete storage system based on hydrogen can be used for the storage of large amounts of energy. These systems are discussed in Chapter 9.

REFERENCES

1. Tanaka, H., An 82 MW variable speed pumped-storage system, *Water Power & Dam Construction*, 40(11), 25–26, November 1991.
2. Torres, O., Life cycle assessment of a pumped storage power plant. Master report, Norwegian University of Science and Technology, Trondheim, Norway, July 2011.
3. Lemofouet, S., Investigation and optimization of hybrid electricity storage systems based on compressed air and supercapacitors, Thesis No. 3628, EPFL, Lausanne, Switzerland, 2006.
4. Lemofouet, S., Rufer, A., Hybrid energy storage system based on compressed air and supercapacitors with Maximum Efficiency Point Tracking (MEPT), *IEEE Transactions on Industrial Electronics*, 53(4), 1105–1115, 2006.
5. Reitan, D.K., Bahari-Kashani, M., Superflywheel energy storage and non-synchronous AC/DC/AC electric transmission supplements power system operation, *Proceedings of the IEEE*, 64(10), 1543–1544, October 1976.
6. Proud, N.J., Kelsall, D.R., Alexander, T.M., A drive system for the Pirouette™ kinetic energy storage system. Power electronics and variable speed drives, *IEE Conference Publication*, 429, 342–347, 1996.
7. Ali, M.H., Wu, B., Dougal, R.A., An overview of SMES applications in power and energy systems, *IEEE Transactions on Sustainable Energy*, 1(1), 38–47, 2010.
8. Nomura, S., Chikaraishi, H., Shimada, R., Design study on series compensated thyristor converters for large scale SMES, *2013 15th European Conference on Power Electronics and Applications (EPE)*, Lille, France, 2013, pp. 1–10. DOI: 10.1109/EPE.2013.6634613.
9. Fahrni, C., Rufer, A., Bordry, F., Burnet, J.P., A novel 60 MW pulsed power system based on capacitive energy storage for particle accelerators, *2007 European Conference on Power Electronics and Applications (EPE)*, Aalborg, Denmark, September 2007.
10. William, R.P. et al., Utility scale energy storage system, US Patent, US 8593012 B2, November 26, 2013.
11. Miller, N.W., Zrebiec, R.S., Hunt, G., Design and commissioning of a 5 MVA, 2.5 MWh battery energy storage system, *Proceedings IEEE Transmission and Distribution Conference*, Los Angeles, CA, 1996, pp. 339–345.
12. Miller, N.W. et al., Battery energy storage systems for electric utility, industrial and commercial applications, *Battery Conference on Applications and Advances (11th Annual)*, Long Beach, CA, 1996, pp. 235–240.
13. Akagi, H., Ota, J., Sato, T., Enhancement of performance, availability and flexibility of a battery energy storage system based on a modular multilevel cascaded converter (MMCC-SSBC), *IEEE Transactions on Power Electronics*, 31(4), 2791–2799, 2016 (IEEE xplore early access).
14. Chatzinikolaou, E., Rogers, D.J., A comparison of grid-connected battery energy storage system designs, *IEEE Transactions on Power Electronics*, 32(9), 6913–6923, 2017. DOI:10.1109/TPEL.2016.2629020.
15. Sum, E., Skyllas-Kazacos, M., A study of the V(II)/V(III) redox couple for redox flow cell applications, *Journal of Power Sources*, 15, 179–190, 1985.
16. Blanc, C., Rufer, A., Multiphysics and energetic modelling of a vanadium redox flow battery, *Proceedings of the International Conference on Sustainable Energy Technologies, ICSET2008*, Singapore, 2008, pp. 696–701.
17. Blanc, C., Modeling of a vanadium redox flow battery electricity storage system, PhD Thesis No. 4277, EPFL, Lausanne, Switzerland, 2009. https://infoscience.epfl.ch/record/129758/files/EPFL_TH4277.pdf. Accessed on September 22, 2017.