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Chapter 3

Electrical Energy Storage Devices for Active Buildings

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Status Quo, Challenges and Outlook

The future electricity networks would require backup power as stored energy in order to respond to different kinds of variation and uncertainty. The electrical storages, as one potential type, could be utilized in all scales including the end-user scale. However, utilizing different types of electrical storage on the demand side, e.g. in active buildings, could be challenging due to their operational requirements and their applications. Therefore, the first step is to answer the question that what kind of electrical storage could be utilized in active buildings? What are their characteristics and technology requirements? and which one could be more applicable compared to the others?

3.1 Overview on Energy Storage Systems (ESS)

Several types of energy storage for various applications in electrical networks have been introduced during the last three decades. Their application varies from the power generation system to end-users. Based on the desired application, different energy storage can be deployed. There have been introduced several types of energy storage as follows: thermal energy storage (TES), electrical energy storage (EES), mechanical energy storage (MES), etc. In this chapter, different types of ESS systems in terms of their technologies and applications have been studied.

There are several advantages to utilize ESS in the active distribution networks and microgrids. ESS has a prominent role in increasing the system's efficiency since they can manage the surplus of electricity generated by renewable energy sources (RESs) and reduce energy loss. Therefore, ESSs help to maximize the hosted capacity of the active networks and increase the share of RESs in grid's

demand supply as well [1]. Further, the ESSs can eliminate the fluctuations of consumption/production by providing the required flexibility [2]. Therefore, they can improve the stability and reliability of the active distribution network. Besides, using ESS can help increase supply security and power quality by maintaining frequency/voltage at the required levels. For instance, power storage options can ensure a reliable power supply with voltage drop occurring in the event of a power outage [3, 4].

ESSs can be classified in two groups. One is based on their manufacturing technology and the other is based on their operating time. In general, ESSs have short-term and long-term applications in terms of time. This means, that in some cases we need ESSs to act quickly and inject power [5]. However, in some cases, we need the ESS to stay longer in the grid and its momentary payback does not matter. The first way of operation, which is called the short-term function, whilst the other one, which is performed on a minute to hour scale, is called the long-term function. Short-term applications include the use of ESSs in frequency power converters, transient stability, FACTS devices, and damping of low-frequency fluctuations. The utilization of ESSs as an emergency energy source, alternative energy source, voltage regulation, peak load adjustment, and power management, are amongst its long-term applications [6, 7]. The two important factors distinguish the performance of energy storage technologies includes the amount of energy that the device can store as well as the speed at which energy can be injected into the grid [8]. A graphical overview on different types of energy storage in active buildings (ABs) can be found in Figure 3.1.

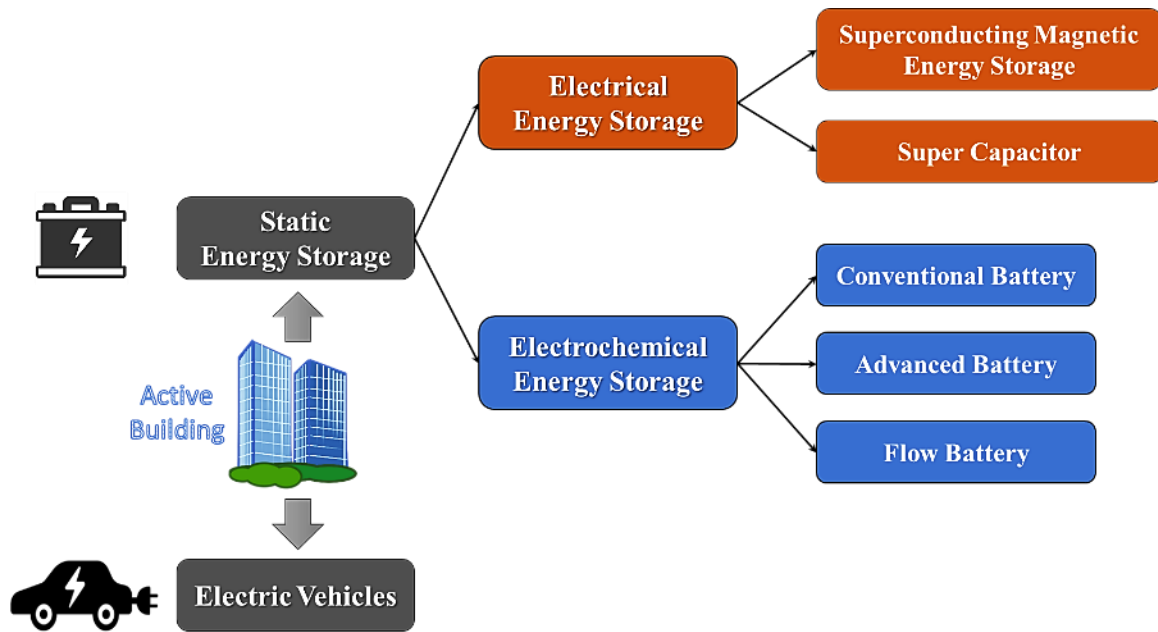


Figure 3.1. Overview on different types of energy storage in ABs

In this chapter, the electrical ESSs in microgrids and ABs are investigated. Firstly, different types of EES and their manufacturing technologies, their benefits and drawbacks are discussed. In the following, the application of each one of the energy storage is illustrated.

3.2 Static Storages

3.2.1 Electrical Storage

Electrical energy can be stored in electric and magnetic fields using super-capacitors (SCs) and superconducting magnets, respectively. They have high power and medium energy density, which means they can be used to smooth power fluctuations, meet maximum power requirements, and energy recovery in transportation devices [3]. In this section, the technology of electrostatic and magnetic energy storage are investigated.

3.2.1.1 Superconducting Magnetic Energy Storage (SMES)

Although the concept of superconductivity was discovered in 1911, its application as a storage for power grids was not considered until the 1980s. SMES is a direct current (DC) storage that stores the energy in the magnetic field generated by DC flows via superconducting coils. The technology of making superconducting magnetic energy storage consists of an inductive coil made of superconducting material [9]. The temperature of the superconducting coil should keep under its critical value. This temperature is retained by a crystal or rotary containing helium or nitrogen fluid vessels.

Since the superconductor has a small internal resistance (almost zero), by passing the DC current through it, low magnetic losses will be created. Energy could be stored as a circulating current meaning that the energy can be received from a SMES with an almost immediate response from a second to a few hours [10, 11]. The SMESs are used in two different shapes: toroid and solenoid. In the Toroid SMES, the external field is low but the cost of its superconductor and another component are higher than the solenoid form. The stored energy and power in the SMES unit can be obtained as in (3.1) and (3.2):

$$E = \frac{1}{2}LI^2 \quad (3.1)$$

$$P = \frac{de}{dt} = LI \frac{dI}{dt} = vI \quad (3.2)$$

In the above equations, I , L , and V represent the DC current, Inductance of the superconductor system, and voltage of the coil, respectively. According to the above formulas, the stored energy in the magnetic field is directly related to the inductance of the coil and the DC current passing through it. Hence, by increasing each one, the energy stored in the coil can be increased. SMES unit is connected to the AC grid in system or grid-connected ABs through a DC/AC power conditioning system. There are two common methods to connect the SMES to the network. In the first one, the current source converter (CSC) could be utilized. The voltage source converter (VSC) could also be utilized as the second method. However, it should be considered that in the VSC manner, the usage of DC-DC chopper is also necessary. The price of SMES depends on two independent factors. One is the cost of the stored energy capacity while the other is the cost of output power management. Costs associated with stored energy, include conductor construction cost, coil building elements, refrigeration tube, cooling system, protection, and control equipment. The component and structure of a SMES unit are depicted in Figure 3.2 and Figure 3.3 **Error! Reference source not found.**, respectively. The costs of output power management include the cost of design/build a power conditioning system.

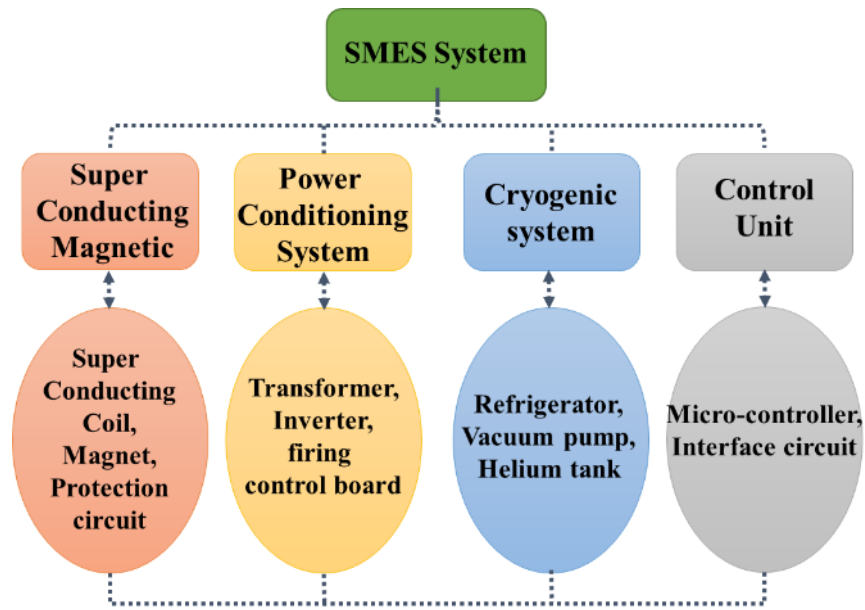


Figure 3.2. Component of a SMES unit

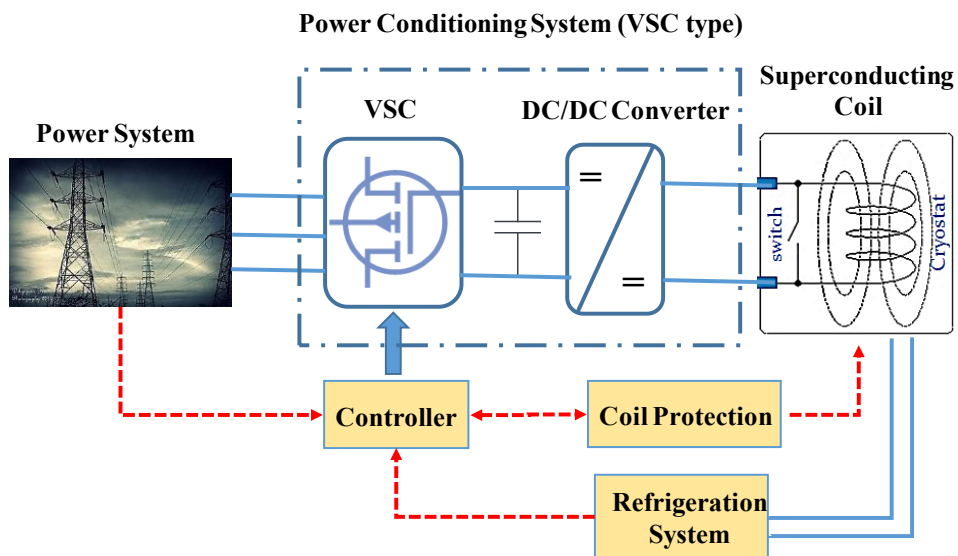


Figure 3.3. Structure of SMES system

It has high accessibility and can provide a lot of energy in milliseconds with an efficiency about 95-98% [12]. The low energy density of the SMES unit is one important drawback of this storage type. Due to its structure requirements, it could be somewhat difficult to use it for large-scale applications. Therefore, a combination of SMES to another storage such as the battery was proposed as an option.

3.2.1.2 Super Capacitor

Capacitors are the well-known devices to store electrical energy. They have fast-response characteristics, long life cycles up to thousands of times, and high efficiency. Due to the low energy

density, high self-discharge rate of conventional capacitors, and to fill the gap between these equipment and conventional batteries, the concept of SCs have arisen. SC is also known as electric double-layer capacitors (ELDC) or ultra-capacitors (UC). The principles of operation of SC and ordinary capacitors are similar. However, in SCs instead of conventional dielectrics such as ceramics, polymer films, etc., an electrolytic physical barrier consisting of activated carbon is used. This means SC including two porous electrodes, usually made up of activated carbon plunge in an electrolyte dilution. The introduced structure effectively makes two capacitors, one at each carbon electrode, connected in series. This ion conduction increases the energy density of the SC [13]. Therefore, the SCs can have the characteristics of conventional capacitors as well as electrochemical batteries at the same time. Due to the low energy density of the capacitors, they can store or inject high currents only for very short time intervals [14]. The maximum operating voltage of the capacitor depends on the insulation endurance of its dielectric. The construction of the individual cell of a SC is shown in Figure 3.4. The physical principles of the capacitors are illustrated as follows:

$$C = \epsilon \frac{A}{d} \quad (3.3)$$

$$E = \frac{1}{2} cv^2 \quad (3.4)$$

Where, C , A , d , E , and ϵ represent capacity, the area of the plates, the distance between two plates, energy, and dielectric constant of capacitor, respectively. As in the previous formulas, the amount of stored energy is proportional to the capacitance C and the square of the voltage V across capacitor terminals. The area of the plates and the thickness of electrodes are higher while the distance between electrodes are lower in SCs than traditional capacitors [15].

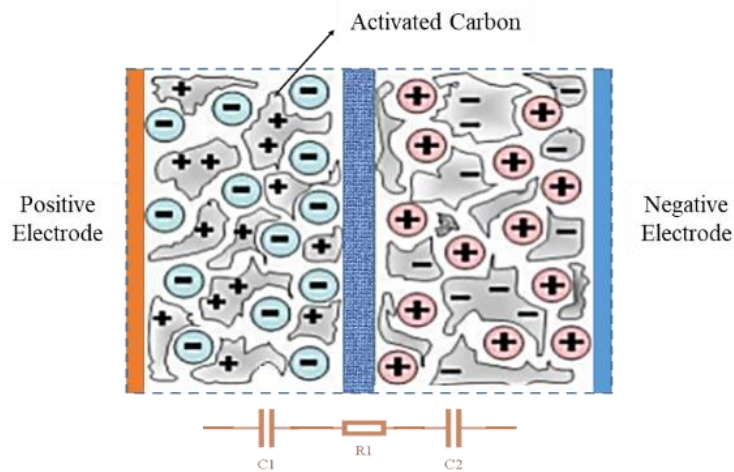


Figure 3.4. Construction of individual cell of a SC

The main application of traditional DC capacitors in distribution systems, in form of large-scale storage, is in dynamic voltage restorer (DVR). DVR is a FACTS device that is used for temporary voltage sag mitigation. SCs are mostly deployed for a specific situation that several charge/ discharge cycles and instantaneous high-power output are needed, e.g. power smoothing and power quality related services [16].

3.2.2 Electrochemical Storage Systems

Electrochemical energy storages transmute chemical energy to electrical energy. At least two reaction parts participate in a chemical procedure during this conversion. The obtained energy from this reaction is accessible as an electric current at a specified voltage. Electrochemical storages can generally be categorized into primary and secondary classification according to their principle of operation. The primary battery is usually not rechargeable. The second type of battery energy storage categorization reclassifies different kinds of rechargeable batteries. Each cell of this storage has three main components including negative and positive electrodes along with an electrolyte. The main factors for the application of battery energy storage systems (BESS) are high energy density, high-energy capability, consecutive charge/discharge ability, longevity, and primary cost. Electrochemical storages can be classified as conventional, advanced, and flow batteries.

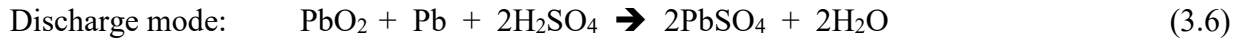
3.2.2.1 Conventional Batteries

3.2.2.1.1 Lead-Acid Battery (Pb-Acid)

Lead-acid batteries were invented by Gaston Planté in 1859 and they have been used for 150 years [17]. They are the most inexpensive energy storage of all the available battery technologies. However, the limited cycling capability of them is an undesirable factor in the economic view of the power network. Lead-acid battery includes lead metal and lead oxide electrodes, and sulfuric acid dilution.

In discharging state, both the positive and negative plates are converted to lead sulfate. The electrolyte then loses most of the dissolved sulfur and converts mainly to water. At full charge mode, the negative plate contains lead, and the positive plate contains lead dioxide. In this case, the electrolyte has a high concentration of sulfuric acid, which stored chemical energy. It should be noted that, since the electrolysis of water will produce oxygen and hydrogen, overcharging with high voltage, causes electrolyte water loss. The following chemical reactions occur at the anode/cathode during the charge/discharge process. These reactions are exactly opposite in charge and discharge mode and are shown in (3.5) and (3.6), respectively.





The Valve Regulated Lead Acid (VRLA) battery is a special type of lead-acid battery that have special advantages over ordinary acid batteries, which makes them easier to use. These batteries do not need to add acid or distilled water, are completely closed, and do not require any vents. It can also be placed in any position (i.e. vertical, horizontal, and inverted). They are also commonly known as sealed batteries or maintenance-free batteries. In order to mathematically model lead-acid batteries, an equivalent nonlinear Thevenin-based circuit is proposed. This model is shown in Figure 3.5 [8]. In this model, R_C and R_D represent the charge and discharge resistance that the battery current encounters them, and C illustrates the capacitive effect of the battery.

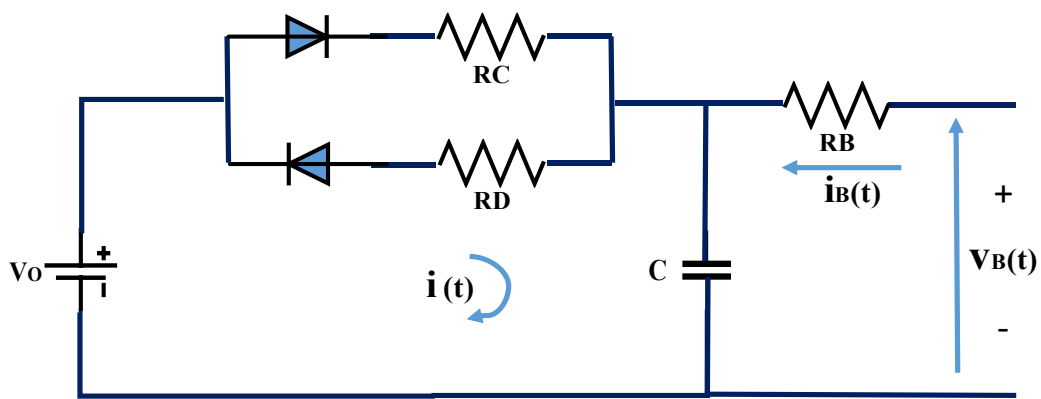


Figure 3.5. Equivalent nonlinear Thevenin-based circuit of Lead-Acid battery

The schematic diagram of Lead-Acid battery principle operation could be seen in Figure 3.6.

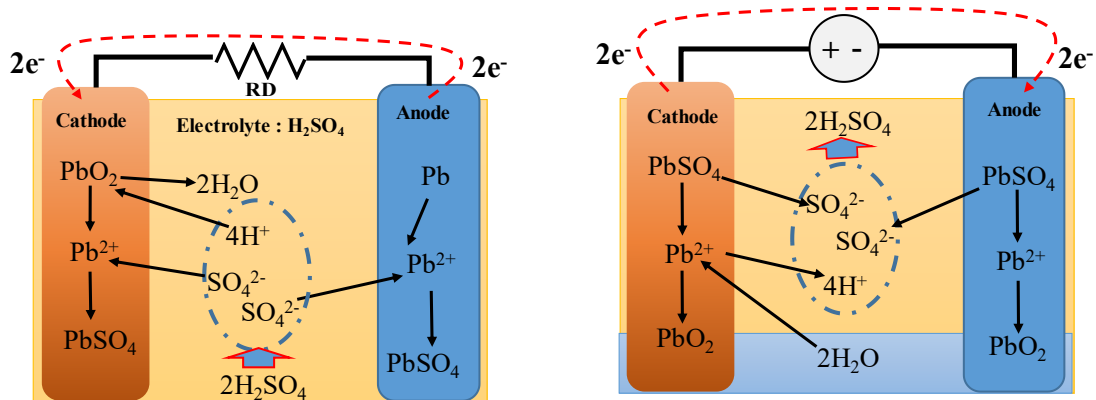


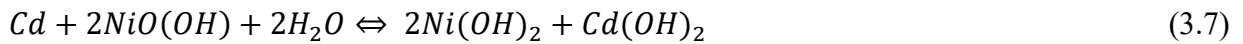
Figure 3.6. Schematic diagram of Lead-Acid battery's principle operation

One of the best features of this battery is longer storing capability due to its low self-discharge rate. Lead-acid batteries are used for starter device in motor vehicles, and usually applied for emergency power supply, renewables in energy communities such as wind turbine units and photovoltaic systems, and for grid-scale integration. This is caused by their safety, temperature

endurance, and low cost. The VRLA batteries have low initial cost, fast charge ability, high power density, and also low maintenance mostly used for electric vehicles (EVs) applications [18].

3.2.2.1.2 Nickel-Cadmium (NiCd)

In the Nickel-based storages, nickel hydroxide is used for positive plate and various negative plate materials, in which according to the negative electrode, there are several types of nickel-based batteries such as Ni-Cd and Ni-MH, etc. The electrolyte of these batteries is potassium hydroxide. Equation (3.7) illustrates the chemical reactions occur at anode/cathode during the charge/discharge process in a Ni-Cd battery.



The schematic diagram of Ni-Cd battery principle operation is also depicted in Figure 3.7.

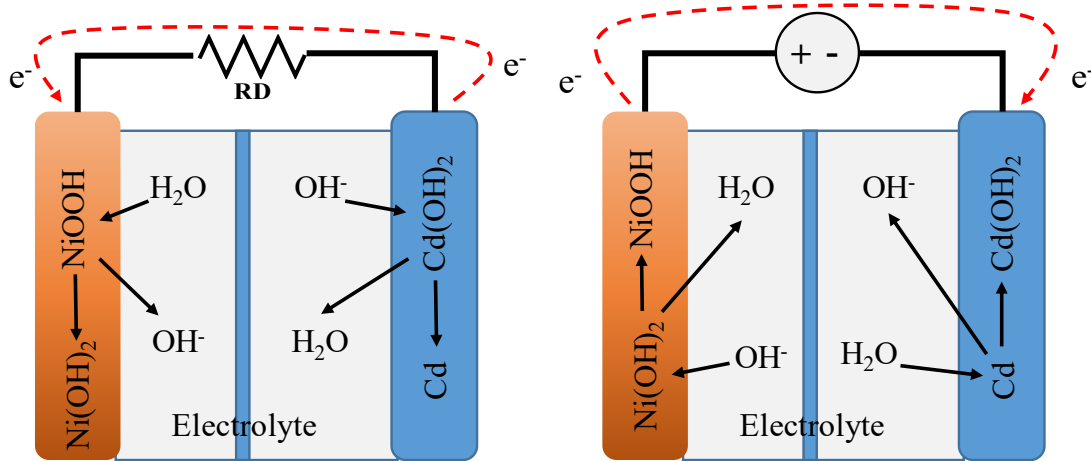


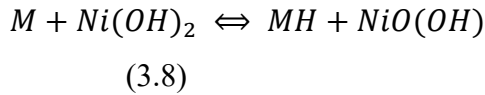
Figure 3.7. Schematic diagram of Ni-Cd battery principle operation

In this battery type, the alkaline electrolyte unlike lead-acid battery is not consumed in its chemical reaction. Therefore, its electrolyte gravity is almost constant and cannot be used to determine the state of charge. The advantages of Ni-Cd batteries such as high energy density, reliability and less maintenance make them more popular for power system applications, portable instrument, industrial UPS, telecommunication, etc. The disadvantages of Ni-Cd batteries are environmental issues due to the toxic feature of Cadmium and Nickel, memory effect, and capacity reduction during repeatedly recharging after several insignificant discharges [19].

3.2.2.1.3 Nickel Metal Hydride (NiMH)

NiMH batteries are a type of Ni-Cd battery that has been developed to improve its characteristics. The NiMH battery was patented in 1986 by Stanford Ovshinsky while researching hydrogen storage materials. In order to become more environmentally friendly, cadmium was eliminated from their electrodes. As mentioned earlier, in the Nickel-metal Hydride (NiMH) battery, a hydrogen-

absorbing alloy is used in place of cadmium. Contrary to Ni-Cd storages, NiMH batteries have lower memory and environmental effect. Ni-MH batteries are maintenance-free. Therefore, these benefits show that the Ni-MH batteries are more applicable than Ni-Cd storages to use in EVs [20, 21]. The schematic diagram of Ni-MH battery principle operation Figure 3.8. The overall reaction of Ni-MH batteries is as in (3.8):



Where M is an intermetallic alloy that forms a metal hydride phase.

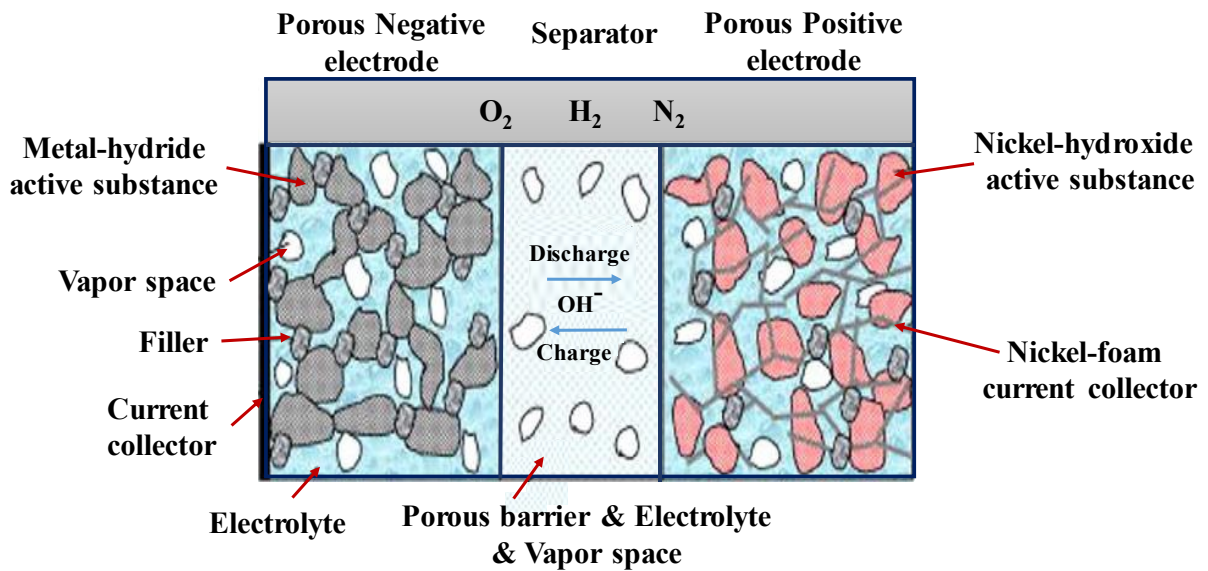


Figure 3.8. Schematic of Ni-MH battery's principle operation

3.2.2.2 Advanced Batteries

3.2.2.2.1 Lithium-Ion (Li-ion)

In Li-ion batteries, the positive electrode anode is made of lithiated metal oxide, and the negative electrode is made of graphitic carbon with a layering structure. Since the Lithium element is extremely reactive, the Li-ion batteries do not utilize elemental lithium. Instead, they typically contain lithium-metal oxide, such as lithium cobalt oxide (LiCoO₂), which means Li-ion batteries provide power through the movement of ions.

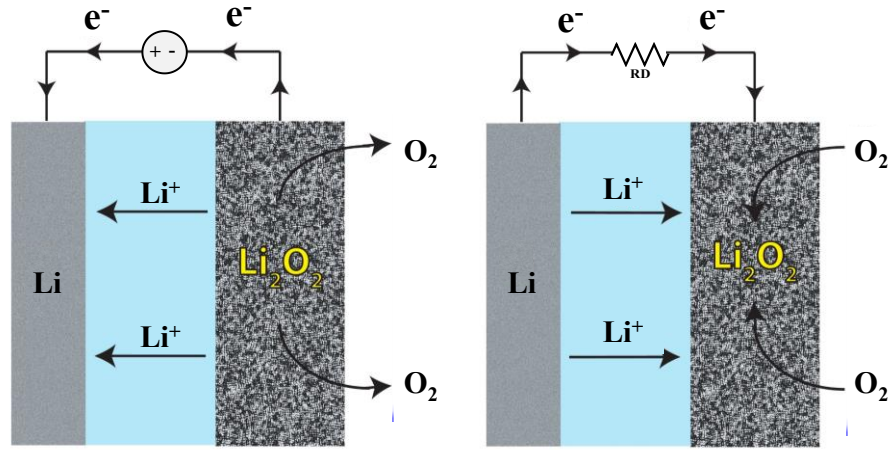
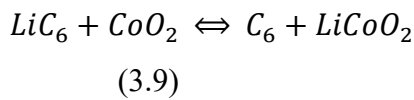


Figure 3.9. Schematic diagram of Li-ion battery's principle operation

The performed electrochemical reaction in this storage is as in (3.9):



As depicted in Figure 3.9, in discharge mode, Li^+ transfer from the cathode electrolyte to anode ones, and during its processes, the lithium atoms formed. In the charge mode, a reverse reaction is executed. This type of batteries has high energy/power density as well. Hence, Li-ion batteries are widely used in mobile electronic equipment, such as cell phones and EVs.

3.2.2.2.2 Sodium Sulphur (NaS)

Molten salt technology is used in NaS batteries. The negative and positive plate consists of molten sodium and molten sulfur, respectively. Moreover, solid ceramic sodium alumina is used as the electrolyte. The performed reaction inside these batteries is as in (3.10):



To ensure the molten status of the negative and positive plate of NaS, a temperature around 574–624 °K is required. The acceptable features of NaS batteries can be considered as following:

- It has partly high energy densities and higher capacity
- The daily self-discharge rate of this battery is nil.
- The utilized material is not toxic and expensive.
- The main disadvantage of this type of secondary battery is its operating temperature and the requirement of an extra sensing system to ensure its operating temperature.

3.2.2.3 Flow Batteries

3.2.2.3.1 Redox-Flow Battery (RFB)

In RFBs, similar to other types of batteries, materials react in reversible chemical reactions during energy conversion. Flow Batteries (FB) store energy in active electricity Species. Electrically active species are dissolved in the fluid electrolytes in tanks. Converting chemical energy to electrical energy is performed by pumping the liquid by the electrochemical cell. RFB is one type of these batteries. The most important feature of FB is that its power rating and capacity are not dependent to each other [12]. This means that the power rating is determined by the active region of the cell stack while the capacity is determined by the volume of dilution of electrolytes. RFBs demonstrate a long life cycle, stability, high output efficiency, and energy flexibility that all lead RFBs to become more popular to apply in any standalone networks such as microgrids and energy communities [22]. As shown in Figure 3.10, the two liquid electrolytes are pumped toward the reverse sides of the cell with dissolved metal ions. This storage has a lifetime of around 15-20 years and it can discharge for 4-10 hours. The efficiency of FBs is about 60-70 % [23].

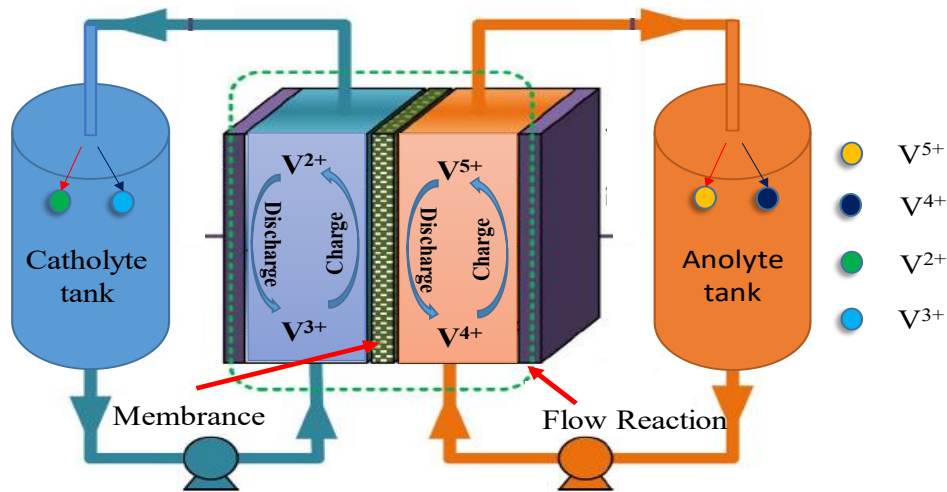


Figure 3.10. Schematic diagram of Vanadium redox flow battery principle operation

3.3 Electric Vehicles

Totally, there are several types of EVs utilized by occupants of buildings. These vehicles include Battery-based EVs, Internal combustion engine/electric hybrid vehicle, solar-powered vehicles, flywheels, or SCs based EV and fuel cell-based EVs [24]. Some EVs type is depicted in Figure 3.11.

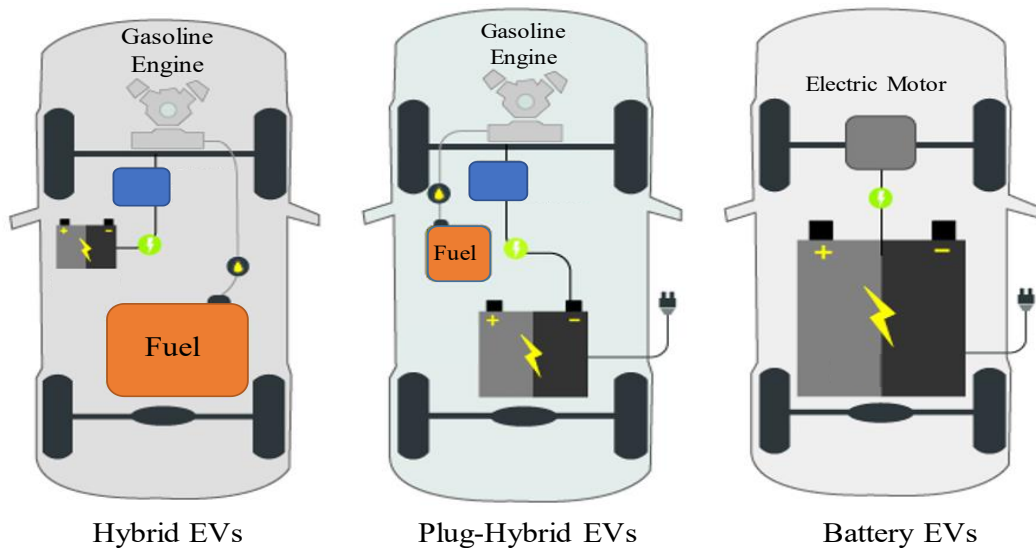


Figure 3.11. Different types of EV

In an active distribution network, distributed energy resources play important roles in providing the required energy and flexibility to the grid. Solar panels, wind turbines, and grid-connected EVs of the building are some examples of DERs. In recent decades, due to environmental benefits as well as advances in energy storage technology, a tendency to the high utilization of EVs has increased. However, an increase in the number of EVs and their uncertain charging behavior can also result in some issues in the electrical grid. For this reason, the use of these vehicles has an enormous impact on the load curve, performance, and design of the power system [25-27]. Recent studies demonstrate that drivers use their car for only around 2 hours during the day and for the rest of it, the car is in the building's parking. Thus, the long presence of EVs in the building can help the energy management system to schedule charging/discharging the EVs in a more efficient way. For example, if these cars have the ability to inject energy back to the grid (V2G), the energy stored in their batteries can be used to reduce peak power and provide other auxiliary services to the grid [28-30]. In this way, not only the grid flexibility requirements can be satisfied. However, the building can also enjoy the monetary benefits of providing services. It is worth mentioning that considering the parameters of reducing battery life, the use of EVs in frequency control will be more profitable for car owners than using them to reduce the peak [31].

Regarding active network management, the main aim of the contribution of EVs to the grid service provision is minimizing costs and improving network reliability. In this regard, the use of EVs with network connection ability in smart grids will reduce network dependency on large-scale expensive units. Since the number of EVs as small-scale generation units is great and they are located at different nodes of distribution networks they can highly participate in providing energy and

flexibility. However, due to a huge number of these vehicles, the problem of optimizing their application will be more complicated [32-34]. Therefore, the management of these resources in distribution networks is of vital necessity. The optimal (charging/discharging) scheduling of these vehicles can also assist islanded microgrid with its required energy and flexibility. In addition, adaptive charging/discharging EVs is one of the important factors facilitating active distribution management of distribution networks. Nevertheless, the preference of the owner needs to be taken into account when determining the EV's charging/discharging schedules. In addition, the owner must be compensated sufficiently if the EV was supporting the grid through the provision of flexibility services.

3.4 Comparison of Energy Storages in ABs

It is obvious that the efficient operation of network requires different types of storage-based resources. In addition, each building can be equipped with different kinds of storage-based resources. At present, each type of energy storage technology has its specific advantages and disadvantages to use in an active distribution network and microgrids. Several criteria can affect choosing energy storage for a specific application. Some of them are mentioned as follows:

- Power rating
- Lifetime
- Response time
- Cost
- Memory effects
- Self-discharge
- Environmental impact, etc.

A comparison of power and energy density of various types of ESS is also depicted in Figure 3.12. According to this figure, in case of high power and high energy density for a specific amount of energy, the total required storage volume is reduced.

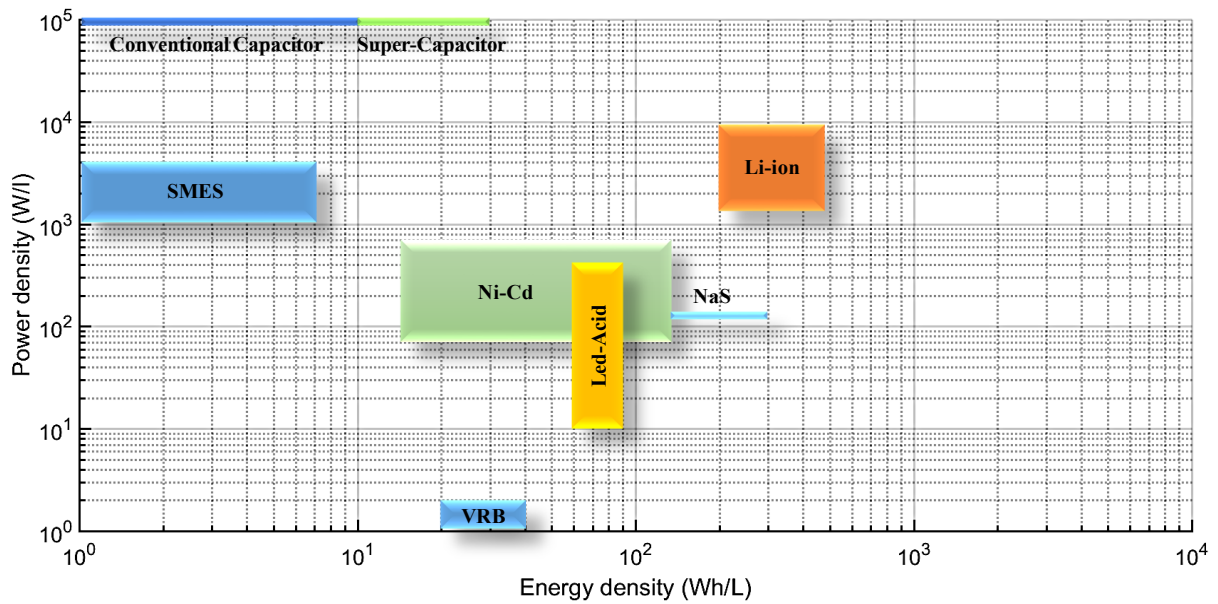


Figure 3.12. Comparison of energy storages in term of power and energy density

Although the application of energy storages in grid scale, microgrids and AB scale are almost the same, there are still apparent differences between these applications. The application of ESS in the grid-scale aims to optimize energy consumption, provide flexibility through time-shifting, peak shaving, and renewable energy resources integration in a low and medium voltage scale [35]. Besides, the energy storage type used for the grid-scale applications can be classified based on their operational power rate. For instance, mechanical storages such as pumped hydro and compressed air storages are mostly used in large-scale cases. On the other hand, regarding medium and small-scale power rating, flow battery and conventional battery (in large-scale) are generally used. Despite the recent development of energy storage technology such as SMES and Super-capacitor, they have not received much attention in grid-scale application yet due to their high costs [14].

The main goal of energy storage integration into the microgrids and active distribution networks (through ABs), can consist of power quality (PQ) improvement, stability issues, enhancing the hosting capacity of RES [36], etc. A wide range of applications in grid-scale applications has led to the possibility of utilizing various types of energy storage technologies. For instance, regarding maintaining PQ, the ESS technology with very fast response (in *ms* time intervals) is needed. As can be seen in Figure 3.11, SMES, capacitors, super-capacitors, and also conventional batteries are suitable for power quality applications [37].

Due to the stochastic feature of renewable energy resources such as wind and solar, they have fluctuations in their output power that can cause several problems for the grid. Application of EES, in this case, can overcome some of those problems, and can increase the maximum hosting capacity

of the network. For instance, the device could store power at off-peak hours and inject it back to the grid during peak moments. In addition, the intermittent production of RES can be smoothed and stabilized by using EES [38]. In this case, several ESS technologies can be deployed including Ni-cd and Lead-Acid batteries and super-capacitors. However, it seems that the use of hybrid energy storage is more suitable especially for power fluctuation compensation. Using hybrid energy storage can increase the lifetime of each energy storage device. It is possible to utilize a combination of ESS disregarding different types of storages. For instance, by combining battery storage and SC relatively high capacity and high energy density can be obtained.

Another important proposed application for energy storage is for balancing between production and load demand in real-time. In this regard, ESS can help the system stay reliable and stable. This application of EES is highly helpful especially for microgrids with high penetration of intermittent RESs, and uncertain loads. EES also can also be used for black-start applications. It means they can help the system to startup from a black-shutdown without catching high power from the main grid. FBs and conventional batteries can be more suitable for this application [39, 40].

On the other hand, by increasing the installation of highly sensitive electric equipment in the distribution system that is very sensitive to the power outage, the necessity of EES application becomes more important. In this way, power bridging with ESS maintains supplying sensitive equipment or grid during the transition period. Therefore, the deployed energy storage devices must have a moderate power rating and response time ranges, between 100 kW to 10MW and around 1 second, respectively. Conventional and FBs are proper for this type of application because they have an approximately fast response and almost long discharge time (up to several hours) [41, 42].

Regarding building-scale applications, consider the case in which the building is not responsible for providing any flexibility services to the grid. In this situation, the building mostly utilizes the ESS to increase its self-sufficiency. However, a cost-benefit analyze should be performed in order to assess the profitability of the ESS. In other words, the ESS should bring monetary profits for the building in order to cover its capital and installation cost. A comprehensive technical comparison of different types of EES from several aspects is gathered in Table 3.1.

Table 3.1. Electrical energy storages' technologies

Type	Year	Power Rating (MW)	Power Density (kW/m ³)	Energy Density (kWh/m ³)	Life Time (cycle)	Response Time	Self Discharge (%/ day)	Operating Temp. (°C)	Discharge Time
Pb-acid	1859	<70	90–700	75	2000	ms	0.1–0.3	+25	s – 3h
Ni-Cd	1899	<40	75–700	<200	1500	ms	0.2–0.6	-40 to +45	s – h
NaS	1960	0.5–50	120–160	<400	2000 – 45000	ms	20	+300	s – h
Ni-MH	1967	10–6–0.2	500–3000	<350	300–500	ms	0.4–1.2	-20 to +45	hour
SMES	1969	0.01–10	2600	6	10000	ms	10–15	-270 to -140	ms – 5min
SC	1978	0.01–1	(4-12) ×10 ⁴	10–20	>5×10 ⁵	ms	2–40	-40 to +85	ms – 1h
V-redox	1984	0.03–7	250–270	20–35	>13000	<1ms	0–10	0 to +40	s – 10h
Li-ion	1985	0.1–5	1300–10 ⁴	250–620	>4000	ms – s	0.1–0.3	-10 to +50	min – h

3.5 Summary and Conclusion

By changing the structure of traditional electrical networks to active networks, the role of ESSs has been highlighted. There are several types of currently accessible energy storage including TES, EES, MES, etc. This chapter provides a comprehensive overview of the main features of EES and EV, their technologies, and their various applications regarding the active electrical network. Electrical ESS is regarded as a promising solution to deal with variable/uncertain renewables. The ESSs act as key elements of the grid that contribute to creating a more reliable and flexible power system. By having a rapid bi-directional flow capability, ESSs can rapidly smooth the fluctuations in both over-frequency and under-frequency situations. Moreover, ESSs have a rapid response to unexpected variations, which is crucial for the system's stability. Different types of EESs presented in this chapter with their characteristics have several value functions for the grid as well as demand-side ABs such as (1) helping to meet required peak load, (2) balancing between generation and demand, (3) power quality/reliability improvement, (4) supplying isolated loads, (5) reducing the total cost. Furthermore, deploying EVs can create many potential opportunities for active distribution management such as vehicle-to-grid technology, which can also support RESs integration.

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