Hybrid Energy Storage Systems: A Brief Overview

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Abstract. In this paper, a brief overview on the Hybrid Energy Storage Systems (HESSs) is provided. In literature, different architectures are chosen to realize the HESSs, and they are based on the principal aim of the HESSs employment. In this paper, the most used HESS topologies are presented, with particular attention to the active, passive and semiactive topologies, highlighting their characteristics. To have a complete schematic idea of the HESSs application, a focus on the principal sizing methodologies is provided, distinguishing the conventional approaches and the advanced ones, exploiting their main applications. Together with a proper sizing, a correct power-sharing strategy is one of the HESSs key points. For this reason, several control strategies are described, focusing on the energy management control and on the underlying control.

Keywords: Hybrid energy storage system · Sizing · Control

1 Introduction

The transition to a low-carbon and green economy includes the goals of a 40% reduction in greenhouse gas emissions, 32% of consumption provided by Renewable Energy Sources (RES) and a 32.5% improvement in energy efficiency [1, 2]. In order to achieve these objectives, the development of power generation systems from non-programmable renewable sources, such as eolic and photo-voltaic (PV), will be of fundamental importance. Thanks to incentive policies and technological developments, the price of renewable technologies has been significantly reduced in recent years [3, 4], with an 80% reduction for PV panels between 2009 and 2015, and a 30–40% reduction for wind turbines in the same period. The typical generation prole of the PV panel repeats daily, with a peak around noon and minimum values during the darkest hours. In addition, cloudiness can cause sudden changes in power generation within a few minutes, posing a challenge for balancing the power grid. In the case of wind-based generation, fluctuations in the produced energy usually affect longer periods, typically days or weeks. However, these fluctuations must be balanced by the power grid. In this scenario, energy storage systems can be a turning point. The use of such systems can lead to:

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- Improved network management
- Speed of reaction in case of rapid power loss or power surges
- Interfacing of different grid elements for cost-effective balancing of RES over different time windows.

In automotive and grid connected applications, the Energy Storage Systems (ESSs) usually experiences irregular and frequent discharging/charging pattern which truncates the ESS lifespan; therefore, the replacement cost of the ESS increases significantly. High energy density storage technologies such as batteries and fuel cells have limited power capability. On the other hand, high power density technologies such as supercapacitors or flywheels have limited energy storage capability. The drawback of each technology can be overcome with the so-called Hybrid Energy Storage Systems (HESSs). Depending on the purpose of the hybridization, different energy storages can be used as a HESS. Generally, the HESS consists of high-power storage (HPS) and high-energy storage (HES) where the HPS absorbs or delivers the transient and peak power while the HES meets the long-term energy demand. HESSs provide many benefits: improving the total system efficiency, reducing the system cost, and prolonging the lifespan of the ESS. Due to the various types of energy storage technologies with different characteristics, a wide range of energy storage hybridization can be realized.

Figure 1 shows an example HESS that is composed of batteries (high specific energy storage) and supercapacitors (high specific power storage), and three possible power flow management strategies. Figure 1 (a) shows the case of high-power demand from the load. Both energy storage sources supply power to the load. Figure 1 (b) shows the case of low power demand. The battery supplies power both to the load (continuous arrow) and the supercapacitors (dashed arrow). Figure 1 (c) shows the case of negative power. The peak power is absorbed by the supercapacitors, the remaining power can be supplied to the batteries.

2 HESS Topologies

Based on the nature and on the dynamics of the power sources composing the HESSs, different architectural structures can be realizable. The choice of the proper one principally depends on the HESS purpose of use and on the control strategies. Principally, depending on the connection of the different sources to the system, three main classes can be defined: passive, semi-active and active topologies.

2.1 Passive Topology

The passive HESSs interface the different storage systems directly, without using additional converters. The terminal voltage of the sources is not regulated and the power flow management is addressed only by the source's internal resistance and voltage-current characteristic.

The main advantages are related to the ease of implementation and the cost effectiveness, while the main disadvantage is related to the limited power split management [5]. A structure of a passive HESS is shown in Fig. 2 (a).

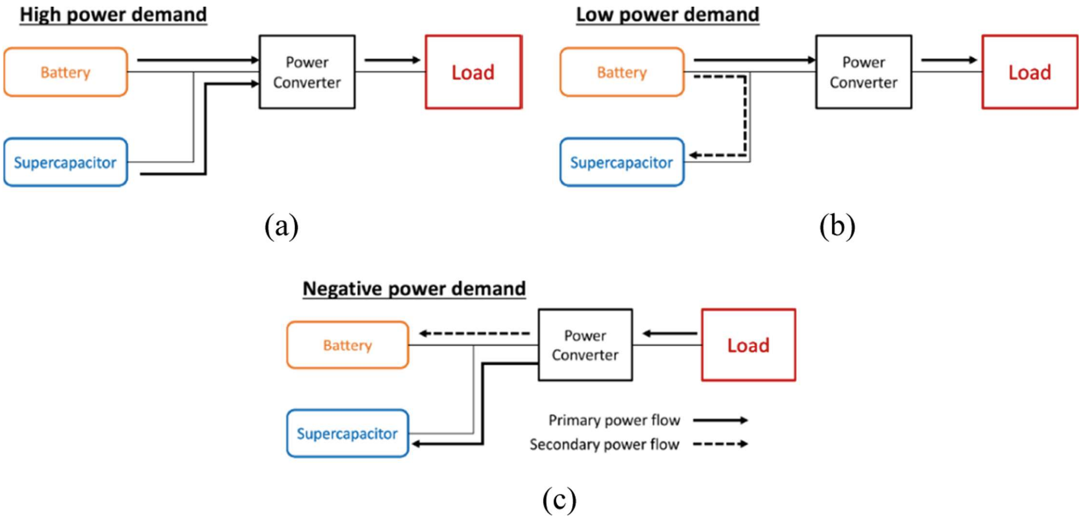


Fig. 1. Hybrid energy storage system power flow in case of (a) high power demand, (b) low power demand, (c) negative power demand.

2.2 Semi-active Topology

The semi-active topology provides for the employment of a DC/DC converter able to control one of the sources, as depicted in Fig. 2 (b). In this case, even if the power flow management is improved, extra space is needed and, if compared to the passive ones, costs are higher. In most cases, the sources to be controlled by the DC/DC converter are chosen based on their dynamics [6]. In particular, the high energy density sources are preferred, in order to facilitate the power delivery during the fast transients and the reverse power flow through the high-power density sources connected directly to the load.

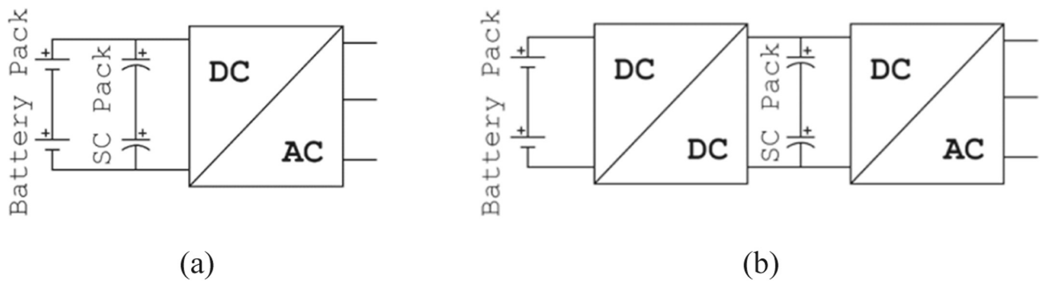
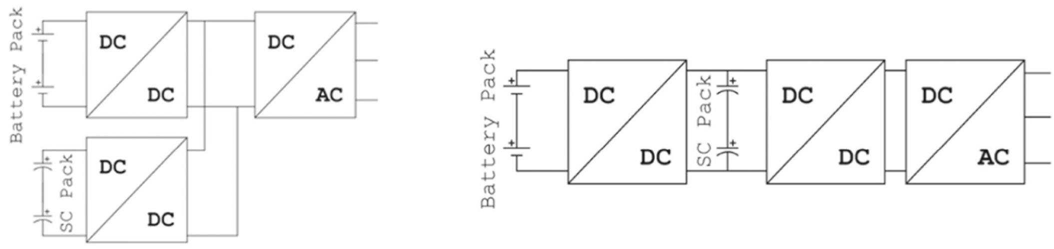


Fig. 2. (a) Structure of a passive HESS. (b) Structure of a semiactive HESS.

2.3 Active Topology

In this topology, each energy source is connected to the system through a power converter. In particular, two main configurations are available in literature: parallel and cascade, on the base of the chosen control method as reported respectively in Fig. 3 (a) and (b). At the expense of a lower efficiency and higher cost, the active HESSs allow for an accurate power flow management [7]. In Fig. 4, a synoptic diagram is shown with the aim of comparing the three different presented topologies.



(a) (b)

Fig. 3. Structure of an active HESS: (a) parallel, (b) cascade.

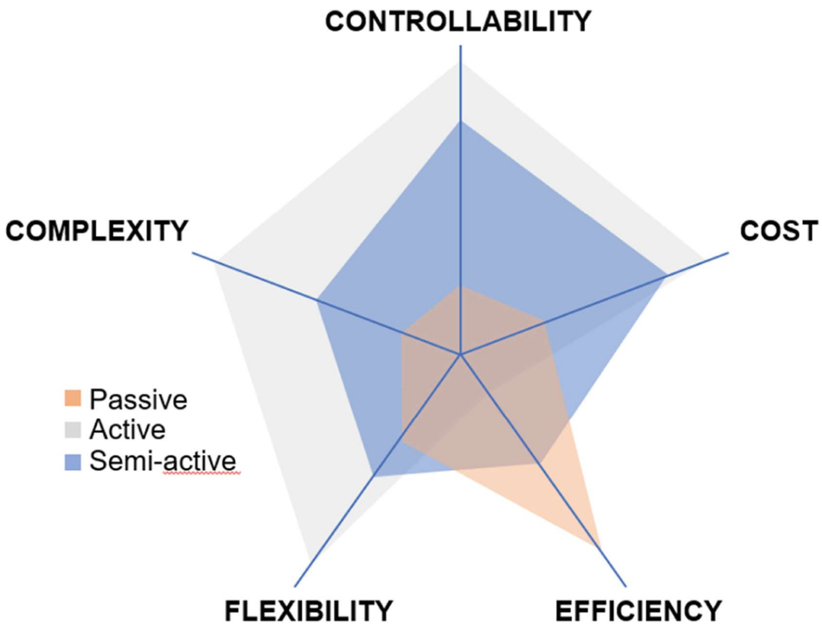


Fig. 4. Comparison between HESSs topologies.

3 Sizing Methodologies

Literature shows different methodologies for the proper sizing of the energy sources composing the HESSs. Different approaches are presented in literature, they can be divided into two main classes: conventional and advanced methods.

3.1 Conventional Methods

Among the conventional methods, the analytic approach is one of the most used, it is based on analyzing a series of operational configurations by varying the elements of the system to be optimized, such as cost, volume and weight of the energy sources, cost and size of the power converters and systems stability [8]. Besides, a probabilistic method can be used, it is preferred for the Renewable HESS for which the uncertainty of the renewable source must be taken into the account [9]. For this reason, they are mainly used for the grid-connected applications, and they are based on the simultaneous analysis of the load conditions and the energy generation probabilistic distribution.

3.2 Advanced Methods

The advanced methods are mainly based on the resolution of non-linear problems. They allow for an accurate sizing at the expense of a high computational effort. One of the most employed approaches is the Particle Swarm Optimization Method [10]. It is based on a multi-objective optimization analysis for which the energy sources sizing is carried out through the definition of cost function to be minimized. They are mostly employed for the automotive application, for which different aspects such as the storage weight and life-time are relevant. Other advanced methods are based on Pinch Analysis and they are used mostly for the smart-grid applications.

4 Control Strategies

One of the main issues of a HESS is to design and implement a suitable control system. The choice of the control method depends on several factors: the reason for using the HESS (life extension, power quality, cost minimization, volume, weight), the speed of response and the hybridization architecture. To achieve safe, stable and efficient operation, HESSs need a power-split (or power-sharing) strategy. Generally, the management and control system of a HESS can be divided into two parts: energy management control and underlying control.

4.1 Energy Management Control

The goal of the energy management control is the power allocation among the different sources composing the HESS. Depending on the scope of the power-split strategy, different approaches are proposed in literature. They can be divided into two main categories: classical and intelligent controls. For both the categories, the output of the employed algorithm is the reference power of the HESS. The latter is than employed as the input of the underlying control to effectively act on the power converters. Among the classical controls, the filtering-based one is one of the most used. This control method is based on applying a filter (e.g., lowpass, moving average) to the power profile required by the load [11]. In particular, the control acts in order to split the power profile into as many components as there are the HESS sources. The low-frequency components are than imposed as a reference to the low-dynamic high energy density sources (e.g., fuel cells, batteries), while the high-frequency components are given as a reference to the high-dynamic high power density sources (e.g., SCs).

In order to take into the account, the system parameters (e.g., SoC, maximum delivered current, temperature), a rule-based control can be used [12]. It is based on the definition of a set of constraints related to the HESS source parameters (e.g., SoC, maximum current, temperature) and a set of deterministic rules, then the power to be delivered by each source is obtained by the simultaneous check of the employed rules. The classical controls are characterized by their ease of implementation, but most of them are designed to be performed online. In order to have a real-time control, advanced methodologies can be employed. Among them, the Sliding Mode Control [13] and the Model Predictive Control are the most used [14].

4.2 Underlying Control

The reference power, given as an output of the energy management control, has to be effectively employed to act on the power converters. Among the different control methods, the most used are the PI control [15], the non-linear control and the fuzzy logic control.

5 Conclusions

In terms of power and energy, a single nature ESS cannot satisfy all an application's needs. Additionally, most applications require both quick reaction times and lengthy discharge times, allowing for the provision of energy for periods ranging from minutes to days. HESSs, which combine two or more ESS technologies, are a desirable option for satisfying these needs since they even allow for a decrease in the system's total cost and lifespan. This paper analyzed the feasibility of the HESSs. It focused the different topologies mainly employed in the literature and it also provided a brief overview of the capacity sizing of the energy sources composing the HESSs. Different control strategies have been described. As an added value, this paper helps to have a brief schematic idea about the principal challenges in the field of the storage systems.

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