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Original articles

Direct sizing and characterization of Energy Storage Systems in the Energy-Power plane

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Abstract

This paper presents an original sizing method for Energy Storage Systems (ESS) based on directly matching their capabilities – as specified by their energy-power Safe Operation Area (SOA) in the Energy-Power (EP) plane – with the energy and power demand required to accomplish their missions. Starting from the system requirements and from an energy management strategy, the power demanded by a set of representative operating scenarios and its associated energy are calculated and represented as trajectories in the EP plane. The objective is to size the ESS such as its SOA contains these trajectories. Comparison between different technologies of Energy Storage Devices (ESDs) is possible using this SOA characterization. Special attention should be paid to compare specific SOAs across devices. Diverse energy management strategies can be synthesized in the EP plane where they can be compared and analyzed. The sizing method converges extremely fast and is suitable for its integration in an optimization loop. The method allows to determine directly and efficiently the technology and the size most appropriate (in terms of indicators such as mass or cost) to a given EP demand. In the paper, three different technologies (SuperCapacitor, Li-Ion and H_2/O_2 batteries) are characterized and compared in terms of sizing synthesis.

Keywords: Energy storage systems; Sizing method; Energy vs power characterization

1. Introduction

Energy Storage Systems (ESSs) are key elements in electrical systems especially in hybrid systems or smart grids. They allow for increased integration of renewable energy sources connected to the grid [18,24] as well as to increase reliability, stability and resilience of various systems [3,10,15,17,19]. There are several kinds of ESSs technologies such as: Pumped Hydro Storage, Compressed-Air Energy Storage, Battery Energy Storage (BES), Capacitor Storage, Super-Capacitor Energy Storage (SCES), Super-Conducting Magnetic Energy Storage, Thermal

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Energy Storage, Hydrogen Energy Storage (HES), and Flywheel Energy Storage. Each technology has its benefits and its drawbacks [9,11,19]

The ESS technology selection is a critical stage in a system development. In this aspect the Ragone plot [8,21] is a well-known graphical characterization tool that exhibits the storage types differences in terms of their specific-power and specific-energy. Many other aspects are characterizing such as efficiency, durability, reliability, response time or power vs energy capability [11,19]. According to the application these aspects can be decisive in the early stages of technology selection.

An ESS can be constituted by just one or many Energy Storage Devices (ESDs), in the latter case, of a unique or of diverse technologies. These two situations are defined here as single and hybrid-technology ESS. In this paper only single-technology ESS is considered. Normally, an ESS is composed of a certain number of ESDs. The ESS sizing consists mainly in finding this number of ESDs in order to fulfill the system requirements. There are several sizing methods of high computational-cost requiring multiple simulations, such as Brute Force, Genetic Algorithm [2,22], and Efficient Global Optimization [22].

One method commonly used to size ESS is the maximum power and energy demand method. This simple method consists in taking into account the power span and energy span separately and size the ESS to supply these energy and power [4,13]. But this may result in an over-sizing of the ESS as the method treats the power and energy demand in an uncorrelated way.

In [20] a SCES system is sized based on the constant power discharge over a maximum time interval. In [23] the EP capabilities are taken into account to validate the sizing of a SCES by comparing it with the energy and power demand in the EP plane.

The present work combines the ESD characterization and the complete demand profile in the EP plane in order to match them and directly obtain the ESS size able to satisfy this demand [6].

The first stage of this sizing method is to characterize each ESD according to its EP capabilities. These capabilities are calculated from the limits of the ESD-variables (such as voltage limits, current limits, and state of charge limits) within which the device is expected to operate safely and is represented in an Energy vs Power plane: a SOA (Safe Operating Area) is consequently defined for each ESD. The second stage is the synthesis of a demand profile. Starting from the system requirements and from an energy management strategy, the power demanded by a set of representative operating scenarios and the associated energy are calculated and represented as trajectories in the EP plane, constituting the Demanded Energy-Power Trajectory (DEPT). The third and last stage is to size the ESS such that its SOA contains the DEPT assuring that the EP capabilities of the ESS are not exceeded.

It is worth mentioning that stages 1 and 2 are independent, a change in one does not affect the other. E.g. if a new ESD is to be tested the DEPT does not need to be recalculated; even more if the SOA of this new ESD was already obtained from a previous analysis, only the last stage should be performed reducing the total calculation cost.

The SOA may also be defined in *specific EP plane* by considering *mass specific plane* (in Wh/kg vs W/kg), which is of interest for embedded systems, or *cost specific plane* (in Wh/$ vs W/$), especially for stationary applications. This allows a rapid comparison between ESD (either of the same or different technologies) and realizing which one is more effective in terms of power/energy per specifying parameter (mass, cost, etc.).

The remainder of this work is organized as follows: Section 2 shows the Energy vs Power characterization particularized for the 3 energy storage technologies considered (SCES, BES and HES). In Section 3 the demanded profile synthesis is analyzed. Section 4 deals with the sizing procedure. In Section 5 the results of applying this method in 2 case studies with numerical validation (and experimental for case study 2) are shown. Finally the main conclusions are summarized in Section 6.

2. Energy vs Power characterization of energy storage devices

ESDs can be characterized by their power capability which strongly depends on the State of Charge (SoC) and the safe operating limits of their variables, imposed by the manufacturer or also by the system designer.

Analogously to the commonly known voltage vs current Safe Operating Area,[1] the EP SOA (here after only SOA) of an ESD can be defined as the EP conditions over which the device can be expected to operate without self-damage.

[1] The power semiconductor devices Safe Operating Area is defined by the voltage and the current conditions over which the device can be expected to operate without self-damage [1].