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Theoretical dimensioning and sizing limits of hybrid energy storage systems

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HIGHLIGHTS

- A single energy storage can always be split into two hybrid energy storages.
- These hybrid storages have the same total energy and power as the single storage.
- The potential for storage hybridisation depends on the shape of the power profile.
- A higher potential allows a higher spread of the power/energy-ratios of the storages.
- Automobile and pulsed power applications are well suited for storage hybridisation.

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ABSTRACT

Aim of a storage hybridisation is a beneficial usage or combination of different storage technologies with various characteristics to downsize the overall system, decrease the costs or to increase the lifetime, system efficiency or performance. In this paper, the point of interest is a different ratio of power to energy (specific power) of two storages to create a hybrid energy storage system (HESS) with a resulting specific power that better matches the requirements of the application. The approach enables a downsizing of the overall system compared to a single storage system and consequently decreases costs. The paper presents a theoretical and analytical benchmark calculation that determines the maximum achievable hybridisation, i.e. possible spread in specific power, while retaining the original total energy and power capacities of an equivalent single storage system. The theory is independent from technology, topology, control strategy, and application and provides a unified view on hybrid energy storage systems. It serves as a pre-dimensioning tool and first step within a larger design process. Furthermore, it presents a general approach to choose storage combinations and to characterize the potential of an application for hybridisation. In this context, a Hybridisation Diagram is proposed and integral Hybridisation Parameters are introduced.

1. Introduction

To this date, electric energy storage systems are generally expensive. This creates the need for an effective utilisation of energy storages. Since all available storage technologies have differing characteristics regarding their power and energy density, specific power, response time, efficiency, self-discharge rate, cycle stability, life expectancy or aging behaviour, they come with different advantages or disadvantages and are therefore more or less suited for certain applications [1–3].

Within the field of HESS, it is tried to combine different storage technologies to generate a system with an increased performance regarding the aforementioned parameters. A common approach is to complement a high energy storage with slow response rate (e.g. a battery) with a high power storage with fast response rate (e.g. a super capacitor) [2]. This way, the power density and response rate of the system is increased. Moreover, the number of cycles and the stress induced by high transients can be reduced, leading in turn to a smaller size and longer life time compared to the battery-alone system, which also reduces costs [1,2].

To achieve this goal, a major research subject within the field of HESS is control, which addresses the distribution of power and energy between the storages. It includes filter-based, rule-based or model predictive control strategies as well as fuzzy controllers, neural networks or combinations of them [2]. Topological studies, including passive, semi-active, and active power electronics, are also common [2] and battery-supercapacitor combinations in automotive, regenerative power or pulsed load applications are widely investigated [2,4].

Most studies do not focus on dimensioning explicitly. It is rather only a consequence and not considered solely. The simultaneous

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treatment of control strategy, topology and dimensioning seems to be reasonable since they are all interdependent, yet, it blurs the view for a comprehensive system design. Either, dimensioning is made with an inherent control strategy [5–9], or generic global optimizations are performed [10–15] with the drawback of hiding the influence of the design variables. Moreover, simulations are carried out with detailed storage models, which makes the results less general and applicable to similar problems.

The aim of this paper is to provide a general top level view on HESS, allowing an investigation of the dimensioning problem independent of technology, control strategy, and application. From energetic considerations, every application has a inherent power and energy demand, and consequently a specific power. Storages seldomly fit this specific power, it is either too high or too low, which leads to an overdimensioning in power or energy capacity. This paper presents a theory that allows the combination of two storage technologies with varying specific powers to generate an HESS with a resulting specific power that lies in between and matches the requirements of the application, and in return reduces the size of the overall storage system. Afterwards, a beneficial mapping to existing storage technologies is easily possible. It is an analytical approach that solely considers the specific power by neglecting storage specific nonidealities such as system response times or cycle stability. By itself, it does not inherently improve any of these criteria. It is intended as a pre-dimensioning tool within a larger design process and subsequent analysis have to address the aforementioned issues.

The paper is structured as follows: First, a thorough description of the idea and its resulting insights are presented in Section 2. The underlying model is deferred to Section 3. Note, that this section is not obligatory for the understanding and usage of the theory and its results, and can be omitted from the users point of view. An expansion of the theory, which provides a mapping of the results to specific technologies and allows an economic investigation, is shown in Section 4. In Section 5, the theory is applied to two examples before the paper is concluded and summarized in Section 6.

2. General theory description

This section presents the idea, insights, limitations and value of the theory without a formal mathematical introduction. In this way, the purpose becomes clearer and the model and derivations presented in the following section can be understood more easily.

2.1. Idea and aim

For a given periodic power profile of the storage system, hereinafter referred to as signal, the required power capacity P_s and energy capacity E_s of a single storage can be determined easily. By neglecting losses and other nonidealities, the required power capacity P_s is the maximum of that signal and the required energy capacity E_s is the maximum of the integral of that signal. The signal must be handled by the storage system and the control strategy or energy management system is not allowed to dismiss provided or required power.

It is assumed that no storage exists that has the specific power required by these considerations. Therefore, the single storage, which acts as a reference shall now be split into two hybrid storages, namely a base and a peak storage. The power capacity of the base storage P_b is a fraction $\chi \in [0,1]$ of the single storage power capacity P_s and the peak storage power capacity P_p is determined by the residual fraction $(1-\chi)$ of the single storage power capacity P_s. Consequently, the powers P_b and P_p of the base and peak storages add up to the power of the single storage P_s. The dimensioning of the energy capacities of base and peak storages shall fulfil the same requirement: Base storage energy capacity E_b and peak storage energy capacity E_p shall add up to the single storage energy capacity E_s. Further, for a given fraction or power cut χ, the peak storage energy E_p shall become minimal in a way that control strategies still exist that can distribute the power between the two storages without exceeding the energy and power capacities of the storages at some point in time.

A control strategy, which preserves the energy and power capacities of the single storage system while minimizing the energy capacity of the peak storage, can be formulated verbally as follows: The peak storage shall be only charged if necessary, i.e. when the input power exceeds the power capacity of the base storage, and shall be discharged whenever possible. Some exceptions exist to ensure a failsafe operation. They are presented within the mathematical formulation in Section 3.

2.2. Insights and consequences

A single storage that fulfills the requirements of a given signal can always be separated into a base and a peak storage, whose power capacities (P_b,P_p) and energy capacities (E_b,E_p) add up to the power capacity P_s and energy capacity E_s of the single storage. Moreover, the introduced control strategy minimizes the energy capacity E_p of the peak storage. This way, the specific powers of the two storages

$$\omega_i(\chi) = \frac{P_i(\chi)}{E_i(\chi)} \qquad i \in \{\mathrm{b,p}\} \tag{1}$$

are spread as much as possible, providing more potential of using different storages with regard to their specific power. The introduced specific power ω is similar to the C-Rate commonly used for the characterisation of batteries. However, the C-Rate relates current to capacity. In this paper, it is generalized by relating power to energy. The specific power of the base storage ω_b is always lower than that of the original single storage ω_s and the specific power of the peak storage ω_p is always higher.

Each power cut χ generates a tuple of base and peak storages, which can be represented in a $P(E)$–diagram called Hybridisation Diagram, as shown in Fig. 1. The axes are limited to the dimension of the single storage, i.e. power and energy capacities P_s and E_s. The dotted diagonal line is the specific power line of the single storage, which fulfils the requirement of the signal.

The solid Hybridisation Curve in Fig. 1 represents the dimension of

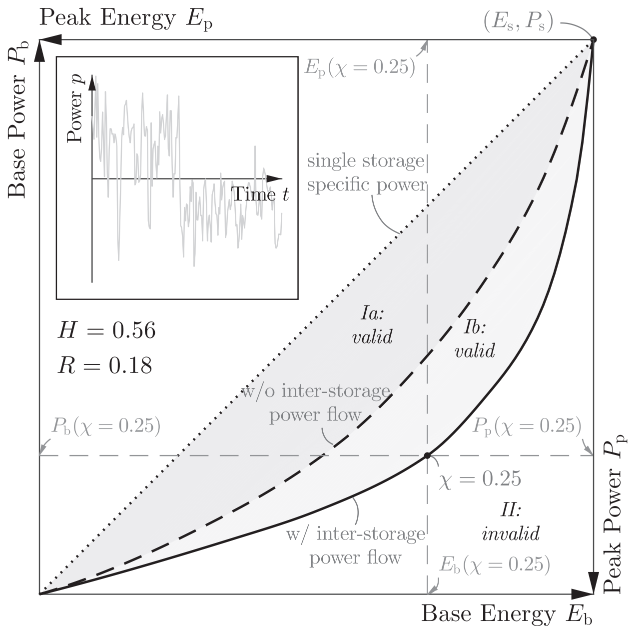

Fig. 1. Hybridisation Curve in $P(E)$-diagram; Note the two coordinate systems, where the first regular one represents base storage, and the second one is rotated by 180° and translated to the point of the single storage for representation of peak storage. For a power cut χ, the base and peak storage sizes can be read in the according coordinate systems.