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Review of system topologies for hybrid electrical energy storage systems

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ABSTRACT

Battery electric vehicles (*BEVs*) are the most interesting option available for reducing CO_2 emissions for individual mobility. To achieve better acceptance, BEVs require a high cruising range and good acceleration and recuperation. To meet these requirements, hybrid energy storage systems can be used, which combine *high-power* (*HP*) and *high-energy* (*HE*) storage units. To date, the coupling of the two energy storage types has been realized passively or actively by using DC/DC converters. In this paper, the corresponding topologies, described in the literature, are presented and reviewed with focus on the usable voltage window of the energy storage types, the utilization of stored energy, the connection to a power train/load, and additionally required power electronics. Besides, reconfigurable topologies on cell level and module level, without the need of additional DC/DC converters, have been investigated in the literature and are also presented and reviewed.

We then suggest a new topology class of *discrete hybrid energy storage topologies*, which combine both research topics. In the proposed topology class, standardized *energy storage modules* (*ESMs*) consisting of either HP or HE devices are combined. Each ESM is equipped with switching elements, which can activate, bypass, or disable the module and therefore allow reconfigurations. Four sub-topologies emerge when these ESMs are arranged to form an energy storage system.

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1. Introduction

Nine countries and regions, including the United States, the European Union, Japan, Canada, China, and Australia, have adopted emission standards for passenger cars and light-weight vehicles [1]. Within the European Union, the emission of CO_2 per driven kilometer is limited to an average of 95 g for a passenger car registered after 2020. To reduce emissions sufficiently to meet these limits, the manufacturers of large cars in particular need to electrify the power train of most of the cars they produce [2].

Today's *battery electric vehicles* (*BEVs*) use a battery storage system made up of many individual energy storage elements or cells. The storage elements used are of the same cell type and have the same cell chemistry. Hard wiring of identical storage elements is easy to realize and allows only a few interconnection variants. To achieve the necessary design system output voltage or increase storable energy, the energy storage elements are interconnected in series (Fig. 1a), whereas a parallel interconnection of storage elements leads to an increase in capacity, maximum current, and storable energy (Fig. 1b). Both interconnections are combined to achieve an increase in the output voltage, maximum current, capacity, and storable energy of the system (Fig. 1c).

Nowadays, the dimensioning of such an energy storage system is done for a specified operating point, and the design is a compromise between multiple requirements. Divergent operation of such an electrical energy storage system can lead to incomplete utilization of the stored energy. To better fulfill the requirements, *hybrid energy storage systems* (*HESSs*) have been developed that combine two or more different energy storage types [3–13]. Usually, these combine *high-energy* (*HE*) and *high-power* (*HP*) storage elements. The advantage of such hybrid systems is an overall increase in specific power and/or specific energy. HP storage enables acceleration or deceleration of power and in general uses *electrical double-layer capacitors* (*EDLCs*) or HP batteries. In contrast, HE storage ensures the long-term supply and is in general realized using HE Li-ion cells.

The combination of HP and HE storage cells to form an HESS can be realized in different ways. In contrast to the hard wiring of energy storage elements which have the same cell chemistry, a variety of connection topologies exists for HESSs (Fig. 2). The topologies examined in the scientific literature to date can be divided into the *passive hybrid energy storage topology* (*P-HEST*), which is presented in Section 2, and the *active hybrid energy storage topology* (*A-HEST*), which is presented in Section 3. In Section 4, we present scientific literature on reconfigurable topologies on cell level and module level, which is presented in Sections 4.1 and 4.2, respectively. Afterwards in Section 4.3, we propose reconfigurable hybrid topologies on module level and suggest a new topology class called *discrete hybrid energy storage topology* (*D-HEST*).

2. Passive hybrid energy storage topology

The simplest hybridization is achieved by the direct parallel connection of two or more different cell technologies. Fig. 3 shows an example of this *passive hybrid energy storage topology* (*P-HEST*) using a combination of battery storage and EDLC. The coupling of the cell types is carried out passively, without use of an intermediary power electronic converter [14]. The voltage of the two energy storage devices V_{BATT1} and V_{EDLC1} is identical to the voltage of the load ($V_{power\ train}$) [15]. The voltage window of both energy storage systems must therefore match the load. In automotive applications, the power train is the load. Likewise, the operating voltage windows of the respective storage technologies should have the largest possible intersection with each other.

In previous studies [7,14,16–51], HESSs have been analyzed in which an EDLC is connected directly to a battery. This topology is cost-effective, requires little space, and is weight-saving because no additional power electronics are required and the wiring is straightforward. The distribution of energy flows between the different storages depends on the equilibrium voltages and the internal resistances of the energy storage devices, $R_{i,BATT1}$ and $R_{i,EDLC1}$ [18].

The internal resistance depends on factors such as cell design, the current *state of charge* (SOC_{BATT1}, SOC_{EDLC1}), temperature (T_{BATT1}, T_{EDLC1}), and aging [52]. As the two energy storages are directly linked, the power distribution cannot be controlled. It has

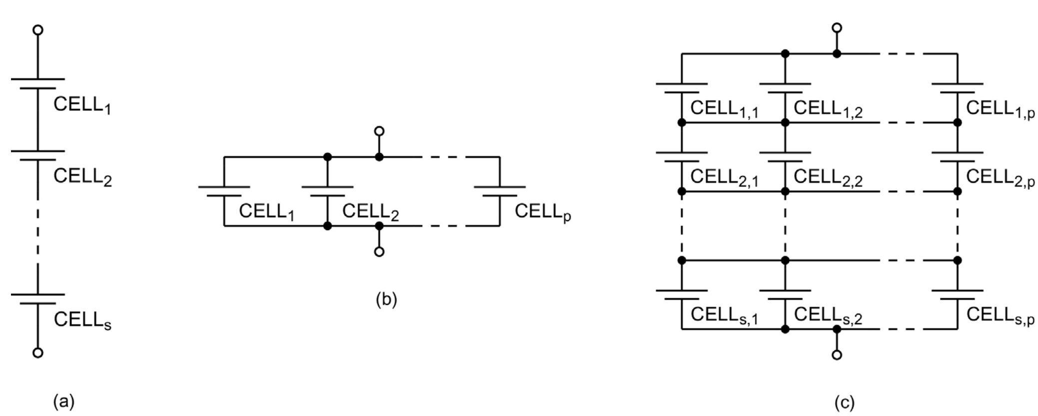

Fig. 1. Basic interconnection topologies of energy storage elements having the same cell type and chemistry. (a) Serial interconnection, (b) parallel interconnection, and (c) parallel–serial interconnection to increase storable energy, capacity, or ampacity and/or achieve a higher output voltage.