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The AC battery – A novel approach for integrating batteries into AC systems

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ABSTRACT

The growing share of renewable energy technology is continuously transforming the energy sector. Using storage capacities becomes crucial to sustainably guarantee stable energy supply. In particular battery storage systems (BSS) are expected to successfully compete with alternative options for energy storage in the near future. Major issues with state-of-the-art BSS include comparatively high costs, limited efficiency as well as reliability, and a low fault tolerance. A leap in power electronics technology might meet these challenges, as the aforementioned characteristics are predominantly determined by existing power converter and BSS architectures.

This paper presents the so-called AC Battery – a novel modular multilevel parallel converter based split battery system for AC applications, enabling dynamic switching of battery cells in parallel and in series. Each individual battery cell may be interconnected to its neighbors according to operational needs, e.g. to provide optimum source resistance, lowest state-of-charge (SOC) cycling, and balanced aging, rendering separate battery management systems (BMS) unnecessary. Applying the proposed technology in grid scale BSS may fundamentally change existing system architectures, as it merges battery storage system and power converter. This forms the basis for a highly integrated power electronics unit that includes bidirectional grid connection capability, energy storage, and BMS.

1. Introduction

1.1. Increasing demand for energy storage

In the past decades, many countries have experienced a significant change in their energy structures. Fossil-based resources are increasingly being replaced by renewable energies, while smart and distributed energy systems are prevailing. One of the main drivers for this change is the demand of reliable and environmentally friendly electricity generation from renewable energy systems (RES). Thus carbon dioxide emissions may be reduced while crucial resources are sustainably secured for later generations [1]. Among various renewable power systems, wind turbine system and PV system technologies are still the most promising technologies, accounting for a large portion of renewable energy generation, and are very likely to expand more. In 2015, for example, renewable energies accounted for approximately one third of the German power generation. On a stand-alone and short-term basis, solar power is already capable of covering up to 35% of the electricity demand on working days and 50% on non-business days, respectively [2].

However, the increasing adoption of RESs comes along with major challenges, as the overall energy production becomes increasingly weather-dependent. There are significant fluctuations on a short, medium and long-term basis. Nonetheless the resulting volatility might be balanced by using a diverse combination of energy sources and by counterbalancing with geothermal and hydroelectric power plants. Those have sufficient energy storage and load shifting potential, e.g. for base load applications [3]. In general, fluctuations can be compensated through transregional and long-distance energy exchange, which requires substantial investments in performant transmission grids, or through temporal load averaging, which requires storage [4]. The latter has been identified as an effective tool for different applications, ranging from home energy storage systems (HESS) [5] to micro as well as utility-scale grid applications for low, medium and high voltage levels [6,7].

At the same time, technological advancements of battery storage systems support their competitiveness vis-à-vis pumped hydropower storage, as they are not limited by geographic restrictions [8] and as they refer to technology leaps with regard to their energy density and cost structures [9].

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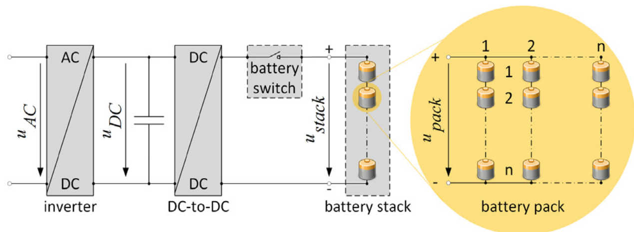

Fig. 1. State-of-the-art Battery storage system.

1.2. State-of-the-Art battery storage systems

State-of-the-art battery storage systems consist of a high voltage battery stack, a BMS and a bidirectional converter. The battery stack is comprised of several battery packs connected in series to increase the system voltage. To increase the overall system capacity and ampacity, these battery packs can be built with several battery blocks switched in parallel. In turn, these battery blocks are composed of several secondary battery cells switched in series (see Fig. 1) [10].

Despite decreasing manufacturing tolerances – standard divergences amount to $\pm$ 0.1% for the active material's weight fraction or $\pm$ 1% for electrode thickness and density [11] – 10–20% deviation of the secondary battery cells' capacities and resistances are typical. At the same time battery cell parameters are continuously drifting apart during the battery storage systems' lifetime. The reason are temperature gradients within the battery stack as well as slightly differing load curves, as manufacturing tolerances and resistance variations occur [12]. To avoid thermal run-away of the battery cells, and to increase usable capacity and lifetime of the whole battery stack, a BMS is needed to balance the battery cells' SOC [13]. These management systems ensure that the battery cells are not operated beyond their threshold parameters (safe operating area). Therefore, their voltage, current, and temperature in particular have to be monitored [10]. The options for SOC balancing range from passive systems – they are characterized by dedicated balancing circuits that allow discharging battery cells with higher SOCs through a resistor – to active systems, which shift energy from one battery cell to another. The latter are comparatively more efficient, but also more expensive, as they require additional active and passive electronic components as well as elaborate control and measurement systems [14]. Furthermore, active BMSs may accelerate cell ageing, under certain circumstances [13].

Conclusively there are several obstacles that hinder a faster market penetration with existing battery storage systems. Typically, they come along with higher costs compared to fossil energy generation and alternative technologies for energy storage. Many applications require special-purpose solutions and still have limited efficiency as well as reliability [15]. Additionally, as the internal structure of the battery storage systems is hard-wired, operation parameters and key economic metrics, such as usable capacity, lifetime, and ampacity, are determined by the weakest cell in the system [10].

1.3. Modular multilevel converter based split battery systems

Modular multilevel converters (MMC) with split batteries are a promising approach for lessening the aforementioned disadvantages. Today – while they are still broadly discussed in literature – first systems are already being implemented [16]. One of their main characteristics is the integration of low voltage battery packs. Those are replacing the low voltage capacitors that are commonly used in MMCs [17]. While even traditional MMCs are increasing the round-trip efficiency of a system by more than 2% compared to two level voltage source converters [18], there is potential for further enhancement through merging battery storage system and converter [19]. As shown in [20], MMC based split battery systems also boost partial load efficiency. Despite their increased component complexity, they proof to be cost competitive to state-of-the-art battery storage systems.

Numerous variants of MMC based split battery systems have been introduced yet. They differ in their implementation of how the battery packs are interconnected with the corresponding power electronics. Also power electronic circuits and MMC topologies vary.

Taking the simplest topology as an example, the battery packs can be merged with the power electronics of an MMC module by only replacing its capacitors [21]. In some cases, pulse-width modulation (PWM) is used to reduce total harmonic distortions (THD). The PWM is generated by the modules, whereby the battery packs are exposed to ripple charging and discharging currents with PWM equivalent frequencies and a magnitude that equates to the overall system current. These current pulse shapes are well known from common multilevel converter systems where they can be ignored, as they do not harm the installed capacitors. In MMC based split battery systems the battery packs' interconnections with the MMC modules are often realized through dedicated electric circuits (often DC-to-DC converters) that smoothen the battery current shapes. Those circuits can either be isolated [22,23] and are thus inherently reducing the ripple currents, or non-isolated [10,16,24]. The latter use capacitors that are parallelized to the battery packs instead of smoothing the current shape.

A key feature of MMC based split battery systems is their capability to dynamically address each individual battery pack according to operational needs. At the same time those systems come along with several constraints: Each battery pack is being charged and discharged with pulse currents that amount to the overall system current. This results in high battery pack current slew rates and major filtering effort. In addition, higher average charging and discharging currents correlate with a limitation in efficiency [25]. The system's inherent operation strategy – battery packs are bypassed whenever they are not needed – is also a limiting factor.

Nonetheless, MMC based split battery systems are a promising approach for a further improvement of battery technology. They represent the preliminary stage for the AC Battery, as proposed in this paper.

2. Methods

This paper discusses a disruptive approach to integrally meet the aforementioned disadvantages of state-of-the-art battery storage systems, including MMC based split battery systems. The basic idea is to apply and adopt Modular Multilevel Parallel Converter (MMPC) technology to battery storage systems. Therefore, influencing factors for a successful converter design (e.g. voltage step size) are being defined and evaluated. After chapter 3 describes the system's micro and macro topology, operating strategies and their impact on current loads and system efficiency are being derived (see chapter 4). Here, first experimental analyses are presented, either. The closing two chapters give an outlook to future applications and draw a conclusion.

3. Converter topology

The AC Battery expands traditional MMC split battery systems (SBS) [26] by the ability to dynamically switch neighboring battery modules not only in series, but also in parallel. This essential characteristic refines those systems' capability to address each battery module individually and to operate it under consideration of its individual parameters and properties.

3.1. Micro topology

Qualifying the system for a parallel connectivity of each AC Battery module affects both micro topology and macro topology. As the basic converter structure is a serial one, every module is connected only to its immediate neighbors, whereat two interconnections between two successive modules need to be established.