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A comparison of system architectures for high-voltage electric vehicle batteries in stationary applications

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ABSTRACT

An increasing global interest in clean energy alternatives requires new concepts for local storage of electricity. This leads to new research demand regarding suitable system architectures based on high-voltage batteries from electric vehicles. In this study, a new method for evaluating stationary system architectures is described. The assessment focuses on the system efficiency of different architectures. A sensitivity analysis is included to show further distinctions in criteria such as volume, weight and cost. Three system topologies for the use of new and second-hand batteries extracted from electric vehicles in stationary applications are presented. All components need to be able to operate in a bidirectional mode — the ability to absorb and release electricity from and into the grid. The first two topologies include one battery connected to the grid either with a DC/DC converter and a DC/AC inverter or with a DC/AC inverter and a transformer. The third topology involves the connection of two batteries in series with a DC/AC inverter, providing better characteristics in terms of the required power electronic components. The results show differences between one to two percentage points in efficiency. Moreover, the influence of parallelisation and various power distributions delivers close to five percentage points higher efficiency for the first topology with a DC/DC converter. Combined with the outcome of the sensitivity analysis, the topology with the DC/DC converter connected to the DC/AC inverter exhibits the best performance in the overall evaluation criteria.

1. Introduction

Over the last years the Global Energy Transition [1–4] has gained in importance worldwide, driven by growing urbanization [5,6], scarcity of fossil based fuels [7–10], as well as accumulating pollution [11–13]. This results in an increasing need for renewable energy sources [14–16], more stringent environmental regulations [17,18], and changes in consumer consciousness [19,20]. The combination of these factors promotes the expansion of Electro-Mobility (E-Mobility) [21,22] but also means an increasing level of complexity within the grid structure [23,24]. Increasingly decentralized and volatile energy production systems, like photovoltaic systems or wind power generators [25], have to be efficiently integrated into the present electrical transmission and distribution network. This, in conjunction with more photovoltaic producers wanting to consume their self-generated energy [26], results in a high demand of local storage for electrical energy [27–30].

The increased importance of E-Mobility and the need to integrate more unpredictable renewable energy sources into the grid complement each other in an interesting way. E-Mobility [22,31] is accelerating lithium-ion battery manufacturing, thus providing a supply of local energy storage in the form of high-voltage batteries installed in electric vehicles (EVs). Conversely, the increased need for local storage creates a unique opportunity for automotive companies to enhance the sustainability of their battery systems by extending the battery lifecycle [23]. This can be accomplished by enabling alternatives to immediate recycling, e.g. through second life local energy storage applications, such as frequency regulation, peak shaving, arbitrage, etc. The breadth of stationary applications requires that the system architectures must be deployable from small systems, consisting of only one battery unit, up to large-scale systems. Moreover, both used (Battery 2nd Life) and new batteries should be considered as a cost effective way of enabling the grid of the future [32–39].

Realising the potential of EV batteries for stationary storage applications calls for the development of suitable system architectures that will enable the connection of the batteries to the grid. These architectures need to meet the requirements of the application in terms of capacity, power ramp rates, operating time, regulations, and at the

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Abbreviation

DAB	dual active bridge
E-Mobility	electro-mobility
EV	electric vehicle;
IGBT	insulated-gate bipolar transistor
SOC	state of charge
SOH	state of health

same time optimise volume, weight, cost, and efficiency to make the application economically viable. Currently, in the majority of pilot and industrial solutions (BMW Group [51,52], Tesla [53], Daimler [54]), architecture selection is effectively done ad hoc based on commercially available components and concentrating on the optimal cell interconnection [44,46]. The resulting architectures are thus often under- or over-provisioned for the application in question. Other focuses of research include the development of new power electronic components, e.g. Dual Active Bridge (DAB) [40]. The connection of battery with DC/DC converter and DC/AC inverter is presented in [42,43,48]. Similarly, [49,50] show the same architecture for second life batteries. The parallelisation of multiple smaller power electronic components instead of one huge unit [45] and their influence on system efficiency as well as the power losses of each component [41,47] are two possibilities to evaluate system architectures. The optimal control strategy for the power electronics and the optimal power flow during operation is a further research field, which is analysed by Graditi et al. [55]. The optimal power flow is not part of this work.

To the best of our knowledge there is no established systematic procedure for comparing the relative merits of different architectures and assessing their attractiveness for specific stationary storage applications based on EV batteries. Developing such a framework is essential due to the diversity of battery properties, applications and architectures that are becoming available.

This work performs a systematic investigation on the different topologies of system architecture for stationary applications connecting EV batteries. Our ultimate goal is to develop a semi-automated decision support toolkit that practitioners can use to design appropriate architectures given the properties of available batteries, target storage application, available volume and individual budget. In this paper we present the first step in this direction, namely a comparison framework to allow one to compare different architectures that enable the operation of second life EV batteries in stationary storage applications without rebuilding the batteries. We then use this framework to define the optimal design for a stationary application consisting of power electronic components based on the outcoming simulation results. Addressing the design question is the topic of current research, based on optimisation methods.

In Section 2, the benefits and disadvantages of three system topologies are illustrated. In Section 3, the equivalent circuit model to simulate the losses of power electronic components is explained. Sections 4 A, 4 B, and 4 C present the influence of parallelisation, power distribution, and further contributing factors like volume, weight, and cost, respectively. Finally, the conclusion and future work are presented in Section 5.

2. Topology description

The main objective is to connect the EV batteries (e.g. BMW i3) with a voltage of around 400 V (DC) to the three phase AC grid of 400 V (low voltage network). A DC/AC inverter can be used to transform the direct current from the EV battery into an alternating current comparable to

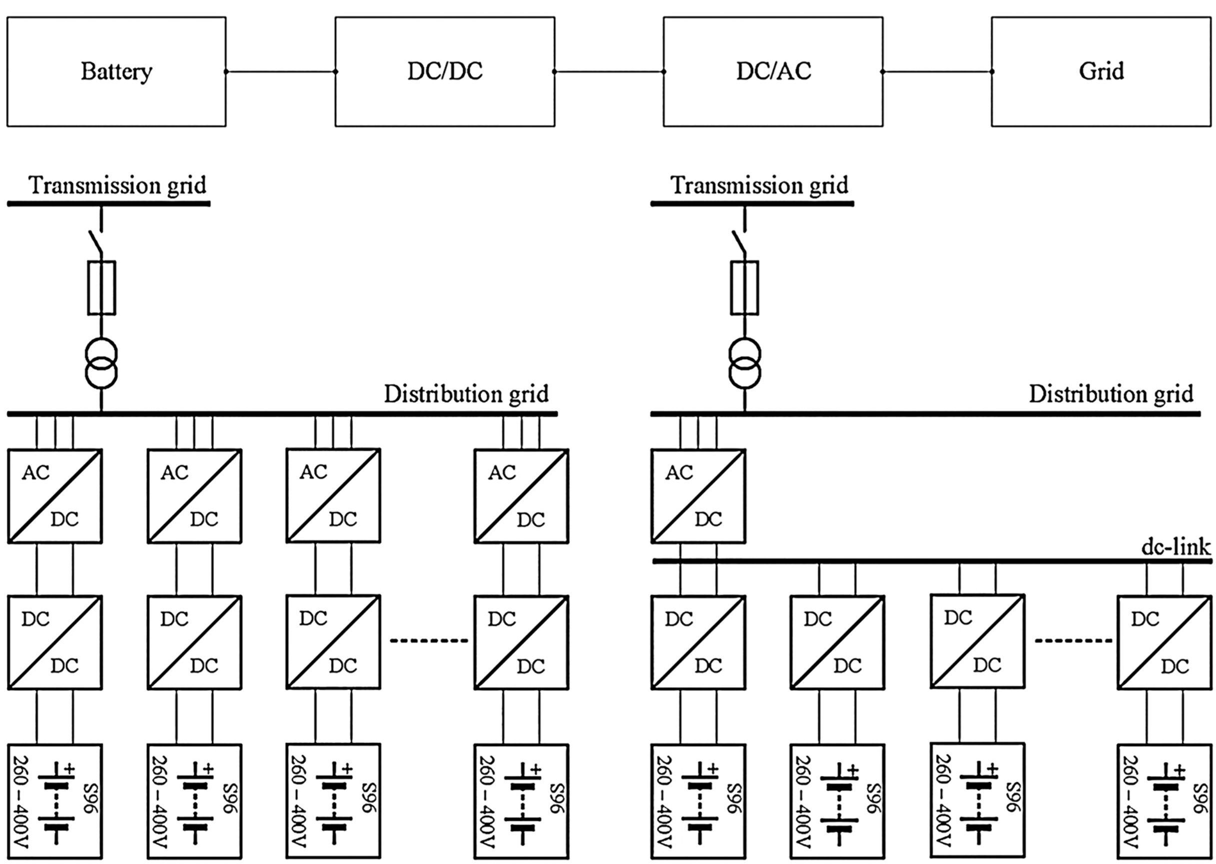

Fig. 1. Topology 1, DC/DC converter with DC/AC inverter, different levels of parallelisation (left and right side). The battery is symbolized by 96 cells in series, in line with the BMW i3 battery.