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Control of an isolated single-phase bidirectional AC-DC matrix converter for V2G applications

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ABSTRACT

This paper describes a new current control method that enhances the dynamic performance of a single-phase bidirectional AC-DC battery charger to provide a high-frequency link between the grid and electric vehicle. The single-stage structure and the bidirectional power flow make the matrix converter an attractive solution for electric vehicle (EV) battery charging applications in the context of smart grids. The operating principles and modulation method are analyzed and discussed in detail. Furthermore, a current controller improved with a Smith predictor is proposed to decrease the phase delay in the measurement of the average current in the battery pack. The SP reduces the rise time to around a third and the settling time to half when compared with a PI controller. Simulations and experimental results from a laboratory prototype are shown to verify the feasibility of the proposed control scheme.

1. Introduction

In today's environmentally conscious world, transport electrification is becoming a vital issue [1]. In fact, during the last few years there has been a growth in the interest of the electric vehicle (EV) market, with the principal automakers introducing several new models, both hybrid or pure electric. This paradigm shift from internal combustion engines to hybrid and electric power trains will have a profound impact on the electric power system. At the same time the power systems is facing the challenge of integrating large shares of distributed renewable power sources, storage devices and increased demand response – distributed energy resources (DER) – leading towards the need of development of a smarter grid [2]. In this context, the EVs must be considered as part of cyber-physical system. The recent trend in the research on Smart Grids is strongly oriented to accommodate all generation devices and storage options [3], while the idea of gridable electric vehicles (GEVs) appears as a concept that defines the necessary technologies for future integration of EVs on distribution networks [4,5]. The vehicle-to-grid (V2G) and vehicle-to-home (V2H) technologies consists of feeding power to the grid or home taking advantage of the vehicle's energy storage capacity [6], which can be used for peak shaving, reduce transport power losses and increase the integration of electric vehicles into electric power system [7,8]. Other ancillary services such as voltage and frequency regulation and spinning reserves can also be provided to improve reliability and quality of the electric power supply [9,10].

The electric vehicles currently available on the market are provided with an onboard battery charger that only allows unidirectional power flow. Recent research have proposed diverse single-phase unidirectional conversion topologies with improved efficiency and power density [11–15]. However, in order to implement V2G or V2H, the power electronic interface should implement bidirectional power flow and preferably offer galvanic isolation between the grid and the batteries. Traditional solutions for bidirectional EV battery chargers are based on standard two or three-stage architectures [16–18]. The first stage is typically an AC-DC bidirectional converter, which is necessary to achieve an appropriate interface with the grid such as unity power factor, reactive and harmonic power compensation [19,20]. The second stage in the architecture is a bidirectional DC-DC converter to regulate battery current [21]. A typical approach to implement galvanic isolation and simultaneously reduce the size of the charger consists in the adoption of an high-frequency transformer (HFT) in the DC-DC stage instead of a bulky low-frequency (LF) transformer [22].

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Common solutions for this stage are based on resonant DC-DC converters [23], or dual active half bridge (DAHB) [24] and dual active bridge (DAB) [25,26], where the leakage inductance of the HFT is used in the energy conversion process. These circuits provide a fast control and higher power density when compared with LF transformer based solutions. However, the bulk DC link capacitor between the AC-DC and DC-DC stages, used to store the ripple power of two times the grid frequency, is a main barrier to increase the power density [27]. Moreover, a short service life of the charger is expected if electrolytic capacitor is used [28]. If the battery is able to accept the low-frequency current ripple, the high-voltage DC link capacitor can be significantly reduced or eliminated. In [29,27,30–33] are presented different single-phase topologies that explore this type of battery charging for further increase the power density. Lithium-ion is the dominant technology for the battery pack of electric vehicles. Study in [34] shows that the ripple at two times the grid frequency causes a slight but noticeable increase in the heat generated, but is not significant enough to justify any changes in the charger circuit. In [35] is also show that the heat generated by frequencies above 100 Hz is not a major cause of capacity decay. Furthermore, by taking the impedance model of lithium-ion cells into account, the use of variable frequency pulse charge system can even improve the battery-charge response [36]. In this way, it is perfectly justified and relevant to explore the application of different topologies that work with low-frequency ripple in the charging current.

Several single-stage power converters were proposed to perform bidirectional AC-DC power conversion as a possible alternative for the traditional two-stage solutions. The use of a matrix converter for the front-end is an interesting solution as it provides the capability to perform a direct AC to AC conversion without a DC-link [37]. Using matrix converters can lead to a simpler and more compact power circuit, resulting in a higher power density and longer service life [38,39]. Taking this idea into account and knowing that the output stage of the power interface is to be connected to a battery pack, it is possible to use a single-phase matrix converter (SPMC) on the AC side and a full bridge (FB) on the DC side, connected by a high-frequency transformer in DAB configuration. One of the first works proposing the application of a matrix converter for bidirectional and isolated AC/DC power conversion was [40]. More recently, other modulations and control strategies have been proposed in [41–44]. A single-phase version of this topology is presented in [45], which has several advantages such as single-stage power conversion, high power density, isolation, bidirectional power flow and zero current switching (ZCS) for the SPMC. This work only investigates the open-loop operation of the charger. A strategy to control the DC voltage at the battery pack was investigated in [46]. However, the charging and discharging process of lithium-ion and other types of batteries require control of the charger output current, which has not been considered until now.

In this paper, a comprehensive analysis and design formulations related with the framework developed in the previous work [47] are presented. A mathematical model of the charger in the state-space is provided along with a detailed steady state analysis. In order to facilitate the deduction of these models and to normalize the nomenclature, some equations from [47,45] are repeated in Sections 2 and 3. The original contribution of this work is on the control methodology proposed for the battery charging process. The new current controller is capable to solve the problem associated with the measurement of the averaging current at the charger output. By incorporating a Smith predictor (SP) in the feedback loop, to compensate the delay time associated with the measurement, the achievable bandwidth of the controller is increased. This results in faster response to track different set-points of current. It is proved in the paper that the rise time and the settling time are reduced when compared with a PI controller. An analysis of the robustness of the SP against parametric variation in the converter parameters and additional delays in the control loop is provided. Simulations and experimental results are carried out to validate the proposed solution. To the knowledge of the authors, until now the implementation effort of this prediction method has not been investigated for the control of this charging topology.

The remainder of the paper is organized as follows. Section 2 presents the proposed topology and explains the operation principles, including the revision of the modulation method. The mathematical model of the system to be controlled and the steady state analysis are introduced in Section 3. In Section 4, the design of the control architecture for the bidirectional battery charger based on the Smith prediction method is presented. Section 5 shows simulation results in the time-domain and Section 6 describes the experiments carried out in the laboratory to validate the solution. Conclusions are drawn in the last section.

2. Power circuit topology and operation

2.1. Principle of operation

The proposed topology for the bidirectional charger is based on the *AC-DC Dual Active Bridge* structure, as shown in Fig. 1. This structure has two full bridges, one in the grid side and another connected to batteries. The full-bridge (FB) on the grid side consists of the single-phase matrix converter (SPMC) that converts the 50 Hz voltage into a voltage at high frequency, v_1. This voltage is applied to the primary of the high frequency transformer (HFT) which provides galvanic isolation to the charger and makes it possible to store energy using its leakage inductance, L. The matrix converter comprises two commutation cells formed by bidirectional switches, and is built with discrete IGBTs in a common emitter configuration. These switches allow current to flow in both directions and are capable of performing reverse voltage blocking, thereby enabling bidirectional power control. The full bridge on the battery side is bidirectional in current and applies the voltage v_2 to the secondary of the HFT. Therefore, the proposed topology can naturally allow bidirectional power flow, using the same principle as for a dual active bridge. The SPMC and the FB respectively apply an AC voltage to the terminals of the transformer leakage inductance L. The difference between voltages v_1 and v_2 result in voltage v_L which is applied to the inductance. The operating principle can be simply explained: if v_1 and v_2 are exactly equal, current in the inductance stays the same. When voltage v_1 and v_2 are different, a non-constant current circulates in inductance L, i_L, according with the voltage v_L. If $v_1 = v_2$ a constant current circulates in inductance L. Thus, the power transfer between the two sources can be controlled by the amplitude and the phase-shift between the voltages v_1 and v_2.

2.2. PWM technique

A pulse-width modulation (PWM) method for the three-phase version of the AC-DC DAB topology was proposed in [41]. Then, experimental results for the single-phase version of the AC-DC DAB topology were provided in [47], that demonstrated the flexibility of the proposed power structure as well as its modulation performance. In addition, a phase-shift plus PWM voltage control was also applied to the single-phase version in [46]. More recently, the modulation method used in this work was presented in [45]. Due to certain twists on realization of that PWM technique, its basics are invoked here. Fig. 2 depicts a period of the proposed modulation for the bidirectional charger. It shows the output voltage of the SPMC, v_1, the terminal voltage of the FB, v_2, and the high frequency voltage and current, v_L and i_L respectively, in the leakage induc-