A Common Ground Switched-Quasi-Z-Source Bidirectional DC–DC Converter With Wide-Voltage-Gain Range for EVs With Hybrid Energy Sources

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***Abstract*—A common ground switched-quasi-*Z*-source bidirectional dc–dc converter is proposed for electric vehicles with hybrid energy sources. The proposed converter is based on the traditional two-level quasi-*Z*-source bidirectional dc–dc converter, changing the position of the main power switch. It has the advantages of a wide-voltage-gain range, a lower voltage stress across the power switches, and an absolute common ground. The operating principle, the voltage and current stresses on the power switches, the comparisons with the other converters, the small signal analysis, and the controller design are presented in this paper. Finally, a 300 W prototype with $U_{high} = 240$ V and $U_{low} = 40 \sim 120$ V is developed, and the experimental results validate the performance and the feasibility of the proposed converter.**

***Index Terms*—Bidirectional dc–dc converter, common ground, electric vehicles (EVs), hybrid energy sources, switched-quasi-*Z*-source, wide-voltage-gain range.**

I. Introduction

With the increase of per capita car ownership in the world, the increases in fossil fuel consumption and greenhouse gas emission are having a serious effect on the climate and environment [1]–[5]. New energy vehicles with renewable energy as the power source, which can achieve operation with zero pollution emissions, are considered as one of the solutions to effectively alleviate the energy crisis and the environmental pollution associated with transportation [6], [7]. As one of the most important “new energy” vehicles, electric vehicles (EVs) with hybrid energy sources mainly comprise high energy density power batteries and high power density super capacitors. The low-voltage batteries are used to maintain the high voltage of the dc bus during steady-state, even when the required energy has low-frequency fluctuations. The super capacitors can be used to provide or absorb high-frequency instantaneous power during the EV’s accelerating or braking process. Thus, these two hybrid energy sources can greatly reduce the degradation impact on the power batteries caused by the sudden load change of the EV, as well as improve the dynamic response of the whole powertrain system [8], [9].

The voltage level of hybrid energy sources for EVs is relatively low. In order to realize the matching of the voltage levels between the hybrid energy sources and the high-voltage dc bus, as well as the bidirectional power flow of energy sources, a wide voltage-gain range bidirectional dc–dc converter is needed to interface the energy sources and the dc bus.

With regard to the wide voltage-gain range bidirectional dc–dc converter, basically, it can be classified into two categories: isolated and nonisolated. The isolated types of bidirectional converters include Fly-back converters, forward converters, and half-bridge and full-bridge bidirectional converters. One of the advantages of these bidirectional dc–dc converters is that they have a wide voltage-gain range in the step-up and step-down modes. Although the Fly-back converter has a simple structure and can be controlled easily, the leakage inductor loss caused by the high frequency transformer mean the converter has a low efficiency. In addition, the leakage inductor causes high voltage spikes, which means the power switches see a high voltage stress.

Nonisolated bidirectional converters include conventional two-level converters and multilevel converters, Cuk/Sepic/Zeta converters, coupled-inductor converters, switched-capacitor and switched-inductor converters, and Z-source and quasi-*Z*-source converters. The conventional two-level converters have a high voltage stress on the power switches, a narrow voltage-gain range, and their efficiencies and dynamic responses are limited by the extreme duty cycles of the power switches. Therefore,

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they are not suitable for the hybrid energy sources system of EVs. As to the three-level dc–dc converters, although the voltage stress on the power switches is significantly reduced, the practical voltage gain in the step-up and step-down modes is relatively low due to the parasitic parameters [10], [11]. Multilevel dc–dc converters have a wide-voltage-gain range, but they need more power switches, other additional hardware circuits and a control strategy to maintain the balance of the voltage stress on the power switches [12]. Although the voltage gain range of the Cuk/Sepic/Zeta converters is wider, the cascaded structures limit the conversion efficiency [13]–[15]. Coupled-inductor dc–dc converters can achieve a high voltage gain by adjusting the turns ratio of the coupled inductor, but they require more power switches and need to address the problem of the leakage inductance, which make their structure more complex. In addition, the power conversion and transmission capability of the converter is also limited by the performance of the coupled inductor [16]–[18]. The structures and control schemes of the Z-source, the quasi-Z-source, and the switched-capacitor dc–dc converters are simple and easy to expand, and the capacitors in these converters deliver energy through different paths during the charge and the discharge processes. Thus, a high voltage gain can be achieved [19]–[22]. Switched-inductor bidirectional dc–dc converters can also achieve a wide-voltage-gain range and a low voltage stress while avoiding extreme duty cycles. However, more inductors limit the power density [23], [24].

A new nonisolated single capacitor bidirectional dc–dc converter is presented in [25]. Although it has a wide-voltage-gain range, the voltage stress on the power switches is relatively high. In [22], a switched-capacitor-based dc–dc converter is proposed. Although the voltage gain is improved, more devices are used, and the converter does not have a common ground. A bidirectional switched-capacitor dc–dc converter is presented in [26]. This converter improves the efficiency, but the converter needs more power switches. A hybrid bidirectional converter with a switched-capacitor cell, which is suitable for a dc microgrid, is proposed in [27]. It has a wider voltage gain range and lower power voltage stress across the power switches, but the converter does not have an absolute common ground between the input and output sides, which produces an additional du/dt issue between the input and output grounds. Thus, its applications are limited. In [28], a novel coupled-inductor bidirectional dc–dc converter is proposed with increased voltage gain. However, the leakage inductance of the coupled inductor and the additional du/dt problems between the input and output grounds should be considered additionally, and the voltage stress on the power switches that are near the high voltage side is too high.

This paper presents a novel switched-quasi-Z-source bidirectional dc–dc converter for EVs with hybrid energy sources, which not only achieves a wide-voltage-gain range, but also has a common ground. The proposed converter is based on the traditional two-level quasi-Z-source bidirectional dc–dc converter: It simply changes the position of the main power switch. As well as a wide-voltage-gain range and a low voltage stress on power switches, this converter also has a simple structure. As a result, the proposed converter can select the power switches with the low rated voltage, and the low on-state resistance, which in turn can improve the conversion efficiency. Simultaneously, the voltage-gain of the proposed converter is just reduced a bit, which can still meet the requirement of the application of EVs with hybrid energy sources. The absolutely common ground also avoids the additional du/dt issue between the input and output grounds, which is beneficial for the operation of the proposed converter.

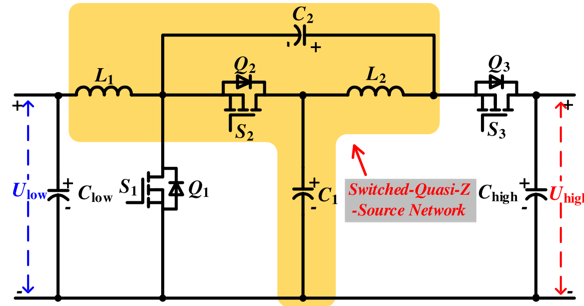

Fig. 1. Configuration of the proposed converter.

The structure of the paper is organized as follows. Section II introduces the configuration of the proposed converter and analyzes the operating principle in detail. The design and analysis of the converter are given in Section III. The experimental results and analysis are shown in Section IV. Finally, Section V presents conclusions.

II. Operating Principle and Analysis of the Proposed Converter

A. Configuration of the Proposed Converter

The configuration of the proposed bidirectional dc–dc converter is shown in Fig. 1. It can be seen that the proposed converter consists of a switched-quasi-Z-source network (L_1, L_2, C_1, C_2, and Q_2), power switches Q_1 and Q_3, and high/low voltage side energy storage/filter capacitors C_{high} and C_{low}. The gate signals S_2 and S_3 of the power switches Q_2 and Q_3 are identical, and they are complementary to the gate signal S_1 of Q_1. The proposed converter can operate either in the step-up or in the step-down mode, enabling the bidirectional power flow between the high-voltage and low-voltage sides.

B. Operating Principle of the Proposed Converter

To simplify the analysis, the following assumptions are made.

1) All the components are ideal, ignoring the on-state resistance R_{DS}(on) of the power switches and equivalent series resistance of the inductors and capacitors.
2) The currents of the inductors and voltages of the capacitors increase and decrease linearly.
3) The voltages across capacitors are constant.

The two main operating modes ***Mode I*** and ***Mode II*** of the proposed converter are analyzed as follows:

Mode I. Step-Up Mode of the Proposed Converter: When the proposed converter operates in the step-up mode, namely the energy flows from the low voltage side to the high voltage side. In this operating mode, Q_1 operates as a main power switch, and