Development of a Bidirectional DC/DC Converter with Dual Battery Energy Storage for Hybrid Electric Vehicle System

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Abstract: *This study develops a newly designed, patented, bidirectional dc/dc converter (BDC) that interfaces a main energy storage (ES1), an auxiliary energy storage (ES2), and dc-bus of different voltage levels, for application in hybrid electric vehicle systems. The proposed converter can operate in a step-up mode (i.e., low-voltage dual-source-powering mode) and a step-down (i.e., high-voltage dc-link energy-regenerating mode), both with bidirectional power flow control. In addition, the model can independently control power flow between any two low-voltage sources (i.e., low-voltage dual-source buck/boost mode). Herein, the circuit configuration, operation, steady-state analysis, and closed-loop control of the proposed BDC are discussed according to its three modes of power transfer. Moreover, the simulation and experimental results for a 1 kW prototype system are provided to validate the proposed converter.*

1. Introduction:

Distributed Energy Resources or DER are electric power generation or storage systems which are typically located at or near the end user. The electricity that we receive in our buildings through electric grids, are generated from centralized power plants, which are located far from cities. Distributed energy resource (DER) systems are small-scale power generation technologies located at or near the end user (typically in the range of 3–10,000 kW) used to provide an alternative to or an enhancement of the traditional electric power system. [1] To discuss about Der some of the terms are needed to be familiar with, Distributed Generation— Any technology that produces power outside of the utility grid (e.g., fuel cells, microturbines, and photovoltaics) Distributed Power— Any technology that produces power or stores power (e.g., batteries and flywheels) Distributed Energy Resources—Any technology that is included in DG and DP as well as demand-side measures. Under this configuration, power can be sold back to the grid where permitted by regulation. [2] Der is like how it was during Thomas Alva Edison's DC current, when DC power plants used to be situated near the end users. But DC currents could not transfer higher voltages too far. That is why AC currents are used. Because of AC currents power plants got centralized, meaning one power plant could transmit electricity from far to the whole city.

2. Related Work

Global climate change and energy supply is declining have stimulated changes in vehicular technology. Advanced technologies are currently being researched for application in future vehicles. Among such applications, fuel-cell hybrid electric vehicles (FCV/HEV) are efficient and promising candidates. In the past, Ehsani et al. studied the vehicles' dynamics to look for an optimal torque-speed profile of the electric propulsion system [1]. Emadi et al. discussed the operating properties of the topologies for different vehicles including HEV, FCV, and more electric vehicles [2]. Emadi et al. also integrated power electronics intensive solutions in advanced vehicular power system to satisfy huge vehicular load [3]. Schaltz et al. sufficiently divide the load power among the fuel cell stack, the battery, and the ultracapacitors based on two proposed energy-management strategies [4]. Thounthong et al. studied the influence of fuel-cell (FC) performance and the advantages of hybridization for control strategies [5]. Chan et al. reviewed electric, hybrid, and fuel-cell vehicles and focused on architectures and modeling for energy management [6]. Khaligh and Li presented energy-storage topologies for HEVs and plug-in HEVs (PHEVs). They also discussed and compared battery, UC, and FC technologies. Furthermore, they also addressed various hybrid ESSs that integrate two or more storage devices [7]. Rajashekara reviewed the current status and the requirements of primary electric propulsion components-the battery, the electric motors, and the power electronics system [8]. Lai et al. implemented a bidirectional dc/dc converter topology with two-phase and interleaved characteristics. For EV and dc-microgrid systems, the converter has an improved voltage conversion ratio [9]. Furthermore, Lai also studied a bidirectional dc to dc converter (BDC) topology which has a high voltage conversion ratio for EV batteries connected to a dc-microgrid system [10]. In FCV systems, the main battery storage device is commonly used to start the FC and to supply power to the propulsion motor [2, 3]. The battery storage devices improve the inherently slow response time for the FC stack through supplying peak power during accelerating the vehicle [7]. Moreover, it contains a high power-density component such as supercapacitors (SCs) eliminates peak power transients during accelerating and regenerative braking [11]. In general, SCs can store regenerative energy during deceleration and release it during acceleration, thereby supplying additional power. The high power density of SCs prolong the life span of both FC stack and battery storage devices and enhances the overall efficiency of FCV systems[2-8, 12].

3. PROPOSED METHOD

The proposed BDC topology with dual-battery energy storage is illustrated in Fig. 1, where VH, VES1, and VES2 represent the high-voltage dc-bus voltage, the main energy storage (ES1), and the auxiliary energy storage (ES2) of the system, respectively. Two bidirectional power switches (SES1 and SES2) in the converter structure, are used to switch on or switch off the current loops of ES1 and ES2, respectively. A charge-pump capacitor (CB) is integrated as a voltage divider with four active switches (Q1, Q2, Q3, Q4) and two phase inductors (L1, L2) to improve the static voltage gain between the two low-voltage dual sources (VES1, VES2) and the high-voltage dc bus (VH) in the proposed converter. Furthermore, the additional CB reduces the switch voltage stress of active switches and eliminates the need to operate at an extreme duty ratio. Furthermore, the three bidirectional power switches (S, SES1, SES2) displayed in Fig. 2 exhibit four-quadrant operation and are adopted to control the power flow between two low-voltage dual sources (VES1, VES2) and to block either positive or negative voltage. This bidirectional power switch is implemented via two metal-oxide-semiconductor field-effect transistors (MOSFETs), pointing in opposite directions, in series connection. To explain the concept for the proposed converter, all the conduction statuses of the power devices involved in each operation mode are displayed in Table I. Accordingly, the four operating modes are illustrated as follows to enhance understanding.

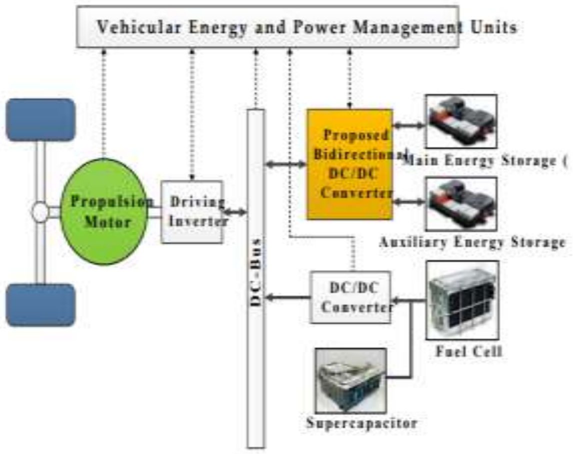

Fig. 1. Typical functional diagram for a FCV/HEV power system.

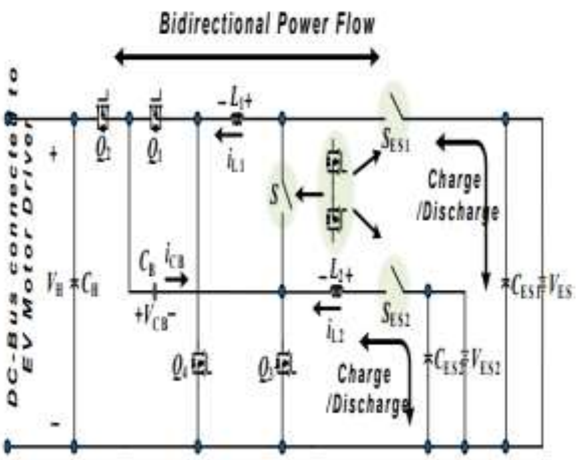

Fig. 2. Proposed BDC topology with dual-battery energy storage.

A functional diagram for a typical (FCV/HEV) power system is illustrated in Fig. 1 [4, 13]. The low-voltage FC stack is used as the main power source, and SCs directly connected in parallel with FCs. The dc/dc power converter is used to convert the FC stack voltage into a sufficient dc-bus voltage in the driving inverter for supplying power to the propulsion motor. Furthermore, ES1 with rather higher voltage is used as the main battery storage device for supplying peak power, and ES2 with rather lower voltage could be an auxiliary battery storage device to achieve the vehicle range extender concept [13]. The function of the bidirectional dc/dc converter (BDC) is to interface dual-battery energy storage with the dc-bus of the driving inverter. Generally, the FC stack and battery storage devices have different voltage levels. Several multiport BDCs have been developed to provide specific voltages for loads and control power flow between different sources, thus reducing overall cost, mass, and power consumption [14-27]. These BDCs can be categorized into isolated and nonisolated types. In isolated converters, high-frequency power transformers are applied to enable galvanic isolation. A few isolated multiport BDC topologies have been investigated, such as the flyback, half- or full-bridge circuits, dual-active bridges, and resonant circuits [14-17, 20, 22, 24]. The literature suggests that nonisolated BDCs are more effective than typical isolated BDCs in EVs [18, 19, 21, 23, 25-27]. Liu et al. [18] derived nonisolated multi-input converter topologies by way of a combination of buck, boost, Ćuk, and Sepic. In [23], Wu et al. developed the three-port nonisolated multi-input-multi-output (MIMO) converter topologies for interfacing a renewable source, a storage battery, and a load simultaneously. The three double-input converters developed in [19] comprise a single-pole triple-throw switch and only one inductor. A modular nonisolated MIMO converter was presented in [26]. This converter is applied to hybridize clean energy sources of EVs and the basic boost circuit was modified and integrated. However, the voltage gain of the MIMO boost circuit is limited in practice, because of the losses associated with some components such as the main power switch, inductor, filter capacitor, and rectifier diode. To overcome this drawback, three-port power converter that has high-gain characteristic and contains FC, battery sources and stacked output for interfacing HEV, as well as a dc-microgrid was presented [27]. Although the multiport BDC discussed in [25] can interface more than two sources of power and operate at different voltage levels, it still has limited static voltage gains, resulting in a narrow voltage range and a low voltage difference between the highand low-side ports. This study proposes a new BDC topology for FCV/HEV power systems that consists of an interleaved voltage-doubler structure [9, 28] and a synchronous buck-boost circuit. It features two main operating modes: a low-voltage dual-source-powering mode and a high-voltage dc-bus energy-regenerating mode. In addition, the proposed converter can independently control power flow between any two low-voltage sources when in the low-voltage dual-source buck/boost mode. A similar topology was introduced in [29] that only describes a brief concept. By contrast, this study presents a detailed analysis of the operation and closed-loop control of this new topology as well as simulation and experimental results for all its modes of operation. Moreover, this study expanded the topology presented in [29] because the proposed converter can operate over a wider range of voltage levels. The main characteristics of the proposed converter are summarized as follows: 1) interfaces more than two dc sources for different voltage levels, 2) controls power flow between the dc bus and the two low-voltage sources and also independently controls power flow between the two low-voltage sources, 3) enhances static voltage gain and thus reduces switch voltage stress, and 4) possesses a reasonable duty cycle and produces a wide voltage difference between its high- and low-side ports.

A. Low-Voltage Dual-Source-Powering Mode

Fig. depicts the circuit schematic and steady-state waveforms for the converter under the low-voltage dual-source-powering mode. Therein, the switch S is turned off, and the switches (SES1, SES2) are turned on, and the two low-voltage dual sources (VES1, VES2) are supplying the energy to the dc-bus and loads. In this mode, the low-side switches Q3 and Q4 are actively switching at a phase-shift angle of 180°, and the high-side switches Q1 and Q2 function as the synchronous rectifier (SR).

4. RESULTS

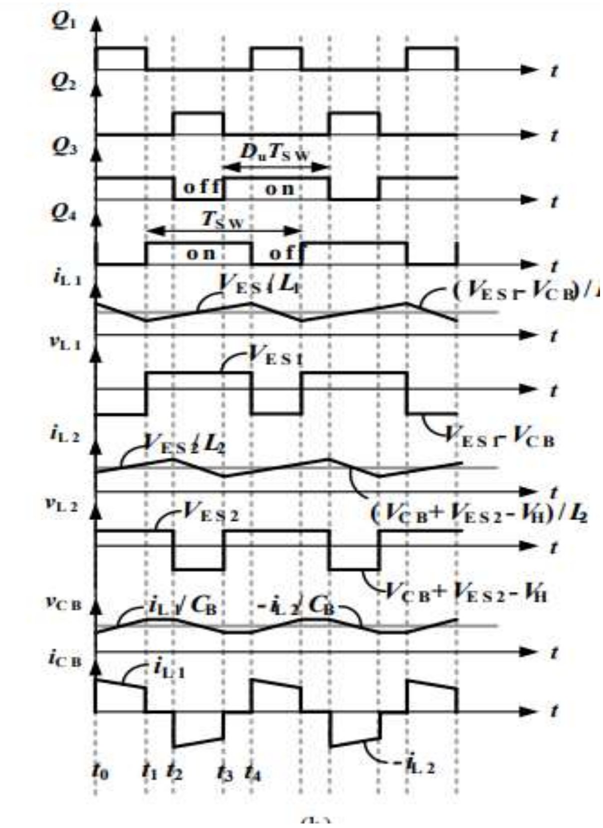

Fig. 3. Low-voltage dual-source-powering mode of the proposed BDC: (a) circuit schematic and (b) steady-state waveforms.

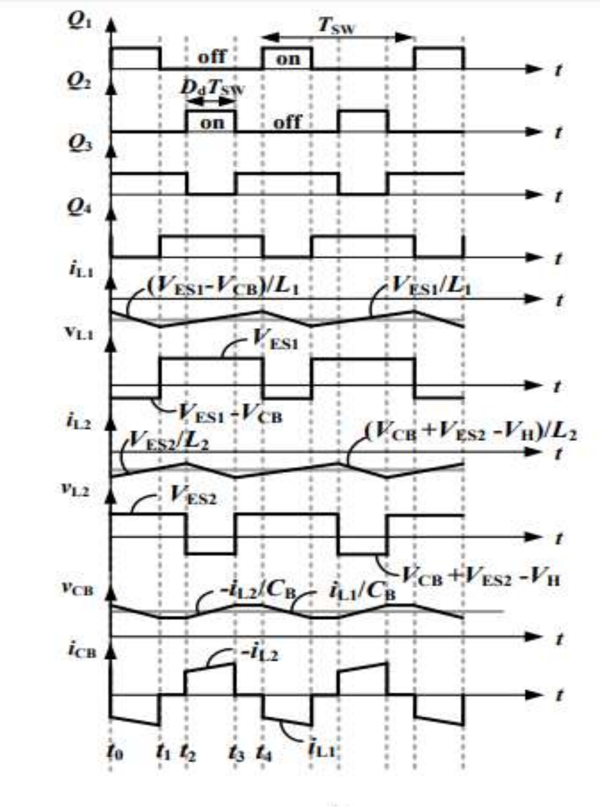

Fig. 4. High-voltage dc-bus energy-regenerating mode of the proposed BDC: (a) circuit schematic and (b) steady-state waveforms.

5.CONCLUSION

A new BDC topology was presented to interface dual battery energy sources and high-voltage dc bus of different voltage levels. The circuit configuration, operation principles, analyses, and static voltage gains of the proposed BDC were discussed on the basis of different modes of power transfer. Simulation and experimental waveforms for a 1 kW prototype system highlighted the performance and feasibility of this proposed BDC topology. The highest conversion efficiencies were 97.25%, 95.32%, 95.76%, and 92.67% for the high-voltage dc-bus energy-regenerative buck mode, low-voltage dual-source-powering mode, low-voltage dual-source boost mode (ES2 to ES1), and low-voltage dual-source buck mode (ES1 to ES2), respectively. The results demonstrate that the proposed BDC can be successfully applied in FC/HEV systems to produce hybrid power architecture (has been patented [37]).

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