

# Application of Bidirectional DC/DC Converter in Low Voltage Dual Powering Mode for Electric Vehicle

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**Abstract:** Bidirectional dc to dc converter (BDC) is used as a key appliance for interfacing the storage devices between source and load in renewable energy system for continuous flow of power. It interfaces the main energy storage (ES1), auxiliary energy storage (ES2), and dc-bus of system having different voltage levels. In our study, it is essentially focused for application in hybrid electric vehicle systems. Here, the converter is required to operate at step up mode or low voltage dual powering mode. In this study, a thorough glance of the circuit configuration, operation, and steady-state analysis of the BDC is discussed

**Keywords-** *bidirectional converter, dual storage, electric vehicle, operating modes*

## I. INTRODUCTION

Global climate changes and rapid decline in the energy supply is stimulating changes in the vehicular technology. Transportation system is gaining a lot of focus with policy changes; government policies to promote Electric vehicles, closure of diesel engine usage for domestic vehicles are some of the decisions that are witnessed recently. As far as transportation sector is concerned, government is focused on pushing in Electric vehicle sector. The R&D machinery is working on making technologies for application in electric vehicles to make it suit Indian market and Indian roads. Among such applications, fuel-cell hybrid electric vehicles (FCV/HEV) are efficient and promising candidates. Bidirectional dc to dc converter is used as a key device for interfacing the storage devices between source and load in renewable energy system for continuous flow of power because the output of the renewable energy system fluctuates due to change in weather conditions. The 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. Also, the model can independently control power flow between any two low-voltage sources (i.e., low-voltage dual-source buck/boost mode).

## II. LITERATURE REVIEW

Electric vehicle has been studied as an alternate traction system from ages. Our study is focused on the control scheme of Electric vehicle. Ehsani et al. studied the vehicles' dynamics to look for an optimal torque-speed profile of the electric propulsion system. Searching for a suitable traction motor is devised when vehicle dynamics, system architecture, characteristics, extended speed range-ability and energy efficiency, from vehicular system perspective.[1]

Emadi et al. discussed the operating properties of the topologies for different vehicles including HEV, FCV, and more electric vehicles. Series hybrid, parallel hybrid, and fuel cell-based propulsion systems are studied. Fuel-cell propulsion applications for light-duty passenger cars are also studied as an option. [2] In another study, Emadi et al. integrated power electronics intensive solutions in advanced vehicular power system for application huge vehicular load. The paper details the use of DC-DC and DC-AC converters to optimize the function of EV traction system [3].

Schaltz et al. sufficiently divide the load power among the fuel cell stack, the battery, and the ultra capacitors 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], also in another report, 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. In FCV systems, the

main battery storage device is commonly used to start the FC and to supply power to the propulsion motor [10].

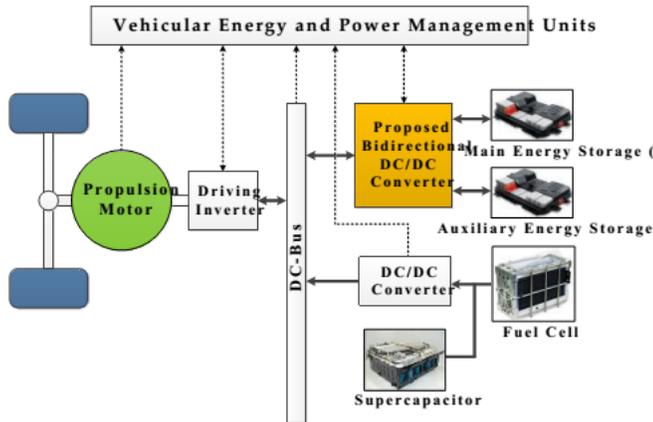


Fig.1.Functional diagram for a FCV/HEV power system

The battery storage devices improve the inherently slow response time for the FC stack through supplying peak power during accelerating the vehicle. Moreover, it contains a high power-density component such as super capacitors (SCs) eliminate 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 prolongs the life span of both FC stack and battery storage devices and enhances the overall efficiency of FCV systems [12].

The function of the bidirectional dc/dc converter (BDC) is to interface dual-battery energy storage with the dc-bus of the driving inverter. The study proposes a new BDC topology for FCV/HEV power systems that consists of an interleaved voltage-doublers structure [13] 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 [14] that only describe 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 [15] because the proposed converter can operate over a wider range of voltage levels. The main characteristics of expected from a good EV converter are:

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
4. Possesses a reasonable duty cycle and produces a wide voltage difference between its high- and low-side ports.

II. METHODOLOGY

The proposed BDC topology with dual-battery energy storage is illustrated in Fig. 2, where  $V_H$ ,  $V_{ES1}$ , and  $V_{ES2}$  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 ( $S_{ES1}$  and  $S_{ES2}$ ) 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 ( $V_{ES1}$ ,  $V_{ES2}$ ) and the high-voltage dc bus ( $V_H$ ) 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. This bidirectional power switch is implemented via two metal-oxide-semiconductor field-effect transistors (MOSFETs), pointing in opposite directions, in series connection.

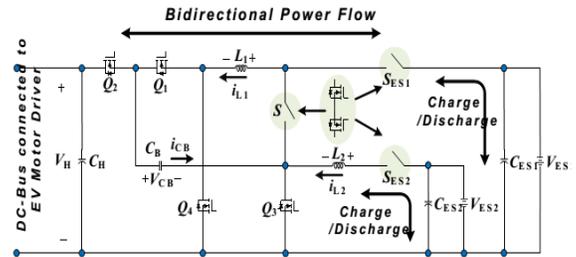


Fig.2. Proposed BDC topology with dual-battery energy storage

TABLE I: OPERATING MODES OF BIDIRECTIONAL DC/DC CONVERTER

ON	OFF	Control Switch	Sync. Rectifier (SR)	Operating Modes
SES1, SES2	S	Q3, Q4	Q1, Q2	Low-voltage dual-source-powering mode
SES1, SES2	S	Q1, Q2	Q3, Q4	High-voltage dc-bus energy-

				regenerating mode
SES1, SES2	Q1, Q2, Q4	S	Q3	Low-voltage dual-source buck mode
SES1, SES2	Q1, Q2, Q4	Q3	S	Low-voltage dual-source boost mode
-	SES1, SES2, Q1, Q2, Q3, Q4	-	-	System shutdown

### III. SYSTEM ANALYSIS

In this section, we analyze the voltage gain, switch voltage stress, and uniform average current sharing characteristics of the proposed BDC when operating in a steady state.

**A. Voltage Gain:** The voltage gains of the proposed BDC can be derived by applying the principle of inductor volt-second balance to the different modes. To enhance simplicity and practicality, the equivalent series resistances (ESRs) of the inductors L1 and L2 have been substituted into the state equations as non-ideal cases, and the parameters  $R_{L1}=R_{L2}=R_L=50m\Omega$  are also given.

#### 1) Low-Voltage Dual-Source-Powering Mode

The relationship among the voltage gains of the three dc sources under steady-state operation are given by;

$$\frac{V_H}{V_{s2}} = \frac{k+1}{1-D_u}$$

$$\frac{V_H}{V_{s1}} = \frac{k}{(1-D_u)(k+1)}$$

Where k is the ratio of  $V_{s1}=V_{ES1}$  to  $V_{s2}=V_{ES2}$ , and  $D_u$  is the duty cycle of Q3 and Q4 and is  $>50\%$ . Accordingly, the relation between dc-bus voltage  $V_H$  and the dual-source voltages ( $V_{ES1}, V_{ES2}$ ) is given by;

$$\frac{V_H}{V_{s1} + V_{s2}} = \frac{1}{1-D_u}; V_{s1} = kV_{s2}$$

**2) High-Voltage DC-Bus Energy-Regenerating Mode:** Under steady-state operation, the relationship among the voltage gains of the three DC sources is given by;

$$\frac{V_H}{V_{s1} + V_{s2}} = \frac{1}{1-D_u}; V_{s1} = kV_{s2}$$

$$\frac{V_{s1}}{V_H} = \frac{D_d k}{k+1}$$

$$\frac{V_{s2}}{V_H} = \frac{D_d}{k+1}$$

Accordingly, the relation between the dual-source voltages ( $V_{ES1}, V_{ES2}$ ) and the dc-bus voltage  $V_H$  is given by;

$$\frac{V_{s1} + V_{s2}}{V_H} = D_d; V_{s1} = kV_{s2}$$

Although these voltage gains are reduced by the ESR of the inductors under the non-ideal situation, the parasitic effect is relatively small and thus the reduced voltage gain can be easily compensated for by increasing the duty control.

#### 3) Low-Voltage Dual-Source Buck/Boost Mode

The relation between the two low-side voltages

$$V_{ES2} - V_{RL2} = D_s V_{ES1}; (\text{Buck mode})$$

$$V_{ES1} = \frac{1}{1-D} (V_{ES2} - V_{RL2}); (\text{Boost mode})$$

Where,  $D_s$  is the duty cycle of S for the energy transferred from the main energy storage to the auxiliary energy storage, whereas D is the duty cycle of Q3 for the energy transferred from the auxiliary energy storage to the main energy storage. The relationship between the two low-side voltages without the effect of the ESR of inductors can be expressed as;

$$V_{ES2} = D_s V_{ES1}; (\text{Buck mode})$$

$$V_{ES1} = \frac{V_{ES2}}{1-D}; (\text{Boost mode})$$

#### B. Charge-Pump Voltage

The voltage across the CB under different modes can be derived as follows.

##### 1) Low-Voltage Dual-Source-Powering Mode

$$V_{ES1} D_u + (V_{ES1} - V_{CB})(1 - D_u) = 0$$

$$V_{CB} = \frac{V_{ES1}}{(1 - D_u)}$$

##### 2) High-Voltage DC-Bus Energy-Regenerating Mode

$$V_{ES1}(1 - D_d) + (V_{ES1} - V_{ES2})D_d = 0$$

$$V_{CB} = \frac{V_{ES1}}{D_d}$$

**C. Voltage Stresses on Switches:** To simplify the voltage stress analyses of the converter, the voltage ripples on the capacitors were ignored. The maximum voltage stresses of the main power MOSFETs Q1~Q4 can be obtained directly as;

$$V_{Q1,max} = V_H$$

$$V_{Q2,max} = V_H - V_{CB}$$

$$V_{Q3,max} = V_H - V_{CB}$$

$$V_{Q4,max} = 2V_{ES1} - V_{CB}$$

**D. Characteristic of Uniform Average Current Sharing:** Through charge balance principles and the state-space

averaging technique, the averaged state equations can be obtained directly as;

$$\frac{2(i_{l1} - i_{l2})(1 - D_u)}{C_B f_{SW}} = 0$$

$$\frac{2(i_{l1} - i_{l2})D_d}{C_B f_{SW}} = 0$$

$$\frac{(i_{l1} + i_{l2})R_H - V_H}{R_H C_H} = 0$$

Where  $I_H = V * C_H / R_H$ .

Also;

$$i_{l1} = i_{l2} = \frac{i_H}{2}$$

From above equation, the uniform average current sharing can be determined, independent of the values of the capacitors.

IV. CONVERTER CONTROL

The converter control structure is as shown in figure 3, which consists of a vehicular strategic management level and the proposed BDC controller. The corresponding realized DSP flowchart for selecting operating modes of the proposed BDC is also shown in fig.4 for reference. The strategic management level involves electrical power demand estimation and contains a vehicular power and voltage management unit. The global results of the management must maximize the use of the source that best suits the power train power demand, fulfilling the driver and route requirement. In FCV/HEV power systems (Fig. 1), the dc-bus voltage of the driving inverter is regulated and powered by the FC stack through a dc-dc converter. Hence, instead of controlling the converter output voltage of each operation mode, the inductor current  $i_{L1}$  or  $i_{L2}$  is detected and compared with the reference current to control the power flow.

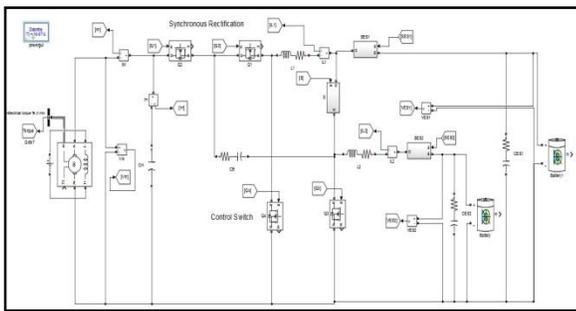


Fig.3. Closed-loop control Scheme

In the converter control structure, the vehicular energy and power and voltage management unit selects the BDC mode according to the operating conditions of the vehicle, such as power demand of different driving state ( $P_{dem}$ ) and the dual-source voltages ( $V_{ES1}$ ,  $V_{ES2}$ ). It then selects the appropriate current references  $i_{L1}$ , for  $i_{L2}$ , that can control the active

switches (S, Q1~Q4) with proportional integral (PI) or more advanced methods. Furthermore, referring to Table I, two switch selector ( $x1$ ,  $x2$ ) of BDC controller can be defined for various operating modes. The pulsed-width-modulation (PWM) switching scheme converts the duty cycle determined by different switch selector statuses into gate control signals for the power switches.

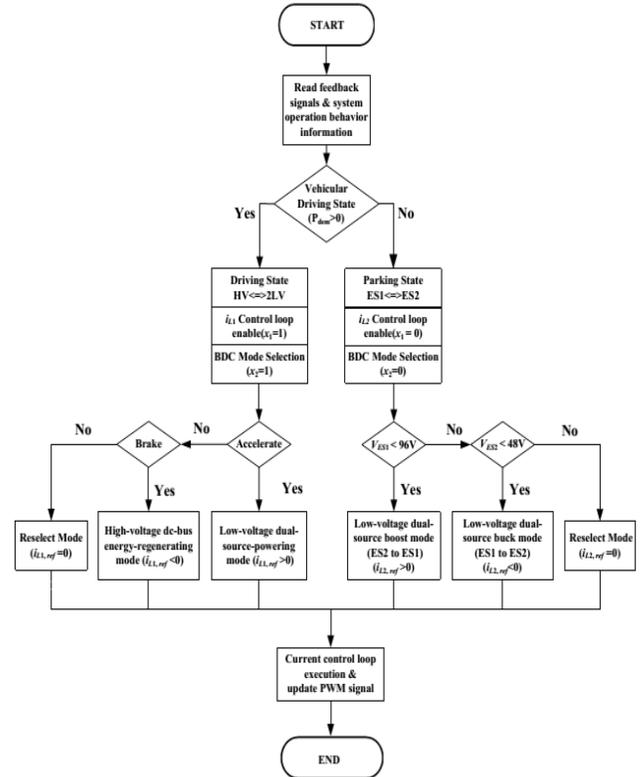


Fig.4. Flowchart for various operating modes of the proposed BDC

The current reference  $i_{L1,ref}$  is used to control the bidirectional power flow between the low-voltage dual-source and the high-voltage dc-bus (i.e., 2 LV to HV or HV to 2 LV). In either case, the average inductor current  $i_{L2}$  is equal to the controlled average inductor current  $i_{L1}$  because of the inherent uniform average current sharing in the proposed BDC topology. By contrast, the current reference  $i_{L2,ref}$  is used to control the power flow between the main energy storage and the auxiliary energy storage (i.e., ES1 to ES2 or ES2 to ES1). The procedure of mode switching is shown in Fig. 4. To design the closed-loop controller and simplify the mathematics of the proposed BDC, the MATLAB circuit model is built under the following three assumptions:

1. Power switches and diodes are ideal

- Equivalent series resistances of all inductors and capacitors of the converter are considered to obtain a relatively precise dynamic model
- The converter is operated under a continuous conduction mode.

### V. RESULTS AND DISCUSSION

Simulations were conducted to verify the performance of the system for low voltage dual source powering mode.

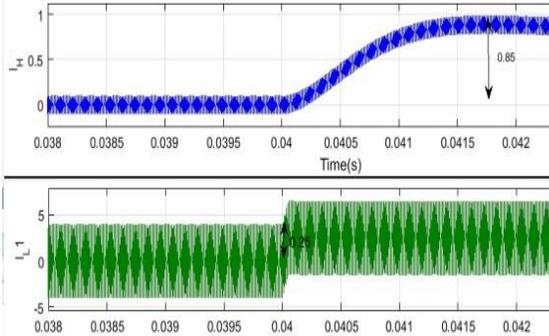


Fig.6. Controlled current step change in the low-voltage dual-source-powering mode: by simulation

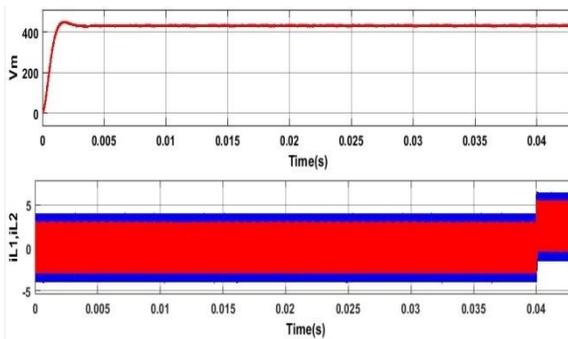


Fig.7. (a) Output voltage at HEV node in the low-voltage dual-source-powering mode (b) Variation of Inductor currents  $I_{L1}$ ,  $I_{L2}$

The system developed in this study included two loads for the low-voltage dual-source-powering mode. The waveform as shown in fig.6 represents that the current  $I_H$  has a considerable increase in its value by 0.85A as well as current through inductor  $L1$  increases by 0.25A with the operating mode of bidirectional converter.

### VI. CONCLUSION

BDC topology studied here interfaces a 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 BDC are shown on the basis of different modes of power transfer. Simulation highlights the performance and feasibility of BDC topology. The highest conversion efficiencies were 95.32% for low-voltage dual-

source-powering mode. The result demonstrates BDC can be successfully applied in FC/HEV systems to produce hybrid power architecture.

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