Novel Modular Multiple-Input Bidirectional DC-DC Power Converter (MIPC)

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Abstract- This paper proposes a novel multiple-input bidirectional DC-DC power converter to interface more than two dc sources of different voltage levels. This finds applications in distributed energy resources (DER), micro grid, and hybrid electric/fuel cell vehicles, where different dc sources of unequal voltage levels need to be connected with bidirectional power flow capability. Converter can be used to operate in both the buck and boost modes with bidirectional power control. It is also possible to independently control power flow when more than two sources are actively transferring power in either direction. This paper presents a power converter topology based on three switching legs of a standard 3-phase inverter module. The operation, analysis and design of the converter are presented with different modes of power transfer. Proposed converter is demonstrated for fuel cell vehicle application using real-time hardware-in-the-loop system. Results for a 5kW system are presented validating the theoretical analysis.

Keywords — Distributed Energy Resources (DER), Micro grid, Hybrid Electric/Fuel Cell Vehicles, Multiple Input Converter, DC-DC converter, Battery, Ultracapacitor.

I. INTRODUCTION

In a system like micro grid, different sources like diesel generator, fuel cell, solar photovoltaic (PV), and energy storage systems like battery or ultracapacitor need to be interfaced to three phase grid or to the load. Power conditioning circuitry is necessary to match the differences in voltages from these sources and storage systems. This also serves the purpose of control of power flow to achieve maximum power point tracking and strategies for energy storage system. A block diagram of such a system is shown in Fig. 1. Energy source could be PV, wind, fuel cell, or diesel generator supplying power to the dc link of the inverter through a power converter. Bidirectional power converter is necessary to assimilate energy storage like battery and ultracapacitors with the rest of the system to interface with the grid.

A number of topologies are proposed in literature [1-9] to transfer the power from one source to another in HEV and microgrid applications. In [1], multiple sources are interfaced at a common high-frequency transformer where each source is connected through full-bridge cells utilizing twelve switches for three sources. Both phase shift and duty ratio modulations are suggested. Similar operation is proposed with a half bridge circuit at each source in [2] with half the number of switches and supplementary capacitors. In order to reduce the ripple

current in the battery, current-fed half-bridge topology has been proposed in [3] with the phase shift modulation. Similarly multiple input isolated buck-boost and forward converters along with the stability analysis have been presented in [4]. All these bidirectional converters have galvanic isolation and are coupled together magnetically. Energy sharing between various sources is difficult to control in these types of topologies, although isolation gives better safety and more flexibility in selecting voltage levels. In non-isolated topology presented in [5], the battery and the ultracapacitor are cascaded using a bidirectional converter, which is connected in parallel to the fuel cell supplying a load. This does not provide the flexibility to vary the voltage across battery and ultracapacitor as they are connected directly across the fuel cell. Multiple bidirectional boost converters with various voltage sources are connected in parallel with output connected to common dc link to supply the inverter [6-8]. Voltages from several sources are boosted to dc link voltage with independent control of individual current delivered to the load. Similarly, regenerative energy is shared between the storages during braking. Voltage levels of input auxiliary sources are limited to below dc link voltage because it can only boost the input voltages and number of inductors required is equal to number of sources. Instead of additional dc-dc converter, Z-source (LC) network is used to interface fuel cell and battery in Z-source inverter topology [9]. Although this topology is suitable with optimal devices and components, number of voltage sources is limited to two and unable to extend this topology for multiple sources.

Disadvantage of most of these topologies is the difficulty in independent transfer of power between any two sources with wide variation in voltage levels. Few of the topologies have problems in scaling it to multiple sources. Hence, this paper proposes a multi-input power converter with the following characteristics:

- (a) *It is possible to interface more than two dc sources of different voltage levels and can be extended to any number of sources,*
- (b) *Ability to transfer power in both directions i.e. bidirectional power flow capability,*
- (c) *It is possible to control power flow between any two of the sources independently, and*
- (d) *It is simpler to design, implement and control.*

The topology shown in Fig. 2 can be built by connecting a switching leg with the sources through an inductor and a switching leg for each source. In order to interface a larger number of sources, connecting an

additional inductor and switching leg for each additional source can extend the topology. Although a similar topology is presented in [10], this paper presents detailed analysis and operation during all possible conditions. In addition, this topology has been extended to operate the converter over wide voltage levels. In [10], power flow between only two of the sources is demonstrated operating in boost mode from the battery/ultracapacitor to the dc link and buck mode in opposite direction.

Fig. 1: Block diagram showing application of multiple-input bidirectional converter.

The objective of this paper is to present the operation and steady state analysis of the proposed converter topology. The mode-by-mode operation of the converter is explained. The design procedure of the converter is presented. Analysis and design details for various modes of operation have been verified for a 5kW system using a real-time emulator based on Typhoon HIL-400.

II. OPERATION AND ANALYSIS OF THE CONVERTER

The proposed topology consists of a standard three-phase inverter modified by adding two high frequency inductors as shown in Fig. 2.

Fig. 2. Schematic of the proposed multiple-input bidirectional converter topology.

In the block diagram, sources V_{Bt} and V_{UC} represents energy storage system like battery and ultracapacitor, which are interfaced with the dc link of inverter V_{dc} . Two

legs of switch modules are connected to the DC voltage sources instead of dc bus. Another leg of the converter is connected to the dc link of the inverter, which is also fed by energy source through a dc-dc converter. If necessary more power/energy sources can be added by adding additional legs to the inverter. Operation of the converter under these modes of operation is discussed in the following sections.

A. Battery and Dc Link

In this mode of operation, energy stored in battery is transferred to dc link to supply load/grid. Switching sequence in this mode of operation is given in Table I. Inductor L_1 , connecting battery and dc link is storing energy from battery at first time interval T_1 by turning-on switches S_2 and S_3 . Battery voltage V_{Bt} appears across L_1 resulting in increase of current with a slope of V_{Bt}/L_1 . During time interval T_2 both the switches are turned-off. Inductor current i_{L1} , flows to dc link capacitor by forward biasing diodes D_1 and D_4 . Energy stored in L_1 during time T_1 is being discharged to C_{dc} in this interval with a negative slope of V_{dc}/L_1 . The flow of current through these diodes results in a voltage drop of around 1V-1.2V each. In the next time interval T_3 , switches S_1 and S_4 are turned-on. Current continues to flow from L_1 to the dc link through the switches as opposed to the diodes in T_2 . Switches S_1 and S_4 are made to operate as synchronous rectifier resulting in a reduced voltage drop to a level of around 0.2V, thereby improving system efficiency.

Under steady state operation, relation between dc link voltage and battery voltage is given by,

$$V_{dc} = \frac{T_1}{T_2 + T_3} \cdot V_{Bt} = \frac{D}{1-D} \cdot V_{Bt} \quad (1)$$

Where, D is the duty ratio defined by T_1/T_S . T_S is the time period of switching cycle, which is total of all three time intervals. If battery voltage V_{Bt} is less than the dc link voltage V_{dc} , the converter boosts V_{Bt} to V_{dc} by operating at $D > 0.5$. If battery voltage V_{Bt} is greater than dc link voltage V_{dc} , the converter charges the battery from dc link by operating at $D < 0.5$. The switching sequence for this operation is given in mode A(ii) of Table I. Principle of energy transfer remains the same; energy is stored in L_1 in interval T_1 and used to charge the battery in intervals T_2 and T_3 . Considering duty ratio D to be T_1/T_S , the relation between two voltages is given in (2).

$$V_{Bt} = \frac{T_1}{T_2 + T_3} \cdot V_{dc} = \frac{D}{1-D} \cdot V_{dc} \quad (2)$$

B. Ultracapacitor and Dc Link

Energy transfer from ultracapacitor to the dc link is explained in this subsection where voltage level of ultracapacitor needs to be boosted to the higher dc link voltage. Switching sequence for three distinct time intervals of operation is given in mode B(i) in Table I. For the time duration T_1 , inductor L_2 is charged by the ultracapacitor by triggering the switches S_2 and S_5 while the remaining switches are turned off. Current i_{L2} , increases linearly with a slope of V_{UC}/L_2 . Once inductor L_2 is charged for a predetermined time, both the switches S_2 and S_5 are turned off resulting in conduction of diodes

D_1 and D_6 . Energy stored in the inductor L_2 by the ultracapacitor is being utilized to charge the dc link capacitance and hence to supply the load. Since, voltage drop across these diodes are higher, corresponding MOSFETs S_1 and S_6 are turned on in the time interval T_3 . This effectively makes it a synchronous rectifier with reduced voltage drop subsequently reducing the losses in the converter. Voltages V_{dc} and V_{UC} are related by duration of these three time intervals and it can be calculated using (3).

$$V_{dc} = \frac{T_1}{T_2 + T_3} \cdot V_{UC} = \frac{D}{1-D} \cdot V_{UC} \quad (3)$$

In a hybrid vehicle system, ultracapacitor voltage V_{UC} is generally kept smaller than V_{dc} . However, this converter enables to interface two sources without changing the topology even though one voltage is either higher or lower than the other just by varying duty ratio D . Whenever, ultracapacitor needs to be charged from dc link, similar devices are switched as given in mode B(ii) in Table I. Direction of current flow in inductor L_2 is opposite to that of mode B(i), as the direction of power flow is now reversed. In this mode, it is important to observe the changes in switching devices in three different time intervals. Considering duty ratio D to be T_1/T_S , the relation between two voltages is given in (4).

$$V_{UC} = \frac{T_1}{T_2 + T_3} \cdot V_{dc} = \frac{D}{1-D} \cdot V_{dc} \quad (4)$$

In order to charge the ultracapacitor from dc link that is at higher voltage, converter is operated at $D < 0.5$.

C. Battery and Ultracapacitor

Whenever, energy stored in the battery needs to be transferred over to the ultracapacitor or vice versa, switching sequence given in Table I is followed. There are various permutations possible by switching four switches S_3 to S_6 , depending on the voltage levels of the two energy sources. While charging the ultracapacitor from the battery in mode C(i), converter can be operated in boost mode, buck mode, or buck-boost mode. Boost mode of operation is given where ripple in the battery current is smaller as compared to other two modes. This is chosen to improve the life of battery by reducing the peak value of charging or discharging current. If the ultracapacitor voltage is lower than the battery voltage, then buck mode can be adopted. During the process of charging of ultracapacitor, if its voltage increases from less than V_{Bt} to above V_{Bt} , then the controller needs to be seamlessly maneuvered from buck mode to boost mode of operation. On the other hand, buck-boost mode can be implemented simplifying the control by changing the value of duty ratio. Switching states given in Table I, the battery voltage is being boosted to charge the ultracapacitor. In this mode of operation, both the inductors L_1 and L_2 are storing energy during interval T_1 from the battery through switches S_3 and S_6 . At the end of this interval, switch S_6 is turned-off forcing the inductor current to flow through diode D_5 to charge the ultracapacitor. To decrease the voltage drop across D_5 , switch S_5 is gated on in the subsequent time interval T_3

operating as synchronous rectifier. Relation between the two voltages are given as,

$$V_{UC} = \frac{T_S}{T_2 + T_3} \cdot V_{Bt} = \frac{1}{1-D} \cdot V_{Bt} \quad (5)$$

Where, D is the duty ratio defined by T_1/T_S . In a similar operation, energy can be transferred from the ultracapacitor to the battery by switching same set of active switches S_3 , S_5 and S_6 but with different on-time durations resulting in opposite direction of current through the inductors as compared to mode C(i). Energy transferred from the ultracapacitor to the battery depends on the time duration T_1 for which switch S_5 is retained ON given by,

$$V_{Bt} = \frac{T_1}{T_S} \cdot V_{UC} = D \cdot V_{UC} \quad (6)$$

It is clear from the above equation that the energy can be transferred in this mode only if V_{Bt} is smaller than V_{UC} . If this condition is not met, then different mode of operation like boost or buck-boost can be used to control the switches without changing the circuit topology.

TABLE I CONDUCTION OF DEVICES IN DIFFERENT TIME INTERVALS OF THE MODES

	T_1	T_2	T_3
Mode A(i)	S_2, S_3	D_4, D_1	S_1, S_4
Mode A(ii)	S_1, S_4	D_2, D_3	S_2, S_3
Mode B(i)	S_2, S_5	D_6, D_1	S_1, S_6
Mode B(ii)	S_1, S_6	D_2, D_5	S_2, S_3
Mode C(i)	S_3, S_6	D_5, S_3	S_5, S_3
Mode C(ii)	S_5, S_3	D_6, S_3	S_3, S_6

D. Battery and Ultracapacitor to Dc Link

During peak power demand from the load/grid, battery unit and ultracapacitor provide the peak power demand due to its faster dynamic response as compared with the energy source like fuel cell system. In fuel cell vehicles, the auxiliary sources have to deliver rated power during the process of cold startup of the fuel cell system.

TABLE II. CONDUCTION OF DEVICES IN DIFFERENT TIME INTERVALS WHEN ALL THE THREE SOURCES/LOADS ARE ACTIVE

	T_1	T_2	T_3	T_4	T_5
Mode D	S_2, S_3, S_5	S_2, D_4, S_5	S_2, S_4, S_5	D_1, S_4, D_6	S_1, S_4, S_6
Mode E	S_1, S_3, S_5	D_2, S_3, S_5	S_2, S_3, S_5	S_2, S_4, S_5	S_1, D_3, S_5

Switching states during this mode of operation is given in Table II dividing the switching cycle T_S into five time intervals. Identical gate signals are given to switches S_1 and S_6 with a duty ratio of d_2 and complementary of this signal is being provided to switches S_2 and S_5 as demonstrated in Fig. 3. Gate signal for the switch S_3 is synchronized with that of switch S_1 having duty ratio of

d_1 . S_4 is switched complementary to switch S_3 with a dead time.

Fig. 3. Steady-state waveforms for mode D.

During interval T_1 , switches S_2 , S_3 and S_5 are gated-on charging both the inductors L_1 and L_2 by corresponding sources V_{Bt} and V_{UC} . Current increases with a slope of V_{Bt}/L_1 and V_{UC}/L_2 respectively as demonstrated in Fig. 4. At the end of this interval, switch S_3 is turned off providing freewheeling path for i_{L1} through D_4 . In interval T_3 , switch S_4 is switched-on in order to avoid voltage drop across the diode D_4 while inductor L_2 continues to charge from the ultracapacitor. Switches S_2 and S_5 are turned off at the end of interval T_3 , forcing current to flow through anti-parallel diodes of their corresponding complementary switches. Energy stored in the inductors L_1 and L_2 are transferred to the dc link through diode D_1 resulting in a voltage drop of 1V-1.2V. This voltage drop is reduced to the level of around 0.2V by gating on switch S_1 to act as synchronous rectifier. At the end of this interval, gating signals for each switching leg are complemented to start charging the inductors L_1 and L_2 going back to interval T_1 .

Current through and voltage across the inductors under steady state operation is given in Fig. 3. Applying volt-second balance for both the inductors, relation between the three voltages are given by (7) and (8).

$$V_{Bt} = \frac{T_4 + T_5}{T_1} \cdot V_{dc} = \frac{d_2 T_s}{d_1 T_s} \cdot V_{dc} = \frac{d_2}{d_1} \cdot V_{dc} \quad (7)$$

$$V_{UC} = \frac{T_4 + T_5}{T_1 + T_2 + T_3} \cdot V_{dc} = \frac{d_2 T_s}{T_s - d_2 T_s} \cdot V_{dc} = \frac{d_2}{1 - d_2} \cdot V_{dc} \quad (8)$$

Where, d_1 is the ratio of on-time of switch S_3 to total switching period T_s and similarly d_2 corresponds to switch S_2 . From (8), it can be observed that the d_2 can be calculated for a required boost ratio of V_{UC} to V_{dc} . Since the ultracapacitor voltage is assumed to be smaller than V_{dc} , the duty ratio d_2 is being functioned always below 0.5 with the voltage gain defined as M_2 . Variation in M_2 for change in d_2 between 0 and 0.5 is as shown in Fig. 6. On the other hand, the switch S_3 can be controlled with a duty ratio between 0 to $(1 - d_2)$ in order to boost the battery

voltage to dc link. The gain M_1 connecting V_{Bt} and V_{dc} is given in (9).

$$M_1 = \frac{V_{Bt}}{V_{dc}} = \frac{d_2}{d_1}; \quad M_2 = \frac{V_{UC}}{V_{dc}} = \frac{d_2}{1 - d_2}; \quad (9)$$

For a given value of d_2 , the minimum voltage gain M_1 can be obtained considering maximum value of duty ratio d_1 . It is clear from Fig. 4 that the maximum value of the boost ratio for the battery to dc link cannot exceed the boost ratio of the ultracapacitor to the dc link. Hence, this switching sequence can be employed only if V_{Bt} is higher than V_{UC} . However, switching sequence corresponds to the switching legs of battery and ultracapacitor needs to be interchanged if V_{UC} is higher than V_{Bt} . With the proposed converter it is possible to transfer energy from two sources of unequal voltage by independently controlling the share from each.

Fig. 4. Relationship between voltage gains between the three sources for mode D.

The proposed converter can be either voltage or current controlled, depending on the role of source in the overall system and their constraints. Total power required from the auxiliary sources can be shared between the battery system and the ultracapacitor bank based on factors like, charging current limitations of battery, state of charge (SOC), dynamics of the converter, etc.

E. Dc Link to Both Battery and Ultracapacitor

Kinetic energy stored in the traction drive is fed back to the source during regenerative braking operation. Since, a fuel cell stack lacks bidirectional power handling capability; battery bank plays an important role. During sudden braking condition, regenerative power can be much higher than the battery can absorb. Additional energy which battery cannot capture is utilized in charging ultracapacitor, which has higher power density as compared to battery. Switching sequence during this mode of operation is given in mode E of Table 2. In this mode of operation, L_2 is always connected to the ultracapacitor by keeping S_5 and S_6 in ON and OFF state respectively throughout the cycle. The switch pairs S_1 - S_2 and S_3 - S_4 are operated in complementary fashion with duty ratios of d_1 and d_2 as shown in Fig. 8 where d_2 is greater than d_1 .

Switches S_1 , S_3 and S_5 are turned-on in the time interval T_1 transferring energy from the dc link to charge both the auxiliary sources. Inductor currents i_{L1} and i_{L2} increase as V_{dc} appears at point A. At the end of T_1 , switch S_1 is turned-off providing free wheeling path for the inductor currents through diode D_2 . In order to reduce

the voltage drop across the diode, switch S_2 is gated ON to effectively function as a synchronous rectifier in T_3 . In order to control the charging of two sources independently, switch S_3 is turned-off and S_4 is turned-on maintaining the current through inductor L_1 as shown in Fig. 5. During this time interval, the inductor current i_{L2} continues to charge the. Switches S_2 and S_4 are turned-off at the end of the interval T_4 . Current in inductors flow from dc link to battery and ultracapacitor through switches S_1 , S_5 and diode D_3 . One cycle of operation completes when the switch S_3 is turned on providing path for i_{L1} by reducing the voltage drop across it.

Fig. 5. Steady-state waveforms for mode E.

Relationship between the three voltage sources can be derived by applying volt-sec balance across the inductors, which has been demonstrated in Fig. 5.

$$V_{Bt} = \frac{T_1 + T_5}{T_1 + T_2 + T_3 + T_5} \cdot V_{dc} = \frac{T_1 + T_5}{T_s - T_4} \cdot V_{dc} = \frac{d_1}{d_2} \cdot V_{dc} \quad (10)$$

$$V_{UC} = \frac{T_1 + T_5}{T_s} \cdot V_{dc} = d_1 \cdot V_{dc} \quad (11)$$

The ultracapacitor voltage V_{UC} is controlled by varying d_1 , which is related by (11). Energy transferred to the battery is regulated by changing the variable d_2 for a given value of d_1 . Voltage gain functions for both the voltage sources are defined and are obtained as,

$$M_1 = \frac{V_{UC}}{V_{dc}} = d_1; \quad M_2 = \frac{V_{Bt}}{V_{dc}} = \frac{d_1}{d_2}; \quad (12)$$

Fig. 6 shows the variation of voltage gain M_1 with respect to duty ratio d_1 , which is a linear function. However, the voltage gain for battery i.e. M_2 is a function of both d_1 and d_2 that can be changed by varying value of d_2 from 0 to $(1-d_1)$. For a given value of d_1 , minimum gain is obtained at a duty ratio of $(1-d_1)$ which is shown in Fig. 6. When both the auxiliary source voltages are less than dc link voltage, it is clear that the duty ratio d_1 has to be less than 0.5. Moreover, V_{Bt} needs to be higher than V_{UC} for this specific switching sequence. Otherwise,

S_3 has to be kept on while switching S_5 - S_6 at a duty ratio of d_2 .

Fig. 6. Relationship between voltage gains between the three sources for mode E.

III. DESIGN OF THE CONVERTER

For grid tied applications, it is assumed that a battery bank is required to support full power until ancillary sources can reach full power and/or peak efficiency. Similarly, during times when the auxiliary source needs to be reduced, excess energy can be stored into the battery bank. For a 5kW power converter, a battery bank of 144V, 17Ah will provide a maximum continuous current of at least 51A, providing a runtime of 30 minutes. Coupling this system with an ultracapacitor bank rated at 125V, 15F provides an additional 20 seconds of high power runtime for quick power bursts where the battery may not need to be engaged. The results of the operation of this grid-tied converter are presented in the following section.

In most practical systems, a traction motor, or grid-tied connection, is driven by a voltage source inverter (VSI) with a constant dc link voltage. A fixed voltage of 300V is chosen. The proposed converter can be built from a standard three-phase inverter by connecting three sources namely V_{dc} , V_{Bt} and V_{UC} to collector terminal of the top switches. Two inductors are inserted between midpoints of the three switching legs. Hence, it is very easy to construct the proposed converter without modifying driver part of the inverter. Values of inductors are designed to limit ripple current to a specific amount for a given switching frequency. Similarly capacitance at the dc link is also designed based on the allowed value of ripple in V_{dc} and switching currents.

IV. RESULTS

The proposed multiple-input dc-dc converter has been tested in various modes of operation discussed in previous section. For validation purpose, the following specifications are taken. $V_{dc} = 300$ V, output power $P_o = 5$ kW, switching frequency of 20 kHz. The details are as follows:

1. Battery bank: 144V, 17Ah Lithium-ion battery bank, voltage varies from 120V to 140V, series resistance of 30mΩ.
2. Ultracapacitor tank: 125V, 15F, parasitic inductance of 10μH, series resistance of 18mΩ.
3. Dc link capacitor: 3mF
4. Inductors: 0.75mH each.

5. The switches are controlled from DSP320F2808.

The above specified system has been implemented in a 'Typhoon HIL-400' Hardware-In-Loop (HIL) system to validate the analysis and performance of the system. The HIL real-time emulator comprises of an application-specific processing architecture based on a FPGA with fast analog/digital input and output interfaces with a supporting front-end software tool-chain performing the function of power electronics and energy storage systems like battery and ultracapacitors. With the minimum step time of $0.5\mu\text{s}$ and ultra-low latency of $1\mu\text{s}$, most of the experiments of power electronics and drives having switching frequency up to 50 kHz can be emulated. Accuracy and latency of HIL has been proved for various complex systems like grid-connected inverter [11]. Control of the semiconductor devices is being executed externally at a constant switching frequency of 20kHz using DSP.

In order to verify the analysis, the proposed converter is tested for different modes of operation explained in Section II and results are presented in Fig. 7 to Fig. 14. In mode A(i), energy is transferred from the battery to dc link shown in Fig. 7. V_{Bt} of 130V is boosted to V_{dc} of 300V to supply the grid load by transferring energy through inductor L_1 . Positive current of i_{dc} indicates the current flowing into dc link capacitor from the MIPC and similarly positive value of i_{Bt} shows discharge current of the battery. A smooth current of around 70A with small ripple is flowing through L_1 maintaining zero current from the ultracapacitor, which can be seen in i_{L2} . For power flow from dc link to the battery, experimental results are shown in Fig. 8. A negative current of approximately 20A through L_1 shows reversal of direction of flow with zero current flowing through L_2 and hence through ultracapacitor. Voltages across the switches S_2 and S_4 show dc link voltage and battery voltage respectively along with their states. Whenever, S_1 is ON, voltage V_{dc} appears across the switch S_2 which can be observed in waveform of V_{S2} . Similarly V_{dc} appears across S_4 when S_3 is gated on for the duration of $(1-D)T_s$. Peak to peak ripple current of 5A in L_1 validates the design selection of the inductors.

Fig. 7. Waveforms for operation in mode A(i): current through L_1 , i_{L1} (scale: 50A/div), current supplied to dc link, i_{dc} (scale: 100A/div), voltage across switch S_2 , V_{S2} (scale: 500V/div), and voltage across switch S_4 , V_{S4} (scale: 100V/div) (X-axis: 40μs/div).

Likewise, waveforms for transfer of energy from the ultracapacitor to the dc link are presented in Fig. 9. It is clear from the figures that voltage V_{UC} is being boosted to

V_{dc} by transferring current through L_2 maintaining zero current from the battery. Power flow control of each sources are possible without affecting the remaining sources. Since voltage across the ultracapacitor varies during discharge, current drawn from the ultracapacitor needs to be regulated by inclusion of closed loop control to vary the duty ratio based on the feedback information of current. Charging of the ultracapacitor from the dc link is performed by using switching sequence given in mode B(ii) and corresponding results are presented in Fig. 10. Current is fed from the dc link, hence negative waveform is seen in Fig. 10 along with the negative current i_{L2} charging the ultracapacitor tank.

Fig. 8. Waveforms for operation in mode A(ii): (a) current through L_1 , i_{L1} (scale: 25A/div), current supplied to dc link, i_{dc} (scale: 25A/div), voltage across switch S_2 , V_{S2} (scale: 200V/div), and voltage across switch S_4 , V_{S4} (scale: 200V/div) (X-axis: 20μs/div).

Fig. 9. Waveforms for operation in mode B(i): (a) voltage across switch S_2 , V_{S2} (scale: 200V/div), voltage across switch S_6 , V_{S6} (scale: 100V/div), current through L_2 , i_{L2} (scale: 50A/div), and current flowing into dc link, i_{dc} (scale: 50A/div) (X-axis: 40μs/div).

Fig. 10. Waveforms for operation in mode B(ii): (a) current through L_2 , i_{L2} (scale: 25A/div), current through L_1 , i_{L1} (scale: 100A/div), voltage across switch S_2 , V_{S2} (scale: 500V/div), and current flowing from dc link, i_{dc} (scale: 50A/div) (X-axis: 20μs/div).

Fig. 11 shows results for transfer of energy from the battery bank to the ultracapacitor. Waveform of V_{S4}

demonstrates the voltage across the switch S_4 . Top and bottom switches in each leg are operated complementary to each other and top switch of one leg is switched with bottom switch of another leg. Whenever switch S_3 and S_6 are ON, battery voltage V_{Bt} appears across switch S_4 and inductor current is getting charged from the battery. Ripple in i_{L1} or i_{L2} have reduced by half since the two inductors are in series in this mode of operation. Dynamic behavior of the converter in mode C(i) is presented in Fig. 11. Operating converter in a fixed duty ratio inductor current increases initially to charge the ultracapacitor and reduces the charging rate once it has reached the specific voltage. Negative current in L_2 implies charging of the ultracapacitor. Pulsating current flowing from the battery is also given which has envelope similar to waveform of i_{L2} but with opposite polarity.

Fig. 11. Steady state results for operation in mode C(i): (a) current flowing through L_2 , i_{L2} (scale: 25A/div), current flowing from the battery, i_{Bt} (scale: 25A/div), voltage across switch S_4 , V_{S4} (scale: 200V/div), and battery voltage V_{Bt} (scale: 100V/div) (X-axis: 20μs/div).

Functioning of the converter in mode C(ii) is same as that of mode C(i) except variation in duty ratio according to the voltages V_{Bt} and V_{UC} to reverse the direction of current flow from the ultracapacitor to the battery as shown in Fig. 12.

Fig. 12. Steady state results for operation in mode C(ii): current flowing through L_1 , i_{L1} (scale: 25A/div), current transferred to the battery, i_{Bt} (scale: 50A/div), and voltage across switch S_4 , V_{S4} (scale: 200V/div) (X-axis: 40μs/div).

In mode D, both the auxiliary sources are transferring energy to the dc link to drive the traction motor. Two sources with different voltage levels are boosting voltage to V_{dc} by switching all the devices as explained in Section II. Switch pair S_2 - S_5 is gated with the same signal of duty ratio d_2 with complementary signal given to switches S_1 - S_6 . When S_3 and S_5 are turned on, inductors L_1 and L_2 are

storing energy supplied from the battery and the ultracapacitor respectively as shown in Fig. 13(a). Switch S_3 is turned-off maintaining current i_{L1} for a short time before turning S_1 and S_6 to ON state. Since V_{dc} and V_{UC} are of same order, difference between the duty ratios d_1 and d_2 is very small. Energy is transferred to the dc link whenever switch S_1 is turned-on. The current flowing into the dc link capacitor, i_{dc} can be observed when V_{dc} appears across switch S_2 . Fig. 13(b) shows peak value of i_{dc} is sum of i_{L1} and i_{L2} indicating that the energy transferred to dc link is resultant of both the auxiliary sources.

(a)

(b)

Fig. 13. Steady state results for operation in mode D: (a) current flowing from the battery, i_{Bt} (scale: 50A/div), current through L_1 , i_{L1} (scale: 50A/div), current through L_2 , i_{L2} (scale: 10A/div), and current flowing into dc link, i_{dc} (scale: 50A/div) (X-axis: 20μs/div), (b) dc link voltage, V_{dc} (scale: 200V/div), voltage across switch S_2 , V_{S2} (scale: 200V/div), voltage across switch S_6 , V_{S6} (scale: 100V/div), and voltage across switch S_4 , V_{S4} (scale: 200V/div) (X-axis: 20μs/div).

Energy is being restored back to the battery and the ultracapacitor from dc link during regenerative braking. Since the battery voltage V_{Bt} is higher than the ultracapacitor voltage V_{UC} in this example, switch S_5 is maintained in ON state throughout this mode of operation, while switches S_1 and S_3 are being switched with duty ratio of d_1 and d_2 respectively. Voltage across S_2 and S_4 shown in Fig. 14(a) demonstrates unequal duty ratio in order to pump in regenerative energy to auxiliary sources of uneven voltages. Current through L_2 is also shown in the figure, which is same as current flowing into the ultracapacitor. Fig. 14(b) shows waveform of current supplied from dc link i_{dc} and charging current of battery i_{Bt} along with the voltage across ultracapacitor V_{UC} .

Fig. 14. Steady state results for operation in mode E: (a) current through L_1 , i_{L1} (scale: 10A/div), current through L_2 , i_{L2} (scale: 10A/div), voltage across switch S_2 , V_{S2} (scale: 200V/div), and voltage across switch S_4 , V_{S4} (scale: 200V/div) (X-axis: 20μs/div), (b) current flowing through L_2 , i_{L2} (scale: 10A/div), charging current flowing into the battery, i_{Bt} (scale: 25A/div), and current transferred from dc link, i_{dc} (scale: 50A/div) (X-axis: 20μs/div).

Emulation results shown here validate the proposed multiple-input DC-DC bidirectional converter topology. It can be observed that the experimental waveforms coincide well with the analytically predicted steady-state operating waveforms. Though the results have been emulated using hardware-in-the-loop real-time system for verification of the proposed converter, this can be applied to practical system finding applications in electric vehicles, smart-grid, and distributed energy resources. In this paper, an application for fuel cell hybrid electric vehicle has been demonstrated. However, the proposed topology can be applied to different applications where more than two dc sources of unequal voltage levels need to transfer energy between themselves. This can also be used in charge balancing of multiple battery banks.

V. SUMMARY AND CONCLUSION

This paper proposes a multiple-input bidirectional dc-dc converter to interface more than two sources of different voltage levels. The converter can be operated either in buck mode or boost mode in either direction of power flow. It is possible to control power flow between each pair of sources independently when more than two sources are active. The major advantage of the proposed topology is that it can be built from a standard three-phase inverter with few changes in connections.

This paper gives detailed analysis, modulation and operation of the converter for various modes. In each mode, relationship between the sources are derived which

assists in implementation of the controller. Design of the converter for a typical hybrid fuel cell vehicle has been explained where dc-link of the inverter, lithium-ion battery bank and ultracapacitor tank are being interfaced together. Typhoon based hardware-in-the-loop (HIL) real-time system has been used to emulate the designed converter to validate the performance. Results obtained from this system have been presented and match very well with the analytically expected waveforms. This converter not only finds application in fuel cell vehicles, this can be utilized in DER, smart and micro grid, battery management systems etc. where more than two dc sources need to be interfaced with bidirectional power flow capability.

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