A Novel Hybrid Energy Based Bidirectional Converter Using Space Vector PWM Control Strategy

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Abstract

This paper proposes a Novel Hybrid Energy based bidirectional dc–dc power converter using space vector pwm to interface more than two dc sources of different voltage levels. This finds applications in hybrid electric/fuel cell vehicles (FCVs), where different dc sources of unequal voltage levels need to be connected with bidirectional power flow capability. The converter can be used to operate in both the buck and boost modes using SVPWM with bidirectional effective power control. It is also possible to independently control power flow between any two sources when more than two sources are actively transferring power in either direction.

Index Terms—DC–DC power converter, fuel cell vehi-cle (FCV), hybrid electric vehicle (HEV), multiple-input converter.

I. INTRODUCTION

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A fuel cell vehicle (**FCV**) or fuel cell electric vehicle (FCEV) is a type of electric vehicle which uses a fuel cell, instead of a battery, or in combination with a battery or supercapacitor, to power its on-board electric motor. To start the operation of the FC system and also to share the load, a battery unit that can supply power to the same dc link is used. The battery unit also helps to overcome the slower response time providing peak power during the acceleration of the vehicle. In addition, the peak power transients during acceleration and regenerative braking can be avoided by the inclusion of a higher power density element such as an ultra capacitor. This can be used to store regenerative energy during deceleration to provide the supplemental power during acceleration. The ability of the ultra capacitor to handle higher power for higher number of charge/discharge cycles not only increases the life span of both the FC and battery but also improves the overall system efficiency.

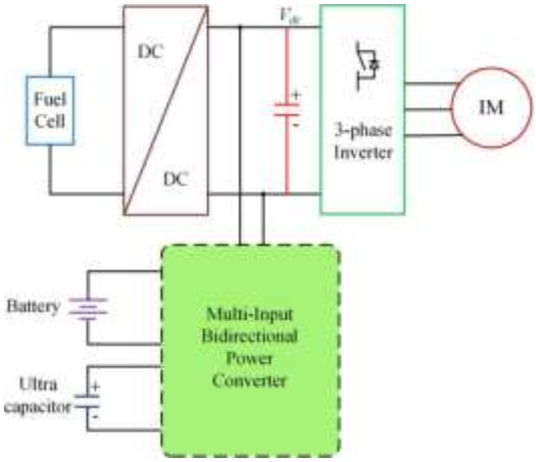


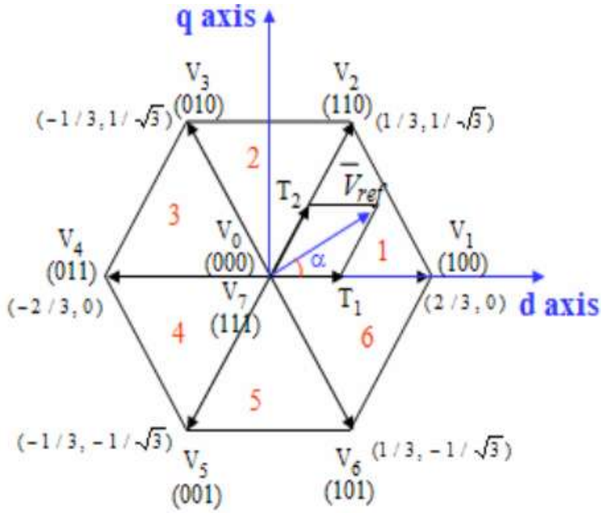
Fig. 1. Functional diagram of a hybrid FCV system.

A power electronic interface unit is required to match the voltage levels of the battery and the ultracapacitor units with the dc-link voltage V_{dc} of the inverter. The typical functional schematic of the power converter interface unit is shown in Fig. 1. The function of this multiple-input power converter is to interface these various sources with the dc link of the inverter and to regulate the power flow between the sources.

Space Vector pulse width modulation:

The space-vector PWM technique is used to produce the switching control signals to be applied to the three-phase inverter. The SVPWM inverter is used to offer 15% increase in the dc link voltage utilization and low output harmonic distortions compared with the conventional sinusoidal PWM inverter.

The fundamental difference between SVPWM and SPWM is the existence of two additional zero voltage states V0 (000), and V7 (111). In addition to the six possible voltage vectors associated with the VSI, there are two zero voltage states associated with having all three of the positive pole switches on or all three of the negative pole switches on. This fact allows more output voltage since the third harmonic component exists. Thus, SVPWM is often considered as an eight state operation.



In [17], multiple sources are interfaced using a common high-frequency transformer, where each source is connected through full-bridge cells utilizing 12 switches for three sources. Both phase shift and duty ratio modulations are proposed for control-ling the converters. A similar operation is proposed with controlling the converters. A similar operation is proposed with a half bridge circuit at each source in [18] using half the number of switches and supplementary capacitors. In order to reduce the ripple current in the battery, a current-fed half-bridge topology has been proposed in [19] with the phase shift modulation. Similarly, multiple-input isolated buck–boost and forward converters along with the stability analysis have been presented in [20]. Power sharing between various sources is difficult to control in these types of converters, although isolation gives better safety and more edibility in selecting voltage levels. In the nonisolated topology presented in [21], the battery and the ultra capacitor are cascaded using a bidirectional converter, which is connected in parallel to the FC supplying a load. This does not provide the edibility to vary the voltage across the battery and ultra capacitors as they are connected directly across the FC. In [22], energy flow between "N" different sources and

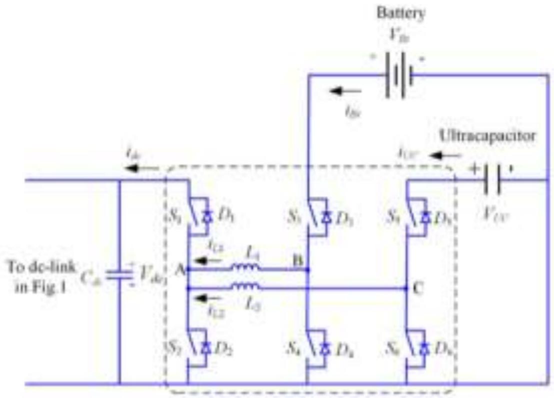


Fig. 2. Schematic of the proposed multiple-input bidirectional converter topology.

Multiple bidirectional boost converters are connected in parallel to interface multiple dc sources with its output connected to the common dc link to supply the inverter [23]–[27]. Voltage levels of the auxiliary sources are limited to below the dc-link voltage because it can only boost the input voltages. In [28], the same functionality is achieved using a Z-source converter. Although this topology is suitable with optimal devices and components, the number of voltage sources is limited to two, and it is not possible to extend this topology for multiple-input sources.

In this paper, a multi-input nonisolated bidirectional power converter with the flexibility of interfacing multiple sources is proposed. This converter has the minimum number of devices with independent transfer of power between any two sources with wide variation in voltage levels.

The main features of the proposed converter are as follows.

1) It is possible to interface more than two dc sources of different voltage levels and can be extended to any number of sources.

2) It has the ability to transfer power in both directions, i.e., bidirectional power flow capability.

3) It is possible to control power flow between any two of the sources independently.

4) It is simpler to design, implement, and control.

The proposed power converter topology shown in Fig. 2 can be built by connecting a switching leg for each source through an inductor. Additional sources can be added by having an additional switching leg and an inductor for each source. A similar topology is presented in [29] and [30], but power flow between only two of the sources is described—in boost mode from the battery/ultracapacitor to the dc link and in buck mode in the opposite direction. This paper presents detailed analysis, operation, and experimental results for all modes of operation. In addition, this topology has been extended to operate the converter over a wide range of voltage levels.

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. In the block diagram, sources V_{Bt} and V_{UC} represent the battery and ultracapacitor, which are interfaced with the dc link of inverter V_{dc}. Two legs of switch modules are connected to these dc voltage sources instead of the dc bus. Another leg of the converter is connected to the dc link of the inverter, which is also fed by an FC through a dc–dc converter. If necessary, more power/energy sources can be added by adding additional legs to the converter. The operation of the converter under these modes of operation is discussed below.

A. Power Transfer Between Battery and DC Link

In this mode of operation, the energy stored in the battery is transferred to the dc link to supply power to the load. The switching sequence of the power devices in this mode of operation is given in Table II.

TABLE I

COMPARISON OF THE PROPOSED CONVERTER

	[17]	[18]	[20]	[22]	[23], [24]	[28]	Proposed
Topology	Full-bridge	Half-bridge	Buck-boost	Buck-boost	Boost	Z-source	Buck-boost
No. of ports	3	3	3	3	3, 4	3	3
Extension to multi-port	Yes	Yes	Yes	Yes	Yes	No	Yes
Isolation	Yes	Yes	Yes	No	No	No	No
No. of switches	12	6	2	7	4	-	6
Bidirectional	Yes	Yes	No	Yes	Yes	Yes	Yes
Voltage range	Wide	Wide	Wide	Wide	Vi < Vdc	Limited	Wide
Power flow between any port	Yes	Yes	No	Limited	Limited	Limited	Yes
Control	Phase-shift	Phase-shift	Duty-ratio	Duty-ratio	Duty-ratio	PWM	Duty-ratio
Independent control of power flow	Yes	Yes	No	No	Yes	No	Yes

B. Power Transfer Between Ultracapacitor and DC Link

In a hybrid vehicle system, ultracapacitor voltage VUC is generally selected to be lower than Vdc. When ultracapacitor needs to be charged from the dc link, similar devices are switched as given in mode B(ii) in Table II. The direction of current flow in inductor L2 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 conducting devices in three different time intervals. Considering duty ratio D to be T1/TS, the relation between two voltages is given in

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

C. Battery and Ultracapacitor

Wheneverenergystoredinthebatteryneedstobetransferred over to the ultracapacitor or vice versa, the switching sequence given in Table I is followed. There are various combinations possible for switching the four devices S3 to S6, depending on thevoltagelevelsofthetwoenergysources.Whilechargingthe ultracapacitor from the battery in mode C(i), the converter can be operated in boost mode, buck mode, or buck–boost mode. The boost mode of operation is used when the ripple current in the battery is lower as compared to the other two modes of operation. This is chosen to improve the life of the battery by reducing the peak value of charging or discharging current. If the ultracapacitor voltage is lower than the battery voltage, it is operated in buck mode, and if its voltage increases from less than VBt to above VBt, then the controller needs to seamlessly maneuver from the buck mode to the boost mode of operation. On the other hand, buck–boost mode can be implemented,

TABLE II
CONDUCTION OF DEVICES FOR DIFFERENT 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_5
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 propulsion drive, the battery unit and ultracapacitor provide the peak power demand due to its faster dynamic response as compared with the FC system. In FCV, the auxiliary sources have to deliver rated power during the process of cold start-up of the FC system. Switching states during this mode of operation is given in Table III, dividing the switching cycle TS into five time intervals

TABLE III
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

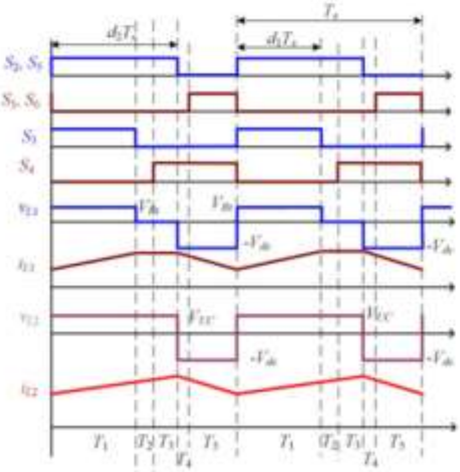


Fig. 3. Steady-state waveforms for mode D.

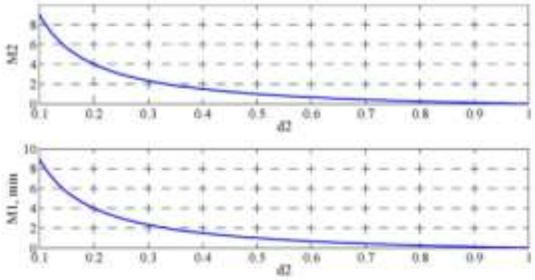


Fig. 4. Relationship between voltage gains between the three sources for mode D.

With the proposed converter, it is possible to transfer energy from two sources of unequal voltage by independently controlling the share from each. The proposed converter can be either voltage or current controlled, depending on the role of the source in the overall system and their constraints. The 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 the battery, state of charge, dynamics of the converter, etc.

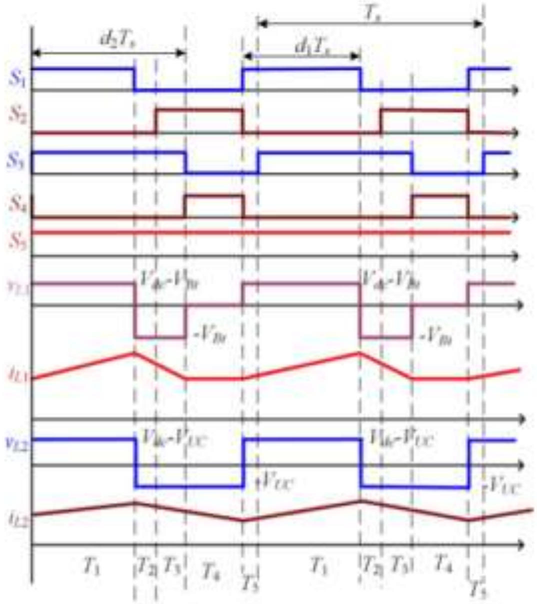


Fig. 5. Steady-state waveforms for mode E.

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. Regenerative power can be much higher than what the battery can absorb. Additional energy which the battery cannot capture is utilized in charging the ultracapacitor, which has higher power density as compared to the battery. The switching sequence during this mode of operation is given in mode E of Table III as shown in Fig. 5.

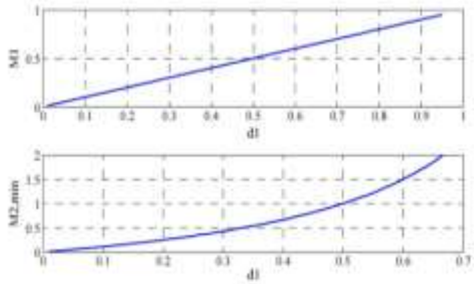


Fig. 6. Relationship between voltage gains between the three sources for mode E.

III. DESIGN OF THE CONVERTER For FCV

Application, it is assumed that a battery bank is required to support full power until FC is capable of generating the required power and/or peak efficiency. For a 5-kW power converter, a battery bank of 144 V and 17 Ah provides a maximum continuous current of at least 51 A, providing a run time of 30 min. Coupling this system with an ultracapacitor bank rated at 125 V and 15 F provides high power run time for quick power bursts where the battery may not need to be engaged. A fixed dc link voltage of 300 V is chosen as input to the voltage source inverter driving the traction motor. In mode A, it is necessary to choose the components to withstand a continuous power of 5 kW. For mode B and mode C, the power rating is chosen depending on the duration of operation in the respective modes. The values of inductors are designed to limit the ripple current to a specific amount for a given switching frequency. The minimum value of inductors required to maintain the specific current ripple in each mode of operation is calculated as given in Table IV. The highest of these inductor values is selected to ensure lower current ripple in any mode of the converter operation. The capacitance at the dc link is designed based on the allowed value of voltage ripple, switching frequency, and current ripple. The maximum value among the capacitance derived for individual modes is chosen. Similar to the selection of the inductors and capacitor, switching devices are designed by evaluating all possible modes of operation.

Mat lab design of case study and results

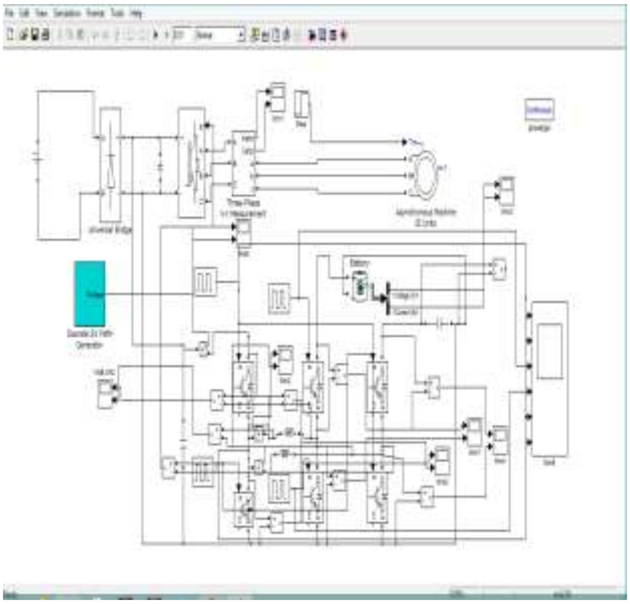


Fig. 7 Simulation Diagram

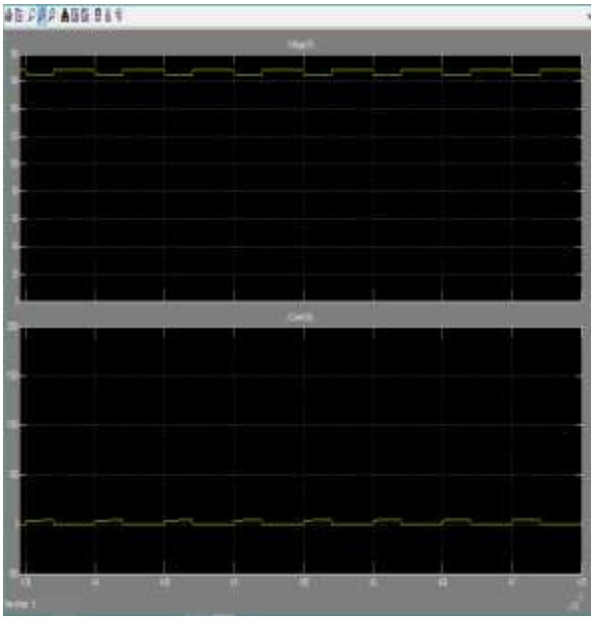


Fig. 8 Results for operation in mode D: (a) Current flowing from the battery, *iBt* and current flowing into dc link, *i*dc.

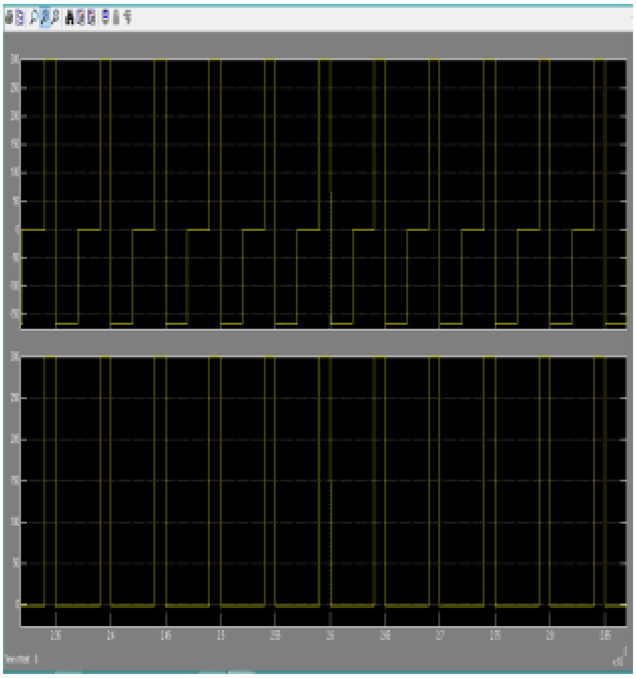


Fig. 9 Steady-state results for operation in mode E: a) voltage across inductor, *VAC*, b) voltage across battery Vcb.

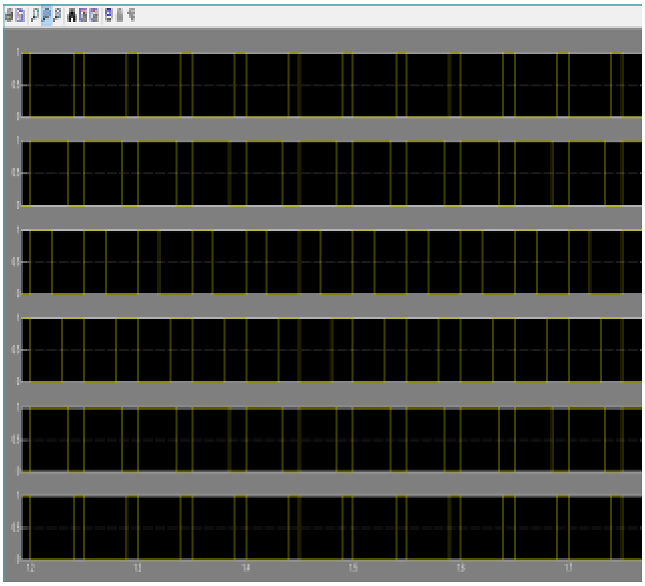


Fig. 10 Time periods of the switches

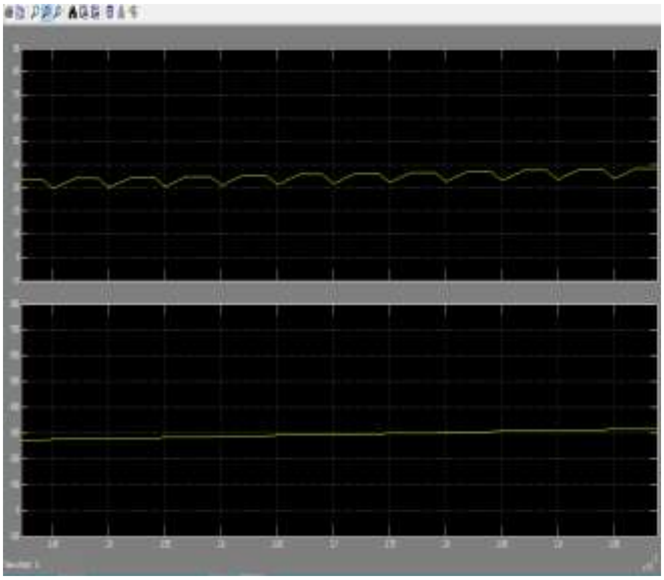


Fig. 11 Results for operation in mode D: (a) Current flowing from the $iL1$, $iL2$.

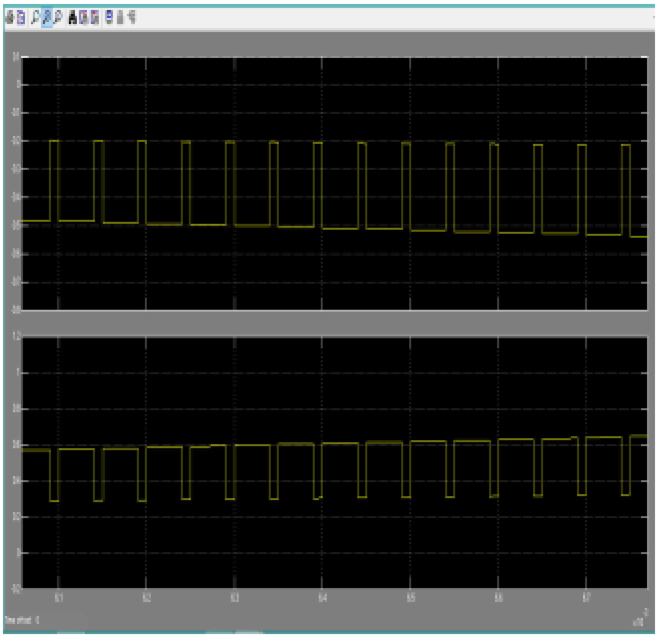


Fig. 12 Waveforms for operation in mode B(i): (a) Voltage across switch $S2$, $VS2$, voltage across switch $S6$, $VS6$.

CONCLUSION

This paper has proposed a multiple-input bidirectional dc–dc converter to interface more than two sources of power/energy operating at different voltage levels by using svpwm control strategy. The converter can be operated

By svpwm either in buck mode or boost mode in either directions of power flow. It is possible to control the power flow between each pair of sources independently when more than two sources are active.

Through various modes the detailed modulation and operation is implemented. In each mode, the relationship between the sources is derived which assists in the implementation of the controller.

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