A Novel Soft-Switching Bidirectional DC-DC Converter for Dual Voltage Automotive Systems

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Abstract—**This paper presents a new zero current switching bidirectional DC-DC converter for dual voltage automotive systems. The improved version of hard-switched DC-DC converter with an additional auxiliary resonant network, which is a combination of two auxiliary switches, two resonant inductors and two capacitors. The operating characteristics of this converter design is to transfer the power flow from low voltage to high voltage and vice-versa. The soft-turn on (ZCS) and soft-turn off (ZCS) operations are achieved by using two auxiliary resonant networks. In addition to that, the auxiliary switches obtain ZCS turn-on/ turn off operations, since additional losses are negligible. Minimized switching losses and improved efficiency are significant merits in this topology. The operation principles and design simulation analysis are reported in this paper in order to validate the theoretical analysis. The simulation of converter design is performed on 100/350V/500W converter system operated at 75 kHz switching frequency.**

Keywords— Automotive systems; Boost converter; ZCS DC-DC converter; Auxiliary resonant networks; Soft-switching DC-DC converter.

I. INTRODUCTION

In recent trends, the power converters plays a major role in energy storage systems based on ultra-capacitors and fuel cells. In early days of research, to balance the battery voltages and reduce electromagnetic interference (EMI), a 14V/42V magnetic less four level bidirectional converter [1] has been introduced. Therefore, usage of compact bidirectional converters were utilized more for such low voltage, low power application. For high power converter systems, another four level converter with switched capacitors [2] was developed. In order to increase the magnitude of output voltages and reduce the input inductor sizes, a multilevel boost converter [3] with a control of differential flatness theory has been introduced. Nevertheless, to attain optimization and stabilization of whole converter system, a voltage balancing technique for electric vehicle charging through the three level DC-DC converter has been reported [4].This technique enhances the usage of ESS (Energy Storage System) and also reduces the hardware requirements of the system. In the same way, to enhance the energy management and improve the performance of three level converter, online management algorithms through fast meta-heuristic approach were used [5]. To eliminate the additional balancing circuit and neutral-point currents, an active dc power balance management (APBM) [6] has been introduced. In recent past, to improve the performance of ultra-capacitors and also to obtain fast charging, a hard-switched three level bidirectional converter was designed [7]. However, this converter achieves the better efficiency at high DC bus voltages and high output power. To avoid usage of

the converters such as multilevel and galvanic isolated, a hybrid storage system is implemented with a series-parallel connection of three port converter [8]. However, this converter has minimized switching losses and ratings of the switching devices. Then researchers focused on reducing the number of semiconductors and efficiency to be increase in bidirectional converters for dual voltage automotive systems, which resulted in a hybrid switched capacitor BDC [9] topology with a combination of switched capacitors and conventional BDC. Therefore, this hybrid topology has reduced the current ripple in input inductor and improved efficiency over the existed ones.
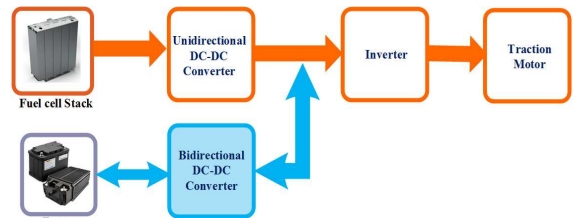

Fig.1 General structure of dual voltage automotive systems

BDCs with 360V/220V [8] and 14V/42V [10], are developed for dual voltage automotive systems to allow power flow to charge the battery and also to supply the required voltage to the inverter, when battery is in discharging mode. Fig.1 shows the general structure of dual voltage automotive system.
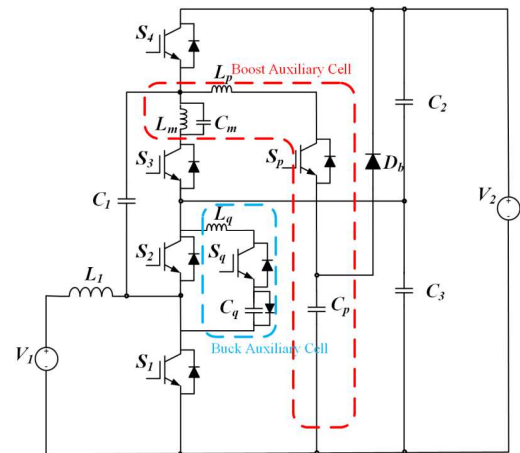

Fig.2 Proposed soft-switching bidirectional DC-DC converter

The additional feature, ZCS turn-on and ZCS turn-off conditions are achieved by utilizing two auxiliary cells in the proposed circuit, which work on wider voltage range unlike earlier versions. The switching losses and high power capability, are the main concern in the performance of the BDCs. Thus it is of interest to implement a new soft-

switching BDC with minimized losses and improved efficiency. The main attention of this paper is to design a new soft-switching three level BDC for dual voltage automotive systems. The soft-switching for the semiconductors results in improving the efficiency and provide flexibility to operate at high output power.

II. PROPOSED SOFT-SWITCHING BIDIRECTIONAL CONVERTER STRUCTURE AND ITS OPERATION

The proposed converter structure is illustrated in Fig.2, which comprises of four IGBTs S_1, S_2, S_3, S_4 which are the main switching devices, three capacitors C_1, C_2, C_3 and one inductor L_1. In addition to main converter devices, two auxiliary resonant networks are added to the conventional hard-switched BDCs [8] [10]. These auxiliary networks are named as boost and buck auxiliary cells. Auxiliary resonant network consists of two IGBTs S_p, S_q, two resonant inductors L_p, L_q and two capacitors C_p, C_q. In boost mode operation, the boost auxiliary cell provides soft-switching for the main switching devices. Similarly, in buck mode operation, the buck auxiliary cell provides soft-switching for the main switching devices. .
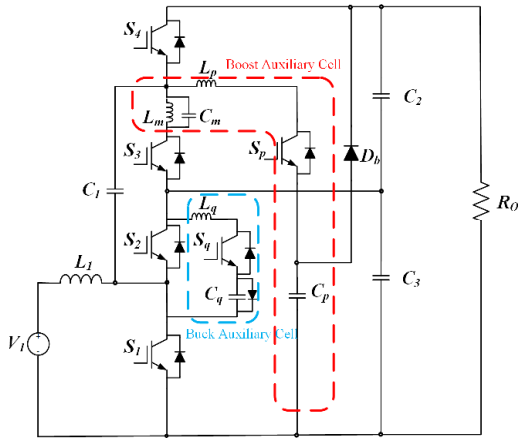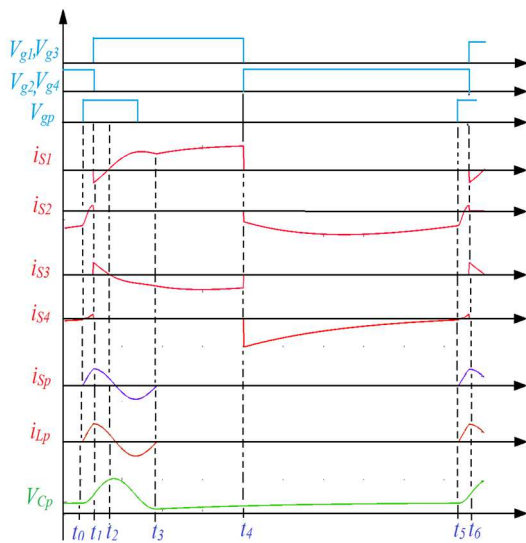

Fig.3 Equivalent schematic : Boost mode

Fig.4 Key waveforms : Boost mode

Equivalent circuits for boost and buck modes are illustrated in Fig.3 and Fig.6. Operation of boost mode are divided into

six modes for time intervals t_0-t_6 with the help of key waveform shown in Fig.4. Fig.5 (a, b, c, d, e) shows the boost mode equivalent current flow schematics of operating modes for time intervals t_0-t_5.
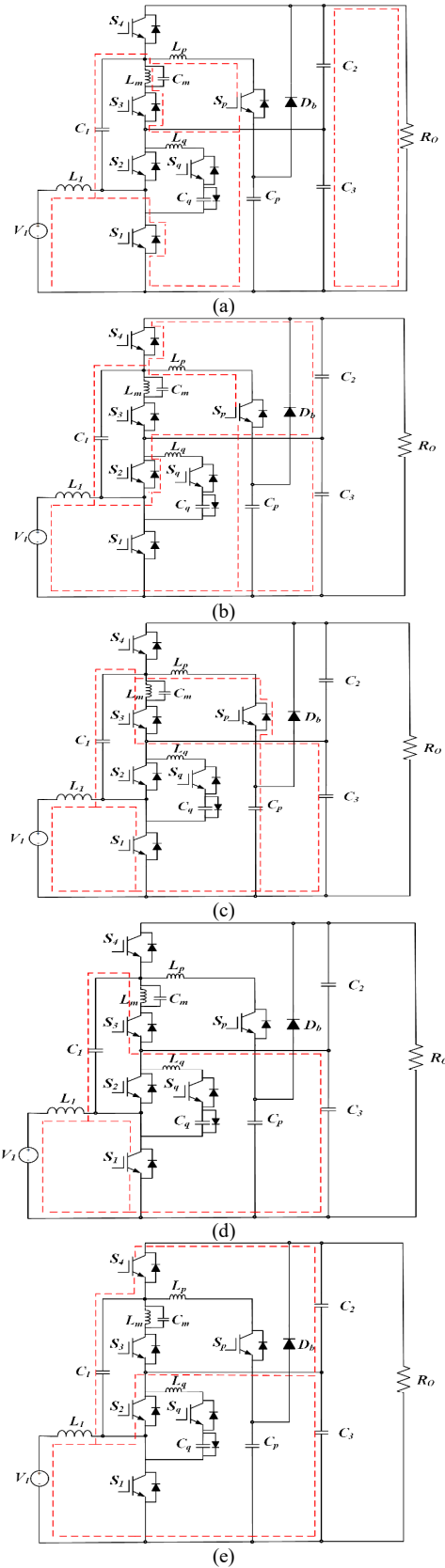

(a)

(b)

(c)

(d)

(e)

Fig.5 Operating modes (a) Interval(t_0-t_1) (b) Interval (t_1-t_2) (c) Interval(t_2-t_3) (d) Interval (t_3-t_4) (e) Interval (t_4-t_5) :Boost mode

A. Boost mode operation

At the beginning of this interval t_0, the auxiliary IGBT S_p is turned on and prior to t_0, S_2, S_4 are already in conducting state. L_p and C_p are resonating with each other, L_p current increases linearly and C_p charges to the level of input voltage. The current through the S_p increases from zero, since the ZCS turn on operation is achieved. The current through the S_2, S_4 falls to zero and after half of this interval, their body diodes conduct to allow resonant current. Therefore, the ZCS turn off operation is obtained.

At time t_1, the IGBTs S_1, S_3 are turned on, L_p current starts reducing and C_p discharges. This resonant current flows through the body diodes of S_1, S_3 until t_2. Hence, ZCS turn on is achieved in S_1, S_3. At t_1, the S_p current is reaches zero. At t_2, S_1, S_3 are turned on, a resonant peak current flows through the IGBTs S_1 and body diode of S_p starts conducting. During t_2-t_3 interval, the output power delivers via L_1-C_1-S_3-C_3-R_o-C_2-S_1. During the interval t_3-t_4, S_1, S_3 are in conduction state and the output power is delivered via L_1-C_1-S_3-C_2-R_o-C_3. At t_4, IGBTs S_2, S_4 are turned on and the output power flow through C_1-S_4-R_o-C_3-S_2. From t_5-t_6, repeats the operation same as interval t_0-t_1.

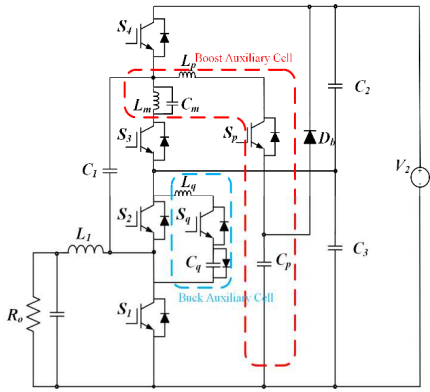## B. Buck mode operation

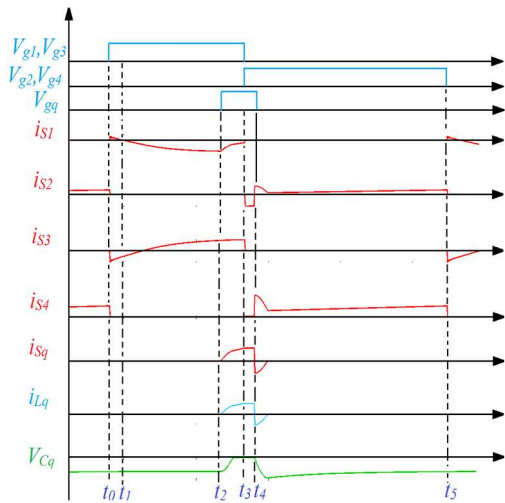Fig.6 Equivalent schematic : Buck mode

Fig.7 Key waveforms: Buck mode

Fig.6 shows the equivalent schematic of buck mode. The buck mode operation is similar to that of boost mode except for the direction of power flow. In this mode, the buck

auxiliary cell is used to obtain soft-switching operation to the main switching devices. Operation of this mode is described with the help key waveform shown in Fig.7. At t_0, S_1 S_3 are turned on. The voltage across these IGBTs reaches zero and their body diodes start conducting. Hence ZVS operation is achieved for IGBTs S_1 and S_3. At t_1, body diodes of IGBTs S_1, S_3 stops conducting. During t_1-t_2 interval, S_1, S_3 are in conduction state. At t_2, the auxiliary IGBT S_q is turned on to provide soft turn-on for S_2, S_4 and C_q is already charged to $-2V_2$. From t_2, C_q starts discharging and L_q current linearly increases to the level of output current. Due to resonance between L_q, C_q, the voltage across S_2, S_4 reduces to zero and current through S_1 reduces to zero. Therefore ZVS turn-on is achieved for S_2, S_4 and ZCS turn off operation is obtained for S_1. At the end t_3, the C_q is completely discharged and L_q current reaches to output current level. At t_3, IGBTs S_2, S_4 are turned on, the body diode of S_2 starts conducting and S_4 current is still zero. At t_4, S_q is turned off and body diode of S_2 stops conducting. At t_4, the body diode of S_q, starts conducting, C_q is charging, and L_q current starts decreasing. At t_5, C_q is charged to $-2V_2$ and L_q current is reduced to zero. During t_5-t_6 interval, S_2, S_4 are turned on. The output power delivers via V_2-S_4-C_1-L_1-R_o-C_3-S_3.

III. SIMULATION RESULTS

The proposed converter is designed by using MATLAB Simulink and its simulation results are presented in this section. The design simulation parameters of this converter are Boost mode input voltage V_1 : 100V, Buck mode input voltage V_2 : 350V, switching frequency : 75 kHz, Output power : 500 W, L_1 :100 µH, C_1, C_2, C_3 : 470 µF, C_p, C_q : 5nF and L_p, L_q : 25 µH.
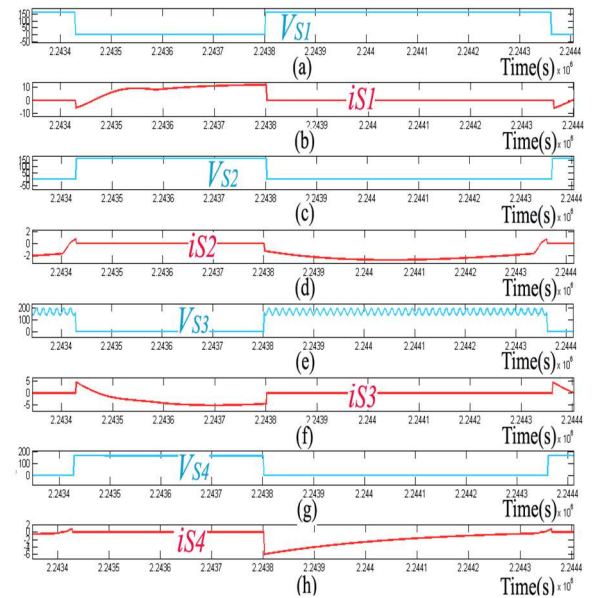

Fig.8 Simulated Results: collector-emitter voltage and collector current waveforms: Boost mode (a) V_{S1} (b) i_{S1} (c) V_{S2} (d) i_{S2} (e) V_{S3} (f) i_{S3} (g) V_{S4} (h) i_{S4}

Fig.8 (a, b, c, d, e, f, g, h) shows the voltage and current waveforms of the IGBTs S_1, S_2, S_3, S_4. It can be seen from the obtained boost mode results, that the zero current switching (ZCS) turn-on operation for IGBTs S_1, S_3 and ZCS turn-off operation for S_2, S_4 are achieved. The current

and voltage waveforms of S_p, L_p, C_p illustrated in Fig.9 (a, b, c, d).It is observed from the obtained results, the auxiliary switch S_p is turned-on and turned-off with ZCS condition. Similarly, simulations are carried out for buck mode operation. Fig.10 (a, b, c, d, e, f, g, h) shows the voltage and current waveforms of the IGBTs S_1, S_2, S_3, S_4. It is observed from these results, that the ZVS turn-on operation is obtained for S_1, S_2, S_3, S_4, IGBTs. The auxiliary switch S_q is turned-on and turned-off with ZCS. Fig.11 (a, b, c, d) depicts the current and voltage waveforms of S_q, L_q, C_q. The auxiliary switch S_q is turned-on and turned-off with ZCS.
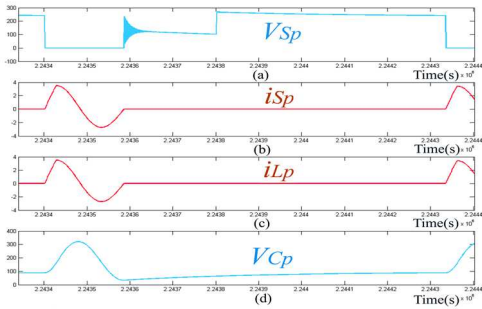

Fig.9. Simulated Results : Boost mode (a) V_{Sp} (b) i_{Sp} (c) i_{Lp} (d) V_{Cp}
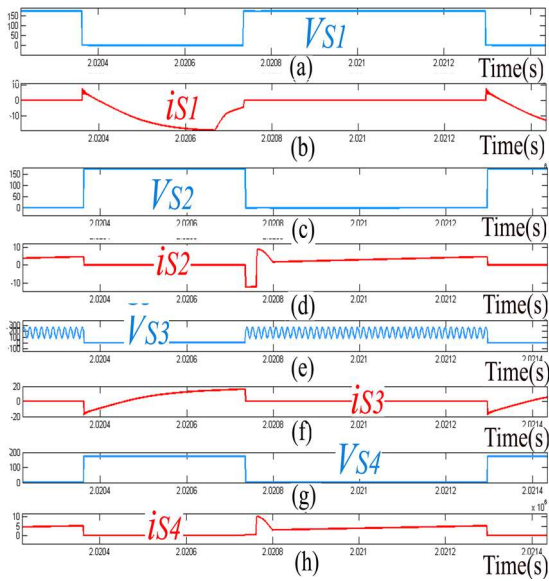

Fig.10 Simulated Results: collector-emitter voltage and collector current waveforms : Buck mode   (a) V_{S1} (b) i_{S1} (c) V_{S2} (d) i_{S2} (e) V_{S3} (f) i_{S3} (g) V_{S4} (h) i_{S4}
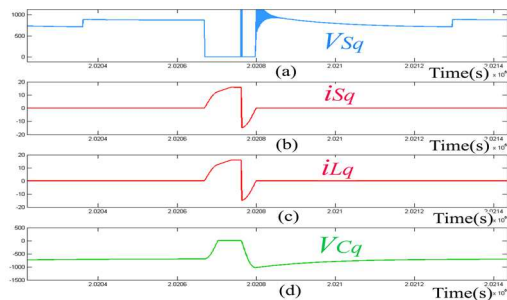

Fig.11. Simulated Results: Buck mode (a) V_{Sq} (b) i_{Sq} (c) i_{Lq} (d) V_{Cq}

IV. Conclusion

This paper proposes a new soft-switched bidirectional converter for battery storage applications in electric vehicles. The principles and simulation results are also discussed. The ZCS/ZVS turn-on is achieved in both the operating modes of boost and buck, respectively. The main advantages of this topology, especially when it is operating in boost mode, the main IGBTs and auxiliary IGBTs are soft turned-on and soft turned-off. While this converter is operating in buck mode, soft-turn-on of the main switch is achieved. The major advantage is that minimal reverse current flows through the diode of the main IGBTs. The simulation results verifies the theoretical analysis. Experimental analysis will be presented in next article. This proposed converter can be used for high power energy storage systems with reduced switching losses and improved efficiency.

Acknowledgement(s)

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