Comparative Simulation Analysis on High Gain Bidirectional and High Step-up DC-DC Converters

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Abstract— **This article mainly focuses on a comparative analysis on high gain bidirectional and high step-up soft-switching DC-DC converters for high gain high power applications. These converters are useful for high step up and step down conversion with reduced switching losses. These converters obtain zero voltage switching turn-on and zero current switching turn-off operation of the semiconductor switches by utilizing the simple series resonant capacitor and inductors respectively. The advantages of these converters are minimized voltage and current stresses, which improves overall converter efficiency. This paper describes the operational principles of bidirectional and high step-up converters as well and their simulation evaluations were compared in order to show their effectiveness of these topologies.**

Keywords - Buck, Boost, non-isolated, Zero voltage switching (ZVS), Zero current switching (ZCS)

I. INTRODUCTION

The bidirectional DC to DC converters are most popularly used to transfer from high voltage to low voltage and vice-versa. These converters are extensively used in many industrial applications such as uninterrupted power supply systems, hybrid electric vehicles, auxiliary supplies and battery banks for storing of energy etc. A variable inductor based bidirectional converter increases the saturation level and reduces its magnetic core size [1] of power inductor, because of variable inductor under the dynamic load variations leads to increasing the additional losses. However, the overall efficiency may reduce. A bidirectional DC-DC converter [2] implemented with the parallel connection of IGBT and MOSFETs were used to reduce conduction losses and improved the voltage gain. A loosely coupled inductor (LCI) based high power density interleaved boost converter [3] obtained improved efficiency and reduced power losses, respectively. However, the converter is cost-effective due to the SiC (silicon carbide) switching devices are used. A dual half bridge DC-DC converter [4-6] are obtained zero voltage switching to the semiconductor devices with the aid of leakage inductances of their high frequency transformer and snubber capacitors with the MOSFETs. They achieved a poorer efficiency, due to high switching frequency operated at higher output power levels. To choose an efficient DC-DC converters, a vast comparison of various converters is presented in [7], which are used to interface fuel cells in electric vehicles. The isolated soft switching converter achieves ZVS and ZCS with low efficiency by operating the circuit in discontinuous conduction mode (DCM) [8]. A non-isolated interleaved boost converter [9-10] achieved high gain and ZVS with the aid of coupled inductors and active clamping circuits, respectively. Furthermore, it has higher efficiency at low power and lower efficiency at high power. A cascaded buck-boost inductor in middle and cascaded buck-boost capacitor in middle converters [10] are comparing their efficiency at 10kW and achieved efficiency is 92%.

This article presents the comparative simulation analysis on high gain bidirectional [11] and high step-up DC-DC converters [12], respectively. The main intention of this paper is to evaluate the performance of DC-DC converters at different output power levels. The following section II presented the operation of high gain bidirectional and high step-up DC-DC converters as well, and then section III gives the simulation evaluations and their comparative analysis.

II. OPERATION OF HIGH GAIN BIDIRECTIONAL AND HIGH STEP-UP CONVERTERS

Fig.1 illustrates the soft switching bidirectional converter [11]. It comprised of dual half bridges (switches S_{1-4}) with a simple resonant circuit (L_a and C_a) to achieve ZVS turn-on operation. The circuit operation is divided into two parts, one is boost mode and another is buck mode. In boost mode of operation at a time two MOSFETs S_1, S_3 and S_2, S_4 are turned-on and due to the resonance of L_a and C_a, the soft switching ZVS turn-on operation is achieved for all the MOSFETs. By the way, when converter operating in buck mode, the MOSFETs S_1, S_3 and S_2, S_4 are turned-on and achieving soft switching ZVS turn-on for all the MOSFETs. Although, the ZCS turn-off obtained for the MOSFETs S_3 and S_4 in boost mode and S_1 in buck mode, respectively.

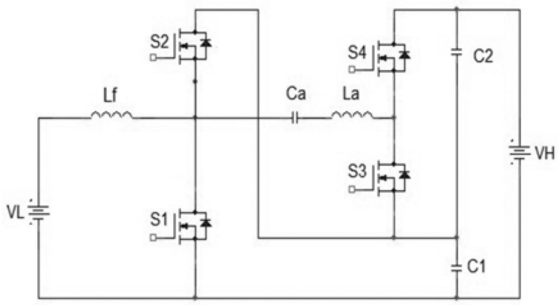

Fig. 1. High gain bidirectional DC-DC converter [11]

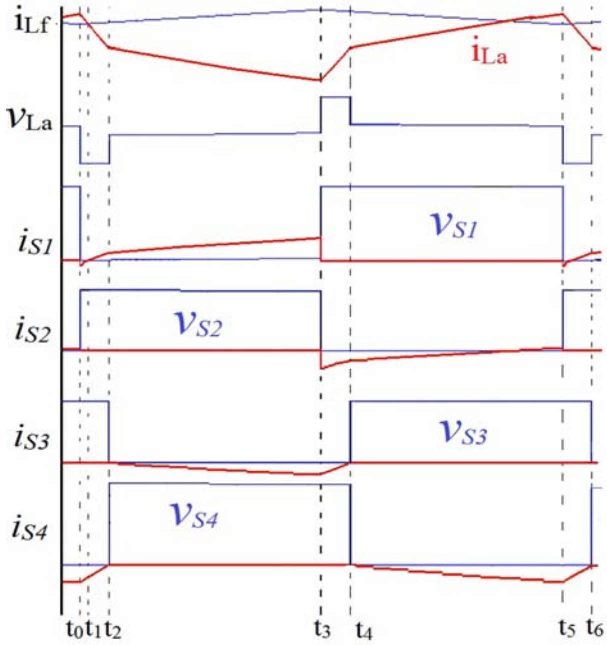

Fig. 2. Key waveforms of boost mode

A. Boost Mode Operation

Fig.2 depicts the chief waveform of boost mode. The operation of this converter is from time interval t_0-t_6, current flow schematics were shown in Fig.3 (a) to Fig.3 (e).

At initial state t_0, the MOSFETs $S_{1,}$ S_2 are in turn-off condition. From t_0, the output diodes of S_1 and S_4 are turned-on and whenever the gating signal supplied to the S_1, which will turn-on under ZVS condition. From the interval $t_{1,}$ current of (L_f) is greater than the inductor current (L_a) and S_1 is turned-on, current flows through the switch S_1 is equal to output current at t_2. The switch S_4 is turned off under ZCS turn off at t_2. From t_2-t_3, the current of L_a reverses and the body diode of S_3 is turned-on and then S_3 turned on under ZVS turn-on operation. From t_3-t_4 the MOSFETs $S_{1,}$ S_3 are turned-off and output diodes of S_2,S_3 are in turned-on respectively. At t_3, the gating signal is applied to S_2 and then turned-on under ZVS operation. From pervious stage, the body diode of S_4 conducts and at t_4, the MOSFET S_4 is turned-on under the ZVS condition.

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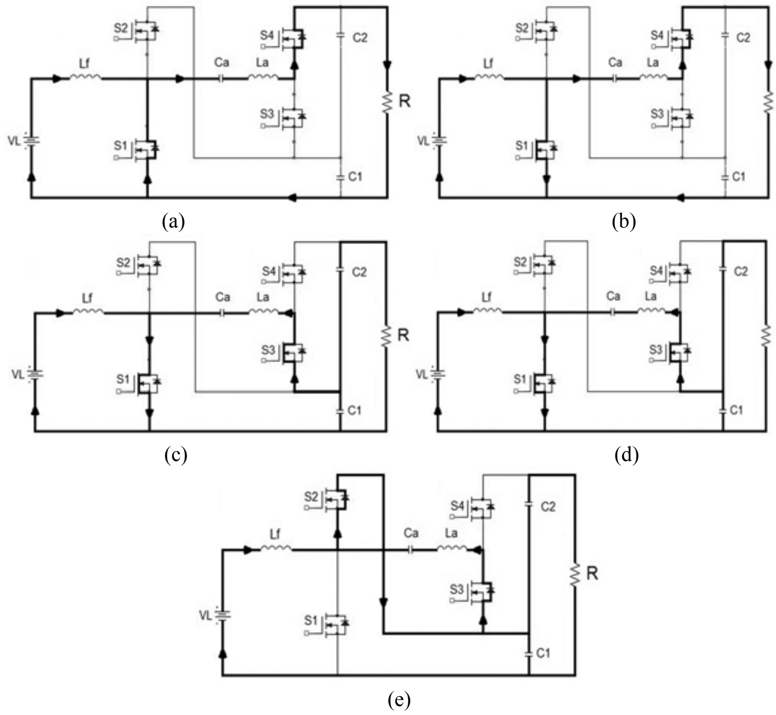

Fig. 3. Operating stages (a) t_0-t_1 (b) t_1-t_2 (c) t_2-t_3 (d) t_3-t_4 (e) t_4-t_5: Boost mode

B. Buck Mode Operation

In buck mode operation all the four MOSFETs are turned-on at different time intervals. In first three stages S_1, S_3 are conducting and second three stages S_2,S_4 will conduct. High voltage side is using S_3,S_4 switches with asymmetrical switching. Fig.4. represents the key waveform of buck mode. During t_0-t_1, the MOSFETs S_2,S_4 are turned-off and the diodes of S_1,S_3 are turned-on.

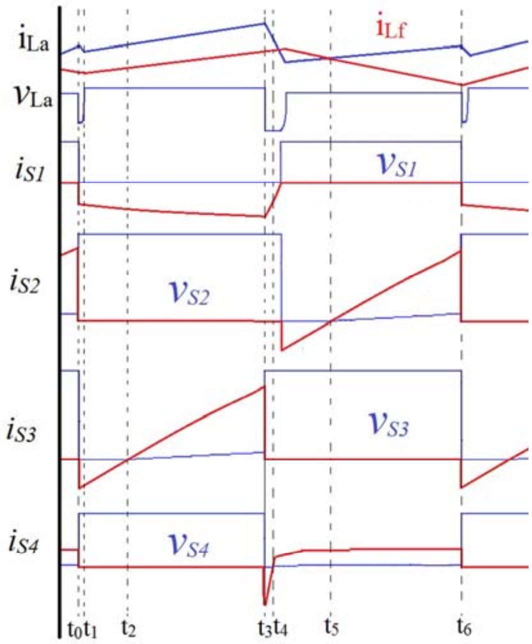

Fig. 4. Key waveforms of buck mode

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At t_1 S_1 ,S_3 are turned-on under the ZVS operation and resonant inductor (L_a) current decreasing smoothly. From t_2-t_3, the switches S_1,S_3 are being conducted and resonant inductor L_a current is reversed. At t_3, the switch S_3 is turned-off in hard-switching condition. And then S_1 is turned-off in zero current operation at t_4. The diodes of S_1,S_4 are turned-on and turned-off, respectively. At the end of this interval t_4, the MOSFET S_2 is turned-on, which implies that ZVS operation is achieved. From t_4-t_5, the S_2 is turned-on under the ZVS operation and the current L_a is greater than the current of L_f. During the interval t_5-t_6, the L_a current gradually increasing towards the output current and the MOSFETs S_2,S_4 are turned-off at time t_6. Fig 5 (a) to Fig.5 (f) shows the current flow schematics of buck mode from t_0 to t_5 intervals.

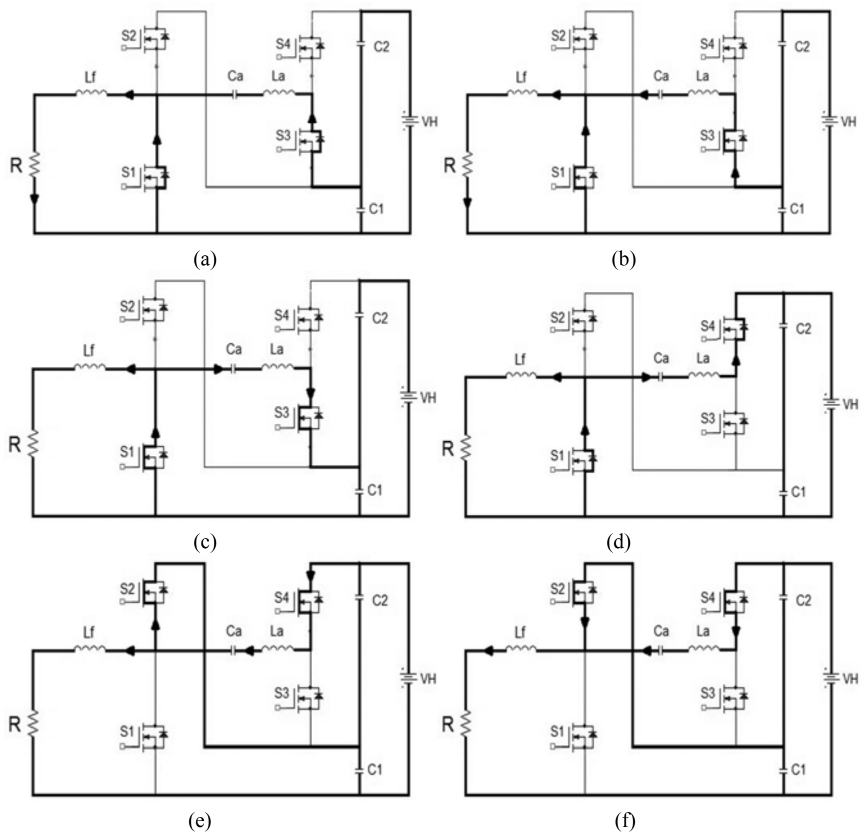

Fig. 5. Operating stages (a) t_0-t_1 (b) t_1-t_2 (c) t_2-t_3 (d) t_3-t_4 (e) t_4-t_5 (f) t_5-t_6: Buck mode

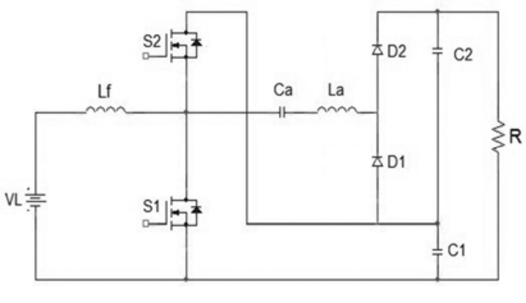

Fig. 6. High step-up DC-DC converter [12]

C. High Step-up Converter

Fig.6 depicts the existing topology [12] comprised of a single half-bridge switches S_1-S_2, diode rectifier (D_1,D_2). The operation of this topology is divided into two regions, one condition is switching frequency is below the resonance L_a,C_a and other is switching frequency above the resonant frequency. While converter is operating in below resonance frequency, the S_1 is turned-on with ZVS operation and the diode D_1 is turned-on with ZCS condition. And then, the ZCS turned-off condition obtained for diode D_1.Similarly for a subsequent period, the soft-switching operations ZVS, ZCS are achieved to the S_2 and diode D_2, respectively.

III. SIMULATION RESULTS & COMPARATIVE ANALYSIS

The circuit is designed and simulated using the MATLAB Simulink. Table I shows the simulation parameters considered for bidirectional converter and step-up converter.

TABLE I. Simulation Parameters

Parameter	**Bidirectional Converter**	**Step-up Converter**
Input Voltage(V_L)	70V	70V
Output Voltage(V_H)	250V	250V
Maximum output Power(P_o)	1.2kW	800W
Switching Frequency(f_s)	30 kHz	50 kHz
Input Inductor(L_f)	130µH	50µH
Resonant Inductor(L_a)	13µH	6µH
Resonant Capacitor(C_a)	30µF	2.7µF
Output Capacitors(C_1,C_2)	470µF	470µF

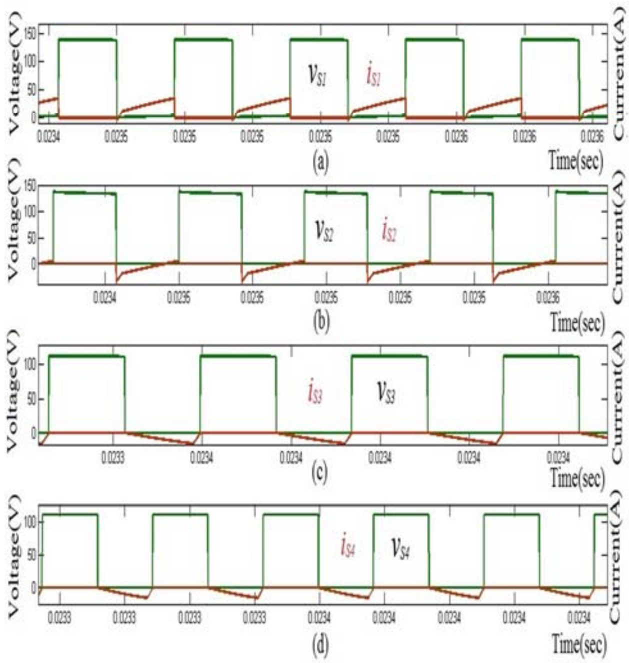

Fig. 7. (a,b,c,d) Simulation waveforms :Boost mode (a) Drain-source voltage (V_{ds}) & drain current(i_d) of S_1 (b) Drain-Source Voltage(V_{ds}) & drain current (i_d) of S_2 (c) Drain-source voltage (V_{ds}) & drain current (i_d) of S_3(d) Drain-source voltage (V_{ds}) & drain current (i_d) of S_4.

The high gain bidirectional DC-DC converter operates in boost and buck modes, respectively. Simulation analysis observed for boost mode in order to verify the theoretical assumptions. Fig.7 (a,b,c,d) shows the simulated waveforms drain-source voltage and currents of all the MOSFETs S_1,$S_2$and S_3,S_4. It is observed the zero voltage switching operation achieved with the all switching devices. Fig.8 (a,b) represents the voltage and current waveforms of L_a when converter operating in boost mode. Similarly, simulations are performed on buck mode simulation results of drain-source voltage and current waveforms are depicted in Fig.9 (a,b,c,d). Fig.10 (a,b) represents the current and voltage waveforms of L_a. The design, simulation analysis observed in two operating conditions for high step-up DC-DC converter. Firstly, simulation analysis made when the converter operating in below the resonance frequency. The resonant inductor (L_a) value 6µH and resonant capacitor (C_a) 1.5µF has chosen respectively. Fig.11 (a,b) illustrated the voltage and current waveforms of S_1 & S_2. Fig.11(c,d) shows current and voltage waveforms of L_a. The second condition considered when converter operating above resonant frequency, obtained results were depicted in Fig.12 (a,b) the voltage and current waveforms of S_1 & S_2.Fig.12(c,d) shows the current and voltage waveforms of L_a.

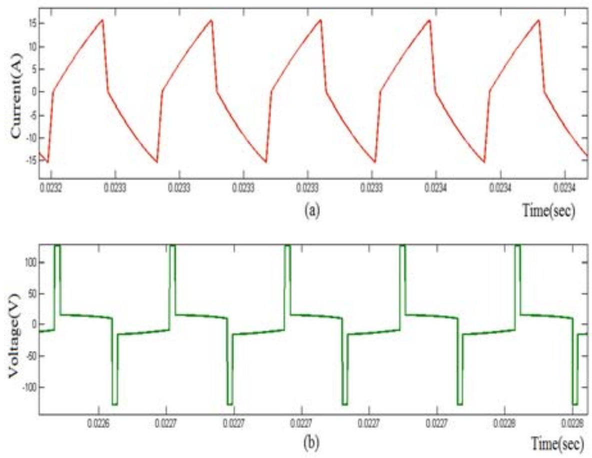

Fig. 8. (a,b) current and voltage waveforms of L_a : Boost mode.

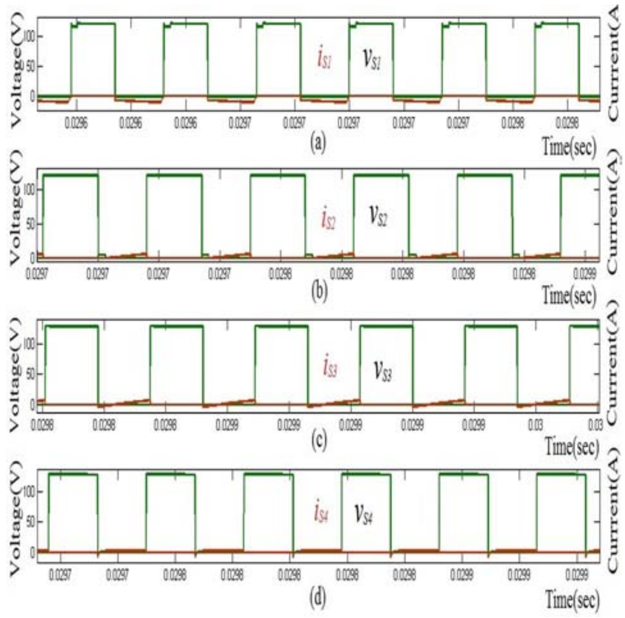

Fig. 9. (a,b,c,d) Simulation waveforms :Buck mode (a)) Drain-source voltage (V_{ds}) & drain current(i_d)of S_1 (b) Drain-source voltage (V_{ds}) & drain current(i_d) of S_2 (c)) Drain-source voltage (V_{ds}) & drain current(i_d)of S_3(d)) Drain-source voltage (V_{ds}) & drain current(i_d) of S_4.

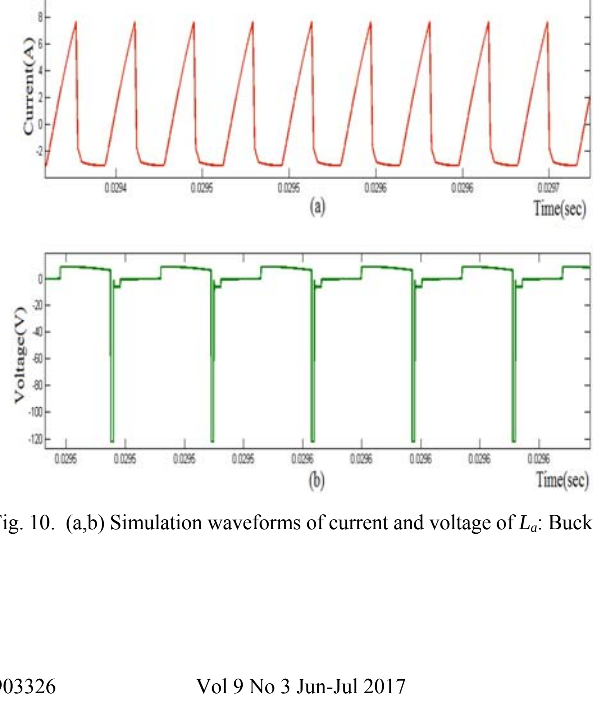

Fig. 10. (a,b) Simulation waveforms of current and voltage of L_a: Buck mode.

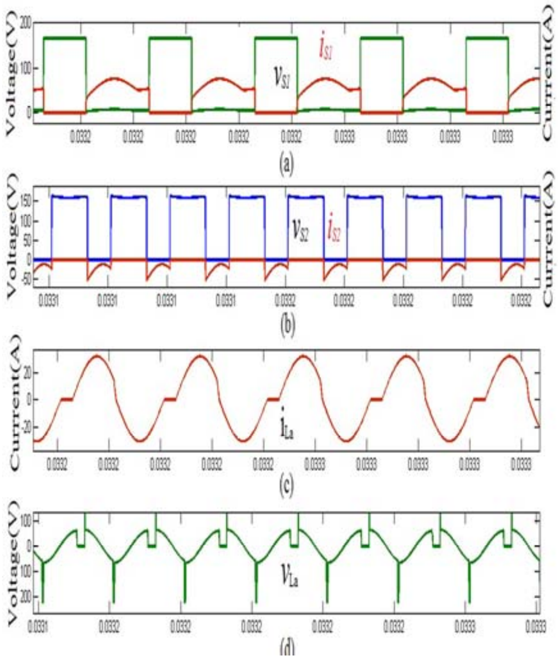

Fig. 11. (a,b,c,d). Simulation waveforms: High Step-up converter (a) Drain-source voltage (V_{ds}) & drain current (i_d) of S_1 (b)) Drain-source voltage (V_{ds}) & drain current (i_d) of S_2 (c) current of i_{La} (d) voltage through V_{La} : Below resonance condition of step up converter.

Table II shows the comparison on various parameters of high gain bidirectional and high step-up DC-DC converters, respectively. Simulated efficiency calculated the function of the output power to the input power for both the converters. The efficiency curves shown in Fig.13 and Fig.14 and the maximum efficiency obtained 99% at 1.2kW output power level for high gain bidirectional converter and 96.5% at 800 W output power level for high step-up DC-DC converter, respectively. The lower efficiency obtained 94.8% at 250W for high step-up and 96.7% at 250W for high gain bidirectional converters.

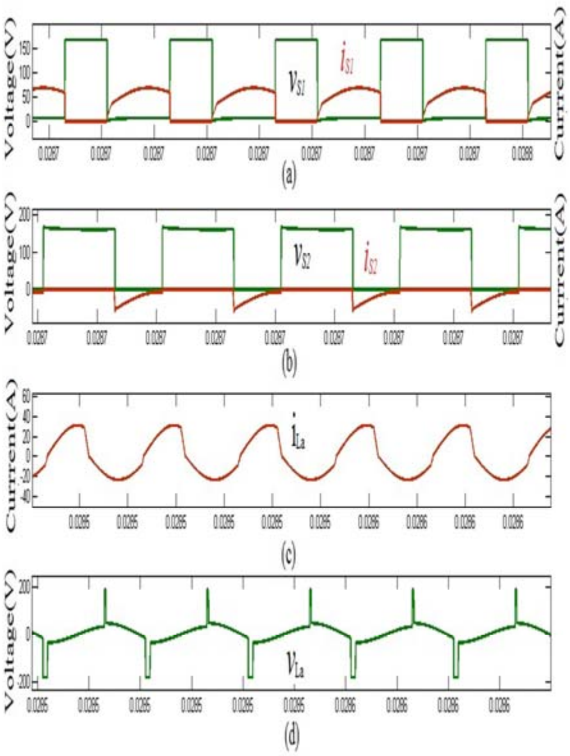

Fig. 12. (a,b,c,d). Simulation waveforms: High Step-up converter (a) Drain-source voltage (V_{ds}) & drain current(i_d) of S_1 S_1 (b) Drain-source voltage (V_{ds}) & drain current(i_d) of $S_1$of S_2 (c) current of i_{La} (d) voltage through V_{La} : Above resonance condition of step-up converter.

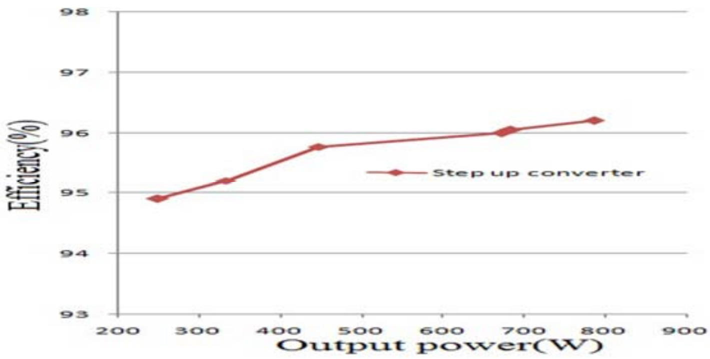

Fig. 13. Simulated efficiency: High Step-up converter

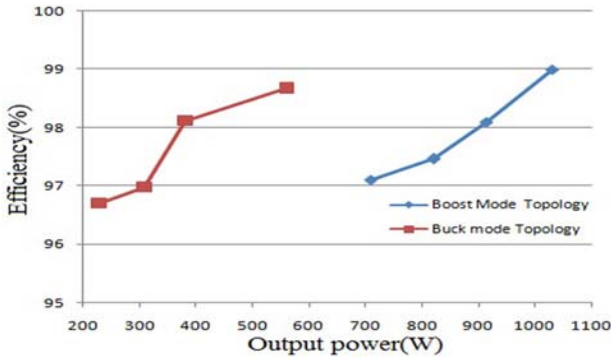

Fig. 14. Simulated efficiency: High gain bidirectional converter

TABLE II. Comparison of Converters

Performance parameter	**Topology[11]**		**Topology[12]**
	Boost mode	**Buck mode**	
Conduction loss	HIGH	HIGH	LOW
Soft switching	ZVS ,ZCS	ZVS ,ZCS	ZVS,ZCS
Total no of Components	HIGH	HIGH	LOW
No of auxiliary component	2	2	2
Simulation conditions	70V,1kW, 30kHZ	250V,700W, 30kHZ	70V,800W, 50kHZ
Simulated Efficiency (%)	99	98	97
Applicable power range	1kW-5kW	1kW-5kW	2kW
Cost	Costlier	Costlier	Less costly

IV. CONCLUSION

This article presented the comparative simulation analysis on high gain bidirectional and high step-up DC-DC converters, respectively. The operation principles, simulation results, and efficiency analysis are presented as well. The simulation evaluations performed on the MATLAB environment for both converters. The efficiencies of high gain bidirectional converter obtained 99% at 1.2 kW and 96.5% at 800 W for high step-up DC-DC converters. The cost of the high gain bidirectional converter is high due to increased component count and cost of the step-up converter is low because device count is reduced. Efficiency wise, the high gain bidirectional converter is preferable for high power application and high step-up converter can be applied for low power applications.

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