International Journal of Power Electronics and Drive System (IJPEDS)
Vol.2, No.3, September 2012, pp. 345~352
ISSN: 2088-8694

Simulation Based Performance analysis of Active Clamp DHB ZVZCS Bidirectional DC-DC converter for Low Power Applications

V.V. Subrahmanya Kumar Bhajana *
* Associate Professor, School of Electronics Engg, KIIT University,Bhubaneswar,India

Article Info

Article history:

Received Aug 9, 2012
Revised Sep 2, 2012
Accepted Sep 10, 2012

Keyword:

Active Clamp
DC-DC Converter
DHB
ZCS
ZVS

ABSTRACT

A novel active clamp dual half bridge DC/DC converter with bidirectional power flow is proposed in this paper and comparative analysis between active clamp DHB ZVZCS and ZVS-ZCS bidirectional DC-DC converter topologies is also presented. By adding active clamping circuits to both bridges, zero voltage and zero current switching are achieved to improve the performance of the bidirectional DC/DC converter. The principle of operation is analyzed and simulated. With the proposed active clamp ZVZCS concept, the MATLAB simulation results of the applications of the fuel cell and battery have been obtained and compared with those of ZVS-ZCS bidirectional converter. The simulation results of proposed converter is compared with the ZVS-ZCS bidirectional DC-DC converter, efficiency, switching losses are the key parameters compared.

Corresponding Author:

V.V.Subrahmanya Kumar Bhajana,
School of Electronics Engineering,
KIIT University,
Bhubaneswar, India 751024
Email: kumarbvvs@yahoo.co.in

1. INTRODUCTION

In Hybrid electric vehicles and rail guided shuttles electric power distribution systems operate at different voltage levels due to the availability of storage devices. Electric motors for traction and fuel cell is connected by a high voltage bus, while batteries and ultra capacitors are mostly connected by a low voltage bus. Bidirectional DC/DC converters controlling g the energy flow between these energy sources are thus required. The current fed Half Bridge and the voltage fed half bridge is the essential structure parts. Two voltage fed half bridge are the sub circuits of the Dual Half Bridge (DHB), which contain less components as the circuit under investigation and ZVS is achieved in the resonant stage [1]. The major advantages of the proposed circuit is that the switching losses are reduced and Low EMI is obtained because of active clamp circuits[2] is adapted to the ZVS bidirectional DC/DC converter [1]. An alternate topology is shown in Fig.2, consisting of current fed half bridge at the lower voltage level and voltage fed half bridge at high voltage side. When the energy flow from low voltage side to high voltage side is referred as boost mode; alternately this circuit works under buck mode. Advantages of this proposed concept is that the current tails through the main switches is reduced due to ZVZCS operating condition, DHB's are symmetrical and reduced components when compared with full bridges. An active clamp circuits is used in current fed half bridge and voltage fed half bridges to achieve the ZVZCS for the boost and buck mode of operations. A simple active clamping circuit is employed in [2] and [11] which suits for bidirectional DC/DC converters [1]. In this proposed circuit, active clamp circuit consists of an active switch and an energy storage capacitor and additional capacitor across main switches. In order to improve the efficiency of the proposed converter the switching stresses and losses has been reduced using this proposed concept for applications of fuel cell and battery. This paper presents a simulation of a new active clamp DHB ZVZCS bi-directional DC/DC converter. The converter is based on a dual half bridge topology with an clamping circuit in primary side and secondary side. The ZCS operation is obtained by both forcing the primary current towards zero and delaying its raise, or by resetting the primary current before the corresponding switch turned off. The ZVZCS bidirectional DC-DC converter has been simulated and developed for rectification and inversion operations in both buck and boost. The operating modes of the converter are described in the following section.The simulations are conducted for switching frequencies of 20 KHz with 50% duty cycle.

2. POWER STAGE DESCRIPTION

The conventional ZVS bidirectional DC-DC converter is shown in Fig.1. The active clamp DHB ZVZCS bidirectional DC-DC converter for fuel cell and battery applications is shown in Fig.2. The active clamping circuits are used in this converter and it can also be used in different DC/DC converter topologies, but this will be the scope of future work. In active clamp ZVZCS bidirectional DC-DC converter the clamping circuit is comprises of one switch, one energy storage capacitor, so that the zero current switching (ZCS) in main switches S_1 & S_2 can be obtained. Switch Sa is turned on under zero current switching (ZCS) condition. When power flows from the low voltage side to high voltage side and High voltage side to low voltage side, the circuit works in ZCS condition to turned off and ZVS condition to turn on the main switches S_1, S_2 in boost mode. In the other direction of power flow similar manner like boost mode, the circuit operates in ZVZCS condition (buck mode) the switches S_3, S_4 turned on/off. The transformer is used to provide isolation and voltage matching. The leakage inductance of the transformer is utilized as an interface and energy transfer element between two half-bridges. The two voltage source half-bridges each generates a square wave voltage applied to the primary and secondary of the transformer, respectively. Because of the symmetry property DHB operates under only one time period. The major drawback of this converter is TDR penalty because of the existence of clamping circuit in primary side. The TDR of the proposed active clamp ZVZCS bidirectional DC/DC converter is calculated as TDR = 2Vdc. Iac. (3 devices) = 6 Po, Where Po is again the output power. The TDR has been increased for the active clamp ZVZCS converter and the ZVS-ZCS bidirectional DCDC converter [15] is same output power. The main advantage of the circuit Fig.1 is that the current stresses are reduced for the low voltage side main switch

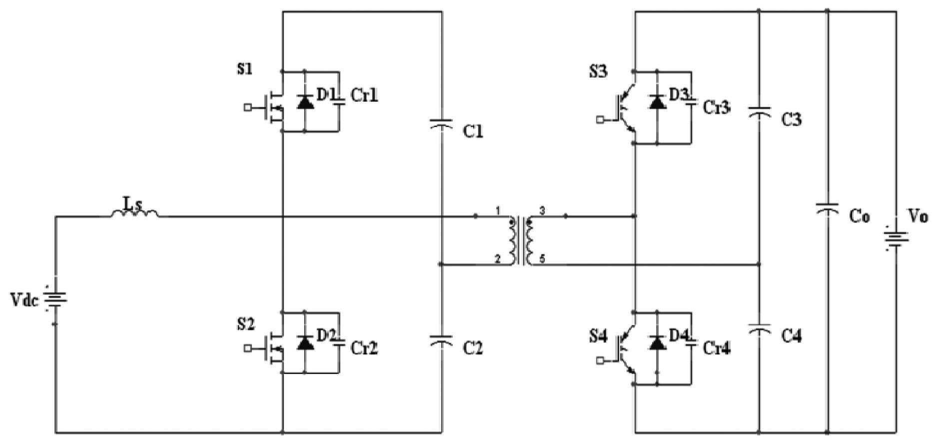

Figure 1. ZVS bidirectional DC/DC Converter

3. OPERATING STAGES

Figure 2 illustrates the converter topology and Figure 3 the commutation waveforms in boost mode. ZCSis achieved by a clamp circuit used in one half-bridge, operating the two half-bridges with a phase shift. Fig 1 is the ZVS bidirectional dc-dc converter circuit. Figure 2 presents the voltage and current waveforms of the transformer during one switching period. In fuel cell applications, when power flows from the low voltage side to high voltage side, the circuit works in boost mode to keep the high voltage at a desired high value before fuel cell can generate power. In other direction of power flow, the circuit works in buck mode similarly to boost mode.

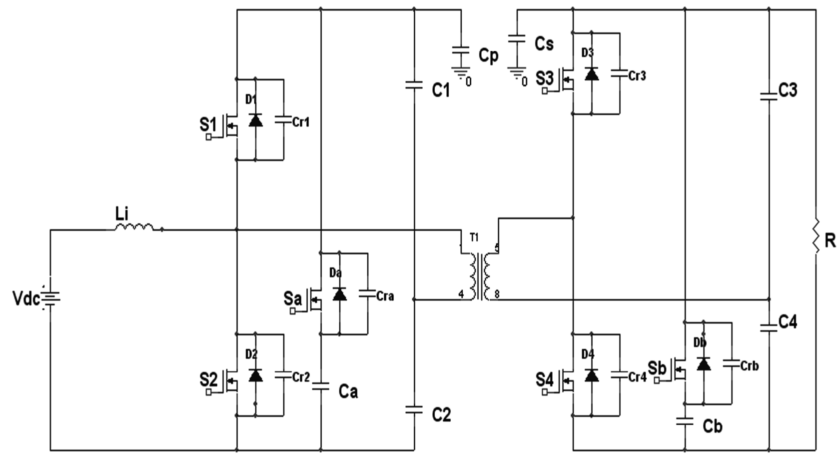

Figure 2. Proposed active clamp Bidirectional DC/DC converter

3.1. Principle of operation

Figure 2 shows the proposed DHB ZVZCS Bidirectional DC/DC converter current-fed converter with an active clamp during the boost mode operation. During this mode the battery Voltage of 24V will be converted to a voltage of 200V on the DC link bus. An active clamp branch placed across the current-fed bridge is used to achieve ZVZCS for the voltage-fed bridge switches in boost mode, and clamp the transient voltage on the current-fed bridge. This active clamp branch consists of an active switch and an energy storage capacitor. In the high-power bi-directional DC-DC converter, the DHB converter with an active clamp has been a good choice due to its effectiveness to limit the overshoot of bridge switch's turn off voltage and to enable the energy stored in the transformer leakage inductance to be used for zero voltage switching [4].

The interval of Fig.4 describes the various intervals of operation during one switching period in boost mode. The converter operation is repetitive in the switching cycle. One complete cycle is divided into four intervals. To aid in understanding each step, a set of corresponding annotated circuit diagrams is given in Fig. 3(a, b, c, d,) with a brief description.

3.2. Boost mode

Interval (t_0, t_1): Switch S1 starts to conduct. During this stage energy stored in C_a is transferred to the load, the voltage across S_1 is becomes zero. Current through the switch S_1 reaches zero and then linearly increases. The body diode D_3 of S_3 gives rectification, the load current flows through $D_{3,}$ C_4

Interval (t_1, t_2): Active clamp switch S_a is turned on to turn off the main switch S_1, when S1 is turned off, the voltage across Cr_1 linearly increases from zero to V_p while voltage vcross Cr_2 decreases to V_{in}. This time interval ends at t_2 , when V_p is equals to zero.

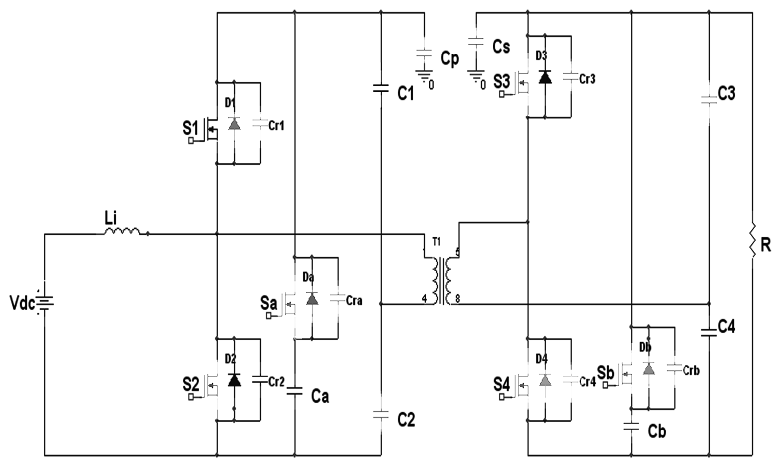

Figure 3 (a). Interval (t0,t1)

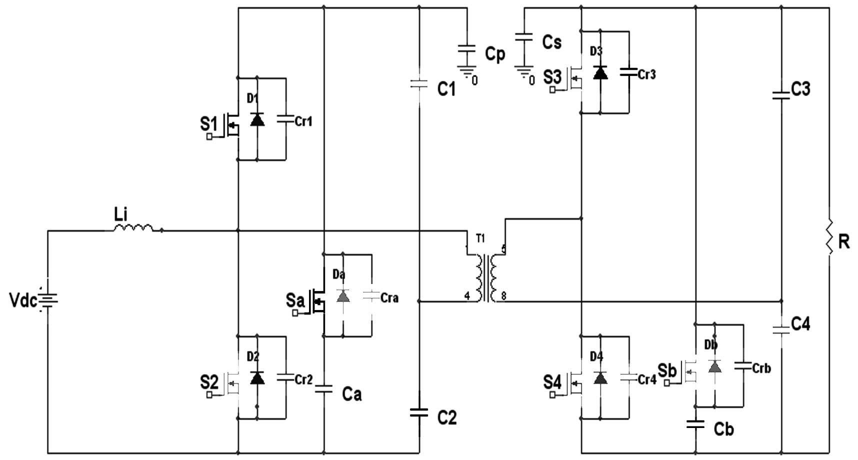

Figure 3(b). Interval (t1,t2)

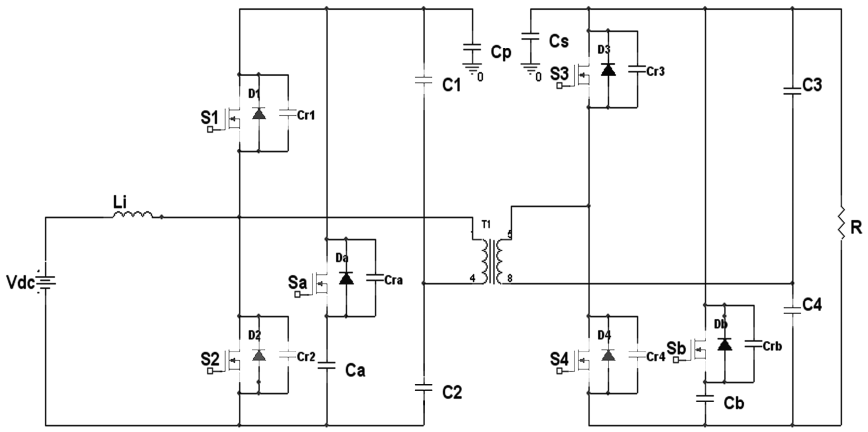

Figure 3(c). Interval (t2,t3)

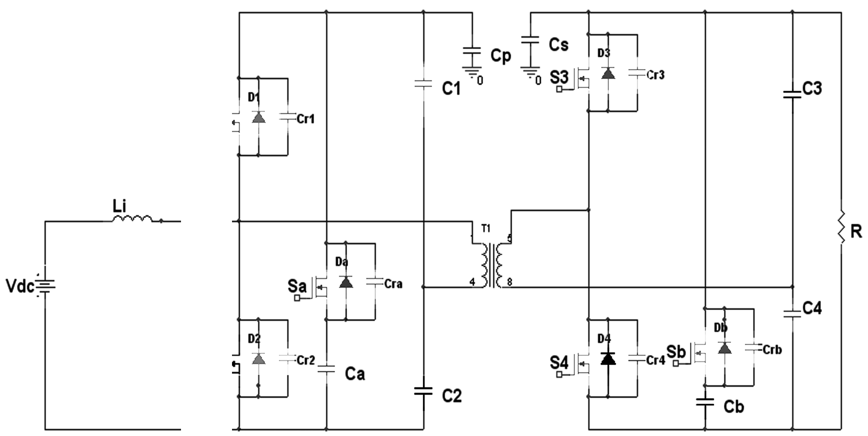

Figure 3(d). Interval (t3,t4)

Interval (t_2, t3): This is the resonant part of S_1 which is turning off. After voltage across Cr_2 reaches V_{in}, V_P becomes negative. During this stage energy stored in C1, C_4 are transferred to the load and Cr_1 is transferred towards the main Switch. The transient voltage at S_1 limit by Cp. This stage finishes when clamp switch Sa turned off.

Interval (t_3, t_4): when S2 is turned on, during this stage energy stored in C_P is transferred to the load. Due to the Cr_2 voltage across S_2 becomes zero. Current through S_2 linearly increases from zero. During this stage V_P still negative. This stage ends at S_a is turned on.

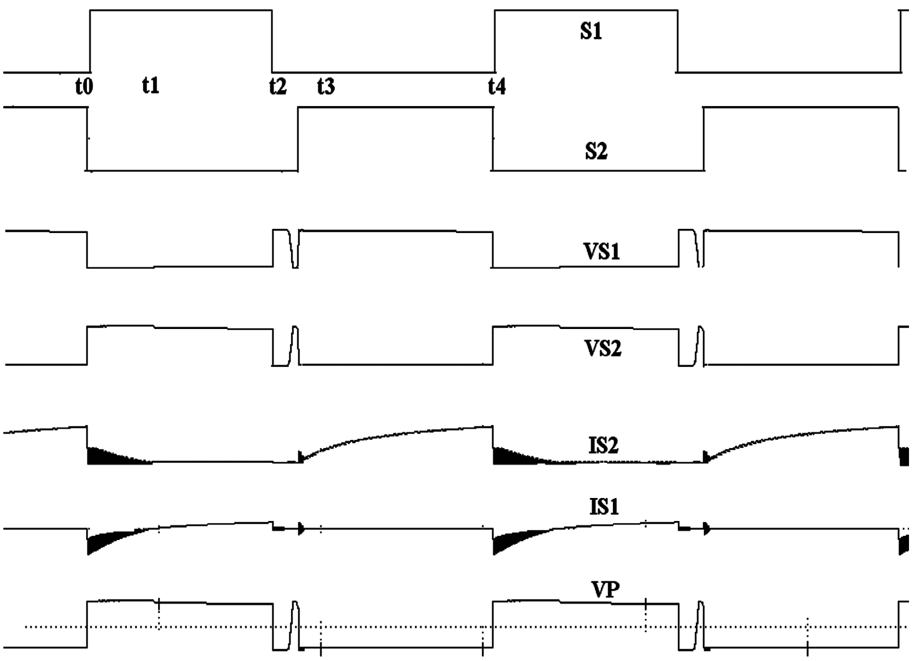

Figure 4. Waveforms for a Switching period.

3.2. Buck mode

The Because of the existence of clamp circuits in DHB, both the two sides are symmetrical. The principle of operations principles in buck mode are similar to those in boost mode. Due to the reversed power-flow direction, the phase of the VS is leading than VP. The inductor current Li is reversed. The buck mode operates under ZVZCS condition same as Boost mode. In this mode the switches in S3 &S4 are turned on at zero voltage by due to the resonant capacitors Cr3, Cr4 and turned off at Zero current switching because of active clamp circuit S_b.

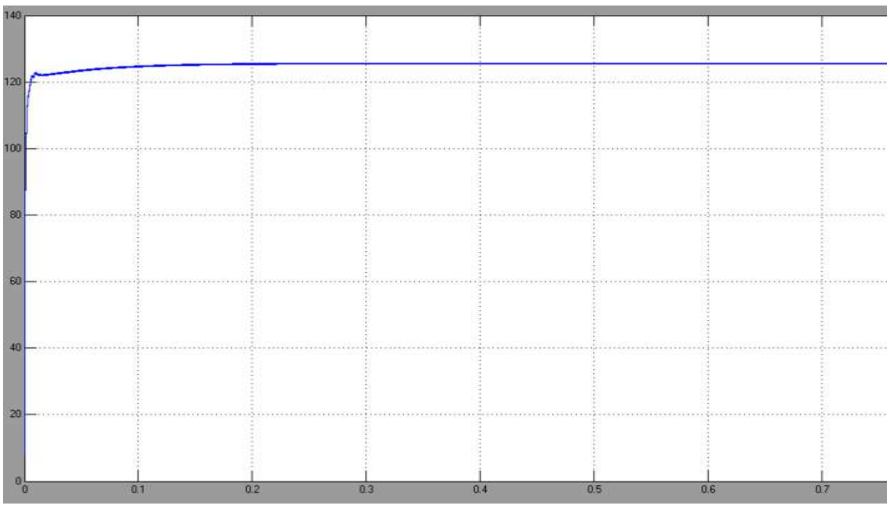

Figure 5. Load Voltage (120V/1A)

4. SIMULATION EVALUATION OF PROPOSED CONVERTER

The detailed active clamp DHB ZVZCS bidirectional circuit model is built using Matlab/Simulink. The simulated results are compared with experimental results to show the performance of the converter.

4.1 Boost mode

The following parameters are selected according to a 120 W for fuel cell and battery applications.Vb =24V, , D = 50%, f_s=*20* kHz, Li= 5µH, CP= CS= 30µF, C1=C2=C3=C4=100µF, Simulations of the ZVZCS bidirectional converter waveforms are presented in Fig.5, 6, 7. shown are the output voltage, primary side transformer current, primary and secondary voltage. Fig.5 illustrates load voltage in boost mode, Fig.6 illustrates the voltages across transformer, Fig.8 illustrates the switching pulses generated for the switches S_1, S_2, Sa.

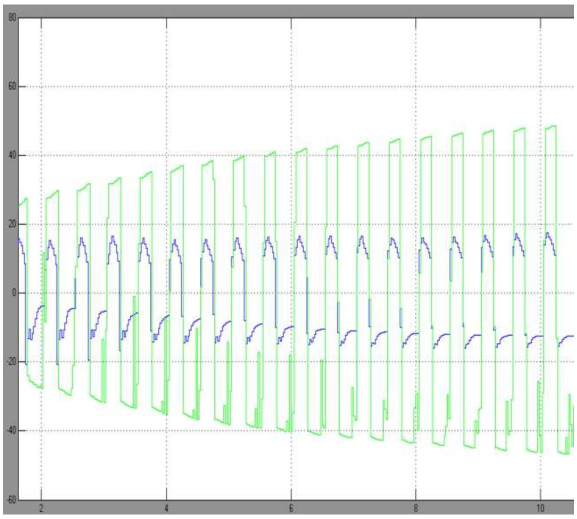

Figure 6. Voltage Through Transformer

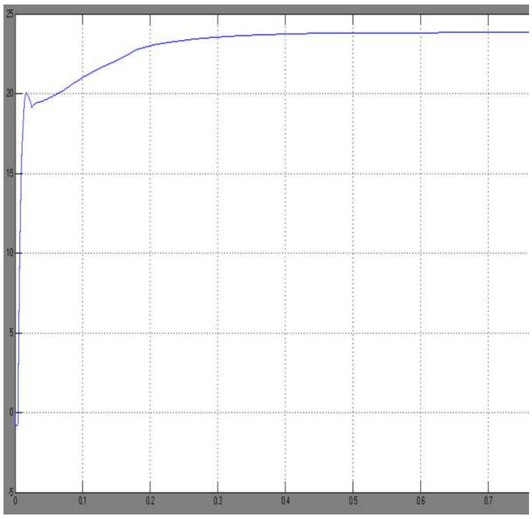

Figure 7. Load Voltage in Buck mode

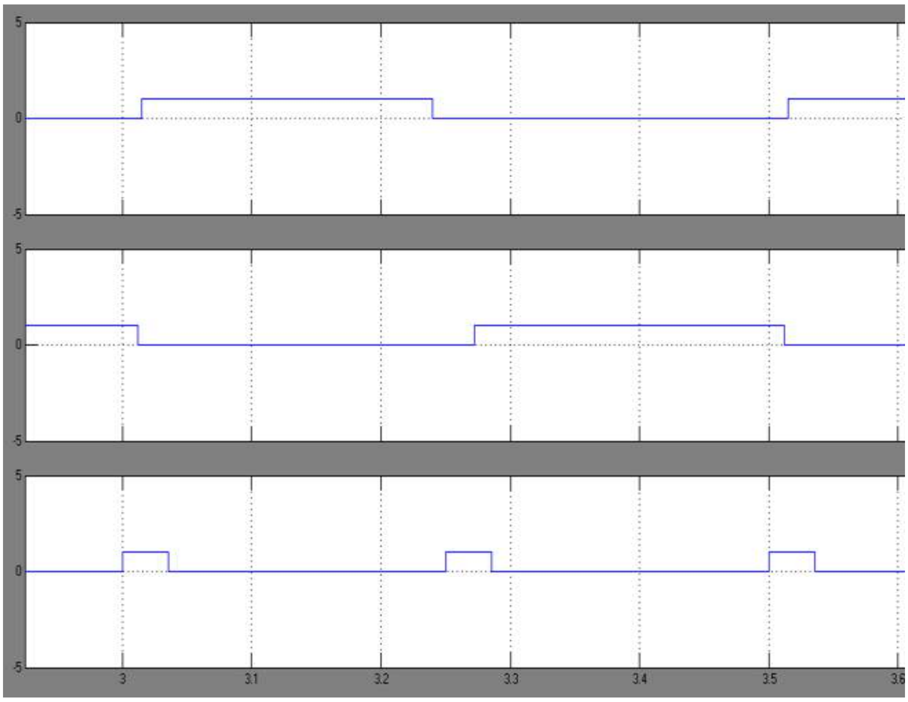

Figure 8. Generated Switching Pulses

4.2 Buck mode

Simulations are conducted for the buck mode and the parameters used in the simulation are same as those used in boost mode. The input voltage applied is 120v the output voltage obtained is 24V. Figure 7 illustrates the load voltage in buck mode.

5. COMPARATIVE ANALYSIS OF ACTIVE CLAMP ZVZCS VERSUS ZVS-ZCS BIDIRECTIONAL CONVERTERS

Comparative simulation studies of DC-DC converters based on two soft switching schemes were conducted. The circuit and parasitic parameters, and switching losses of diodes were not considered in the simulation study.

The simulation conditions were as following.

- Rated output power : $P_O = 120W$
- Input voltage: $V_{in} = 24V$
- Output voltage: $V_O = 120V$
- Switching frequency: $f_s = 20kHz$
- Maximum duty cycle: $D_{max} = 0.45$
- Transformer turns ratio: N1:N2 = 1:2

In Table 1 it is noted that each soft switching technique can reduce switching loss at the cost of increasing the conduction loss. The turn-off loss in ZVS-ZCS[15] has been increased in the main switches $S_1$and S_2.The active clamp ZVZCS can remarkably decrease the turn-off loss for the main switches S_1 and S_2 in boost mode due to active clamp circuit S_a ,which is a major part of its total switching loss. Across each element the values of voltage and currents are measured and the switching loss is calculated thereafter. Energy loss in the transistor is Wd. V_A, I_A are the respective voltage and current in the switches.

$$Wd = \int [V_A(t)\, I_A(t)\, dt]$$

Therefore switching loss $P_s = W_D f_s$ Where f_s = Switching frequency = $1/T_s$.

In Table 2 it can be seen that ZVS-ZCS scheme will cause smallest possible current and voltage stresses in one of the half bridge. The ZVS gives largest voltage stress on one of the half bridge. Active clamp ZVZCS scheme will relieve the main switch S_1 current stresses from 1.64 to 1.24 Amp. Active clamp ZVZCS gives the less voltage stress and losses are reduced on the one half bridges than ZVS-ZCS does by about 12 to 15 %.

Table 1. Loss and Efficiency comparison

	ON (S1)	OFF (S2)	ON (S2)	OFF (S2)	Switching Loss (S1)	Switching Loss (S2)	Total Loss	Efficiency
ZVS-ZCS	0.8	24.4	0.8	25.5	118.9	304.23	423.13	39%
ACTIVE CLAMP	0	21.4	0.8	30.65	33.5	18.50	52.01	52%

Table 2. Switching stress comparison

	V_{rms} (S1)	V_{rms} (S2)	V_{rms} (Sa)	I_{rms} (S1)	I_{rms} (S2)	I_{rms} (Sa)
ZVS-ZCS	10.62	11.4	30.73	1.64	82.4	0.1667
ACTIVE CLAMP	27.07	21.99	10.33mV	1.24	0.8415	10.33mA

6. CONCLUSION

A Novel Active clamp DHB ZVZCS and ZVS-ZCS bidirectional DC-DC converter is proposed and their comparative analyses with ZVS-ZCS bidirectional DC-DC converter are presented in this paper. Simulation results for the 120W and 20 kHz model were shown to verify the principle operation. It is shown that ZVZCS in one direction of power flow is achieved in boost mode with reduced switching losses involved and other direction of power flow involves the ZVZCS with reduced switching losses. Due to the simultaneous boost conversion and inversion provided by the low voltage side half bridge, current stresses on the switching devices and transformer are reduced by switching an Active clamp switch in primary side i.e. ZCS condition. As a result, advantages of the new circuit including ZVZCS with full load range, current stresses are reduced, high efficiency. The major drawback of this converter is its huge cost is due to introduction of the active clamping circuit components, controller and decreased output power. This converter is best suited for medium power applications like fuel cell and battery, with high power density. Excellent dynamic performance is obtained because of the clamping circuits used in DHB. Comparative analysis has been done between the proposed converter and the existing converter, and the simulation analysis shows that the efficiency is increased in the proposed converter.

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BIOGRAPHY OF AUTHOR

V. V. SUBRAHMANYA KUMAR BHAJANA received his B.E. degree in Electronics and Communication Engineering from Sapthagiri College of Engineering, Dharmapuri, Tamilnadu, India (University Of Madras), in 2000 and there after, he did his M.E degree in Power Electronics and Drives from the P.S.N.A College of engineering and Technology, Dindigul, Tamilnadu, India under Anna University, Chennai in the year 2005. PhD awarded by Bharath University in Dec 2011, Chennai, India. His key area of interest is Power Electronics engineering, which includes soft switching DC - DC converters and their applications.