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Design of Power Converter with Coupled Inductor for Aerospace Applications

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Abstract — The bidirectional DC converter with ZVS technique is a topic of research interest in recent years. These type of converters may be either isolated with transformer or non-isolated type. This work studies the design of a non-isolated (transformer less) bidirectional DC to DC converter. Non-isolated converters are not as much of expensive as the isolated converters. They are ideally suited for aerospace applications. It also needs fewer switches and passive components. The objective is to construct a 200W bidirectional converter used to interface a low voltage (24V-30V) and a high voltage (200V) DC bus. The problem is formulated mathematically. The design is achieved through the formulas derived. The feasibility of design is validated through software simulation. Finally a prototype is fabricated and the performance is validated by an experimental setup.

Keywords* — *Bidirectional Converter; ZVS Technique; Non Isolated Type.

1. Introduction

The bidirectional DC-DC converters accomplish transferal of the power among the two dc sources in both the direction. It has the capability to inverse the current flow direction. Now the power remains unchanged, while supporting the voltage polarity at either ends. Some of the applications such as battery charge, automobiles, telecommunications and renewable energy. There are three prospects. They are transformer-segregated or non-confined or non-disconnected with coupled inductors[1]. The exchanging stresses, misfortunes and clamor are decreased. The consistent recurrence semi full switches for the unidirectional DC power transformation were gotten from the variable recurrence exchanging type. Non-separated bidirectional dc-dc converters which use ZVS strategies are assembled as underneath [2,3].

Group 1- In this group, Buck/boost converters operate with an inductor current with high ripple and will drift in both the sides of the directions in each cycle. It consequences in high turn-off losses and also losses in the circulating current[4,5].

Group 2 - In this group, Quasi resonant converters will have high switching peak voltage stresses. In this implementation and control are also difficult [6]. *Group 3* - In this group 3, ZV switch converters utilize helper circuits having with four dynamic switches.

The applications in which the low side voltage source is far lesser than higher side voltage source non-isolated bidirectional converters are implemented with coupled inductors. The coupled inductors greatly reduce the devices stresses[7]. Thus, the converter should be executed with four dynamic switches. This is valid regardless of its single auxiliary circuit[8]. The bidirectional converter with coupled inductors requiring two auxiliary switches will be able to operate using ZVS[9]. In this project non isolated bidirectional converter with coupled inductors requiring only one auxiliary switch is designed.

2. Block Diagram Development And Converter Operation

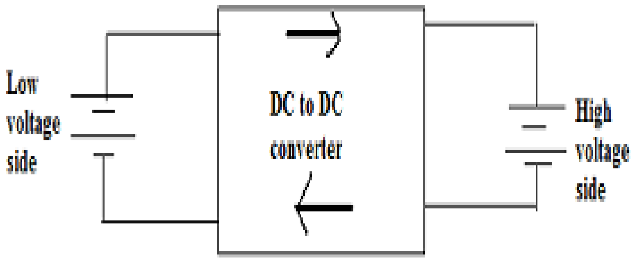

Fig. 1: Illustration of Bidirectional DC to DC converter

The Fig.1 displays the interconnection of two levels of dc voltages through a DC to DC converter. This converter must be capable of handling bidirectional power. Stress on the converter switches are minimized using coupled inductors. Losses in the switches are to be minimized so as to rise the efficiency of conventional bidirectional DC-DC converter [10]. Conventional converter’s efficiency is found to be 75%. By using DC to DC converter based on ZVS and ZCS, the efficiency level can be improved above 85%.

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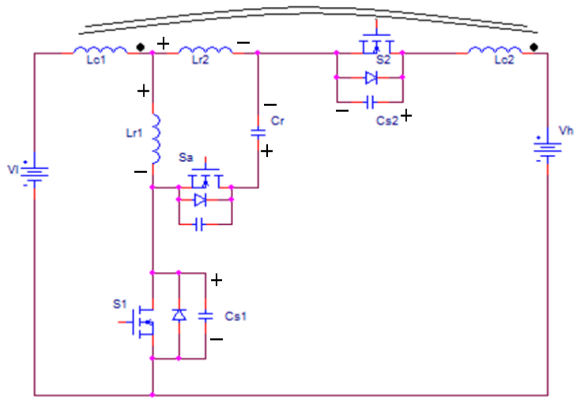

Fig. 2: Bidirectional converter

Fig.2 shows the general configuration of bidirectional ZVS converter along with coupled inductor. The Bidirectional coupled inductor ZVS non-isolated converter usually functions in both boost mode and buck mode. The voltage polarity remains same in both the modes of operation [11,12]. The boost mode has switch S_1 as the main power switch and also switch S_2 is freewheeling diode.

The circuit operation is explained in various sub modes as follows. Initially the switch S_1 is in ON condition. At the instant t_o, S_1 is turned off. During this time, there will be rise in voltage which is limited by C_{s1}. I_{Lr1} charges up C_{s1}. When C_{s1} is fully charged, body diode of S_a becomes forward biased.

The current I_{Lr1} gets diverted to I_{Lr2} and body diode. When the current flows through body diode, it charges up C_r and at the same time I_{Lr2} discharges C_{s2}. At the time t_2, when C_{s2} is fully discharged and C_r fully charged, diode of S_2 will become forward biased and begins to work. Also when C_{s2} is fully discharged, L_{C2} polarity gets reversed and negative voltage is impressed on L_{C1} and I_{Lc1} gets reduced. At some instant t_3, S_a is ON and so C_r gets discharged through C_r – L_{r1} - L_{r2} and thus forming the resonating circuit. At certain value of V_{cr}, body diode of S_a becomes reverse biased and V_{cs1} becomes zero. Thus diode of S_1 conducts and switch is now turned ON at the zero voltage transition mode.

3. Modelling Of Power Converter

The parameters of the system are obtained using mathematical formulas derived. They are mathematically formulated by applying KVL and KCL in each sub modes. The conditions for ZVS in both of the directions is determined as follows. For boost mode of operation, it is given as

$$\frac{1}{2}\left(L_{r1}+L_{r2}\right)\left(I_{in}\frac{Z_1}{Z_a}\right) > \frac{1}{2}\left(C_{s1}\parallel C_{sa}\right)\left(\frac{V_1}{1-D_1}\right)^2 \qquad (1)$$

The auxiliary circuit is designed in such a way that it can give a ZVS turn-on for the main power switch device. In boost mode, the optimal voltage conversion ratio of the linked inductor converter is

$$M_{boost} = \frac{\left(nD_1\right)+1}{1-D_1} \qquad (2)$$

where D1 is duty ratio of boost switch S1

$$n = \frac{n_1}{n_2}$$

,n1 is the ratio of the number of turns of Lc1, n_2 is the ratio of no. of turns of L_{c2}

The volt-second balance between inductors Lc1 and Lc2 is used to calculate it. In boost mode due to the converter's equilibrium, D1 will have the value equal to (1-D2) in buck mode type. When creating the basic converter, the settings of the turning ratio n and duty ratios D1 and D2 will be taken from characteristic graphs of Mboost verses duty ratios D1 and D2.

3.1 Condition to ensure ZVS in both directions

The values of Lr1 and Lr2 are set to be the same to keep the design simple. Eqn. 1 lists the conditions that must be met in order for ZVS to turn on for S1 in boost mode [15].

According to Eqn (3), the main switch voltage will drop to zero during Mode 5 in boost operation.

$$I_{Lr1}(t) = -\left[V_{cr}(t_3)\big/Z_a\right]\cos\omega_s\left(t-t_4\right) \qquad (3)$$

ZVS turn-on condition of the main switch in boost mode is calculated using Eqn (3). Because the energy stored in the resonant inductors in Mode 4 is always superior than the energy in the switch capacitor Cs1, the condition of ZVS occurs.

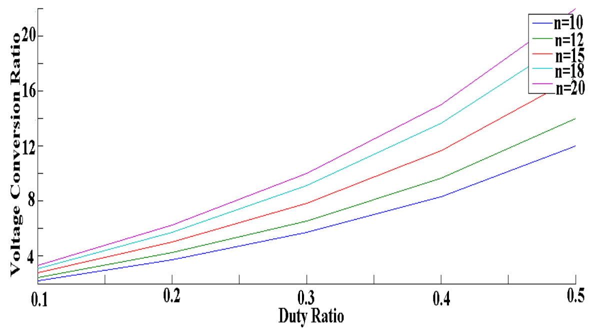

Fig. 3: Characteristic graph of boost mode of operation

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3.2 Values of L_{r1} and L_{r2}

In buck mode, the summation of the values of L_{r1} and L_{r2} is contrary wise relative to average l current in the load side, and when it is in boost mode, the sum of the values of L_{r1} and L_{r2} is not directly proportional to average input current [16]. Inductors L_{r1} and L_{r2} must satisfy Eqn. (1) at the lowest load for ZVS turn-on condition of the main switch.

3.3 Value of C_r

The peak voltage across the switch S_1, is considered by selecting out the resonant capacitor C_r.

$$V_{s1}(t) = \frac{V_h}{1-D_1} + V_{cr,\max} \tag{4}$$

3.4 T_{on} of the switch S_a

The turn on time of the auxiliary switch is the time in which the current through L_{r1} reach their peak. This will happen while C_r resonates with L_{r1} or L_{r2} after auxiliary switch is turned ON and the time is specified by

$$t_{Sa,on} = \frac{\pi}{2}\sqrt{(L_{r1}+L_{r2})C_r} \tag{5}$$

$T_{Sa,on}$ is the ON time of the switch S_a.

4. Result

The converter specifications are listed below.
Low side voltage : 24V – 30V
High side voltage : 200V
Maximum power : 200W
Switching frequency : 66kHz
$L_{r1}=L_{r2}=1.5\mu H$,
$C_r=330nF$
Coupled inductors, $L_{C1} = 5\mu H$ and $L_{C2} = 1.6mH$
Using these specifications, the circuit is simulated using PSpice software and the simulated results are obtained.

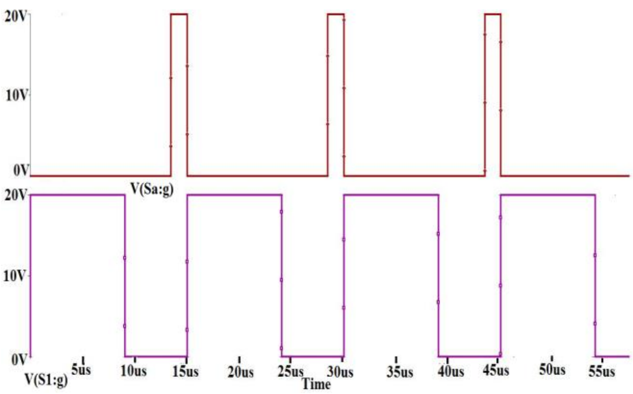

Fig. 4: Gate voltage for the switch S_1 and switch S_a

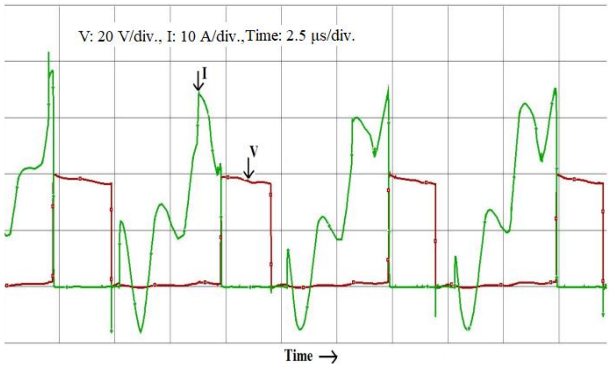

Fig. 5: Voltage and current waveforms for switch S_1

Fig. 4 displays the gate voltage for switches S_1 and S_a. Fig. 5 indications the voltage waveforms and current waveforms of S_1 once it turned on.

The hardware setup is shown in Fig. 6.

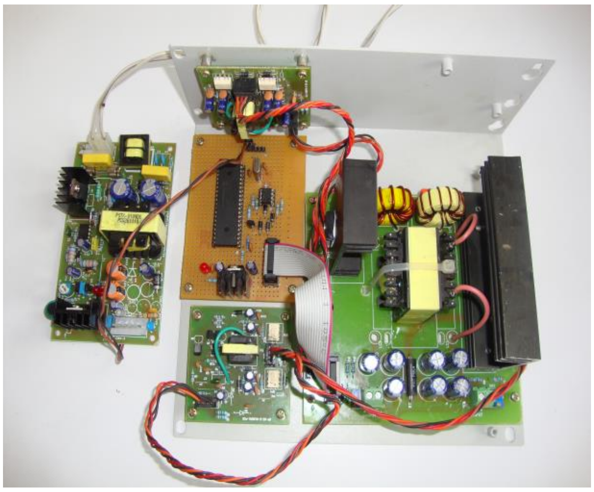

Fig. 6: Experimental Setup

The experimental outcomes are presented in the Fig. 7and Fig. 8.

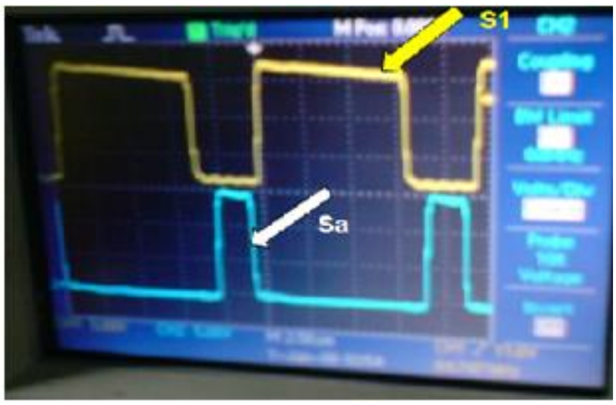

Fig. 7: Gate voltages

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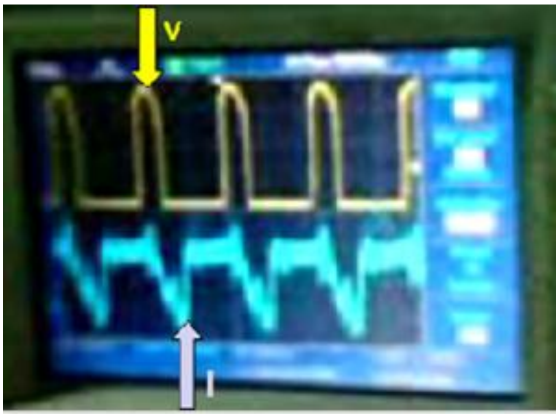

Fig. 8: Voltage and current waveforms

5. Conclusion

This study uses PSpice software to model the circuit and create a non-isolated bidirectional DC to DC converter for the aerospace cell applications. The ZVS switch may be switched on with just one auxiliary circuit, as shown. The switching voltage looks after won’t display any spikes during turn-off because to the active clamp type of auxiliary circuit. Here, the system offers a pathway for energy stored in the linked inductors' leakage inductances to be released in both of the directions of energy transfer when the switch is turned off. The proposed prototype will examine the significance of the work.

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