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COMPARISON BETWEEN ZVS AND ZVS-ZCS BIDIRECTIONAL DC-DC CONVERTER TOPOLOGIES

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Abstract: In this paper exhaustive comparative analysis has been done between a conventional ZVS converter and the ZVS-ZCS bidirectional DC-DC converters. A novel model of a bidirectional converter and its topology is introduced. The key working principles, functionality, simulation results are discussed and subsequently compared with the previous ZVS bidirectional converter system. With respect to switching losses, stresses and efficiency parameters the ZVS-ZCS bidirectional DC-DC converter is emphasized.

Keywords: ZVS, ZCS, DC-DC, PI, TDR

1. INTRODUCTION

In modern times, the vast usage of bidirectional DC-DC converters is improving the fuel cell economy, automobile companies are developing alternative battery operated vehicles suited to different power levels. A major change in the electrical system of the vehicles is gaining importance by varying from one voltage level to another level, so as to meet the increased electrical demands of cell vehicles and to lower the current drawn from the battery and to implement additional safety and comfort features. The ZVS and ZVS-ZCS bidirectional converter topologies should be efficient to improve the range of performance of the battery operated vehicles. The soft switching converters have the advantage of lower switching losses and flexible (High or Low) operating voltage.

This paper presents a analytical comparison between conventional ZVS and a novel ZVS-ZCS bidirectional DC-DC converter. These two converter topologies are based on a dual half-bridge without auxiliary circuit (ZVS) and on the contrary a dual half bridge with auxiliary circuit in primary side (ZVS-ZCS). The ZVS-ZCS model is having the advantages like low EMI, low switching stresses, reduced switching losses as compared to conventional ZVS bidirectional DC-DC converter. The ZCS topology removes the turn-off current tail of the main switch. 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 ZVS and ZVS-ZCS bidirectional DC-DC converter topologies have been simulated and operated for rectification and inversion in both buck and boost modes. The operating modes of the converter are described in the following section. The obtained results show that the switching losses, stresses and efficiency parameters for a ZVS-ZCS converter is superior than that of a ZVS converter.

2. REVIEW OF POWER STAGE DESCRIPTION AND OPERATION OF THE TWO TOPOLOGIES

2.1 ZVS Bidirectional Converter Topology

The ZVS bidirectional DC-DC converter topology is shown in Fig.1. The circuit consists of two half bridges with soft switching technique (ZVS). The equations for the four modes:-

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(1) $i_r = (v1+v4)\theta / \omega L_s + i_r(0)$
(2) $i_r = (v1-v3)(\theta-\phi 1) / \omega L_s + i_r(\phi 1)$
(3) $i_r = -(v2+v3)(\theta-\pi) / \omega L_s + i_r(\pi)$
(4) $i_r = -(v2+v4)(\theta-\pi-\phi) / \omega L_s + i_r(\pi+\phi 1)$

2.2 Novel ZVS-ZCS Converter Topology

In this converter shown in Fig.2 additional auxiliary circuit is implemented with the previous ZVS topology to get the desired ZVS-ZCS condition. In ZVS-ZCS bidirectional DC-DC converter the auxiliary circuit is composed of one resonant inductor L_a ,one auxiliary switch S_a, and also diode D_a, so that the zero current switching (ZCS) in main switches S1 & S2 can be obtained. Switch S_a is turned on under zero current switching (ZCS) condition.

When power flows from the low voltage side to high voltage side, the circuit works in ZCS condition to turned off and ZVS condition to turned on of main switches S1, S2 in boost mode. In the other direction of power flow, the circuit operates in ZVS condition (buck mode). 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. The equations for the six modes are:-

(5) $i_r = (v1+v4)\theta / \omega L_s + i_r(0)$
(6) $i_r = (v1-v3)(\theta-\phi 1) / \omega L_s + i_r(\phi 1)$
(7) $i_r = 0$
(8) $i_r = -(v2+v3)(\theta-\pi) / \omega L_s + i_r(\pi)$
(9) $i_r = -(v2+v4)(\theta-\pi-\phi) / \omega L_s + i_r(\pi+\phi 1)$
(10) $i_r = 0$

The major draw back of this converter is TDR penalty because auxiliary circuit used in primary side. The TDR of the [Fang Z, et al., 2004] ZVS bidirectional DC-DC converter is calculated as $TDR_P = 2V_{dc}.\ I_{ac}.$ (2 devices) = 4 P_o, where P_o is the output power. The TDR of the ZVS-ZCS bidirectional DC-DC converter [Bhajana, S 2009] is calculated as TDR_P = 2Vdc. Iac. (3 devices) = 6 P_o, Where P_o is again the output power. The TDR has been increased for the ZVS-ZCS converter and the ZVS bidirectional DC-DC converter is not same output power. The main advantage of the circuit Fig.1 is the current stresses are reduced for the low voltage side main switches S1 and S2.

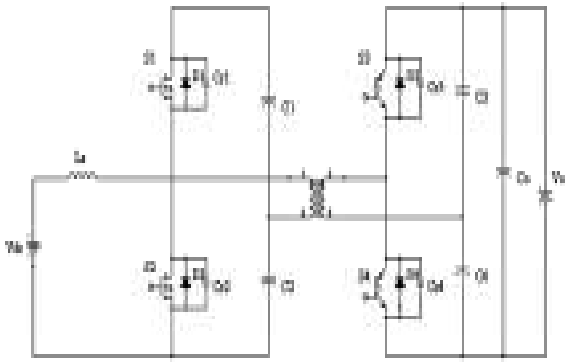

Fig.1. ZVS bidirectional DC-DC converter

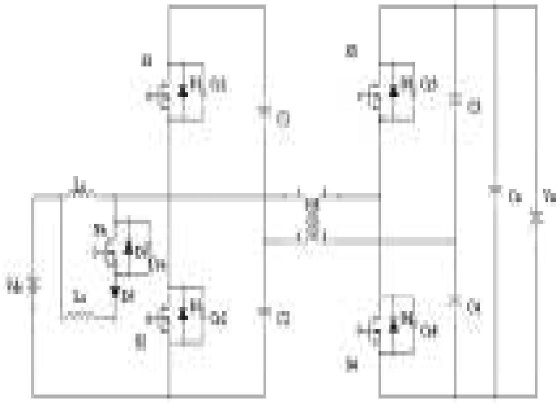

Fig.2. ZVS-ZCS bidirectional DC-DC converter

3. DESCRIPTION OF OPERATING STAGES

Fig.1 and Fig.2 illustrates the two converter topologies. Fig.3 the commutation waveforms in boost mode. ZCS is achieved by auxiliary circuit used in one half-bridge, operating the two half-bridges with a phase shift. Fig.2 is the ZVS-ZCS bidirectional dc-dc converter circuit. Fig.3 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 to absorb regenerated energy. Based on the idealized waveforms in Fig.3, there are six operation modes in one switching cycle, and the transformer current i_r of each mode can be calculated as mentioned above equations 5 to 10.

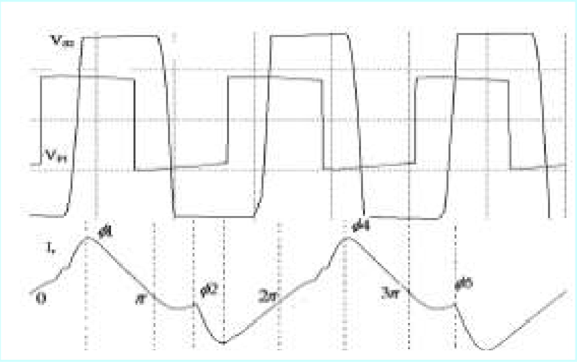

Fig.3. Transformer voltage and current waveforms in Boost mode

The current initial conditions can be solved using the boundary conditions of

(11) $i_r(0) = i_r(\pi)=0$

(12) $i_r(\phi 1) = -i_r(\pi+\phi 1)$

The output power can be regulated by phase shift angle $ø_1$, duty cycle and switching frequency ω. If duty cycle assumed to 50% then the output power equation can be simplified as

(13) $P_o= x_0 / T_s = V_{dc}^2/ \omega L_s [(\pi - ø3)\, ø1/ \pi)]$

Because of the asymmetry property of dual half-bridges, the operation principles of boost mode and buck mode are not the same, polarity of the phase shift angle is also different.

3.1. Principle of operation

3.1.1 Boost mode

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

First stage (0 to$\phi 1$): switch S_1 starts to conduct. Due to the resonant capacitor C_{r1} , the voltage across S_1 is becomes zero. During this stage C_1, C_4 are charged, C_2, C_3 are in discharged.

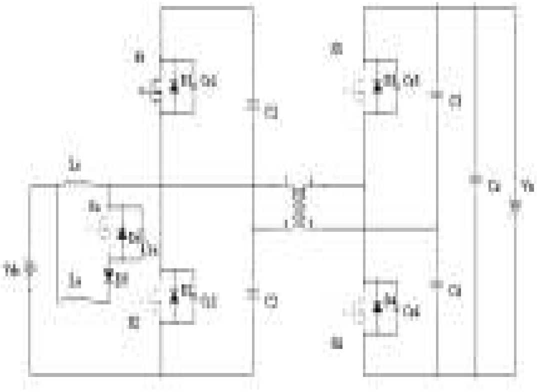

Fig.4(a). First stage

Second stage (ϕ_1 to ϕ_3): S_1 is still turn on state. During this stage C_1, C_4 are charged, energy stored in C_2, C_3 are transferred to the load. When i_r reaches at ϕ_3, S_a is gated to turn off S_1. This stage finishes when S_1 is turned off.

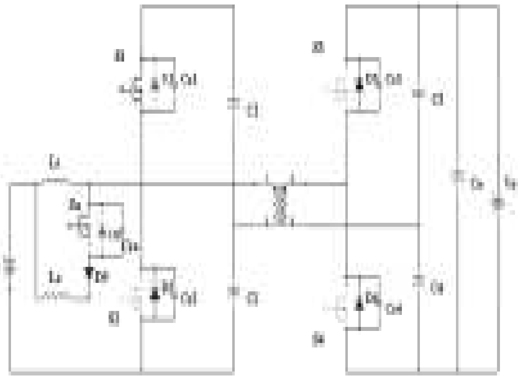

Fig.4(b). Second stage

Third stage (ϕ_3 to π): at this stage S_a is turn on, remaining switches are in off state. During this stage energy stored in C_1,C_4 are transferred to the load. C_3, C2 are in charged.

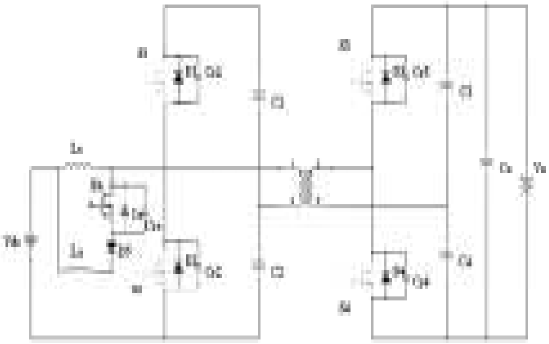

Fig.4(c). Third stage

Fourth stage (π toϕ_4): when S_2 is turned on, C2 & C3 are charged, C_3 & C_4 discharged. This stage finishes when S_a gated to turn-on.

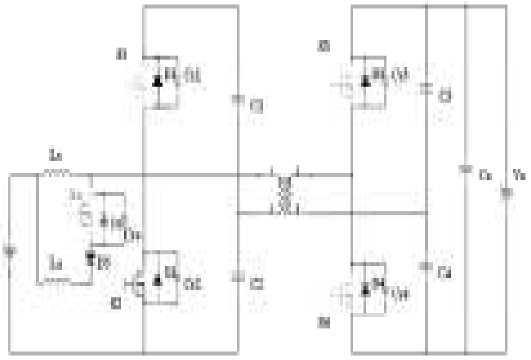

Fig.4(d). Fourth stage

Fifth stage (2π to $\phi 3$): At this stage S_2 is still in turn on state. During this stage C_2, C_3 are charged, energy stored in C_1, C_4 are transferred to the load. When i_r reaches at ϕ_3, Sa is turned on to turn-off the S_2. This stage finishes when S_2 is turned off.

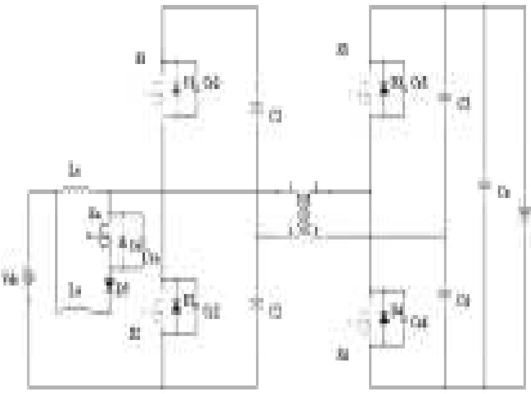

Fig.4(e). Fifth stage

Sixth stage ($\phi 3$ to 3π): at this stage S_a is turn on, remaining switches S_1&S_2 are in off state. During this stage energy stored in C_2, C3 are transferred to the load. C_1, C_4 are in charged.

Fig.4(f). Sixth stage

3.1.2 Buck mode:

Because of the auxiliary circuit in one half-bridge the two sides are asymmetrical; the operation principles in buck mode are similar to those in boost mode except equations 3 & 6. Due to the reversed power-flow direction, the phase of the V_{S2} is leading than V_{P1}. The inductor current L_S is reversed. The buck mode only operates under ZVS condition. This mode of operation can be divided into four steps. In this mode the switches in S_3 &S_4 are turned on and turned off at zero voltage due to the resonant capacitors C_{r3}, C_{r4}. The equations for the modes of buck are:-

$$(14)\ i_r = (v3+v2)\theta / \omega L_s + i_r(0)$$
$$(15)\ i_r = (v3-v1)(\theta-\phi 1) / \omega L_s + i_r(\phi 1)$$
$$(16)\ i_r = -(v3+v2)(\theta-\pi) / \omega L_s + i_r(\pi)$$
$$(17)\ i_r = -(v4+v2)(\theta-\pi-\phi) / \omega L_s + i_r(\pi+\phi 1)$$

We shall now demonstrate the comparison between ZVS and ZVS-ZCS bidirectional DC-DC converter to show the switching losses performance through simulation in next section. The system parameters chosen are listed in Table 1. The simulation results are shown in Table 2 and Table 3 for boost mode of operation.

4. COMPARISION OF THE TOPOLOGIES

A comparative simulation study of DC-DC converters based on two soft switching schemes was 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 : $P_O = 75W$
- Input voltage: $V_{in} = 24V$
- Output voltage: $V_O = 80V$
- Switching frequency: $f_s = 20kHz$
- Maximum duty cycle: $D_{max} = 0.5$
- Transformer turns ratio: N1:N2 = 1:2

It was assumed that the parallel diodes have the same conduction characteristics as their switches do. Table 1 shows the parameters in the resonant element for the simulation. These values are considered during the simulation.

Table 1 Parameters of resonant element

Table 2 and Table 3 give the simulation results obtained for a boost mode.

	L_{dc}(µH)	L_a(µH)
ZVS	5	X
ZVS-ZCS	5	4.96

In Table 2 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 has been increased in main switches $S_1$and S_2.The ZVS-ZCS can remarkably decrease turn-off loss for the main switches S_1 and S_2 in boost mode due to auxiliary switch S_a ,which is a major part of its total switching loss. Across each element the values of voltage and current 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.

$$(18)\mathrm{Wd} = \int_{Ts}^{T0} [\mathrm{VA(t)}\ \mathrm{IA(t)}\ dt\,]$$

Table 2 Switching Stress comparison

	V_{RMS}	V_{RMS}	V_{RMS}	V_{RMS}	I_{RMS}	I_{RMS}	I_{RMS}	I_{RMS}
	S_1	S_2	D_3	S_a	S_1	S_2	D_4	S_a
ZVS	19.06	19.11	37.46	X	6.24	15.92	37.34	X
ZVS-ZCS	10.62	11.44	36.04	30.73	1.64	82.94	36.84	0.1667

Table 3 Loss and Efficiency comparison

	ON	OFF	ON	OFF	Switching Loss	Switching Loss	Total Loss	Efficiency
	S_1	S_1	S_2	S_2	S_1	S_2		
ZVS	0.8	24.44	0.88	25.5	118.9	304.23	423.13	38%
ZVS-ZCS	0	27.5	0	27.5	17.50	3.63	51.13	52%

Therefore switching loss $P_s = W_D f_s$ Where f_s = Switching frequency = $1/T_s$. Ts = switching transition starting ,T0 = switching transition ending.

In Table 3 it can be seen that ZVS-ZCS scheme will cause smallest current and voltage stresses in the one of the half bridge. The ZVS gives largest voltage stress on the one of the half bridge. The peak current in the D_3 and D_4 will be significantly increased also. ZVS-ZCS scheme will relieve the main switch S_1 current stresses from 6.24A in ZVS to 1.648A. ZVS-ZCS gives the less voltage stress and losses are reduced on the one half bridge than ZVS does by about 12 to 15 %.

5. CONCLUSION

A comparative analysis of conventional ZVS converter and a novel ZVS-ZCS bi-directional DC-DC converter has been presented in this paper. The operation and simulation results were illustrated. Simulation results for the 80W and 20 kHz switching frequency model are shown to verify the operation principle. It is shown that ZVS-ZCS in one direction of power flow is achieved in boost mode with no switching losses involved and other direction of power flow involves ZVS with no 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 auxiliary switch in primary side i.e. ZCS condition. Consequently, advantages of the ZVS-ZCS with full load range, current stresses are reduced, and efficiency is high. The major drawback of this converter is increased cost due to the auxiliary circuit components which are not present in the ZVS converter. But superior performance of ZVS-ZCS [Bhajana, S 2009] converter is achieved in terms of reduced switching loss and stress, better efficiency as compared to only ZVS converter. [Fang Z, et al., 2004] These converters are used for medium power applications like fuel cell and battery, with high power density. Excellent dynamic performance is obtained because the auxiliary circuit used in one of half bridge.

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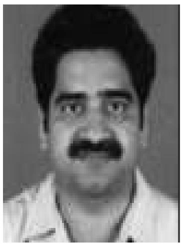

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