A NOVEL ZCS-ZVS HYBRID BIDIRECTIONAL DC-DC CONVERTER FOR FUEL CELL AND SUPERCAPACITOR APPLICATION

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Abstract: This paper proposes a novel ZCS-ZVS hybrid bidirectional DC-DC converter based on fuel cells and supercapacitor devices. The described converter employs only one high frequency transformers to couple the half-bridge and full-bridge circuits together in the primary side and voltage doubler circuit in secondary side. Boost type converter can limit the output ripple current of the fuel cells; hybrid full-bridge structure can change operating modes according to the different input voltage. All the primary side switches can turn on under zero-current-switching condition (ZCS) in boost mode and transformer secondary side switches can turn on under zero-voltage-switching(ZVS). The operating principles of the converter are described in details. The proposed converter provides output voltages of the range 300-400V. With the proposed ZCS-ZVS concept, the MATLAB simulation results of the application of fuel cell and supercapacitor have been obtained and compared to those of hybrid bidirectional dc-dc converter (ZVS based) and the applications in order to show the superior performance of the proposed concept.

Keywords: DC-DC, ZVS, ZCS, ZCS-ZVS, Fuel cell, Supercapacitor.

INTRODUCTION

Of recent times, the hybrid system is generally based on fuel cells (FCs) and supercapacitor devices (SCs) as an environmentally renewable energy system and has been applied in many emerging fields, such as hybrid electric vehicle (HEV), uninterruptible power supply (UPS) and the list goes on. Fuel cells can effectively convert the chemical potential of the hydrogen into electric power directly, with consequent high conversion efficiency and the possibility to obtain the extended range with the desired combustible feed from the outside [1]. But one of the main short comings of the fuel cell is its slow dynamics because of the limitation of hydrogen delivery system. So during the fuel cells warming up or load requirement transient stages, the supercapacitors can be utilized as the auxiliary power source for further smoothing output power. On the other hand, because the fuel cell output voltage varying widely, almost 2:1 turns ratio, then

depending on different load conditions, and the terminal voltage of supercapacitors bank is variable during charging and discharging time periods. It is very important for the conversion system to be capable of harvesting power from different power sources and have superior performance in widely variable input voltage range and keeping in account the load variations also. Many hybrid system structures have been proposed, and they can be classified into four distinct categories, namely:- DC bus structure [2], [3], transformer-coupled structure [4], [5], [6], multi-port structure [8] and multi-stage structure, [9], [10]. For the DC bus structure, each power source is connected by a separate converter to the common voltage DC bus. In this architecture, each subsystem could be design as an individual module, but the complicated control is the primary disadvantage. In high frequency transformer coupled system, transformer design and power flow control are the pivotal to decide the performance of the

system. For the multi-stage structure, efficiency is limited by the cascaded converters. It is proposed that a novel DC-DC converter, as shown in Fig. 1, with fuel cells as main input power source and supercapacitors are connected directly to the low voltage side in this paper. The converter utilizes the boost-type input structure to limit the ripple current of the FCs [11] and hybrid full-bridge structure [12], [13] to change operating modes in terms of the different input voltage values. Phase-shift plus duty cycle modulation scheme can control the bidirectional power flow flexibly. This paper is organized into five sections. Section II gives the operation principle of the proposed converter; Theoretical analysis present in Section III. Section IV shows the simulation results. Section V gives the overall conclusions on the proposed novel ZCS-ZVS hybrid bidirectional dc-dc convertermargins and 1.25 mm (.5 in) header and footer. Paragraphs should be justified, using single spacing, with no paragraph indentation. Use Times Roman font, 10 point. Leave one clear line between paragraphs within a section; two clear lines before a main or secondary heading (if you are not using this document styles).
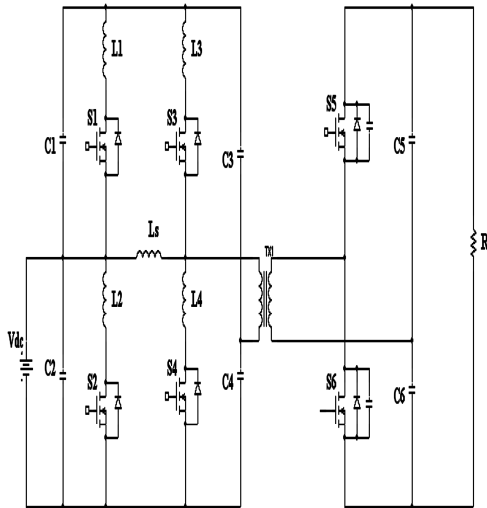
dc-dc converter with Two transformers, T_1 and T_2, with the paralleled primary windings and series-wound secondary windings are utilized to realize isolation and boost the low input voltage.In prevous hybrid bidirectional dc-dc converter all the switches are turned on or off with ZVS condition. Fig.1.shows that the proposed converter all the switches are turned on or off at ZCS condition in boost mode. In the buck mode of operation only S_5,S_6 operates under ZVS condition. Voltage doubler circuit in secondary side of the transformer is to get higher voltage conversion ratio. The leakage inductances of the transformers are the interface and energy transfer elements between the two high frequency inverters.
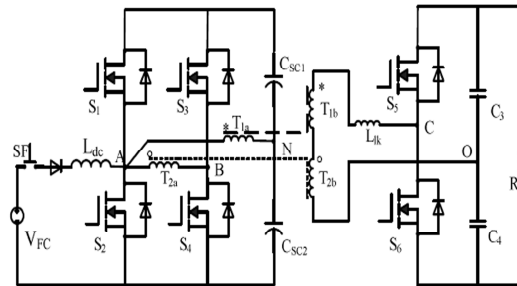

Fig.2 Hybrid bidirectional DC-DC converter (ZVS)

The proposed converter ZCS switching action obtained by means of placing the inductor series to the main switch and parallelly one capacitor is placed [55].

According to different power flow directions, operational modes of the proposed converter can be divided into two modes, Boost mode and Buck mode. In Boost mode, the power
is delivered from the fuel cells and supercapacitors to the high voltage DC bus, which means energy is from low voltage side to the high voltage side. The counterpart is defined as Buck mode. In different modes, Boost or Buck, there are several submodes as well depending on different input or output voltage value to limit the peak currents of the converter, respectively. The detailed operational modes are described as follows.

Fig.1. Proposed novel ZCS-ZVS hybrid bidirectional converter

OPERATING PRINCIPLES

As it is evident from Fig, 1, the boost type half bridge high frequency inverter with the switches operating by 50% duty cycle is in the primary side of the transformer, and supercapacitors C_3 and C_4 are connected on the variable low voltage DC bus as the secondary energy source. S_1,S_2,S_3 and S_4 are controlled by duty-cycle, d, to change the operating modes, when input voltage is variable in the wide range. Fig.2 shows that previous hybrid bidirectional

2.1Boost mode

In Boost mode, when input voltage is around 30 V, S_1, S_4 and S_2, S_3 will turn on synchronously. Phase-shift modulation is used to control the power delivered, as shown in Fig. 2. When the input voltage is higher than 30 V, the converter will work under the multi-level operation sub-mode to limit the rms current value in the primary side of the transformers,

through the duty cycle control on S_3 and S_4, as shown in Fig. 3. If the output voltage, V_o, is controlled well, that means it can be seen
as constant, we can define d as:

$$d = 2\pi \cdot \frac{T_{on\,S3}}{T_s} = 2\pi \cdot (1 - \frac{4 \cdot v_{FC}}{n_1 \cdot V_O}) \quad (\text{rad})$$

Where n_1 is turn ratio of the transformer T_1.

Because the 2-level operation is one special condition (duty cycle of S_3 and S_4 equal to 0.5) of the multi-level mode, only the multi-level sub-mode is analyzed in this paper. For the convenience of analysis, the following assumptions are given:

(1) all the switches are ideal with anti-parallel body diodes and
parasitic capacitors;

(2) The inductance L_{dc} is large enough to be treated as a current source;

(3) Output voltage is controlled well which can be seen constant;

(4) The two transformers are ideal and with series leakage inductor L_{lk} in the secondary side
.

One complete switching cycle can be divided into ten intervals as shown in Fig. 3, and because of the similarity, only a half switching cycle in described in detail.

1) Interval 1 (t_0-t_1): S_1, S_4 and S_6 are conducting. The voltage on secondary side of the transformer is v_{T1a} + v_{T2a} +V_{CO} , so the i_{Ldc} will increase linearly. I_{Ldc} goes though body diode of S_1.

2) Interval 2 (t_1-t_2): at t_1, S_6 is turned off. C_5 and C_6 begin to resonate, C_5 is discharged and C_6 is charged. When voltage on C_5 reduces to zero, the anti-paralleled diode of S_5 are to conduct, and the voltage v_{co} changes the direction. So voltage at transformer secondary side equals to $v_{T1a} + v_{T2a} + V_{CO}$

3) Interval 3 (t_2-t_3): at t_2, S_5 is turned on under ZVS. The current paths are same with these in Interval 2.

4) Interval 4 (t_3-t_4): at t_3, S_4 is turned off. C_3 and C_4 begin to resonate. When the voltage cross S_3 reduces to zero, D_{S3} is vherefore forward based. The voltage cross the primary winding of T_2 is clamped to zero. So secondary side transformer voltage equals to $v_{T1a} + V_{CO}$.

5) Interval 5 (t_4-t_5): at t_4, S_1 is turned off. C_1 and C_2 begin to resonate. C_2 is discharged from $2V_{FC}$. The

rate of change epends on the magnitude $i_{T1a}+i_{T2a}-I_{Ldc}$. At t_5, $v_{CS2.}$

2.2 Buck mode

The function of bidirectional power flow is necessary for charging the supercapacitors in Buck mode. Due to the reversed power-flow direction, the gate drive signal of S_5 is leading to that of S_6 as shown in Fig. 10. During the charging process, the voltage on the supercapacitors is increased, so the phase-shift plus duty cycle control is utilized in Buck mode. Because the half-bridge topology of the two sides is symmetrical, the operation principles in buck mode are similar to those in boost mode. In this buck mode of operation the switches S_1,S_4 are in turned off state. Remaining switches S_5,S_6,S_2,$S_3$are in turned on condition. The Buck mode operation can also be divided into ten stages, and the description of each step can be analogously inferred and will not be discussed here.
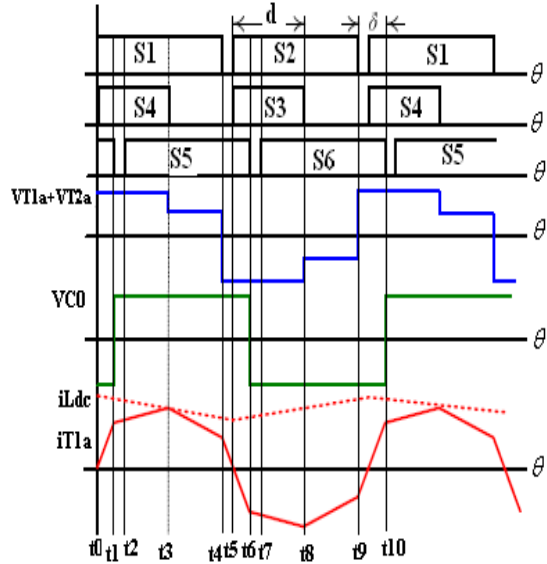

Fig.3.Theoritical waveforms of boost mode

3. CHARACTERISTICS OF NOVEL CONVERTER

3.1.Output power

The phase shift angle δ, which is defined as shown in Fig. 3 is used to control the magnitude and direction of the transmitted power in two-level sub-modes. The output power is similar with what described in [10] and [13], shown as:

$$P = \frac{2 \cdot V_L V_H}{\pi \omega L_{lk}} \cdot \delta\left(\pi - |\delta|\right)$$

where V_L is the peak voltage value of the transformer secondary side, $v_{T1a} + v_{T2a}$; V_H is the peak voltage value of v_{CO} ; ω is the switching angular frequency.

3.2. ZCS-ZVS range

The ZCS-ZVS hybrid bidirectional dc-dc converter operates in total ten modes for the intervals discussed in II section from (t_0-t_1) (t_1-t_2) (t_2-t_3) (t_3-t_4) (t_4-t_5) (t_5-t_6) (t_6-t_7) (t_8-t_9). In the following expression for the transformer current i_r in boost mode of operation. Similarly the modes for the buck mode are same as mentioned below.

Mode 1: $i_r = (v_1 + v_4)\theta \, / \, \omega L_s + i_r(t_0)$

Mode 2: $i_r = (v_1 + v_4 + v_5)(\theta - t_1) \, / \, \omega L_s$

Mode 3: $i_r = (v_1 + v_5)(\theta - t_3) \, / \, \omega L_s + i_r(t3)$

Mode 4: $i_r = (v_2 + v_3 + v_5)(\theta - t_4) \, / \, \omega L_s + i_r(t_4)$

Mode 5: $i_r = (v_2 + v_3 - v_5 + v_6)(\theta - t_5) \, / \, \omega L_s + i_r(t_5)$

Mode 6:
$i_r = (v_2 - v_3 + v_6)(\theta - t_6) \, / \, \omega L_s + i_r(t_6)$

Mode 7:
$i_r = (-v_2 - v_3 + v_6)(\theta - t_7) \, / \, \omega L_s + i_r(t_7)$

Mode 8: $i_r = (v_1 + v_4 + v_6)(\theta - t_8) \, / \, \omega L_s + i_r(t_8)$

Mode 9: $i_r = (v_1 + v_4 - v_6)(\theta - t_9 \, / \, \omega L_s + i_r(t_9)$

4. SIMULATION EVALUATION OF PROPOSED CONVERTER

The detailed proposed circuit model is built using Matlab/Simulink. The simulated results are compared with hybrid bidirectional DC-DC converter (ZVS) to show the performance of proposed converter.

4.1. Boost mode

The following parameters are selected according to a 400W for fuel cell and battery applications.
V_b =30V, D = 50%, f_s=20 kHz, L1=L2=L3=L4 = 8µH, C_{P1}= C_{S1}= 20mF, C_0= 150mF, R_L= 0.5Ω. V_o= 220V
The simulations revealed modes of operation where the primary side switches operate under ZCS and secondary side of the transformer switches are operate under ZVS conditions.

The Fig.4 and Fig.5 shows that load voltage and generated pulses. The Fig.6 shows that voltage through primary side and secondary side.

4.2 Buck mode

The following parameters are selected accroding to a 400W for fuel cell and supercapacitor applications. In this mode the switches S_1 & S_4 are in turned off condition. The body diodes of S_1 & S_4 gives the rectification. S_2, S_3, S_5, S_6 are in conducting stage. These switches will gives the power flow.
Vin = 220V, D=50%, f= 20Khz, V_o = 30v, $L_1=L_2=L_3=L_4$ = 8µH

The Fig.7 and Fig.8 shows that load voltage and voltage through primary and secondary side of transformer.Fig.9 shows that the generated pulses for the switches S_2, S_3, S_5, S_6. In this mode the switches S_5 & S_6 are turned on and turned off under ZVS, remaining switches are turned on or turned.Fig.10 shows that transformer current in boost mode.
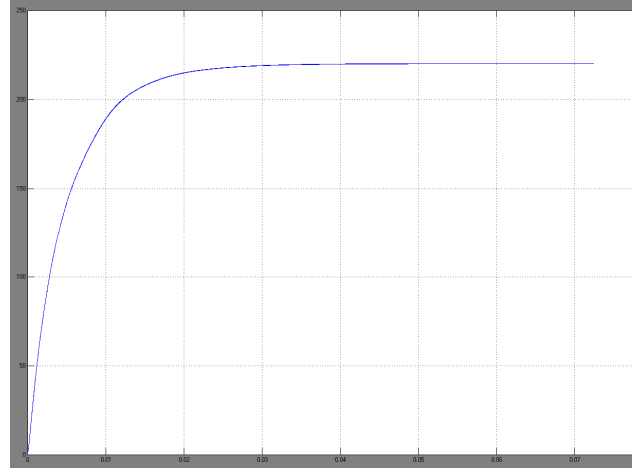

Fig.4. Load voltage
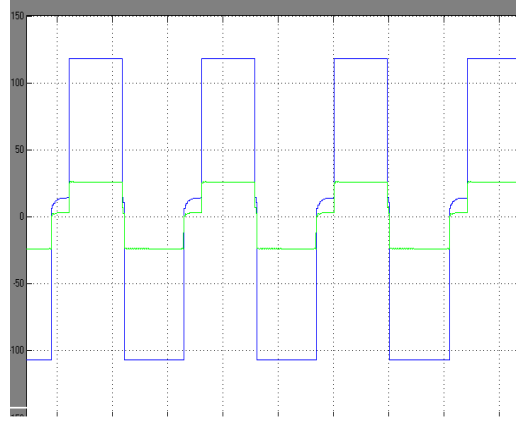
Fig.5. Generated pulses for $S_1, S_2, S_3, S_4, S_5, S_6$

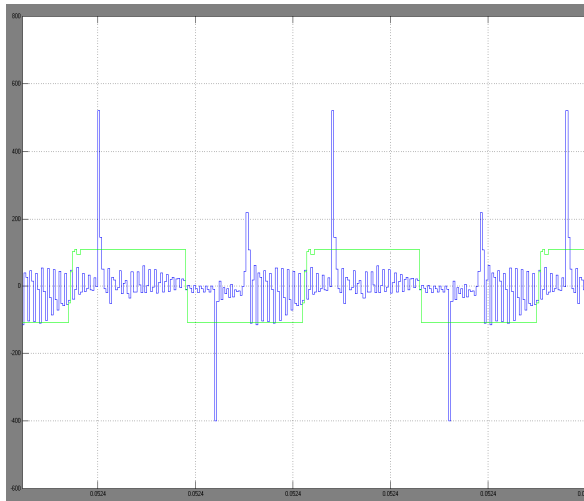Fig.8. Voltage through primary and secondary side
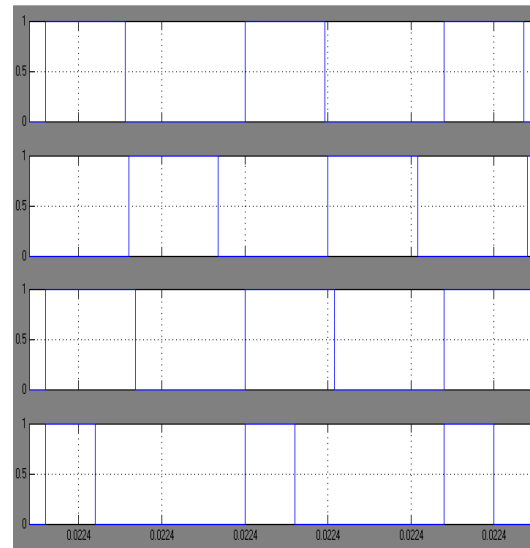

Fig.6. voltage through primary and secondary
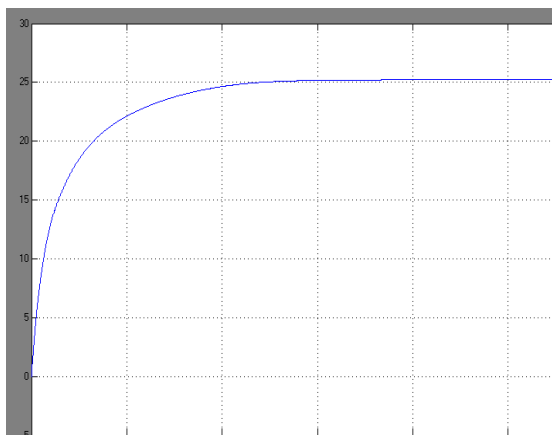

Fig.9. Generated pulses for S_2, S_3, S_5, S_6
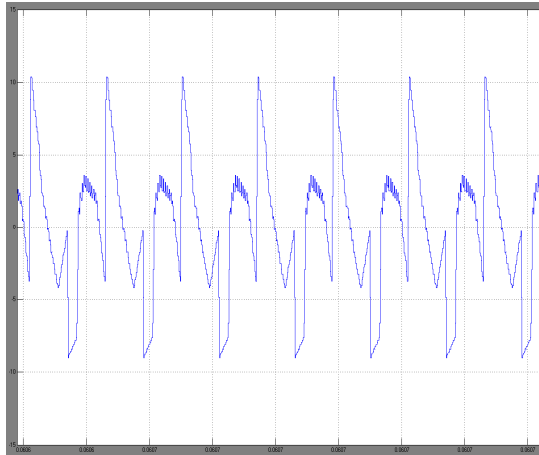

Fig.7. Load voltage in buck mode

Fig.10. Current through the transformer

5. C o n c l u s i o n

This paper proposes a new hybrid bidirectional topology on ZCS approach. It can be used in fuel cell and supercapacitor with effectiveness. The primary merits of this converter are reduced current tails across main switch the draw back of this proposed topology is its increased cost due to the introduction of charging elements in its circuit. But as compared to previous hybrid bidirectional converter(ZVS)[1] this proposed topology has reduced switching losses as well as increased efficiency.

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