Comparative Study of ZCT-ZVT PWM Boost Converter and Interleaved Boost Converter

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Abstract- *This converter introduces interleaved technology with Zero Voltage Transition (ZVT), Zero Current Transition (ZCT) and Pulse Width Modulation (PWM) characteristic. The interleaved approach reduces the ripple of the input current and output voltage. The active snubber cell provides switches to turn on with zero-voltage transition (ZVT) and to turn off with zero-current transition (ZCT). All the semiconductor components softly turn on and turn off with Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS). There is no additional voltage stress across the main and auxiliary components. The proposed converter has simple structure, minimum number of components, and ease of control. The operating stages, waveforms and the simulation results of the proposed converter using MATLAB/Simulink operated for 1.5 kW and 100 kHz is given in detail. Also the prototype of 5W and 10 kHz is designed and implemented using PIC 16F877A and analyse the result.*

Keywords- *Zero Voltage Transition, Pulse Width Modulation, Zero Current Transition, snubber***.**

I. INTRODUCTION

An Interleaved boost converter usually combines more than two conventional topologies and the current in the element of the interleaved boost converter is half of the conventional topology in the same power condition. This commonly preferred in industrial applications as renewable energy sources, electrical vehicles, fuel cell etc. In general, low input current ripple, low output voltage ripple and a higher output voltage gain are desired in these applications. The interleaved converters which are equivalent to two parallel-connected boost converters commonly are used for these aims. Especially, they are preferred in power factor correction applications because of low input current ripple. Moreover, interleaved converters have some advantages as fast dynamic response, smaller filter design and control simplicity. Many soft-switching techniques are introduced to the interleaved boost converter.

The switching frequency needs to be increased for obtaining high power density in interleaved boost converters used in high power applications. But the high switching frequency leads to high switching losses and electromagnetic interference (EMI). So, it causes reduced performance and low efficiency. The soft switching (SS) techniques are proposed for resolving all of these adverse effects in interleaved converters [1-8].The most advanced soft switching techniques are ZVT to turn on and ZCT to turn off. In the traditional ZVT converter, a gate signal is given to the main switch when its voltage falls to zero by means of active snubber cell. Thus, the main switch turns on with ZVT. Therewith, the main diode turns off and the auxiliary switch turns on with ZCS. But turning off of the main switch is not enough good and the auxiliary switch turns off under hard switching (HS) [2].

In the traditional zero current transition (ZCT) converter, firstly the current of main switch is fallen to zero by means of active snubber cell while the main switch is at on state. Then, a gate signal of main switch is cut off while its current is kept at zero value. So, the main switch turns off with ZCT lossless. Additionally, the main diode turns on with SS and the auxiliary switch turns on with ZCS. But turning on the main switch, turning off the auxiliary switch, and turning off the main diode are realized with HS [3]. This paper proposes an interleaved boost converter with an active snubber cell is proposed. The active snubber cell provides both characteristics of zero-voltage transition during turn on of the switch and zero-current transition during turn OFF of the switch. The proposed converter is the parallel of two boost converters with their driving signals stagger 180 and this makes the operation assumed symmetrical. The converter has simple structure, minimum number of components, and ease of control. The soft switching (SS) techniques are for resolving all of these adverse effects in interleaved converters. In this converter, the main switches turn on with ZVT and turn off with ZCT as well as the auxiliary switch turns on with ZCS and turns off with ZVS. The main diodes turn on with ZVS and turn off with ZCS. The auxiliary diodes turn on and turn off with SS. One of the most important benefits of the converter is that the extra voltage stress or the extra current stress does not occur on the main switches and diodes. Moreover, by considering that the main switches and main diodes do not exposed to extra current stresses or voltage stresses in ZCT-ZVT PWM DC-DC interleaved boost converter with active snubber cell. Another important feature of this converter is that the soft switching operating is maintained even in light load conditions. Due to this feature that many converters have not it, one of the important contributions is that the converter operates in light load conditions. Additionally, the study has low input current ripple and output voltage ripple.

II. Analysis And Operation of ZCT-ZVT PWM Boost Converter

A. Basic Circuit Scheme

In this new ZCT-ZVT PWM DC-DC interleaved boost converter having an active snubber cell is used to overcome the drawbacks of converters. The basic circuit scheme of this new soft switching ZCT-ZVT PWM DC-DC interleaved converter is shown in Fig.1. In this converter, the main switches perfectly turn on with ZVT and turn off with ZCT. The auxiliary switch turns on with ZCS and turns off with ZVS. The main diodes turn on with ZVS and turn off with ZCS. Also, any voltage and current stresses do not occur on the main switches and the main diodes. The current stress on the auxiliary switch is acceptable level. All of the other semiconductor devices turn on and turn off with SS. An auxiliary switch, a coupled resonance inductance, a resonance capacitor and four auxiliary diodes are used in the snubber circuit. MOSFET is chosen for main switches and IGBT is chosen for auxiliary switch. In addition to the new converter can operate under light load conditions and it operates a wide range of duty cycle.

In this interleaved DC – DC boost converter shown in Figure 1, V_i is input voltage source, S_1 and S_2 are main switches, L_1 and L_2 are main inductors, D_{F1} and D_{F2} are main diodes, C_{S1} and C_{S2} are parasitic capacitors of the main switches and C_F is output filter capacitor. In the active snubber cell, S_a is auxiliary switch, D_{r1}, D_{r2}, D_a and D_b are auxiliary diodes, L_a and L_b are coupled resonance inductors. The following assumptions are made to simplify theoretical analysis. The input voltage V_i is constant, C_F is selected enough large in order to keep constant to output voltage, L_1 and L_2 is selected enough large than resonance inductor to keep constant the input current and all of the semiconductor devices are ideal, the reverse recoveries of diodes are neglected.

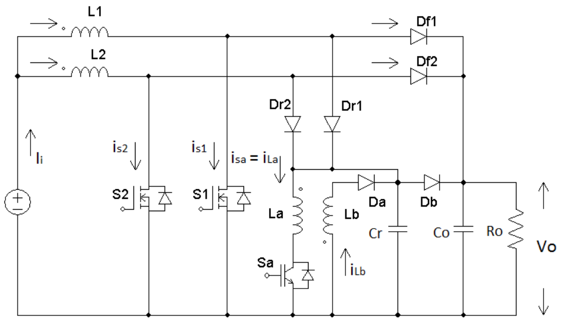

Fig 1: The basic circuit scheme of ZCT-ZVT PWM converter with active snubber circuit

B. Modes of Operation

Eleven stages occur for each switch in the steady state operation of the converter during one switching period. The equivalent circuits of these stages are shown in Fig.2 given below. Here, the operating stages are examined for D > 0.5. So, S_1 switch is turned on and turned off while S_2 switch turns on. This is half of interleaved operation. Then, the same stages are actualized for S_2 switch. The key waveforms of the operating stages are shown

Mode I: The main switches S_1 and S_2 are at on state and the auxiliary switch S_a is at off state. The energy obtained from the input voltage source is transferred to the main inductors L_1 and L_2. At t_0, current through switch S_1 (i_{s1}) and S_2 (i_{s2}) is equal to half of the input current, current through D_{F1}, D_{F2}, L_a, L_b and S_a are equal to zero and voltage across C_r is equal to output voltage are valid.
Mode II: At the beginning of this stage t_1, current through switch s_1 and s_2 is equal to half of the input current, current through L_a and S_a equal to I_{Lamax1}, i_{DF1} equal to i_{DF2} equal to zero and V_{Cr} equal to zero are valid. The current of the resonance inductor I_{Lamax1} flows through body diodes D_1 and D_2 after the voltage of C_r falls to zero. This stage is ZCT interval and it is called freewheeling interval. The main switch S_1 and the auxiliary switch S_a are turned off simultaneously while the body diodes of the main switches are at on state. This stage is finished after the main switch S_1 turns off with ZCT and the auxiliary switch S_a turns off with ZVS.
Mode III: At t_2, i_{S1} and i_{S2} is equal to half of I_i – I_{Lamax1}, $i_{La} = i_{Sa} = I_{Lamax1}$, $i_{DF1} = i_{DF2} = 0$ and $V_{Cr} = 0$ are valid. In this stage, when the main switch S_1 and the auxiliary switch S_a turn off , the parasitic capacitor of S_1 is charged to output voltage. Due to coupling, the current of the resonance inductor is transferred to L_b and a resonance begins via $L_{b,}$ D_a C_r. So, the energy of resonance inductor is transferred to the resonance capacitor C_r. Owing to this resonance, the auxiliary switch S_a turns off with ZVS. At t = t_3, V_{Cr} and the voltage of the main switch S_1 reach to V_o value. Then, the main diode $D_{F\ 1}$ turns on with ZVS.

Mode IV: At the beginning of this stage, at time t = t_3, $i_{S1} = 0$, $i_{S2} = I_i/2$, $i_{Sa} = i_{La} = 0$, $i_{Lb} = I_{Lbmin1}$, $i_{DF1} = I_i/2$, $i_{DF2} = 0$ and $V_{Cr} = V_o$ are valid. During this stage beginning as soon as D_{F1} diode turns on with ZVS, D_b diode turns on with ZVS and the energy of resonance inductor is transferred to the output capacitor through D_b diode. At $t=t_4$, the current of resonance L_b is zero and this stage is finished Mode V: During this stage, $i_{S1}=0$, $i_{S2}= I_i/2$, $i_{Sa} = i_{La} = i_{Lb} = 0$, $i_{DF1} = I_i/2$, $i_{DF2} = 0$ and $V_{Cr} = V_o$ are valid. This stage is equivalent to two parallel-connected boost converters that one of them is at on state and the other is at off state. At $t = t_5$, a gate signal is applied to the auxiliary switch S_a and this stage is finished.

Mode VI: At the beginning of this stage, at time t = t_5, $i_{S1} = 0$, $i_{S2} = I_i/2$, $i_{Sa} = i_{La} = i_{Lb} = 0$, $i_{DF1} = I_i/2$, $i_{DF2} = 0$ and $V_{Cr} = V_o$ are valid. In this stage beginning when a gate signal is applied to the auxiliary switch S_a, the current of auxiliary switch i_{Sa} increases and the current of main diode i_{DF1} decreases simultaneously. So, $D_{F\ 1}$ diode turns off and S_a turns on with ZCS.

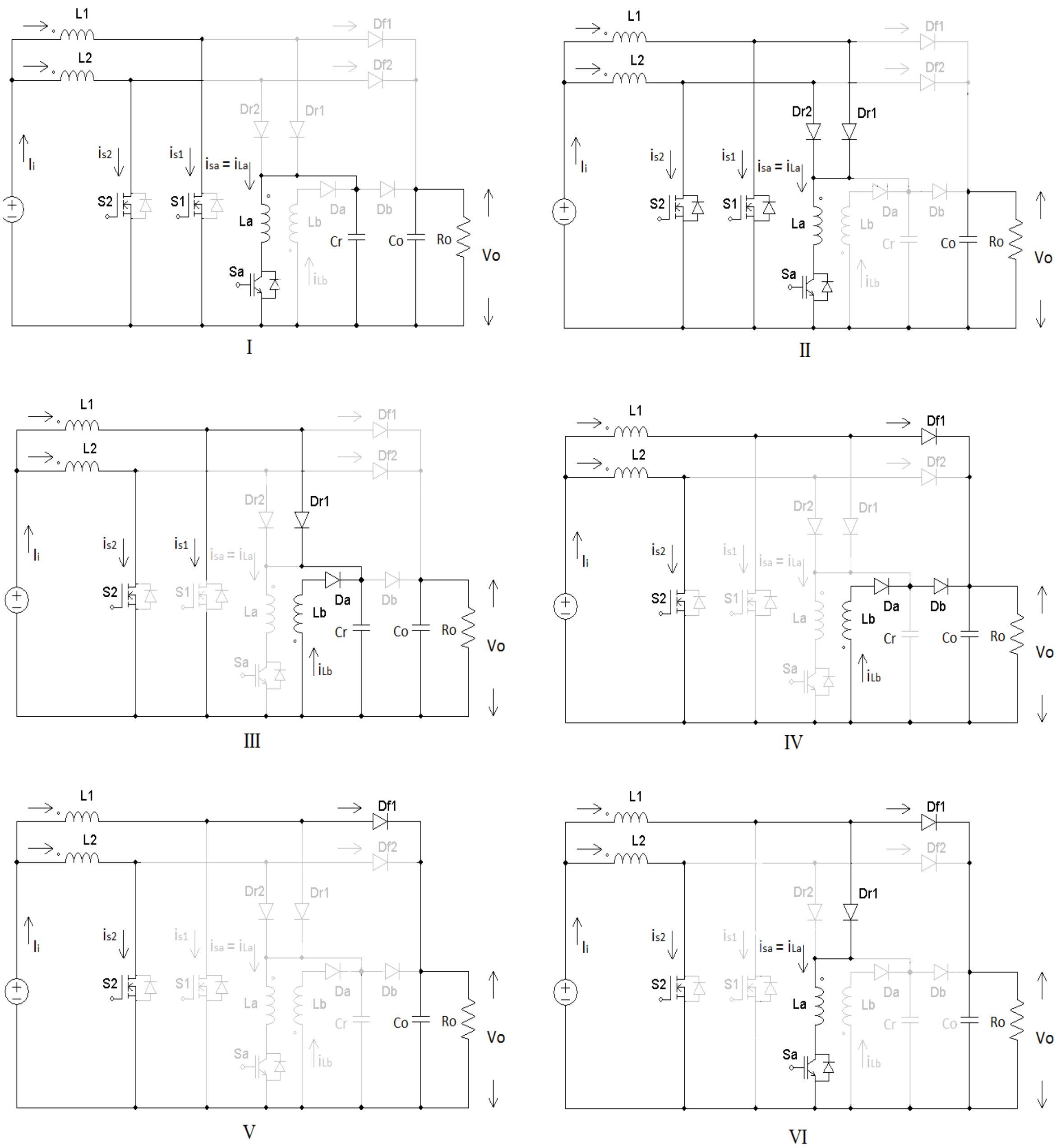

Figure 2a: Modes of Operation

Mode VII: At the beginning of this stage, at time t = t_6, $i_{S1} = 0$, $i_{S2} = I_i/2$, $i_{Sa} = i_{La} = I_i/2$, $i_{Lb} = 0$, $i_{DF1} = i_{D2} = 0$ and $V_{Cr} = V_o$ are valid. In this stage beginning as soon as $D_{F\ 1}$ diode turns off , two resonances begin via $C_{s1} – D_{r1} – L_a – S_a$ and $C_r – L_a – S_a$.

Mode VIII: At the beginning of this stage, at time t = t_7, $i_{S1} = 0$, $i_{S2} = I_i/2$, $i_{Sa} = i_{La} = I_{Lamax2}$, $i_{Lb} = 0$, $i_{DF1} = 0$, $i_{DF2} = 0$ and $V_{Cr} = 0$ are valid. In this stage, the resonance current I_{Lamax2} on resonance inductor La flows through body diodes D_1 and D_2. This stage is ZVT interval and it is called freewheeling interval. At any time of this interval, the main switch S_1 is turned on and the auxiliary switch S_a is turned off simultaneously while the body diodes of the main switches are at on state. Thus, the main switch S_1 turns on with ZVT and the auxiliary switch S_a turns off with ZVS.

Mode IX: At the beginning of this stage, at time t = t_8, $i_{S1} = i_{S2} = I_i/2$, $i_{Sa} = i_{Sa} = 0$, $i_{Lb} = I_{Lamax2}$, $i_{DF1} = i_{DF2} = 0$ and $V_{Cr} = 0$ are valid. Due to coupling, the current of the resonance inductor La is transferred to Lb. Then, a resonance begins via L_b, D_a, C_r. So, the energy of resonance inductor is transferred to the resonance capacitor C_r.

Mode 1X: At the beginning of this stage, at time t = t_9, $i_{S1} = i_{S2} = I_i/2$, $i_{Sa} = i_{La}=0$, $i_{Lb}= I_{Lbmin2}$, $i_{DF1} = i_{DF2} = 0$ and $V_{Cr} = V_o$ are valid. In this stage beginning when D_b diode turns on with ZVS, the energy of resonance inductor is transferred to the output capacitor through Db diode

Mode XI: During this stage, $i_{S1} = i_{S2} = I_i/2$, $i_{Sa} = i_{La} = i_{Lb} = 0$, $i_{DF1} = i_{DF2} = 0$ and $v_{Cs2} = V_o$ are valid. The main switches S_1 and S_2 are at on state and the auxiliary switch S_a is at off state. The energy obtained from the input voltage source is transferred to the main inductors L_1 and L_2.

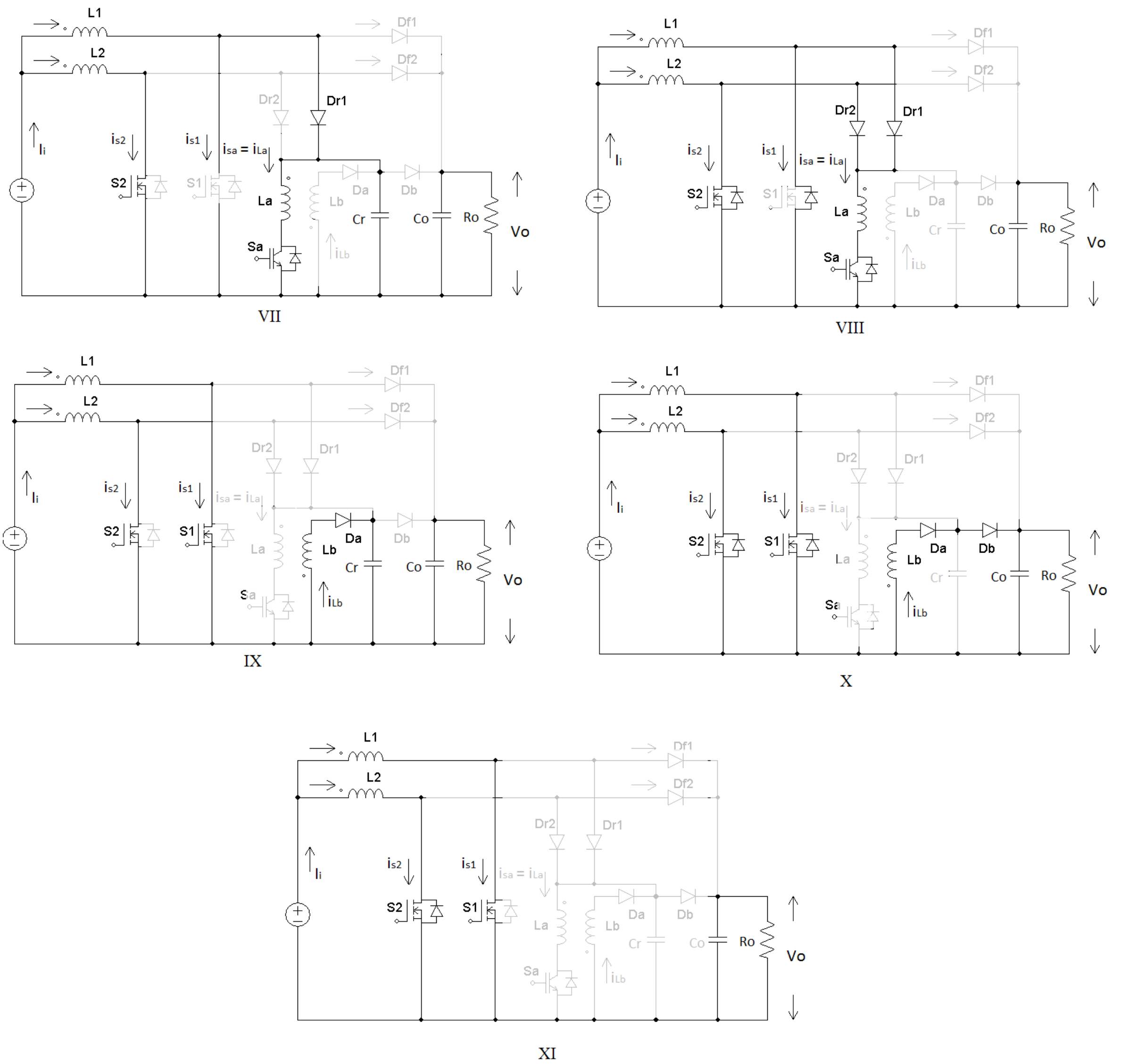

Figure 2b: Modes of Operation

III. Analysis And Operation Of Interleaved Boost Converter

A. Basic Circuit Scheme

Interleaving technique is an interconnection of multiple switching cells that will increase the effective pulse frequency by synchronizing several smaller sources and operating them with relative phase shift. An interleaving technique saves energy and improves power conversion without affecting conversion efficiency. The Circuit diagram of interleaved DC-DC boost converter is shown in figure. The interleaved boost converter consists of two stage parallel connected switches S1, S2; inductors L1, L2 diodes D1, D2 Capacitor C and load resistor R with common input source (Vin). The switches are controlled by phase shifted switching function known as interleaving operation.

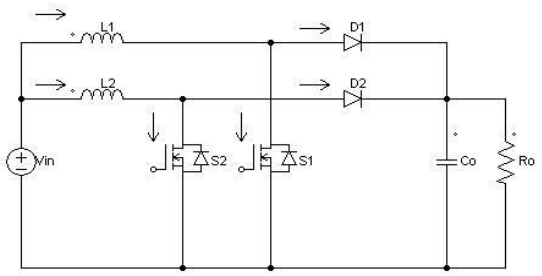

Fig 3: Basic Circuit of Interleaved Converter

B. Modes Of Operation

Mode I: The Circuit diagram of interleaved DC-DC boost converter in mode 1 is shown in fig 6. In this mode, diode D_1 is reverse biased while diode D_2 is forward biased. The input supply energy to the inductor L_1 resulting in rise of the inductor current i_{L1}.At the same time, inductor L_2 supplies energy to the load resulting in decrease in inductor current

Mode II: The Circuit diagram of interleaved DC-DC boost converter in mode 2 is shown in fig 7. In this mode, both switches are on and so both diodes D_1, D are reverse biased. This makes both inductors L_1, L_2 charges and resulting in increase of the inductor current i_{L1} and i_{L2}.

Mode III: The Circuit diagram of interleaved DC-DC boost converter in mode 3 is shown in fig 8. In this mode, diode D_1 is forward biased while diode D_2 is reverse biased. Inductor L_1 discharging and supplying energy to the load resulting in fall of the inductor current i_{L1}.At the same time, the input supplies energy to the Inductor L_1 resulting in increase in inductor current $i_{L2.}$

Mode IV is same as mode 2, after that the cycle repeats.

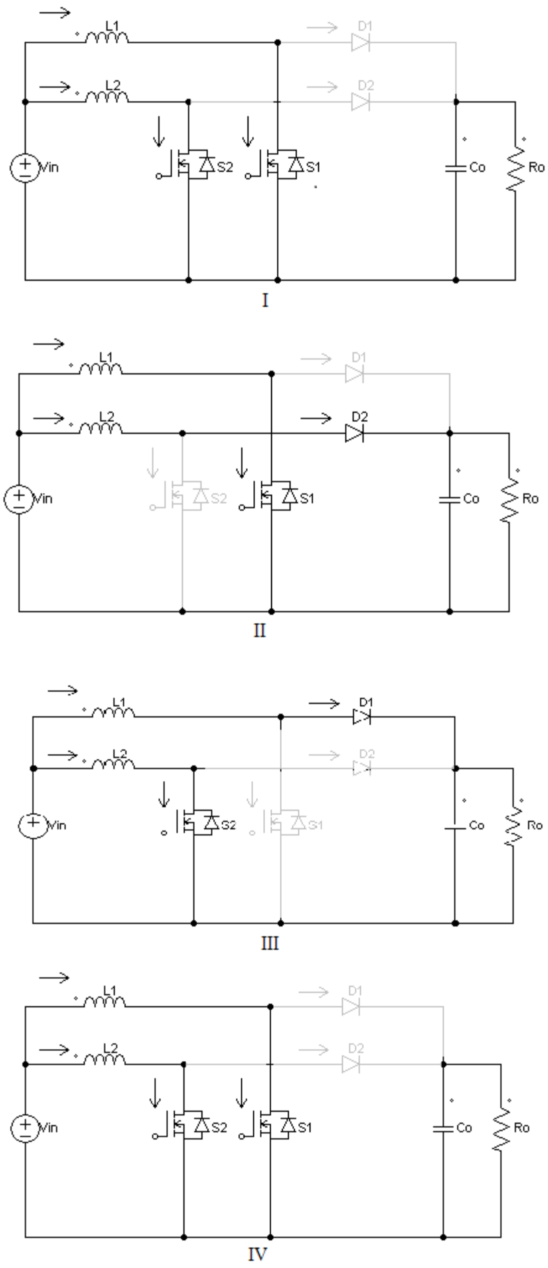

Fig 4: Modes of Operation

IV. Simulation Models And Results

A. ZCT ZVT PWM Boost Converter

Simulation of ZCT-ZVT PWM DC-DC interleaved boost converter with an active snubber cell is done using MATLAB/Simulink 2014.

1) *Simulation Parameters*

Table 1: Simulation Parameters

COMPONENTS	PARAMETERS
Output power (Po)	1.5 kW
Frequency (f)	100 kHz
Input voltage (Vi)	200 V
Output voltage (Vo)	600 V
Main inductors (L1, L2)	500 μH
Coupled resonance inductors (La, Lb)	8 μF
Resonance capacitor (Cr)	5 nF
Output filter capacitor (Co)	470 μF
Parasitic capacitor (Cs1, Cs2)	1 nF

2) *Simulink Model Of ZCT ZVT PWM Boost Converter*

It is realized a prototype of ZCT-ZVT PWM DC-DC interleaved boost converter with an active snubber cell by 1.5 kW and 100 kHz in MATLAB/Simulink model is shown.

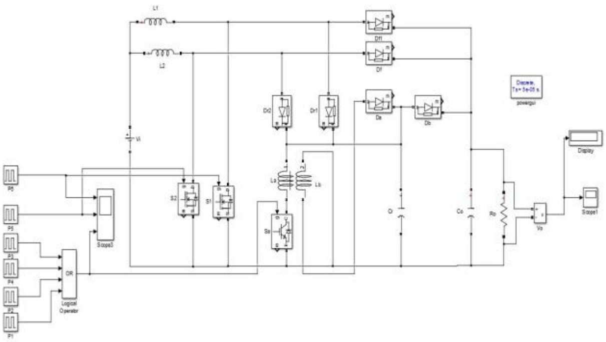

Fig 5: Simulink model of new ZCT-ZVT PWM DC-DC interleaved boost converter

3) *Simulation Results*

Input and corresponding output voltage by simulating ZCT-ZVT PWM DC-DC inter-leaved boost converter is shown in fig. 6

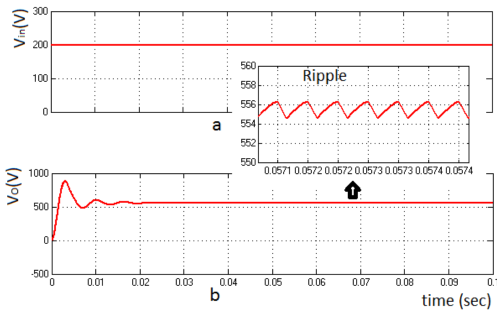

Fig 6: (a) Input voltage (b) Output voltage

The control signals of the main switches and the auxiliary switch, voltage and current waveforms of the main switches and input current are shown in Fig: 7 to 9. As shown in figures, the main switches S_1 and S_2 perfectly turn on with ZVT and turn off with ZCT. Additionally, it is shown that the extra current and voltage stresses do not occur on the main switches.

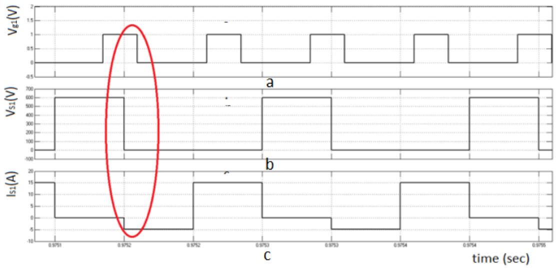

Fig 7: Waveforms of the switch s_1 (a) gate pulse, (b) voltage ,(c) current

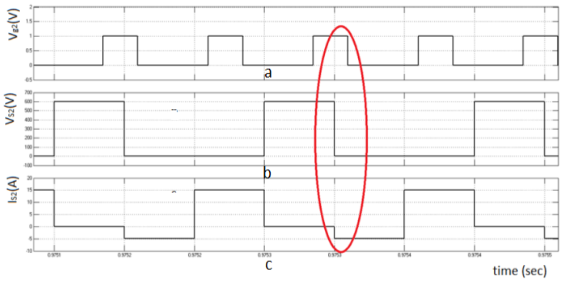

Fig 8: Waveforms of the switch s_2 (a)gate pulse (b)voltage (c) current

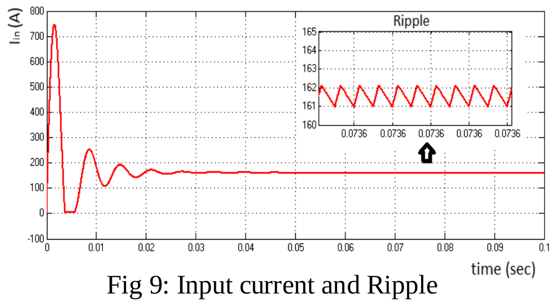

Fig 9: Input current and Ripple

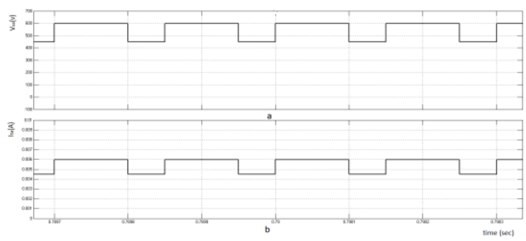

Fig 10: Voltage and current waveforms of the switch s_a (a) voltage, (b) current

The current and voltage waveforms of the auxiliary switch are shown with simulation results in Figure: 10. As shown in waveforms, the auxiliary switch turns on with ZCS and turns off with ZVS in both ZCT interval and ZVT interval. The current stress of auxiliary switch is acceptable level. From simulation studies, the soft switching states of this converter are examined under 1.5 kW power condition. On the other hand, the load is changed to examine behaviour of converter under light load conditions. The converter is operated in light load conditions and analysed by 150 W powers

B. Interleaved Boost Converter

The MATLAB simulation models and switching pulse and results of interleaved boost converter are shown in the fig.5.8 to 5.12.

1) Simulation Parameters

Table 2: Simulation Parameters

COMPONENTS	PARAMETERS
Output power (Po)	1.5 kW
Frequency (f)	100 kHz
Input voltage (Vi)	200 V
Output voltage (Vo)	600 V
Main inductors (L1, L2)	500 µH
Output filter capacitor (Co)	470 µF

2) Simulink Model Of Interleaved Boost Converter

It is realized a prototype of DC-DC interleaved boost converter with an active snubber cell by 5kW and 10 kHz in MATLAB/Simulink model is shown.

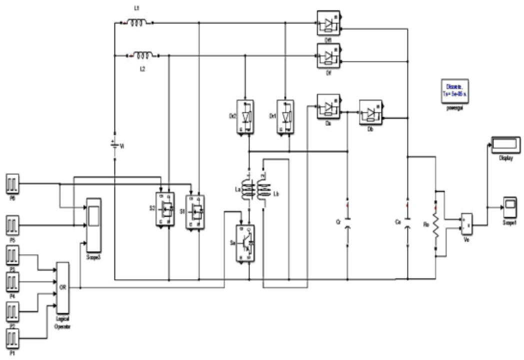

Fig 11: Simulation model of Interleaved DC-DC Converter

3) Simulation Results

Input and corresponding output voltage by simulating DC-DC inter-leaved boost converter is shown in fig. 12

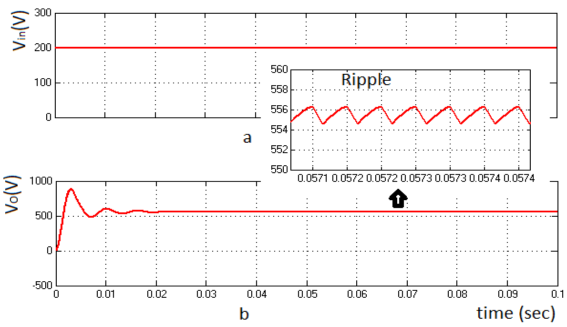

Fig 12: Output Voltage and Ripple

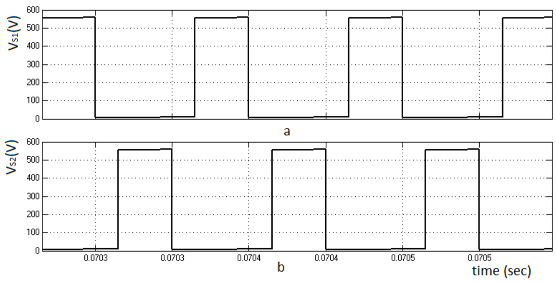

Fig 13: Voltage Stress Across switches a)s_1 b)s_2

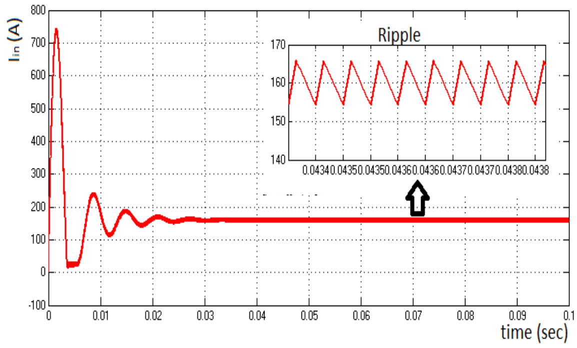

Fig 14: Input Current and Ripple

The output voltage and ripple, voltage waveforms of the switches and input current and ripple are shown in Fig. 12, Fig.13, and Fig. 14. As shown in figures, the main switches S_1 and S_2 not turn on with ZVT and turn off with ZCT. Additionally, it is shown that the extra current and voltage stresses occurs on the main switches From figure it is clear that ripple is much larger compared to ZCT-ZVT PWM DC-DC interleaved boost converter.

C. Comparative Study

Table 3: Comparative Study

Parameters	Interleaved DC-DC Converter	ZCT ZVT PWM Interleaved DC-DC Converter
Input Voltage	200	200
Output Voltage	556.3	555.6
Output Voltage Ripple	1.2V	0.2V
Current Ripple	10A	1A
Voltage Stress Across S1	556.3	555.6
Voltage Stress Across S2	556.6	555.6

For interleaved converter the output power is 1113W and whereas for ZVT ZCT PWM converter it is 1384 for an input power of 1500.That is the efficiency of proposed converter has been increased by 18%

V. EXPERIMENTAL SETUP AND RESULTS

A prototype of 5W is setup in the laboratory and various parameters that indicates the performance of the inverter is measured using a DSO. It is realized a prototype of ZCT-ZVT PWM DC-DC interleaved boost converter with an active snubber cell by 5 W and 50 kHz using PIC16F877A model is shown.

Table 4: Components Used

COMPONENTS	PARAMETERS
Main inductors (L_1, L_2)	1mH
Coupled resonance inductors (L_a, L_b)	47 µH
Resonance capacitor (Cr)	9 nF
Output filter capacitor (Co)	470 µF
Parasitic capacitor (C_{s1}, C_{s2})	1 nF
MOSFET	IRF540
Diode	IN5819

The applied input voltage is 5V and got the output as 10.6V, that is we got a gain of 2.12.

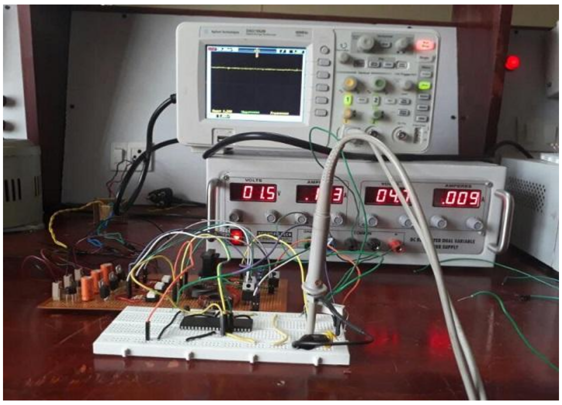

Fig 15a : Experimental Setup

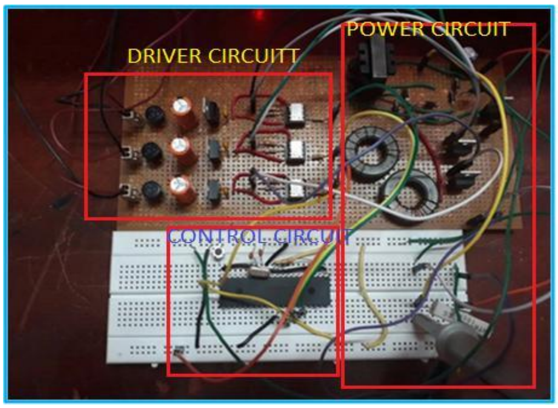

Fig 15b :Experimental Setup

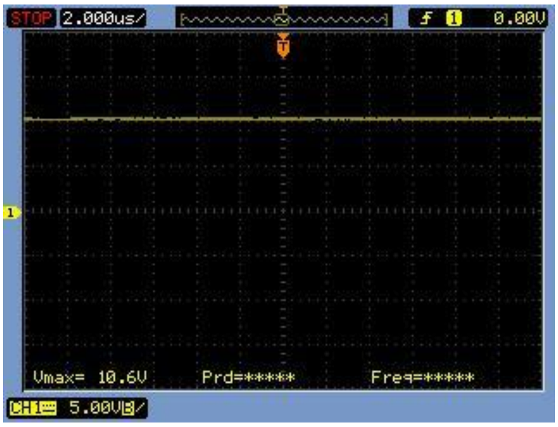

Fig 16 : Experimental Output

VI. CONCLUSION

In ZCT-ZVT PWM DC-DC interleaved boost converter with an active snubber cell the main switches turn on with ZVT and turn off with ZCT as well as the auxiliary switch turns on with ZCS and turns off with ZVS. The main diodes turn on with ZVS and turn off with ZCS. The auxiliary diodes turn on and turn off with SS. The benefits of this new converter are that the extra voltage stress or the extra current stress does not occur on the main switches and diodes. Moreover, by considering that the main switches and main diodes do not exposed to extra current stresses or voltage stresses in new ZCT-ZVT PWM DC-DC interleaved boost converter with active snubber cell. Another important feature of this converter is that the soft switching operating is maintained even in light load conditions. Due to this feature this converter have contributions is that this converter operates in light load conditions. Additionally, this converter has low input current ripple and output voltage ripple. Implemented the hard ware using PIC16F877A and got a gain 2.12.

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