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A NEW ZVT ZCT PWM DC-DC CONVERTER

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Abstract— A new boost converter with an active snubber cell is proposed. The active snubber cell provides main switch to turn ON with zero-voltage transition (ZVT) and to turn OFF with zero-current transition (ZCT). The proposed converter incorporating this snubber cell can operate with soft switching at high frequencies. Also, in this converter all semiconductor devices operate with soft switching. There is no additional voltage stress across the main and auxiliary components. The converter has a simple structure, minimum number of components, and ease of
control as well.

***Index Terms*— soft switching, snubber cell, zero voltage transition(ZVT), zero current transition(ZCT), zero voltage switching(ZVS), zero current switching(ZCS)**

INTRODUCTION

The linear power supplies are replaced by switch mode power supplies because they are huge in size and bulky as they are operated at low frequency (50 or 60 Hz) and also the efficiency is low. Switched mode power supplies are widely used in the industry due to their high-power density, quick transition response, ease of control and high efficiency. In PWM dc–dc converters, higher power density and faster transition response can be obtained by increasing the switching frequency. However, as the switching frequency increases, switching losses and electromagnetic interference (EMI) noise increase. These problems can only be solved by using soft-switching techniques realized by snubber cells.

Resonant converters are a family of soft-switching converters. In these converters, a resonant tank is added to the converter, switching losses are significantly reduced by means of the commutations which are realized with either zero voltage switching (ZVS) or zero current switching (ZCS). But, in these types of converters, excessive voltage and current stresses occur, and power density is lower and control is harder than normal PWM converters. Recently, a number of soft-switching pulse width modulated (PWM) converter techniques have been proposed, aimed at combining the desirable features of both the conventional PWM and resonant techniques.

The recently developed zero-voltage transition (ZVT) and zero-current transition (ZCT) pulse width modulation (PWM) techniques incorporate soft-switching function into PWM converters, so that the switching losses can be reduced with minimum voltage/current stresses and circulating energy.

In this work, a new active snubber cell is developed which provides perfectly ZVT turn on and ZCT turn off together for the main switch of a converter by using only one quasi resonant circuit. The ZVT-ZCT-PWM converter equipped with the developed snubber cell, combines most of the desirable features of both the ZVT and ZCT converters and overcomes most of the drawbacks of ZVT and ZCT PWM converters. The converter has a simple structure, low cost and ease of control. Applications of such ZVT-ZCT PWM DC-DC converter are suitable for the power-factor correction circuits and the renewable energy converters, where high efficiency is considered mainly.

Soft switching technique allows operation of the proposed converter at higher switching frequencies resulting in higher power densities without compromising the efficiency. Switches have to provide a reverse voltage blocking capability and for this reason they have to be constructed by means of an IGBT or a MOSFET having a reverse voltage blocking diode with them. Snubbers can control the voltage and current to a point where switching occurs at zero voltage and zero current and thus increases the reliability of the power stage significantly. In the proposed work, size and weight of the device is reduced as the heat sink is not required.

There are three approaches to have the high efficiency in the proposed converter-

- During the control range of operation, the transistor current and voltage waveforms does not overlap with each other due to which the power dissipation of the circuit is reduced.
- In this converter all the semiconductor devices operate under soft switching, hence switching losses are totally eliminated.
- There is negligible circulating current from the auxiliary circuit to the main switch so that the main switch maximum current and conduction losses are not increased.

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I. PROPOSED ZVT ZCT PWM DC-DC CONVERTER

The circuit scheme of the proposed and developed ZVT-ZCT-PWM boost converter circuit is shown in Fig1. In this circuit, Vi is input voltage source, Vo is output voltage, LF is main inductor, CF is output filter capacitor, S1 is main switch and DF is main diode. The main switch consist of a main transistor T1and its body diode D1 . The snubber circuit shown with dashed line is formed by snubber inductor Ls , a snubber capacitor Cs and auxiliary switch S2. T_2 and D_2 are the transistor and its body diode of the auxiliary switch, respectively. The capacitor C_r is assumed to be the sum of the parasitic capacitor of S_1 and the other parasitic capacitors incorporating it. In the proposed converter, it is not required to use an additional C_r capacitor.

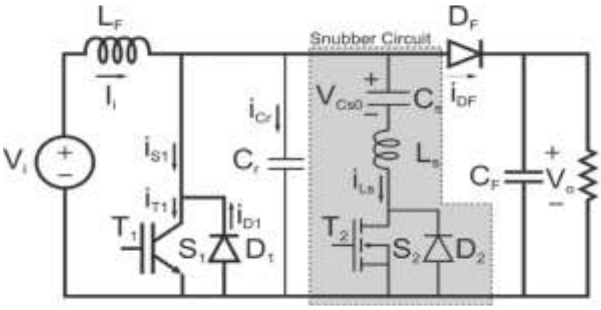

Fig.1 Circuit diagram of ZVT-ZCT-PWM boost converter.

In the proposed converter there are 11 modes of operation modes explained as follows

Mode 1 [$t_0 < t < t_1$] [fig 2(a)]: At the begining of this mode, the main transistor T_1 and auxiliary transistor T_2 are in the OFF state. The main diode D_F is in the ON state and the input current I_i flows through the main diode. At $t = t_0$, $i_{T1} = 0$, $i_{Ls} = i_{T2} = 0$, $i_{DF} = Ii$, $v_{Cr} = V_o$ and $v_{Cs} = V_{Cs0}$ are valid. The initial voltage of snubber capacitor V_{Cs0} is constituted by the efficiency of the resonant circuit. Soft-switching range of the circuit depends on the initial voltage of C_s . Soft switching depends on the value of V_{Cs0} . The main diode D_F is in the ON state and conducts the input current I_i. At $t = t_0$, when the turn on signal is applied to the gate of the auxiliary transistor T_2 , mode 1 begins. A resonance starts between snubber inductances L_s and snubber capacitor C_s . Due to the resonance T_2 current rises and D_F current falls simultaneously. The rise rate of the current is limited because of the L_s snubber inductance connected serially to the auxiliary switch. So that the turn on of the auxiliary switch is provided with ZCS. For this interval, the following equations can be written

$$i_{Ls} = (V_o - V_{Cs0})\sin \omega_s (t - t_0)/L_s\omega_s \quad (1)$$

$$v_{Cs} = V_o - (V_o - V_{Cs0}) \cos \omega_s (t - t_0) \quad (2)$$

At $t = t_1$, snubber capacitor voltage v_{Cs} is charged to V_{Cs1}, i_{T2} reaches I_i and i_{DF} falls to zero. When i_{DF} reaches $-Irr$, D_F is turned OFF and this stage finishes. In this stage, T_2 is turned ON with ZCS due to Ls . D_F is turned OFF with nearly ZCS and ZVS due to L_s and C_r . At the end of the mode it can be written as follows

$$i_{Ls} = i_{T2} = I_i + I_{rr} \quad (3)$$

$$v_{Cs} = V_{Cs1} \quad (4)$$

Mode 2 [$t_1 < t < t_2$][fig 2.(b)]: Before $t = t_1$, $i_{T1} = 0$, $i_{Ls} = i_{T2} = I_i + I_{rr}$, $i_{DF} = 0$, $v_{Cr} = V_o$ and $v_{Cs} = V_{Cs1}$ are valid. The main transistor T_1 and the main diode D_F are in the OFF state. The auxiliary transistor is in the ON state and conducts the sum of the input current Ii and the reverse recovery current of D_F . At $t = t_1$, a resonance between parasitic capacitor C_r , snubber inductor L_s and snubber capacitor C_s starts. The equations obtained for this mode are given as follows:

$$i_{Ls} = Ii + I_{rr} \cos \omega_r (t - t_1) - (VC_{s1} - V_o)\, \omega_r L_s \sin \omega_r (t - t_1) \quad (5)$$

$$v_{Cr} = -(V_{Cs1} - V_o) \cos \omega_r (t - t_1) + V_{Cs1} - L_s\omega_r I_{rr} \sin \omega_r (t - t_1) \quad (6)$$

At $t = t_2$, v_{Cr} becomes 0 and this stage is finished. Thus, the transfer of the energy stored in the parasitic capacitor C_r to the resonant circuit is completed. At this time the diode D_1 is turned ON with nearly ZVS and this stage ends. The capacitor C_r is assumed the sum of the parasitic capacitor of S_1 and the other parasitic capacitors incorporating it. In the proposed converter, it is not required to use an additional C_r capacitor.

At the end of this mode it can be written as follows

$$i_{Ls} = i_{T2} = I_{Ls2} \quad (7)$$

$$v_{Cs} = V_{Cs2} \quad (8)$$

Mode 3 [$t_2 < t < t_3$][fig 2.(c)]: Just after the diode D_1 is turned ON at t_2, $i_{T1} = 0$, $i_{Ls} = i_{T2} = I_{Ls2}$, $i_{DF} = 0$, $v_{Cr} = 0$ and $v_{Cs} = V_{Cs2}$ are valid at the begining of this mode. In this mode, the resonant which is between the snubber inductance Ls and snubber capacitor Cs continues.

$$i_{Ls} = I_{Ls2} \cos \omega_s (t - t_2) - V_{Cs1}\, \omega_s L_s \sin \omega_s (t - t_2) \quad (9)$$

$$v_{Cs} = V_{Cs1} \cos \omega_s (t - t_2) + L_s\omega_s I_{Ls2} \sin \omega_s (t - t_2) \quad (10)$$

At the beginning of this mode the voltage of C_r becomes zero, so that the diode D_1 is turned ON and conducts the excess of snubber inductance L_s current from the input current. The period of this stage is the ZVT duration of the main transistor so that this interval is called ZVT duration. In this mode, control signal is applied to T_1 while D_1 is in the ON state in order to provide ZVT turn ON of T_1. At $t = t_3$, this stage ends when the snubber inductance L_s current falls to input current, and D_1 is turned OFF under ZCS. At the end of this mode it can be written as follows

$$i_{Ls} = i_{T2} = I_{Ls3} = I_i \quad (11)$$

$$v_{Cs} = V_{Cs3} \quad (12)$$

Mode 4 [$t_3 < t < t_4$][fig 2.(d)]: This mode begins when the diode D_1 turns OFF. At the begining of this mode, $i_{T1} = 0$, $i_{Ls} = i_{T2} = I_{Ls3} = I_i$, $i_{DF} = 0$, $v_{Cr} = 0$, and $v_{Cs} = V_{Cs3}$ are valid. The main transistor is turned ON with ZVT and its current starts to rise. The resonant between snubber inductance L_s and snubber capacitor C_s continues. For this mode, the following equations are derived:

$$i_{Ls} = Ii \cos \omega_s (t - t_3) - V_{Cs4}\, \omega_s L_s \sin \omega_s (t - t_3) \quad (13)$$

$$v_{Cs} = V_{Cs4} \cos \omega_s (t - t_3) + L_s\omega_s I_i \sin \omega_s (t - t_3) \quad (14)$$

At $t = t_4$, the main transistor current reaches to the input current level and i_{Ls} becomes zero. The current through the auxiliary transistor becomes zero and this mode ends by removing the control signal of the auxiliary transistor. At the end of this mode it can be written as follows

$i_{Ls} = i_{T2} = I_{Ls4} = 0$ (15)

$v_{Cs} = V_{Cs4}$ (16)

Mode 5 [t₄ < t < t₅][fig 2.(e)]: This mode begins when the auxilary transistor T_2 is perfectly turned OFF under ZCT. For this mode, $i_{T1} = I_i$, $i_{Ls} = i_{T2} = I_{Ls4} = 0$, $i_{DF} = 0$, $v_{Cr} = 0$, and $v_{Cs} = V_{Cs4}$ are valid. In the beginning of this mode the diode D_2 is turned ON with ZCS and its current starts to rise. The resonant between snubber inductance L_s and snubber capacitor C_s still continues. However, i_{Ls} becomes negative, so the current through the main transistor is higher than the input current in this mode. The equations can be expressed as follows

$i_{Ls} = -V_{Cs4}\, \omega_s L_s \sin \omega_s (t - t_4)$ (17)

$v_{Cs}=V_{Cs4}\cos\omega_s(t-t_4)$ (18)

At $t = t_5$, the main transistor current decrease to the input current level and i_{Ls} becomes zero. i_{D2} becomes zero and it is turned OFF under ZCS. At the end of this mode it can be written as follows

$i_{Ls} = i_{T2} = I_{Ls5} = 0$ (19)

$v_{Cs} = V_{Cs5}$ (20)

Mode 6 [t₅ < t < t₆][fig 2.(f)]: At the begining of this mode, $i_{T1} = I_i$, $i_{Ls} = i_{T2} = I_{Ls4} = 0$, $i_{DF} = 0$, $v_{Cr} = 0$, and $v_{Cs} = V_{Cs5}$ are valid. In this mode, the main transistor continues to conduct the input current I_i and the snubber circuit is not active. This mode is the ON state of the conventional boost converter. The ON state duration is determined by the PWM control. For this mode

$i_{T1} = I_i$ (21)

Mode 7 [t₆ < t < t₇][fig 2.(g)]: At the begining of this mode, $i_{T1} = I_i$, $i_{Ls} = i_{T2} =0$, $i_{DF} =0$, $v_{Cr} =0$, and $v_{Cs} = V_{Cs5}$ are valid. At $t = t_7$, when the control signal of the auxiliary transistor T_2 is applied, a new resonance between snubber inductance L_s and snubber capacitor C_s starts through C_s–L_s–T_2–T_1. The equations can be expressed as follows:

$i_{Ls}=-V_{Cs5}\omega_s L_s \sin\omega_s(t-t_5)$ (22)

$v_{Cs}=V_{Cs5}\cos\omega_s(t-t_5)$ (23)

Due to the snubber inductance L_s , the auxiliary transistor T_2 is turned ON with ZCS. The current which flows through the snubber inductance rises and the main transistor current falls due to the resonance, simultaneously. At $t = t_7$, when the curent of T_2 reaches to the input current level, the main transistor current becomes zero and this mode finishes. At the end of this mode it can be written as follows

$i_{Ls}=i_{T2}=I_{Ls7} = I_i$ (24)

$v_{Cs}= V_{Cs7}$ (25)

Mode 8 [t₇ < t < t₈][fig2.(h)]: At the begining of this mode, $i_{T1} = 0$, $i_{Ls} = i_{T2} = I_i$, $i_{DF} = 0$, $v_{Cr} = 0$, and $v_{Cs} = V_{Cs7}$ are valid. This mode starts at $t = t_7$ when T_1 current falls to zero. D_1 is turned ON with ZCS. If T_1 is turned OFF when D_1 is ON, T_1 turns OFF with ZVS and ZCS. The resonance started before continues by through C_s–L_s T_2–D_1 . D_1 conducts the excess of i_{Ls} from the input current. For this mode, the following equations are derived:

$i_{Ls}=Ii\cos\omega_s(t-t_8)-V_{Cs7}\omega_s L_s \sin\omega_s(t-t_8)$ (26)

$v_{Cs}=V_{Cs7}\cos\omega_s(t-t_8)+L_s\omega_s I_i \sin\omega_s(t-t_8)$ (27)

Just before $t = t_8$, i_{D1} falls to zero. i_{D1} reaches $-I_{rr}$ at $t = t_8$ and turns OFF, and this stage ends. At the end of this mode it can be written as follows

$i_{Ls}=_{iT2}=I_{Ls8}=I_i-I_{rr}$ (28)

$v_{Cs}=V_{Cs8}=V_{Cs0}$ (29)

Mode 9 [t₈ < t < t₉][fig 2.(i)]: This mode begins when D_1 is turned OFF under ZCS. For this mode, $i_{T1} = 0$, $i_{Ls} = i_{T2} = I_{Ls8} = I_i-I_{rr}$, $i_{DF} = 0$, $v_{Cr} = 0$, and $v_{Cs} = V_{Cs8} = V_{Cs0}$ are valid. A resonance between parasitic capacitor C_r , snubber inductor L_s , and snubber capacitor C_s starts at $t = t_8$. At $t = t_9$, iLs falls to zero and the capacitor C_r is charged from zero to V_{Cs8} with this resonance. This mode ends by removing the control signal of the auxilary transistor T_2. The auxilary transistor T_2 is turned OFF with ZCS. For this mode, the following equations are derived:

$i_{Ls} = I_i - I_{rr} \cos \omega_r (t - t_8) - V_{Cs8}\, \omega_r L_s \sin \omega_r (t - t_8)$ (30)

$v_{Cr} = V_{Cs8} - V_{Cs8} \cos \omega_r (t - t_8) + L_s\omega_r I_{rr} \sin \omega_r (t - t_8)$ (31)

At the end of this mode it can be written as follows

$i_{Ls}=i_{T2}=I_{Ls9}=0$ (32)

$v_{Cs}=V_{Cs9}=V_{Cs0}$ (33)

Mode 10 [t₉ < t < t₁₀][fig 2.(j)]: At $t = t_9$, $i_{T1} = 0$, $i_{Ls} = i_{T2} = I_{Ls9} = 0$, $i_{DF} = 0$, $v_{Cr} = V_{Cs8}$, and $v_{Cs} = V_{Cs9} = V_{Cs0}$ are valid. During this mode, C_r is charged linearly under the input current. For this mode it can be written as

$v_{Cr}=V_{Cs9}+I_i C_r(t-t_9)$ (34)

At instant t_{10}, when the voltage across the C_r reaches output voltage V_o , the main diode D_F is turned ON with ZVS and this mode finishes.

Mode 11 [t₁₀ < t < t₁₁ = t₀][fig2.(k)]: At $t = t_{10}$, $i_{T1} =0$, $i_{Ls} = i_{T2} = 0$, $i_{DF} = 0$, $v_{Cr} = V_o$, and $v_{Cs} = V_{Cs0}$ are valid. This mode is the OFF state of the conventional boost converter. During this mode, the main diode D_F continues conducting the input current I_i and the snubber circuit is not active. The duration of this mode is determined by the PWM control. For this mode

$i_{DF}=I_i$ (35)

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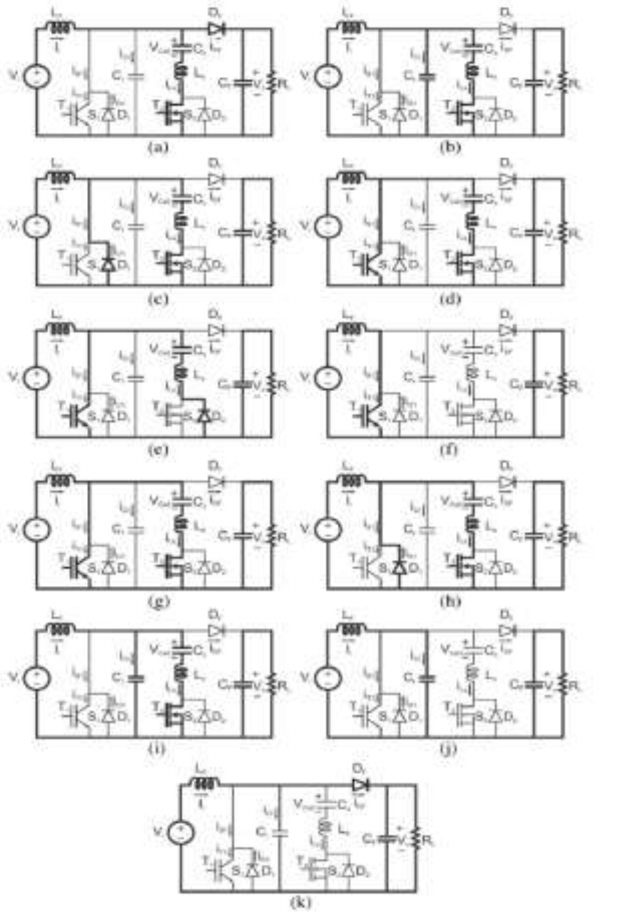

Fig .2 Equivalent circuit for each mode of operation of ZVT ZCT converter

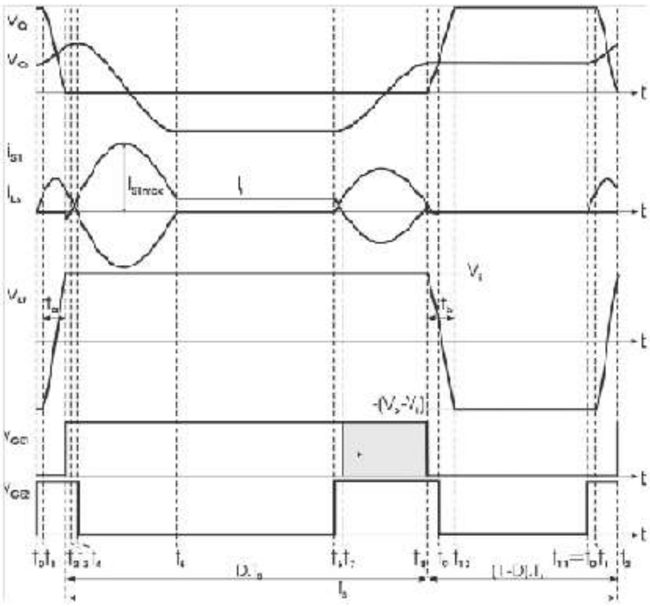

Fig.3 Timing diagram and key waveforms of the converter

II. SIMULATION RESULTS

Simulation is performed using MATLAB/SIMULINK software. The fig.3 shows the simulation model of ZVT ZCT PWM converter.

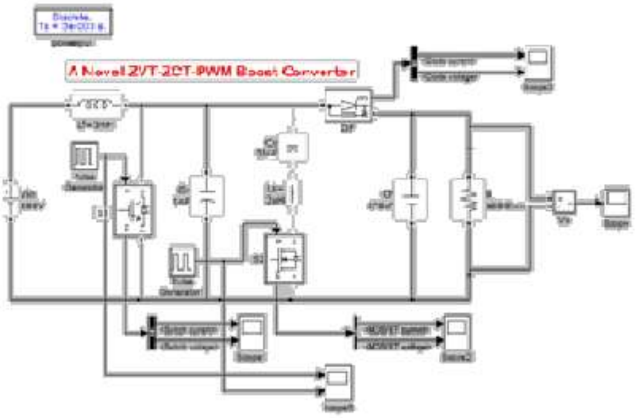

Fig.4 Simulation model of ZVT ZCT PWM converter

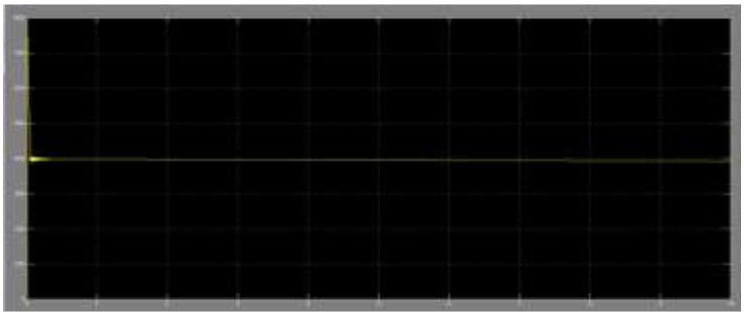

Fig.5 Output voltage at an input 200V

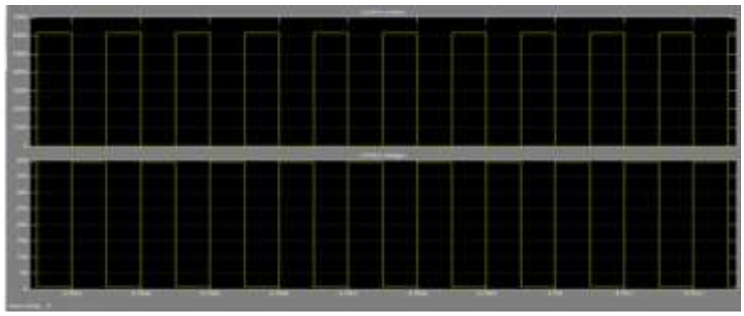

Fig.6 Current and voltage waveforms of main switch S_1

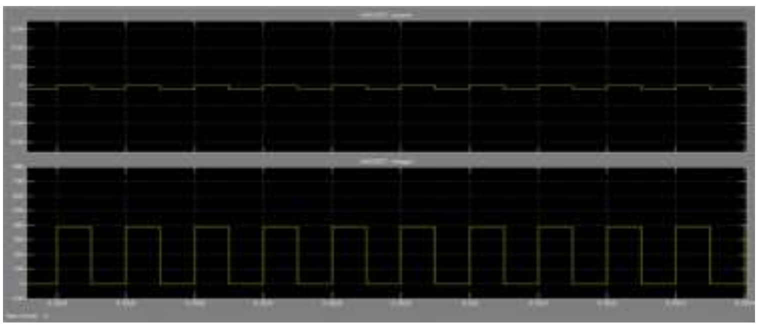

Fig.7 Current and voltage waveforms of axiliary switch in S_2

The Fig.5 represents the output voltage of the proposed converter for an input voltage 200V. The Fig.6 and Fig.7 shows the current and voltage waveforms of the main and auxiliary switch.

III. EXPERIMENTAL RESULTS

An experimental prototype is built to confirm the feasibility of the proposed converter as shown in fig.8. The table shows the simulation results for various input voltages and table 2 shows the hardware result.

Table.1. simulation result for various input voltages

Input voltage(V)	Output voltage(V)
100	200
150	300
200	400
250	500
300	600

Table.2. Hardware result

Input voltage(V)	Output voltage(V)
12	14

Fig.8 Prototype of the proposed ZVT ZCT PWM converter

IV. CONCLUSION

The ZVT-ZCT boost converter provides a complete and perfect zero current and voltage operation of the power electronic switches. The converter has potentially high power density and quick transition response. It is suitable in high power and high input voltage with wide range applications. The new converter has a simple structure,low cost and ease of control. The snubber circuit does not have any coupled inductor or bulky transformers semiconductor devices operate under soft switching, the main devices are subjected to no additional voltage and current stresses, and the stresses on the auxiliary devices are very low in the proposed converter. The ZVT-ZCT PWM DC-DC converter is suitable for the power factor correction circuits and the renewable energy converters, where high efficiency is very important.

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