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A New ZVT-ZCT PWM Boost Converter With Active Snubber Cell

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***Abstract*—This paper proposes a new ZVT-ZCT converter with an active snubber circuit. All the semiconductor devices used in this circuit under goes soft switching. Here the active snubber provides soft swiching for the main switch. The main switch turns ON with zero-voltage transition (ZVT) and turns OFF with zero-current transition (ZCT). Since all semiconductor devices are operating under soft switching, the additional voltage stress can be eliminated. The auxiliary switch in the snubber circuit is turned ON for turning ON and turning OFF the main switch. The presented circuit is analyzed for 100kZ, 1kW converter. The simulation analysis is done using National Instruments Multisim.**

Keywords—Zero Voltage Transition (ZVT); Zero current Transition (ZCT); Snubber circuit; boost converter (dc-dc).

I. INTRODUCTION

Dc–dc converters have wide applications in power factor correction, battery charging, and renewable energy applications due to their high power density, fast response, and control simplicity. For high power operations it is required to operate this converter at higher switching frequencies. But high-frequency operation results in increased switching losses, higher electromagnetic interference (EMI), and lower converter efficiency. So in order to reduce these losses the soft switching technique should be in cooperated. The soft switching becomes necessary especially, at high frequencies and high power levels, to reduce switching losses.

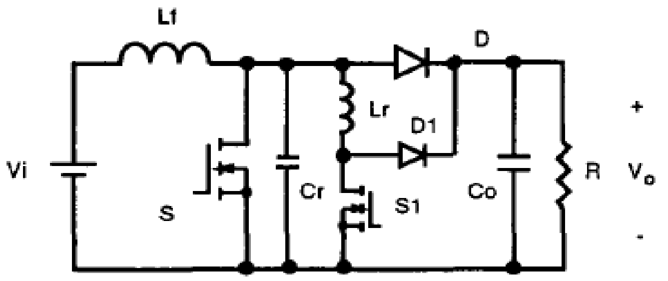


Fig 1- Conventional ZVT Converter

In the conventional zero-voltage transition (ZVT)-PWM converter [1], the main switch turns ON with ZVT perfectly with by means of a snubber cell. On the other hand the main switch turns OFF under near zero voltage switching (ZVS). The main diode turns ON and OFF with ZVS. The auxiliary switch turns ON with near zero-current switching (ZCS) and turns OFF with hard switching. The operating of the circuit is dependent on line and load conditions.

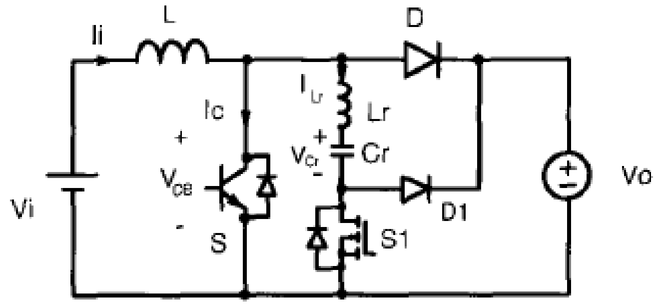


Fig 2- Conventional ZCT converter

In the conventional ZCT-PWM converter [2], the main switch turns OFF under ZCS and ZVS. The auxiliary switch turns ON with approximate ZCS. The operation of the circuit depends on circuit and load conditions. The auxiliary switch turns OFF by hard switching.

A lot of ZCT converters are submitted to solve the problems in conventional ZCT converter. In [13] and [19], the main switch turns OFF with ZCT without increasing the current stress of the main switch and the auxiliary switch operates by soft switching. The voltage stress across the main diode is high. The operation intervals depends on load current.

In this paper, a novel active snubber cell, which overcomes most of the problems of the conventional ZCT-PWM converter is proposed. The main contribution of this paper is the modification of the control technique in the conventional ZCT-PWM converter. ZVT and ZCT properties are obtained from the normal ZCT converter without making any change in the circuit topology. In the proposed converter the base circuit is same as that of the conventional ZCT converter. But the control circuit is changed. Here the main switch turns ON with ZVT and turns OFF with ZCT. All of the semiconductor devices operate under soft switching. This converter can operate with soft switching at high frequencies and as normal PWM converter at higher frequencies.

In this converter, since all the semiconductor devices operate with soft switching no additional voltage stress across the semiconductor devices. Even though the stress is present there, it will be in acceptable range only.

The proposed converter has simple structure and low cost. The operation principles and analysis of the proposed converter are verified with a 1 kW and 100 kHz boost converter.

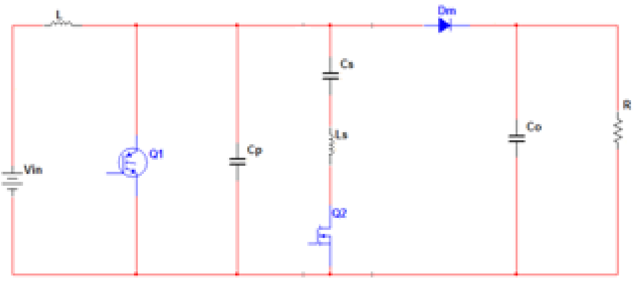


Fig 3- Proposed ZVT-ZCT Boost Converter Circuit Model

Vin input voltage source,

Vo output voltage,

L main inductor,

Cp parasitic capacitor,

Co output filter capacitor,

Cs snubber capacitor,

Ls snubber inductor,

Q1 main switch ,

Q2 auxiliary switch,

Dm main diode.

II. OPERATION & ASSUMPTIONS

A. Assumptions

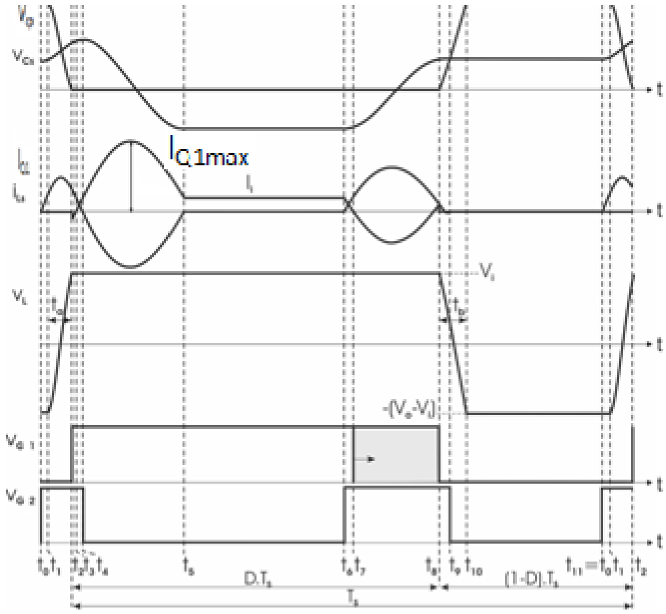
The following assumptions are made in order to simplify the steady state analysis. During one switching cycle it is assumed that the input and output voltages and input current are constant, and the reverse recovery time of *DF* is taken into account. All the semiconductor devices and resonant circuits are assumed ideal for simplification.

B. Operation

The proposed circuit has 11 modes of operation. The auxiliary switch is turned ON & OFF under soft switching by turning ON the auxiliary switch. The wave form under different modes of operation are shown in fig 4.

Mode 1 [$t0 < t < t1$

Before the beginning of this mode, the main transistor *Q1* and auxiliary transistor *Q2* are in the OFF state. The main diode *Dm* is in the ON state and the input current *Ii* flows through the main diode. At $t = t0$, $i_{Q1} = 0$, $i_{Ls} = i_{Q2} = 0$, $i_{Dm} = Ii$, $v_{cp} = Vo$ 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 *Cs* . Soft switching depends on the value of V_{cs0}.

The main diode *Dm* is in the ON state and conducts the input current *Ii*. At $t = t0$, when the turn on signal is applied to the gate of the auxiliary transistor *Q*2 , mode 1 begins. A resonance starts between snubber inductance *Ls* and snubber capacitor *Cs*. Due to the resonance *Q*2 current rises and *Dm* current falls simultaneously. The rise rate of the current is limited because of the *Ls* 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,

$$(V_0\text{-}V_{cs0})\frac{\sin \omega s(t-t0)}{Ls\,\omega s} \quad (1)$$

$$V_{cs} = V_0\text{-}(V_0\text{-}V_{cs0})\cos\omega_s(t\text{-}\ t_0) \quad (2)$$

In these equations,

$$\omega s=1/(LsCs)^{1/2} \quad (3)$$

are valid.

At $t = t1$, snubber capacitor voltage v_{cs} is charged to V_{cs1}, i_{Q2} reaches *Ii* and i_{Dm} falls to zero. When i_{Dm} reaches $-Irr$, *Dm* is turned OFF and this stage finishes.

In this stage, Q2 is turned ON with ZCS due to *Ls* .

Dm is turned OFF with nearly ZCS and ZVS due to *Ls* and *Cp.*

At the end of this mode

$$i_{Ls} = i_{Q2} = I_i+I_{rr} \quad (4)$$

$v_{cs} = V_{c1}$ (5)

can be written.

Mode 2 [t1 < t < t2 : Fig 8]:

Before $t = t1$, $i_{T1} = 0$, $i_{Ls} = i_{Q2} = Ii + Irr$, $i_{Dm} = 0$, $v_{cp} = Vo$ and $v_{cs} = V_{cs1}$ are valid. The main transistor *Q*1 and the main diode *Dm* 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 *Dm* .

Here the resonance between snubber inductor and the parasitic capacitor happens

Then the equations can be written as

$$I_{Ls} = I_i + I_{rr} \cos\omega_r(t- t_1) - (V_0\text{-}V_{cs0})\frac{\sin\ \omega r(t-t1)}{Ls\omega r} \quad (6)$$

$$V_{cs} = (V_0 - V_{cs1}) \cos\omega_r(t- t_1) + V_{cs1} - I_{rr}\omega_r\ Ls \sin\omega r(t- t_1) \quad (7)$$

In these equations

$$\omega_r = 1/(L_sC_r)^{1/2} \quad (8)$$

are valid.

At $t = t2$, *Vcp* becomes 0 and this stage is finished.

Thus, the transfer of the energy stored in the parasitic capacitor *Cp* to the resonant circuit is completed. At this time the diode *D*1(body diode of the switch Q1) is turned ON with nearly ZVS and this stage ends.

. In the proposed converter, it is not required to use an additional *Cp* capacitor since the capacitor *Cp* is assumed the sum of the parasitic capacitor of *S*1and the other parasitic capacitors incorporating it.

At the end of this mode

$$i_{Ls} = i_{Q2} = I_{Ls2} \quad (9)$$

$$v_{cs} = V_{cs2} \quad (10)$$

are valid.

Mode 3 [t2 < t < t3]

Just after the diode *D*1 is turned ON at $t2$, $i_{T1} = 0$, $i_{ls} = i_{Q2} = i_{Ls2}$, $i_{Dm} = 0$, $v_{cr} = 0$ and $v_{cs} = V_{cs2}$ are valid at the beginning of this mode. In this mode, the resonant which is between the snubber inductance *Ls* and snubber capacitor *Cs* continues.

For this resonance

$$I_{Ls} = I_{Ls2} \cos\omega_s(t- t_2) - V_{cs2}\frac{\sin\ \omega s(t-t2)}{Ls\omega s} \quad (11)$$

$$V_{cs} = V_{cs2} \cos\omega_s(t- t_2) + L_s\,\omega_s\,I_{Ls2} \sin\omega s(t- t_2) \quad (12)$$

are achieved.

At the beginning of this mode the voltage of *Cp* becomes zero, so that the diode *D*1 is turned ON and conducts the excess of snubber inductance *Ls* 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. At $t = t3$, this stage ends when the snubber inductance *Ls* current falls to input current, and *D*1 is turned OFF under ZCS.

At the end of this mode

$$i_{Ls} = i_{Q2} = I_i \quad (13)$$

$$v_{cs} = V_{cs3} \quad (14)$$

are valid.

Mode 4 [t3 < t < t4]

This mode begins when the diode *D*1 turns OFF. At the begining of this mode, $i_{Q1} = 0$, $i_{Ls} = i_{T2} = I_{Ls3} = Ii$, $i_{Dm} = 0$, $v_{cp} = 0$, 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 *Ls* and snubber capacitor *Cs* continues.

For this mode, the following equations are derived

$$I_{Ls} = I_i \cos\omega_s(t- t_3) - V_{cs3}\frac{\sin\ \omega s(t-t3)}{Ls\omega s} \quad (15)$$

$$V_{cs} = V_{cs3} \cos\omega s(t- t_3) + L_s\omega_s I_i \sin\omega_s(t- t_3) \quad (16)$$

At $t = t4$, the main transistor current reaches to the input current level and *iLs* 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

$$i_{Ls} = i_{Q2} = 0 \quad (17)$$

$$v_{cs} = V_{cs4} \quad (18)$$

are valid.

Mode 5 [t4 < t < t5]

This mode begins when the auxilary transistor *Q*2 is perfectly turned OFF under ZCT. For this mode, $i_{T!} = Ii$, $i_{Ls} = i_{T2} = I_{Ls4} = 0$, $i_{Dm} = 0$, $v_{cp} = 0$, and $v_{cs} = VCs4$ are valid.

In the beginning of this mode the diode *D*2(body diode of Q2) is turned ON with ZCS and its current starts to rise. The resonant between snubber inductance *Ls* and snubber capacitor *Cs* still continues. However, *iLs* 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,

$$I_{Ls} = -V_{cs4}\frac{\sin\ \omega s(t-t4)}{Ls\omega s} \quad (19)$$

$$V_{cs} = V_{cs4} \cos\omega s(t- t_4) \quad (20)$$

At $t = t5$, the main transistor current decrease to the input current level and *iLs* becomes zero. *iD*2 becomes zero and it is turned OFF under ZCS.

At the end of this mode

$$i_{Ls} = i_{Q2} = 0 \quad (21)$$

$$v_{cs} = V_{cs5} \quad (22)$$

are valid.

Mode 6 [t5 < t < t6]

At the begining of this mode, $iQ1 = Ii$, $iLs = i_{Q2} = I_{Ls4} = 0$, $i_{Dm} = 0$, $v_{cp} = 0$, and $v_{cs} = V_{cs5}$ *are* valid.

In this mode, the main transistor continues to conduct the input current *Ii* 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

$$I_{Q1} = I_i \quad (23)$$

can be written.

Mode 7 [t6 < t < t7]

At the begining of this mode, $i_{Q1} = Ii$, $i_{Ls} = i_{Q2} = 0$, $i_{Dm} = 0$, $v_{cp} = 0$, and $v_{cs} = V_{cs5}$ are valid. At $t = t7$, when the control signal of the auxiliary transistor *Q*2 is applied, a new resonance between snubber inductance *Ls* and snubber capacitor *Cs* starts through *Cs*–*Ls*–*Q*2–*Q*1.

The equations can be expressed as follows:

$$I_{Ls} = -V_{cs5}\frac{\sin\,\omega s(t-t5)}{Ls\,\omega s} \quad (24)$$

$$V_{cs} = V_{cs5}\cos\omega_s(t-t_5) \quad (25)$$

Due to the snubber inductance *Ls* , the auxiliary transistor *Q*2 is turned ON with ZCS. The current which flows through the snubber inductance rises and themain transistor current falls due to the resonance, simultaneously. At $t = t7$, when the curent of *Q*2 reaches to the input current level, the main transistor current becomes zero and this mode finishes.

At the end of this mode

$$i_{Ls} = i_{Q2} = I_i \quad (26)$$

$$v_{cs} = V_{c7} \quad (27)$$

are valid.

Mode 8 [t7 < t < t8]

At the beginning of this mode, $i_{Q1} = 0$, $i_{Ls} = i_{Q2} = Ii$, $i_{Dm} = 0$, $v_{cp} = 0$, and $v_{cs} = V_{cs7}$ are valid. This mode starts at $t = t7$ when *Q*1 current falls to zero. *D*1 is turned ON with ZCS. If Q1 is turned OFF when D1 is ON, Q1 turns OFF with ZVS and ZCS. The resonance started before continues by through *Cs*–*Ls*–Q2–*D*1 . *D*1 conducts the excess of *iLs* from the input current.

For this mode, the following equations are derived:

$$I_{Ls} = I_i\cos\omega_s(t-t_8) - V_{c7}\frac{\sin\,\omega s(t-t8)}{Ls\,\omega s} \quad (28)$$

$$V_{cs} = V_{cs7}\cos\omega s(t-t_8) + L_s\omega_s I_i\sin\omega_s(t-t_8) \quad (29)$$

Just before $t = t8$, *iD*1 falls to zero. *iD*1 reaches $-Irr$ at $t = t8$ and turns OFF, and this stage ends. At the end of this mode

$$i_{Ls} = i_{Q2} = I_i - I_{rr} \quad (30)$$

$$v_{cs} = V_{c0} \quad (31)$$

are valid.

Mode 9 [t8 < t < t9 : Fig 15]:

This mode begins when *D*1 is turned OFF under ZCS. For this mode, $i_{T!} = 0$, $i_{Ls} = i_{T2} = Ii–Irr$, $i_{Dm} = 0$, $v_{cp} = 0$, and $v_{cs} = VCs0$ are valid. A resonance between parasitic capacitor *Cp* snubber inductor *Ls* , and snubber capacitor *Cs* starts at $t = t8$.

At $t = t9$, *iLs* falls to zero and the capacitor *Cp* is charged from zero to *VCs*8 with this resonance. This mode ends by removing the control signal of the auxilary transistor *Q*2. The auxilary transistor *Q*2 is turned OFF with ZCS.

For this mode, the following equations are derived:

$$I_{Ls} = I_i - I_{rr}\cos\omega_r(t-t_8) - V_{c0}\frac{\sin\,\omega r(t-t8)}{Ls\,\omega r} \quad (32)$$

$$V_{cs} = V_{c0} - V_{c0}\cos\omega_r(t-t_8) + L_s\omega_r I_{rr}\sin\omega_r(t-t_8) \quad (33)$$

At the end of this mode

$$i_{Ls} = i_{Q2} = 0 \quad (34)$$

$$v_{cs} = V_{c0} \quad (35)$$

are valid.

Mode 10 [t9 < t < t10]

At $t = t9$, $iQ1 = 0$, $iLs = iQ2 = ILs9 = 0$, $iDm = 0$, $vCp = VCs8$, and $vCs = VCs0$ are valid.

During this mode, *Cp* is charged linearly under the input current.

For this mode

$$V_{c1} = V_{c0} + (I_i/C_1)(t-t_9) \quad (36)$$

can be written.

At instant $t10$, when the voltage across the Cr reaches output voltage Vo , the main diode DF is turned ON with ZVS and this mode finishes.

Mode 11 [t10 < t < t11 = t0]

At $t = t10$, $i_{Q!} = 0$, $i_{Ls} = i_{T2} = 0$, $i_{Dm} = 0$, $v_{cp} = Vo$, and $v_{cs} = V_{cs0}$ are valid.

This mode is the OFF state of the conventional boost converter. During this mode, the main diode Dm continues conducting the input current Ii and the snubber circuit is not active. The duration of this mode is determined by the PWM control.

For this mode

$$I_{Dm} = I_i \quad (37)$$

can be written.

Therefore, at the moment $t = t11 = t0$, one switching cycle is completed and another switching cycle starts.

III. DESIGN PROCEDURE

In order to get the component values used in the snubber circuit of the proposed boost converter, the simulation is performed and the respective values are noted. The values are obtained by varying the values of the snubber capacitor and the snubber inductor and the respective values are tabulated.

From the values $I_{Q1\ max}$, as tabulated in table 1, it is seen that the maximum value of the main switch current $IQ1max$ decreases when the value of Ls snubber inductance increases. It decreases slightly when the value of Cs snubber capacitance increases.

Form the tabulated values it is clear that the initial voltage of the snubber capacitor decreases with increasing Cs , and increases with increasing Ls. The ZVT duration of the main switch is also shown depending on Ls and Cs . From the table, it is seen that the ZVT interval decreases when Ls and Cs increases. In the variation of the ZCT duration of the main switch is also given. The ZCT duration increases when Cs and Ls increases. The ZCT duration strongly depends on the resonance between Ls and Cs. The smallest values of Ls and Cs components are preferred from the characteristic curves. If the selected component values are high, the sum of the transient intervals and conduction losses increase. We have to take into account that current stress of the main switch should remain at reasonable level.

C. Design Procedure

The output voltage is assumed to be constant. So the output capacitor is taken a large value.

TABLE-1

VARIATION OF Is1 max, $V_{cs0,}$ $t_{ZVT,}$ t_{ZCT}

WITH Ls AND Cs

C_s (nF)	L_s (μH)	I_{s1max} (A)	V_{cs0} (V)	t_{ZVT} (ns)	t_{ZCT} (ns)
22	0.5	`25	70	130	300
	1.0	22.5	100	155	400
	1.5	22	120	155	500
	2.0	21.5	140	155	600
	2.5	20.5	158	148	650
	3.0	20.1	175	140	700
33	0.5	23.2	50	110	380
	1.0	21	72	120	500
	1.5	20	88	120	600
	2.0	19	105	120	700
	2.5	18.5	118	118	780
	3.0	18.5	130	112	850
47	0.5	22	35	84	480
	1.0	19.5	52	90	600
	1.5	18.5	62	82	720
	2.0	17.5	78	78	840
	2.5	17.5	84	70	940
	3.0	17.5	98	62	1020
63	0.5	22	30	60	520
	1.0	19.5	44	60	700
	1.5	18.5	58	50	860
	2.0	17.5	64	40	1000
	2.5	17.5	78	30	1100
	3.0	17.5	84	20	1200

The initial voltage of the snubber capacitor Cs depends on the losses of the resonant circuit. If the value of Cs decreases, the initial voltage of snubber capacitor increases. The initial energy of the Cs should be high enough to provide soft switching.

To turn OFF the main switch with ZCT, the duration of tZCT should be longer than fall time of the main switch ($tf\,1$). This can be defined as follows:

$$t\text{ZCT} \geq tf\,1$$

The snubber inductance can be selected to provide the following conditions with reference to[15]. Here, $tr2$ is rise time of the auxiliary switch. $VcS1$ is assumed constant in $tr2$ duration.

$$\frac{V0-Vcs1}{Ls}.t_{r2} \leq I_{imax}$$

Parasitic capacitor is assumed to be approximately 0.5nF

Snubber inductance Ls = [(400-150)/5]40*10^{-9} ≥ 2µH

In order to decrease ZCT duration Ls is selected as the smallest possible value.

IV. ADVANTAGES

By means of the snubber cell, the switching power losses of main switch, auxiliary switch, and main diode are reduced. The switching losses are not dissipated on the snubber cell. There is only a small amount of circulation energy loss, which only takes a resonant period. This causes a little increase in the conduction losses of the switches. The features of the proposed ZVT–ZCT–

PWM boost converter can be summarized as follows:

1) All of the semiconductor devices are both turned ON and turned OFF under soft switching.

2) All of the semiconductor devices are not subjected to any additional voltage stress.

3) The converter has a simple structure and low cost.

4) Soft-switching conditions are maintained at very wide line and load ranges.

6) The converter can operate at considerably high frequencies and acts as a normal PWM converter.

7) The sum of the transient intervals is a very little part of the switching cycle.

8) The proposed converter does not require any additional passive snubber cells.

The output voltage equation is obtained from *VLF* waveform as

$$V_0 = V_{in} (T_s - t_a - t_b)/(T_s - D{*}T_s - t_b)$$

In this equation,

$ta = t12$ and $tb = t8-10$. ta and tb are transient intervals in the proposed converter.

T_s switching period.

$$\eta = P_0/(P_0 + P_{loss})$$

The main losses in the converter are conduction (Pcond) and switching losses (Psw) of the semiconductor devices, and inductor losses

$$P_{loss} \approx P_{codu} \text{ (of Q1\&Q2)} + P_{sw} \text{ (Q1\&Q2)} + P_{cond\_Dm} + P_{sw\_Dm} + P_{inductor}$$

In the proposed converter, switching losses are eliminated by means of soft switching.

$$P_{loss} \approx P_{codu} \text{ (of Q1\&Q2)} + P_{cond\_Dm} + P_{inductor}$$

Due to the elimination of the switching losses the efficiency is higher than the conventional one.

There is a little increase in the conduction losses as compared with the conventional hard switched boost converter because of the transient intervals.

V. SIMULATION RESULTS

The simulation of the proposed paper is carried out and the result is verified using National Instruments Multisim. The simulation is done for a 1kW, 100 kHz converter. The main switch used here is IRG4BC10UD and the auxiliary switch used in the snubber cell is IRFP462. The voltages and currents are verified. The different voltage waveforms for a load of 160Ω, observed using oscilloscope are shown. The current variations are observed using ac current measurement probe. Here 400V output is obtained for 200V dc input.

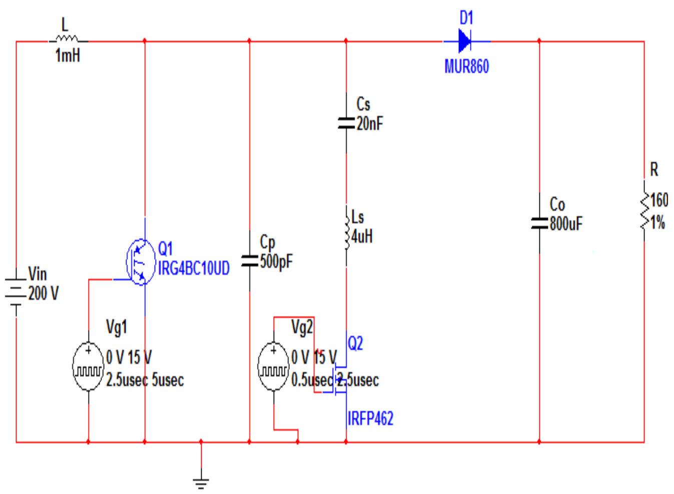


Fig 5-Simulation block for 100kHz 1kW Converter

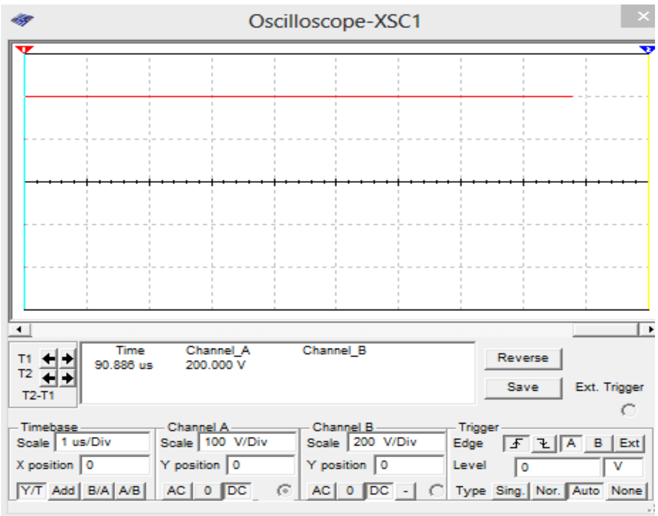


Fig 6- Input given to the converter

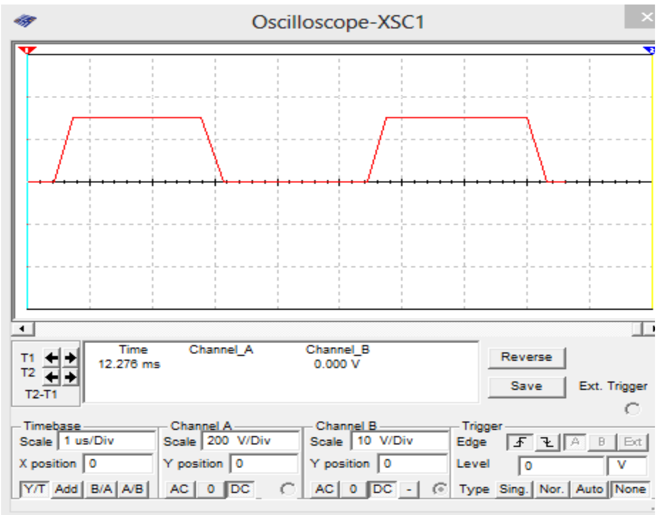


Fig 7- gate pulse for main switch Q1

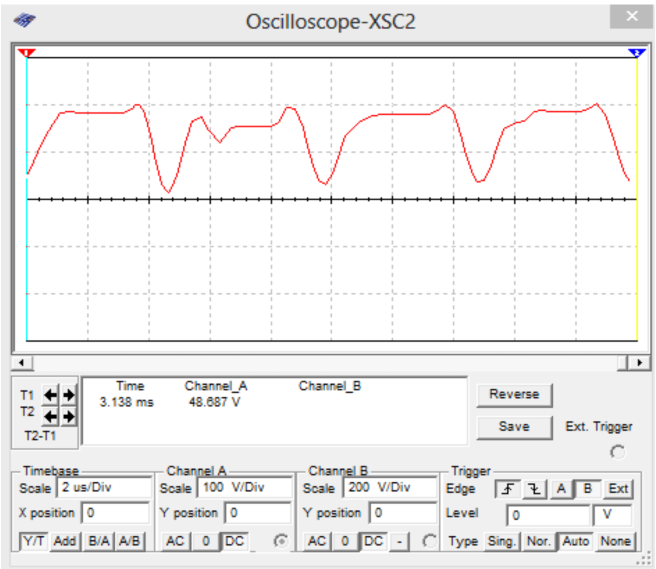


Fig 8-voltage across Cp

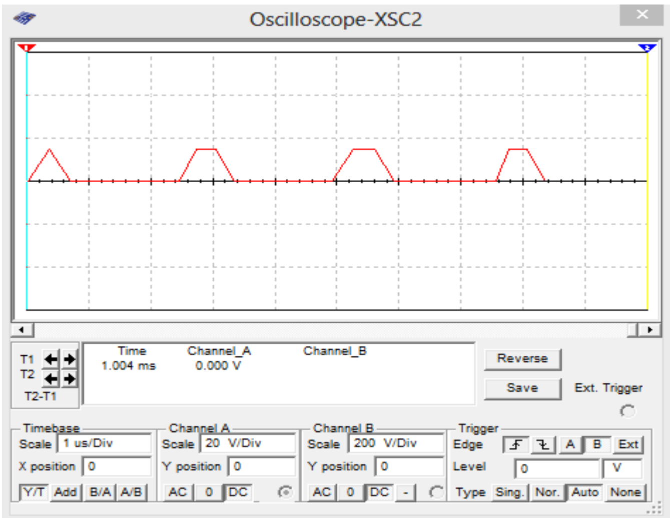


Fig 9- gate pulse given for Auxiliary switch Q2

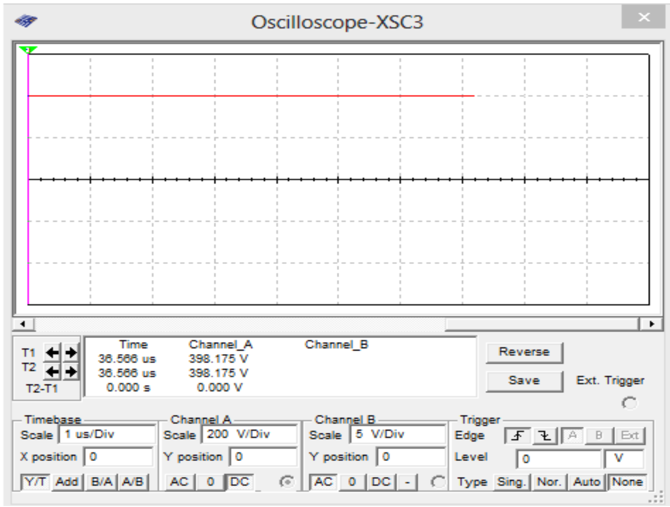


Fig 10-output voltage Vo

VI. CONCLUSION

In this paper a PWM boost converter with a novel active snubber cell has been analyzed in detail. This active snubber cell provides ZVT turn on and ZCT turn OFF together for the main switch of the converter. Also, the proposed snubber cell is implemented by using only one quasi-resonant circuit without an important increase in cost and complexity. In the proposed converter, all semiconductor devices are switched under soft switching. In the ZVT and ZCT processes, the auxiliary switch is turned ON under ZCS and is turned OFF with ZCT and near ZCS, respectively. There is no additional voltage stress across the main and auxiliary switches. The main diode is not subjected to any additional voltage and current stresses. The operation principles and steady-state analysis of the proposed converter are presented. In order to verify the output, the simulation of the proposed circuit is done using electronic workbench multisim.

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