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A SOFT SWITCHED CASCADED BOOST CONVERTER FOR PHOTOVOLTAIC APPLICATIONS

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ABSTRACT

In this paper, a soft-switched cascaded boost converter connected with a single active switch and simple auxiliary resonant circuit is adopted for photovoltaic applications with high transformation ratio and low voltage stress across the switch. Switching losses and electromagnetic interference (EMI) noises are condensed by restricting di/dt of the diode reverse recovery current and dv/dt of Metal-Oxide semiconductor Field Effect Transistor (MOSFET) drain-source voltage. In this converter an auxiliary circuit consists of one auxiliary switch, a resonant inductor and a clamp capacitor is operated under zero current transition technique. The main switch turns-on by means of zero current switching (ZCS) and turns-off by means of zero voltage switching (ZVS), while the auxiliary switch turns-on and turns-off by means of zero voltage switching (ZVS). This switching configuration can improve the system efficiency and reduce the switching losses likewise it is very easy to control. The detailed theoretical analysis and the design equations are described. To verify the performances of the proposed converter, it is demonstrated by PSIM simulation.

Keywords: Soft switching, DC-DC cascaded boost converter, Zero Voltage Switching (ZVS), Zero Current Switching (ZCS), switching loss, hard switching, Zero Current Transition (ZVT), Electromagnetic interference (EMI).

I. INTRODUCTION

Nowadays, more industrial applications require DC-DC converters to provide high conversion ratios with a good efficiency, such as battery powered devices, uninterruptible power supplies (UPS), photovoltaic (PV) systems, fuel cell and some energy harvesting systems. A topology that provides a wider voltage ratio is the cascaded converter, which consists of two or more basic DC-DC converters connected in cascade with the corresponding increase in power losses [1], [2]. An interesting topology is a class of converters which uses a single switch, where the voltage ratio is given as a quadratic function of the duty ratio [3] which results in hard switching.

During the earlier a number of control strategies have been proposed for controlling power electronics converters [4][5][6][7]. Among such control strategies one can find controllers such as: Pulse Width Modulation (PWM), Pulse Peak Control (PPC) or Voltage Peak Control (VPC) and nonlinear controllers *i.e.* sliding mode control, fuzzy logic, feedforward regulators, linear quadratic regulators, etc. Under typical operation conditions, nonlinear controllers have shown good performance; However, as the control complexity increases, it does also the tuning difficulty. To cope with this last limitation of non-linear controllers, a soft switching technique was introduced for control strategy. Such controller is able to regulate the converter output voltage and to limit the input current for safe operation. Several researches have proposed how to improve converter efficiency by designed the ZVS of power switches and ZCS of diodes as proposed in [8] [9] [10]. The advantage of soft switching is reducing switching loss, voltage stress and preventing saturation of the transformer [11] with increasing the system efficiency. Fig.1 shows the block diagram of the proposed converter.

The proposed soft switched cascaded boost converter with single active switch and simple auxiliary circuit as shown in Fig. 2has used Zero Voltage Transi-tion technique to improve the power efficiency and voltage transfer ratio of the converter. The topologies descry-ption and the operating principles for the pro-posed converter are elucidated in Section 2. Section 3 shows the circuit design and design procedure of reso-nant inductor and capacitor. Section 4 includes PSIM model of soft switched cascaded boost converter. Section 5 demonstrates that the results of simulations. Section 6 shows the conclusion.

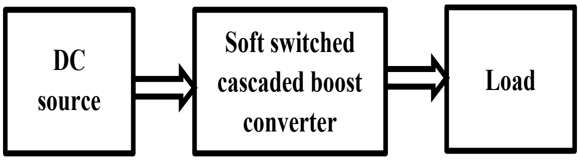


Fig. 1. Block diagram of proposed soft switched cascaded boost converter

II. TOPOLOGY DESCRIPTION AND OPERATION PRINCIPLE OF PROPOSED CONVERTER

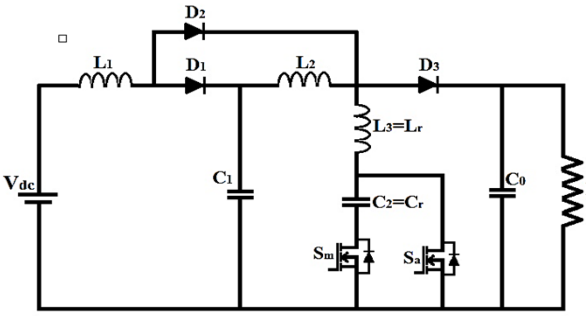


Fig.2 Circuit diagram

which was proposed like step-up in applications with high conversion ratio and reported in [12][13] which is connected with auxiliary circuit. Throughout this analysis, it will be assumed that the converter is working under continuous conduction mode (CCM), in general overall elements are: three capacitors$(C_1, C_2 = C_r, C_3 = C_0)$, two inductors$(L_1 = L_m,\ L_2,\ L_3 = L_r)$, three diodes $(D_1, D_2\&D_3)$ and two power switch$(S_m\&\ S_a)$).

Soft switching takes place by Zero Current Transition (ZCT) technique i.e. the main switch turns-on by means of zero current switching (ZCS) and turns-off by means of zero voltage switching (ZVS), while the auxiliary switch turns-on and turns-off by means of zero voltage switching (ZVS).Besides, it is considered a large output smoothing capacitor, which produces a piecewise linear waveform. In addition, the switch is assumed to operate with a fixed frequency of period and the duty ratio or switch on time to period ratio is denoted.

The following norms are made to simplify the steady-state analysis of the converter circuit.

(1) All switching devices & passive elements remain ideal.
(2) Parasitic components of all switching devices & elements are neglected.

The operating principle of proposed soft switched cascaded boost converteris divided into 7 modes as shown in Fig. 3. Thekey waveforms for the different modes of operation are shown in Fig. 4.

Mode-1:

In the first operating mode the main switch and the auxiliary switch are in off state. The input is connected directly to the output through the main inductor (L_1) and diode ($D_2\&D_3$).

$$IL_1(t) = ID_{3(t)} = IC_3(t) + I_o \tag{1}$$

$$IL_r(t) = 0 \tag{2}$$

$$VC_r(t) = 0 \tag{3}$$

Mode-2:

This mode starts with turning ON of the main switch at time and gets charged. The main switch turns ON by zero current switching (ZCS) because of the resonant inductor. When attains full charge then diode (D_1) is opened. At time the capacitor starts to discharge through main inductor (L_2) to resonant inductor (L_r). The output diode (i_{D3}) current reaches zero when the resonant inductor current (i_{Lr}) reaches the main inductor current (i_{L1}).

At time t_1:

$$IL_1(t_1) + IL_2(t_1) = ID_3(t_1) + IL_r(t_1) \tag{4}$$

$$IL_r(t) = \frac{V_o}{L_r}t \tag{5}$$

At time t_2:

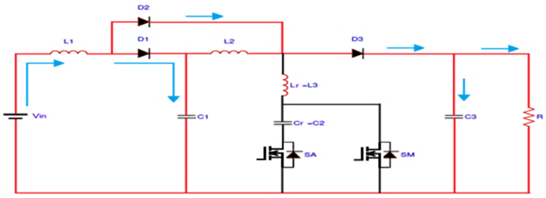
$$IL_1(t_2) + IL_2(t) = IL_r(t_2) \tag{6}$$

$$ID_3(t_2) = 0 \tag{7}$$

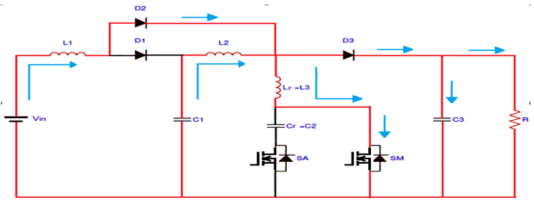
$$Vc_1(t_2) = 0 \tag{8}$$

Mode-3:

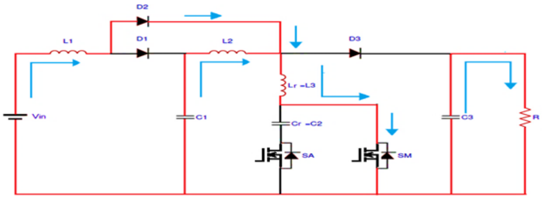
In this mode the input side of the converter is isolated from the output side of the converter. The main inductor (L1) is charged from the input source. The main inductor current (IL_1&IL_2) rises from the minimum value towards the maximum value.



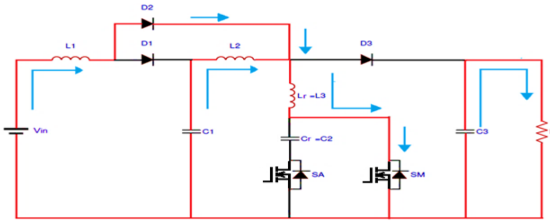
Mode-1



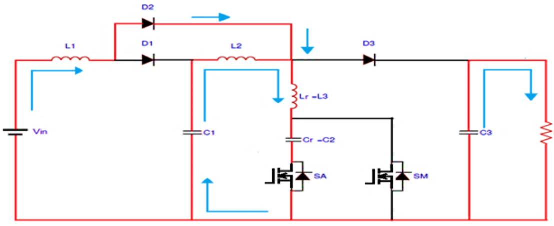
Mode-2



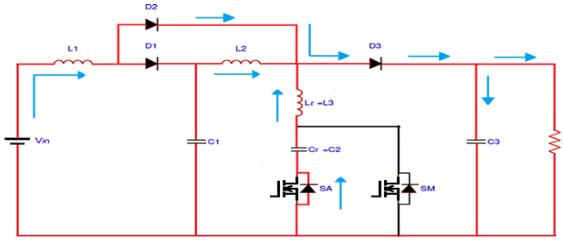
Mode-3



Mode-4 5



Mode-5 6



Mode-6-7

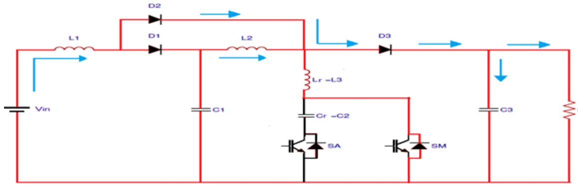


Fig.3 Modes of operation

The main inductor current (IL_1&IL_2) rises from the minimum value towards the maximum value. The resonant inductor current (I_{Lr}) is same as that of the main inductor current (I_{L1} &I_{L2}).

$$IL_1(t_2) + IL_2(t_2) = Imin$$

$$IL_1(t) = Imin + \frac{V_s}{L_1 + L_r}(t) \tag{9}$$

$$IL_2(t) = Imin + \frac{V_s}{L_2 + L_r}(t) \tag{10}$$

(11)

Mode-4:

At time the voltage across the aux itch is clamped to zero by the already conducting main switch. So that there will be no current flow through the auxiliary switch – resonant capacitor branch. At time t_4 the auxiliary switch is turned on under zero voltage switching (ZVS) in this mode.

Mode-5:

At timet_4, the main switch is turned ON by zero voltage condition and auxiliary switch is turned ON by ZVS. The resonance between the resonant inductor and the capacitor starts. The voltage across the resonant capacitor begins to rise, meanwhile the current through the resonant inductor (I_{Lr}) begins to fall and it reaches zero. At time t5, the resonant capacitor (C_r) is charged to maximum value. This mode acts as charging mode of the capacitor.

At timet_4:

$$\omega_o = \frac{1}{\sqrt{L_r C_r}} \quad , \quad Z_o = \sqrt{\frac{L}{C}} \tag{12}$$

$$iL_r(t_4) = IL_{1max} + IL_{2max} = IL_{rmax} \tag{13}$$

$$IL_r(t) = IL_{r\,max} Cos\omega_o t \tag{14}$$

$$Vc_r(t) = Vc_{r\,max}\, Sin\omega_o t \tag{15}$$

$$Vc_{r\,max} = \frac{IL_{r\,max}}{\omega_o C_1} \tag{16}$$

At time t5: (17)

$$Vc_r(t_5) = Vc_{r\,max} \tag{18}$$

$$IL_r(t_5) = 0$$

Mode-6:

This mode is discharging mode of the capacitor (C_r). At timet_5, the capacitor (C_r) discharges its stored energy to the output through the resonant inductor (L_r), the output diode (D_3) and the anti-parallel diode of the auxiliary switch to the load. The direction of the current through the resonant inductor is reversed. Now the current through the resonant inductor is the discharging current of the resonant capacitor. At time the auxiliary switch is turned off under zero voltage condition (ZVS). This mode lasts when the resonant capacitor is fully discharged. At timet_5: (19)

$$ic_r(t) = -\left(V_o - Vc_{r\,max}\right)Cos\omega_0(t) \tag{20}$$

$$iL_r(t) = iC_r(t) \tag{21}$$

$$IL_1(t) + IL_r(t) = i_D(t)$$

(22)

At timet_6:

$$Vc_r(t_6) = 0$$

Mode-7:

At timet_6, the energy which is stored in the resonant inductor is transferred to the load through the main diode (D_3) and the anti-parallel diode of the main switch. This mode ends when the resonant inductor (L_r) discharges completely. At time Diode (D_1) starts to conduct and the capacitor is charged to V_0.

At timet_6:

$$iL_r(t) = iL_r(t) - \frac{V_o}{L_r}(t) \tag{23}$$

At timet_7:

$$iL_r(t_7) = 0 \tag{24}$$

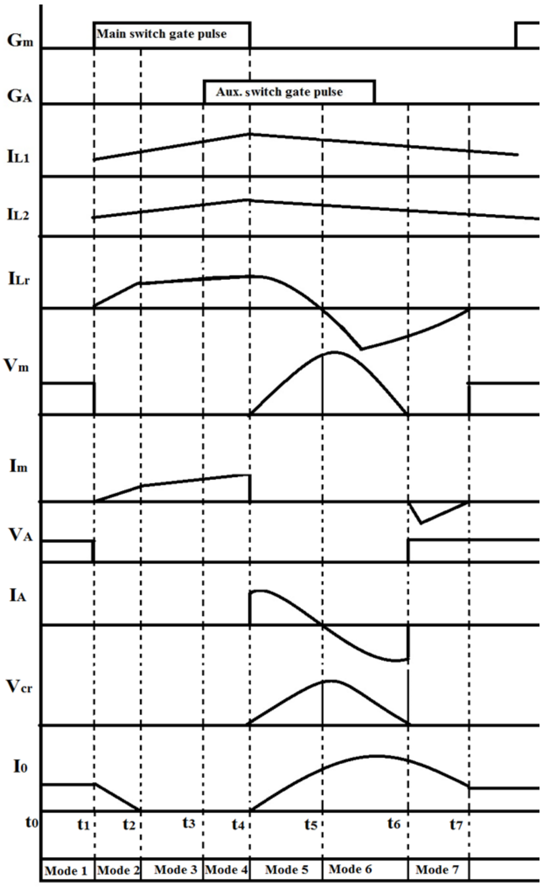


Fig.4 Waveforms of proposed soft switched cascaded boost converter

III. CIRCUIT DESIGN & DESIGN PROCEDURE FOR RESONANT INDUCTOR AND CAPACITOR

This session will introduce the voltage gain ratio of the converter and soft switching technique. The session will be divided into two parts, the first part is voltage gain ratio, and then the second part is soft switching technique.

A. Circuit Design

The first part will derive the voltage gain ratio of the proposed soft switched cascaded boost converter. Choosing a sampling frequency of 30 KHz and a duty cycle of 0.60 the following equations were used to design the converter:

$$V_0 = \frac{V_{in}}{(1-D)^2} \qquad (25)$$

Then the load will equal

$$R = \frac{V^2}{P} \qquad (26)$$

Hence

$$I_0 = \frac{V_0}{R} \qquad (27)$$

The current of the first inductor equals:

$$I_{L1} = \frac{I_0}{(1-D)^2} \qquad (28)$$

And the current of the second inductor is:

$$I_{L2} = \frac{I_0}{(1-D)} \qquad (29)$$

In order to ensure that the cascaded converter is working in the continuous conduction mode (CCM) the current variation ξ through the inductors has to be much lower than unity where:

$$\xi 1 = \frac{\frac{\Delta i_{L1}}{2}}{I_{L1}} = \frac{D(1-D)^4}{2}\frac{R}{fL_1} * 100\% \qquad 30$$

$$\xi 2 = \frac{\frac{\Delta i_{L2}}{2}}{I_{L2}} = \frac{D(1-D)^4}{2}\frac{R}{fL_2} * 100\% \qquad 31$$

B. Design procedure for resonant inductor and capacitor

The zero current transition technique (ZCT) condition of a cascade high gain soft switching boost converter will be derived as follow:

The current flow through the resonant inductor rises from zero to main inductor current value between times t_2–. The time interval –$t_3$is selected as 10% of the. In this time interval the change in the current through the resonant inductor is from zero toI_{min}.

$$\Delta i_{Lr} \cong I_{min} \qquad 32$$

$$\Delta t = t_3 - t_2 = 0.1D_{min} \qquad 33$$

$$L_r = \frac{V_0}{\Delta i_{Lr}}\Delta t \qquad 34$$

The resonant inductor value can be chosen from Eq. (34).From the time intervalt_4–t_6, i.e., the time for half resonant cycle is selected as 10% of the total time period.

$$\Delta t = t_6 - t_4 = \frac{0.10}{f_{sw}} = \frac{T_r}{2} \qquad 35$$

$$f_r = \frac{1}{T_r}\frac{1}{2\pi\sqrt{L_r C_r}} \qquad 36$$

$$C_r < \frac{1}{4\pi^2 L_r f_r^{\,2}} \qquad 37$$

From Eq. (37) Cr can be calculated.

The auxiliary switch is turned off anyplace between t5 and t6. So, the phase shift between the gate pulses of main switch & auxiliary switch can be chosen to be greater than Tr/4 but less than Tr/2.

IV. MODEL OF SOFT SWITCHED CASCADED BOOST CONVERTER

Simulation model of soft switched cascaded boost converter has been executed by using PSIM 9.0.3 is shown in Fig. 5.

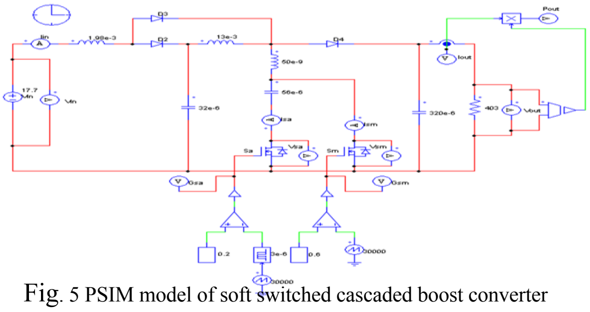


Fig. 5 PSIM model of soft switched cascaded boost converter

V. SIMULATION RESULTS

The design of proposed converter is validated through computer simulation using PSIM® software. The converter is designed for 30W power transfer, with the input voltage of 17.7V DC. The switching frequency is 30 kHz under a duty cycle of 0.60, output voltage in continuous conduction mode (CCM)is 110V Dc.

The simulation results of the proposed converter under the continuous conduction mode (CCM) shown in Fig. 6. Fig. 6(a) shows the simulating gate deriving signals and the drain source voltage and current of the main switch. The performances of ZVS during both turn on and turn off of auxiliary switch is achieved is shown in Fig. 6(b). The input inductor current waveform is shown in Fig. 6(c). The output voltage waveform of the proposed converter is shown in Fig. 6(d).

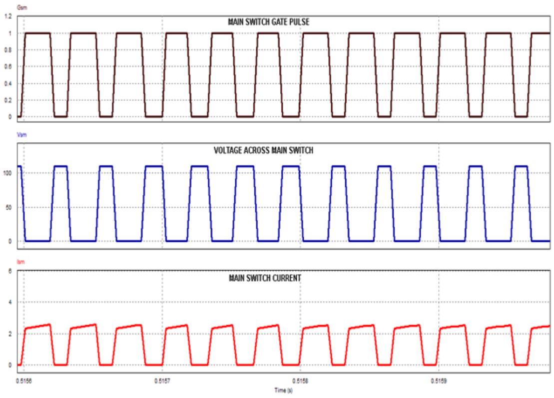


Fig. 6(a) Gate pulse, voltage and current waveform of main switch

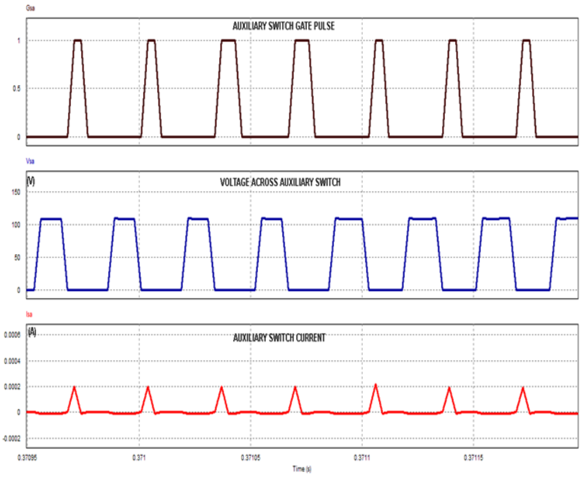


Fig. 6(b) Gate pulse, voltage and current waveform of auxiliary switch

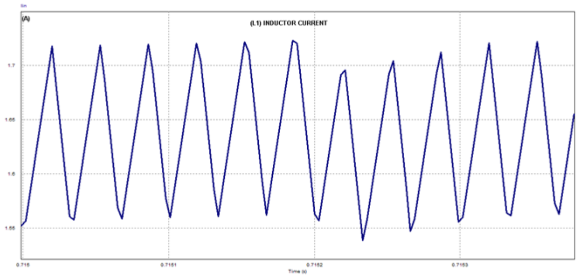


Fig. 6(c) Simulated waveform of (L1) inductor current

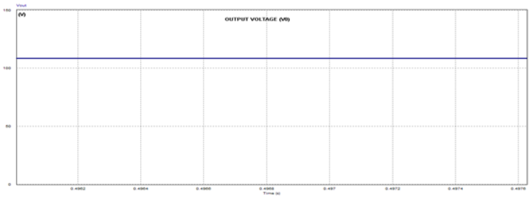


Fig. 6(d) Output voltage waveform of proposed converter

TABLE I. SPECIFICATION OF SOFT SWITCHED CASCADED BOOST CONVERTER

Parameters	Cascaded boost
Input voltage (V_i)	17.7 V
Input current (I_{in})	1.67 A
Output voltage (V_0)	110 V
Output current (I_0)	0.27 A
Switching frequency	30 kHz
Power (P)	30 W

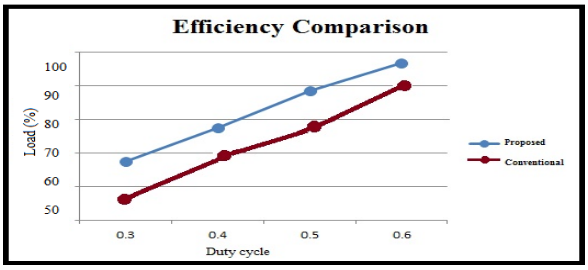


Fig. 7 Efficiency comparison

The efficiency curve of the proposed soft switched cascaded boost converter isplotted for various load condition with fixed duty cycle and input voltage. The efficiency attained for various load conditions as displayed in Fig.7. The proposedsoft switched converter has betterefficiency profile than the conventional cascaded boost converter.

VI. CONCLUSION

It has been revealed that by controlling the switching technique an extra degree of freedom can be gained. A simple auxiliary circuit has been developed to operate in different modes of conduction. The converter is designed to operate at soft switching to achieve higher efficiency and then it can supply more energy than the circuit without soft switching technique. According to the simulation result, the average efficiency of the conventional cascaded boost converter is over 94%, if it is designed with soft switching technique its average efficiency is increased to 98.65%. In the future, if we use high switching frequency then the proposed soft switched cascaded boost converter gives more efficient.

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