



ISSN:1991-8178

## Australian Journal of Basic and Applied Sciences

Journal home page: www.ajbasweb.com



### Edge Resonant Switched Capacitor Cell Assisted Soft Switching PWM Boost DC-DC Converter and its Interleaved Topology

<sup>1</sup>N. Tamizharasi, <sup>2</sup>V.S. Soundarya and <sup>3</sup>I. Gnanambal

<sup>1</sup>PG Scholar, Dept. of Electrical and Electronics Engineering Government College of Engineering Salem, India.

<sup>2</sup>UG Student, Dept. of Electrical and Electronics Engineering, Sona College of Technology, Salem, India.

<sup>3</sup>HOD/Assoc. Professor, Dept. of Electrical and Electronics Engineering, Government College of Engineering Salem, India

#### ARTICLE INFO

##### Article history:

Received 12 January 2015

Accepted 1 May 2015

Available online 8 May 2015

##### Keywords:

PWM Boost DC-DC power converter, ZVS and ZCS soft switching, Edge Resonant Switched Capacitor, Interleaved Topology.

#### ABSTRACT

This paper presents a new soft switching PWM non-isolated boost DC-DC converter embedding an edge-resonant switched capacitor (ER-SWC) cell and its interleaved topology. The proposed technology treated here can achieve a high-frequency ZCS turn on, and ZVS turn off operations in active switches and minimization of reverse recovery current in the freewheeling diode under DCM condition by edge resonance. These properties enable a wide range of soft switching operations achievable together with a high step-up voltage conversion ratio. Extended interleaved topology performs reduction of input current ripple. Based on simulation studies, effectiveness of proposed converter with high efficiency is achieved.

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**To Cite This Article:** N. Tamizharasi, V.S. Soundarya and I. Gnanambal., Edge Resonant Switched Capacitor Cell Assisted Soft Switching PWM Boost DC-DC Converter and its Interleaved Topology. *Aust. J. Basic & Appl. Sci.*, 9(21): 179-187, 2015

#### INTRODUCTION

PWM boost DC-DC converters have been gathering much attention in a variety of power conditioning systems as renewable energy and distributed power generation (Aksoy, H. Bodur, 2013; Araujo, S.V., 2013; Do, H.L., 2010; Park, K.B., 2010; Wai, R.J. and R.Y. Duan, 2012; Roh, Y.S., 2011; Su, B., 2011; Stein, C.M., 2002; Hui, S.Y., 1997; Zang, F., 2008). But most of the dc-dc converters include magnetic components which occupy high volume and weight in the converter, and also produce non-negligible losses. Thus, the PWM boost dc-dc converters require a substantial reduction of switching losses. In addition to this, a high step up ratio is another concern in building a DC power conversion interface for low voltage input sources of energy.

In the literature, there has been a variety of different methods proposed to reduce switching losses and to build high step up ratio. The developed soft switching PWM DC-DC converters have attractive features, but some technological issues such as complexity in circuit design, size, and scale increase remain to be addressed. By adopting DCM scheme, conventional converter can attain soft commutation naturally without any additional

circuit component. In addition, the dc voltage conversion ratio in DCM is higher than in CCM.

However, there exists current stress and high conduction losses in DCM scheme. As a solution to overcome these drawbacks, an employment of edge-resonant switched capacitor (ER-SWC) cell was one of the effective techniques due to its high-efficiency characteristics. In addition, the current stress in the active switches and the use of passive components can also be mitigated due to the Edge Resonance within the switching cell. Furthermore, the ER-SWC soft switching PWM boost DC-DC converter can be usually extended for the interleaved circuit topology which effectively cancels the input current ripple, and it provides higher efficiency than single phase type.

#### Edge Resonant Switched Capacitor Modular:

Nowadays, all power electronics devices operate at high frequency. Also in order to minimize the size of reactive power components, we have to go for high switching frequency. When frequency increases, switching losses and size of component increases. These problems of PWM switching can be overcome by some conventional method of using snubbers and by employing soft switching. It has LC resonant tank which reduces switching losses. But these soft switching suffers from some disadvantage, i.e., Switch current and switch voltage

**Corresponding Author:** N. Tamizharasi, PG Scholar, Dept. of Electrical and Electronics Engineering, Government College of Engineering Salem, India  
E-mail: eeatamizharasi@gmail.com

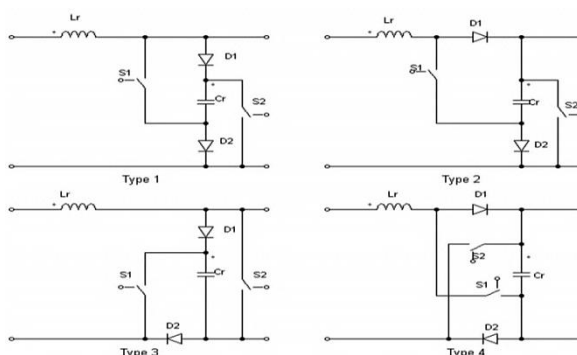
of resonant converters have high peak values which lead to conduction losses. Stray inductive, and capacitive components cause transient effect which causes EMI problem. Also, variable frequency operation makes the filter design and control more complicated. In order to avoid these problems, a new soft switching PWM boost DC-DC converter with an edge resonant switched capacitor modular is proposed. It combines the advantage of hard switching and resonant switching. This proposed converter switching waveform is similar to conventional PWM waveforms except that rising and falling edges are smoothed with no high transient spikes. Here Resonance is allowed to occur at the edge; that is called edge resonance.

**Edge Resonant Switched Capacitor Topologies:**

This paper utilizes some novel switched capacitor converter topologies which use an edge resonant operation instead of conventional soft switching and hard switching operation. Their advantage over conventional switched capacitor converters is a high

efficiency even in a high output region.

The Edge-Resonant Switched capacitor (ER-SWC) modular which consists of two active switches (S1, S2), two diodes (D1, D2) and a resonant capacitor  $C_r$  and it operates efficiently for achieving the soft commutation together with a resonant inductor  $L_r$ . This inductance value is designed to be small enough for realizing the DCM operating condition. Although the current stresses in active switches is a concern in terms of circuit design. The full range of soft switching operations achieved by DCM scheme is attractive, especially for constructing a multi-phase PWM dc-dc converters, as well as sensor-less power factor correction AC-DC converters. The efficiency of an SCC linearly depends on the proportionality between the output voltage and the target voltage  $V_o/V_{Target}$ , where  $V_{Target} = M \cdot V_{in}$  and M is the voltage transfer ratio. High efficiency can be reached if M is widely controllable with high resolution.



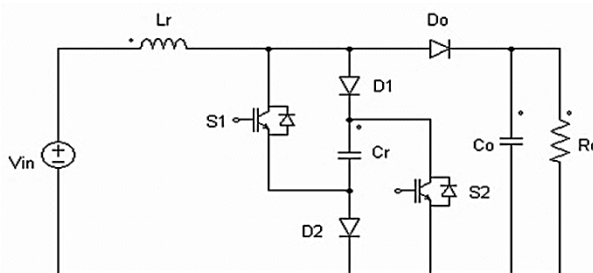
**Fig. 1:** Modified circuit topologies of Edge Resonant Switched Capacitor.

**Proposed Converter:**

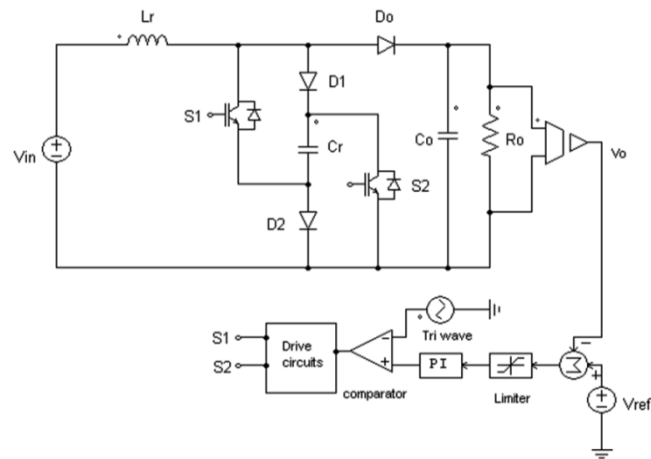
The proposed soft switching PWM boost dc-dc converter with edge resonant switched capacitor circuit is configured either for open loop and closed loop. Under both the circuit configuration, Type 1 Edge resonant switched capacitor topology is used.

Fig.2. Shows the open loop circuit configuration of proposed soft switching PWM

boost dc-dc converter with edge resonant switched capacitor module. This circuit acts as a step-up converter and feeds output voltage to the load. It consists of two active switches S1, S2 and two diodes D1, D2 and a series resonant capacitor  $C_r$ , resonant inductor  $L_r$ , output diode  $D_o$  and output capacitor  $C_o$ .



**Fig. 2:** Open loop Proposed soft switching PWM boost dc-dc converter.



**Fig. 3:** Closed loop Proposed soft switching PWM boost dc-dc converter.

Fig.3. Shows the closed loop circuit configuration of proposed soft switching PWM boost dc-dc converter with edge resonant switched capacitor module. In the closed loop configuration, it has additional feedback path to provide constant output voltage for any input voltage variations. In this circuit, it has voltage sensor, error detector, limiter, PI controller, comparator, triangular wave generator, on-off controller to drive the active switches. Here the voltage sensor is used to sense the output voltage, and it is compared with a reference voltage  $V_{ref}$  using error detector. Thus, the error in voltage is produced at the error detector, and it is fed through the PI controller. Comparator compares the signal coming from the PI controller and the external triangular signal. Thus, the carrier wave and reference DC wave is compared and produces PWM gate signals at the comparator output. Thus, the gate signal is applied to switches S1 and S2 via on-off controller.

Thus in the proposed circuit there are more advantageous properties can be derived from both open loop and closed loop configuration. They are summarized as follows. High step up voltage conversion ratio can be attained due to the DCM and edge resonance by  $C_r$  and  $L_r$ . ZCS turn on achievable in S1 and S2 due to the effect of resonant inductor. Occurrence of Voltage surge at the turn-off transitions of S1 and S2 can be avoided due to the impact of resonant capacitor. Minimized reverse recovery current in the output diode  $D_o$ . The gate pulse patterns for both the switches S1 and S2 can be common, so the gate drive circuits are comparatively simple. In closed loop control, output voltage is maintained constant for any input voltage variations. Thus, duty cycle can be shifted into smaller region and occurrence of conduction losses can be avoided effectively.

#### Converter Operation:

The corresponding mode transitions with the simplified equivalent circuits for the proposed

circuit configuration is shown in Fig.4. The circuit operation during the one switching cycle is divided into the five modes in DCM as described below:

#### Mode I:

The inductor current  $i_{Lr}$  is zero and the active switches S1, S2 are simultaneously turned on at  $t_0$ . Then,  $i_{Lr}$  and the currents across switch  $S_1$ ,  $S_2$  rise gradually from the zero with the edge resonance by  $C_r$  and  $L_r$ . Thereby, ZCS turn-on commutation can be achieved in S1 and S2. During this mode,  $i_{Lr}$  is written as

$$i_{Lr} = \frac{V_{in} + V_o}{Z} \sin \omega_r (t - t_0) \quad (1)$$

The inductor current  $i_{Lr}$  at the end of this mode  $t = t_1$  can be determined by:

$$I_{Lr1} = i_{Lr}(t_1) = \sqrt{V_o} \left( \frac{2V_{in} + V_o}{Z} \right) \quad (2)$$

$$t_1 = \frac{1}{\omega_r} \cdot \cos^{-1} \left( \frac{V_{in}}{V_{in} + V_o} \right) \quad (3)$$

On the other hand, the resonant capacitor  $C_r$  is discharged by the edge resonant current in the ERSWC modular.

#### Mode II:

The resonant capacitor  $C_r$  is completely discharged at  $t_1$ , then the diodes  $D_1$  and  $D_2$  are forward-biased. During this interval,  $i_{Lr}$  rises linearly and it is equally shared by the two branches S1-D1 and S2-D2.

#### Mode III:

The two active switches S1 and S2 are turned off simultaneously at  $t_2$ . Then, edge resonance occurs in the proposed converter and the voltages across S1, S2 increase gradually by the effect of  $C_r$ . Thereby, ZVS turn-off commutation can be achieved in S1, S2. This operation mode continues

until the capacitor voltage  $v_{Cr}$  equals to the output voltage  $v_o$  at  $t_3$ .

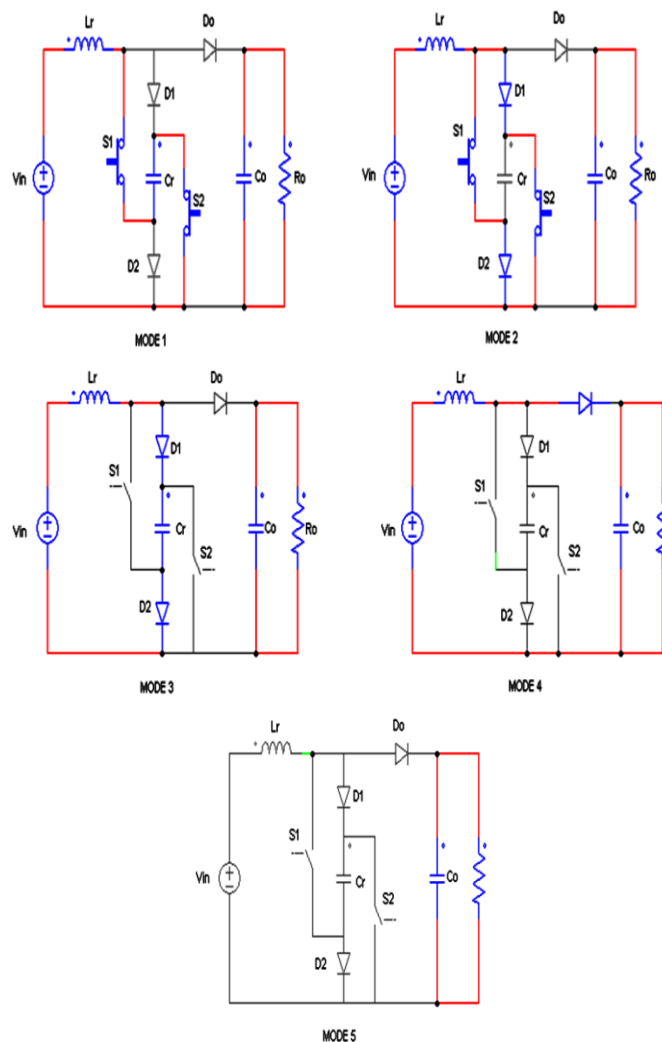
#### Mode IV:

The resonant capacitor voltage  $v_{Cr}$  rises to the output voltage  $v_o$  at  $t_3$ , then the conduction interval of D1 and D2 are terminated. The inductor current  $i_{Lr}$  is forward to the load via  $D_o$ , and thereby the input voltage  $v_{in}$  is boosted to the output voltage  $v_o$ . The inductor current gradually

decreases and naturally becomes zero at  $t_4$ . Thereby occurrence of the reverse recovering current can be mitigated for the output freewheeling diode  $D_o$ .

#### Mode V:

Inductor current  $i_{Lr}$  Reduces to zero level after  $t_4$ , then the load current flows through the output capacitor  $C_o$ . The inductor current keeps zero until the next one cycle starts at  $t_5$ .



**Fig. 4:** Equivalent circuits during switching of one cycle under DCM.

#### Simulation Results:

'Simulation' in general terms can be defined as the representation of any system in its realistic form. Before implementing a new project, by simulation, one can see the effects of various parameters or components on the output accordingly change them to get a desired output. PSIM denotes Power Simulation. PSIM is simulation software specifically designed for the analysis and design of power electronics and control circuits. It provides a powerful environment to display and analyze simulation results. The feasibility of the proposed soft

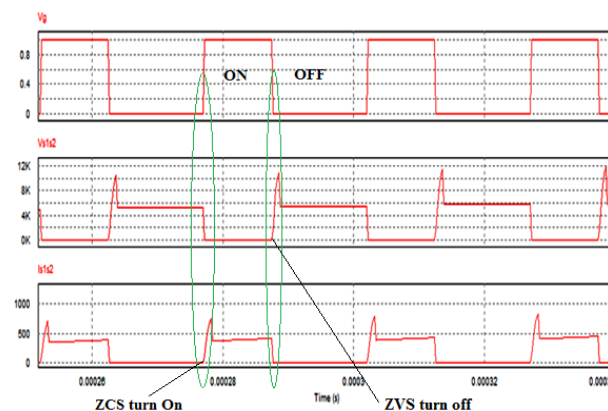
switching PWM Boost DC-DC converter with Edge-Resonant Switched Capacitor was verified with PSIM (a commercially available software package dedicated for power electronic converter simulations) and proposed converter is simulated under both open loop and closed loop configuration based on the following specifications: output voltage  $V_o = 200$  volts, output power  $P_o = 100$  W, Input voltage  $V_{in} = 100$  volts, and switching frequency  $f_s = 40$  KHz, Resonant Inductor  $L_r = 19.8 \mu\text{H}$ , Resonant Capacitor  $C_r = 56$  nF, Variable Load Resistor  $R_o : 40 - 400 \Omega$ , Output Capacitor  $C_o : 1750 \mu\text{F}$ .

The circuit simulation is done by using PSIM Software. Fig.5 demonstrate the Simulated switching waveforms of proposed converter under DCM. In these waveforms gate pulse signals of the IGBT switches S1 and S2 are shown in Fig.5(a). The ZVS and ZCS operation of switches during

turn-on and turn-off are shown in Fig.5(b) and Fig.5(c). The voltage  $V_{Lr}$  and current  $I_{Lr}$  across resonant inductor  $L_r$  under discontinuous conduction mode is shown in Fig.5(d) and Fig.5(e). Also, voltage across the resonant capacitor  $C_r$  is shown.



**Fig. 5:** Simulated switching waveforms of proposed converter under DCM.



**Fig. 6:** ZCS turn-on and ZVS turn-off of active switches.

Fig.6 illustrates the ZCS turn-on and ZVS turn-off of the switch S1 and S2 to demonstrate that the switch can turn on at zero current and turn off at zero voltage.

It can be seen from Fig.6, the switch S1 and S2 can simultaneously turn on with ZCS due to  $L_r$ . This can be seen by the fact that when the switch is turned on (as indicated by the collector to emitter voltage falling to zero), the current rises gradually from the zero value with the edge resonance by  $L_r$  and  $C_r$ . As a result, there is little overlap between switch voltage and current after the switch is turned on, and thus there are few turn-on switching losses. Thereby ZCS turn-

on commutation can be achieved in S1 and S2. Also from Fig. 6, it can be seen that switches S1 and S2 can be turned off with ZVS. Once the switch's gate pulse signal has been removed, then the switch S1 and S2 are turned off simultaneously. Then edge resonance begins, and it can be seen that the switch voltage rises gradually from zero initial value by the effect of  $C_r$ . Thereby ZVS turn-off commutation can be achieved in S1 and S2.

This proposed method combines the benefits of hard switching and soft switching. Switching waveforms are similar to conventional PWM waveforms except that the rising and falling edges

are smoothed by ER-SWC. Here “Resonance” is allowed to occur just before and during the turn on

and turn off process in order to create ZCS and ZVS.

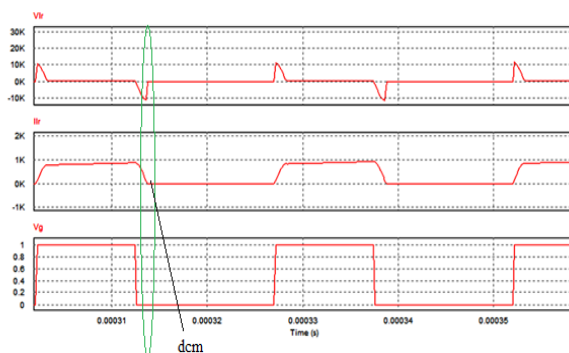


Fig. 7: Current and voltage of  $L_r$  in proposed circuit under DCM.

The inductor current  $I_{Lr}$  and inductor voltage  $V_{Lr}$  of the proposed soft switching boost dc-dc converter under DCM operation is illustrated in Fig.

7. In Fig.7.The inductor current  $I_{Lr}$  goes down to zero level which indicates DCM and time taken to reach zero level depends upon the load power.

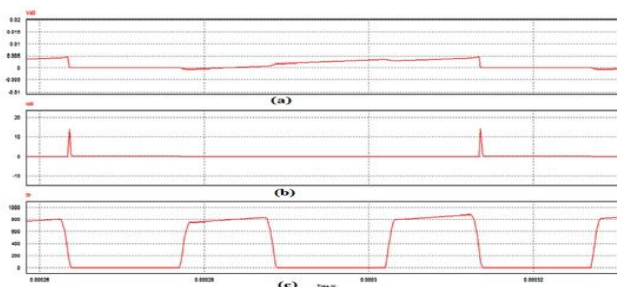


Fig. 8: Mitigation of diode reverse recovery current waveforms (a)&(b) Voltage and current waveforms for freewheeling diode  $D_o$  and (c) Resonant Inductor current waveform.

When gate pulse  $V_g$  is removed, stored inductor energy  $I_{Lr}$  flows. Now  $I_{Lr}$  is forwarded to load via  $D_o$  as shown in Fig. 8(C).  $I_{Lr}$  gradually

decreases and reaches zero. Thus,  $I_{D_o}$  reaches zero. Thereby occurrence of reverse recovery current of  $D_o$  is mitigated, and it is shown in Fig.8(b).

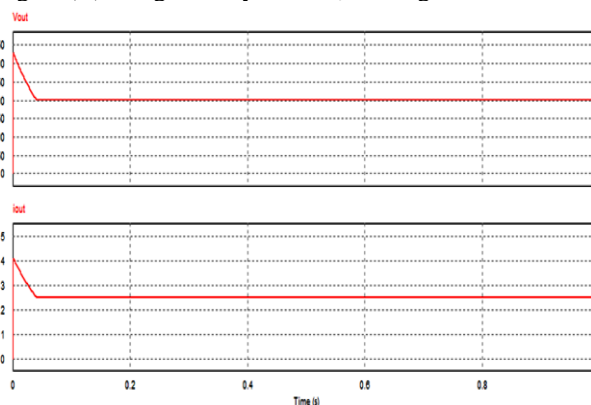


Fig. 9: Open loop Output Voltage and Output Current waveforms for  $R = 80\Omega$ .

Open loop proposed converter with load resistance  $R=80 \Omega$  is simulated and corresponding output voltage and output current waveforms are shown in Fig.9. And also the proposed circuit is simulated for various duty cycle  $d=0.1, d=0.3, d=0.5$  and its voltage conversion ratio  $M$  is calculated using the relation  $M= V_{out} / V_{in}$ . At  $d = 0.1$ , for  $V_{in} = 100$ , the Voltage conversion ratio is  $M = 1.5$

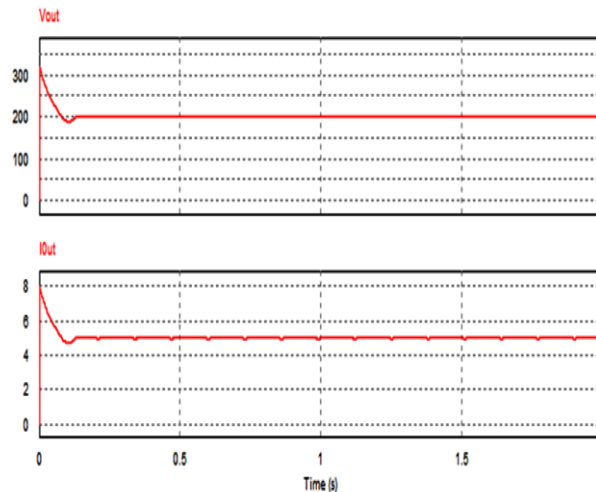
and at  $d=0.2, M=2$ . At  $d=0.3, M= 2.9$  and at  $d=0.5, M=3.8$ . Here for 1KW output power, 97% efficiency is achieved for voltage conversion ratio  $M= 1.5$ .

Similarly Closed loop proposed converter with a load resistance  $R=40 \Omega$  and  $V_{in} = 80$  Volts is simulated, and corresponding output voltage  $V_{out} = 200V$  and output current waveforms are shown in Fig.10. Note that if the input voltage is varied as  $V_{in} =$

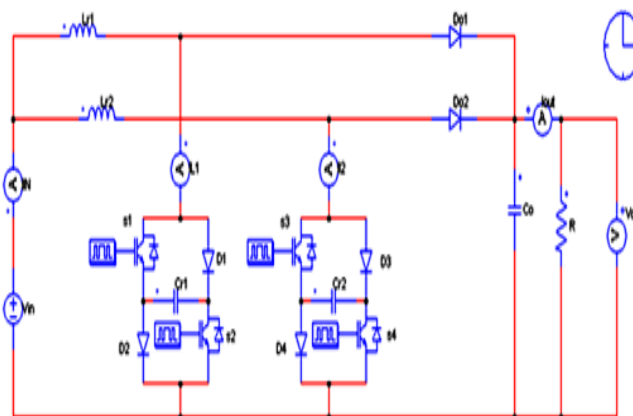
100 V and  $V_{in} = 133V$ , corresponding output voltage remains constant at  $V_{out} = 200 V$ .

The above proposed circuit under closed loop condition is simulated for various load resistance/power levels with three different input voltage conditions  $V_{in} = 80V, 100V, 133V$  and the corresponding output voltage  $V_{out}$ , output current

$I_{out}$ , input current  $I_{in}$ , and output power is measured and hence the efficiency is calculated and observed that the maximum efficiency attains 96% at voltage conversion ratio  $M = 1.5$  for  $V_{in} = 133$  volts,  $P_{OUT} = 1$  kW, Which has good agreement with the results of the open-loop control scheme.



**Fig. 10:** Closed loop Output Voltage and Output Current waveforms for  $V_{in} = 100$  Volts.



**Fig. 11:** Schematic diagram of two-phase (interleaved) ER-SWC soft switching PWM dc-dc converter.

The two-phase interleaved PWM boost dc-dc converter employing the ER-SWC cell is shown in Fig.11. Where two single phase ER-SWC boost dc-dc converter are assembled. The interleaving operation of two-phase prototype cancels the input current ripple over a wide range of loads.

The interleaved topology is simulated with switching frequency of 100kHz,  $L_r = 74\mu H$ ,  $C_r = 56nF$ . The peak value of inductor current  $i_{L_r}$  is well reduced with  $L_r = 74\mu H$  than  $L_r = 19.8\mu H$  which results in increased efficiency. This reduction of peak input current is illustrated in simulation results for different range of loads as shown in Fig. 12. As indicated in these waveforms, the ripple factor of the total input current  $I_{in}$  changes depending on the duty cycle of the ER-SWC cell.

Both interleaved topology and single phase circuits are simulated under same switching frequency condition 100 KHz and clarified that the interleaved topology attains higher efficiency than that of single phase ER-SWC converter.

#### **Conclusion:**

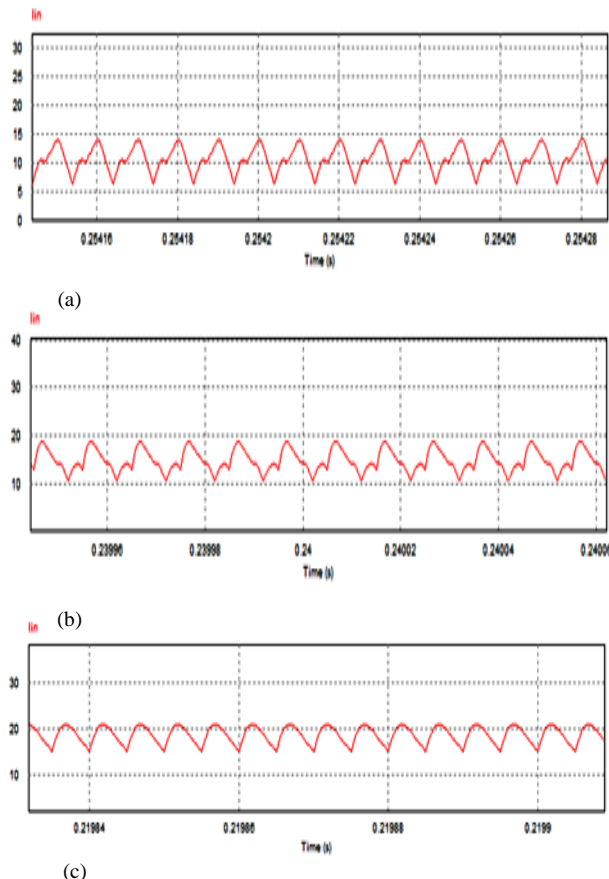
The new soft switching PWM boost DC-DC converter with an edge resonant switched capacitor cell, and its interleaved topology is proposed. The zero voltage and zero current switching operations under open loop/closed loop have been verified in the simulation results to ensure lower switching losses. The inherent properties of the dc-dc converter have been clarified from the simulation results as follows:

- High conversion efficiency over 96% can be achieved.
- Wide range of soft switching operations can be attained.
- High step up voltage conversion ratio which is two times as high as the conventional boost dc-dc converter is available.
- High step up voltage conversion ratio achievable with small duty cycle values, which is effective for

reduction in the conduction losses. It makes the PWM controller scheme simple.

- The major problem of reverse recovery current of boost converter is eliminated.

Furthermore, the two-phase interleaved soft switching boost dc-dc converter with the ER-SWC cells has been newly developed, and its results are clarified in terms of conversion efficiency and reduction of peak input current.



**Fig. 12:** Reduction of Peak input current  $I_{in}$  for different range of loads (a) 50% load (b) 70% load (c) 75% load.

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