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Auxiliary Resonant High Frequency DC/DC Converters

K. Santhi Priya* Mopidevi.Subbarao and Polamraju.V.S. Sobhan*****

Abstract : In this paper soft switching technique of a DC/DC converters are anticipated. Hard switching converters produces switching losses during turn ON and OFF. Due to this switching losses efficiency can be reduced. The resonant converter uses soft switching method for the reduction of switching losses. In this paper ZVS (zero voltage switching) resonance is applied for buck converter and auxiliary resonance is applied for boost converter and compare the performance of converters with and without resonance using MATLAB/Simulink software.

Keywords : Buck converter, boost converter, resonant circuit, auxiliary resonant circuit, soft switching converters.

1. INTRODUCTION

The switching devices are ready to turn ON and OFF the total load current at maximum value of di/dt. Due to the maximum value of di/dt also experience maximum voltage stresses across the switches. Major drawback of high di/dt and high dv/dt caused by rapid on and off of the switching devices is the electromagnetic interference .The problems can be minimized at the instant of switching the voltage across the switch and current flowing through the switch is zero. Then that converter employs ZVS/ZCS . These type of converters are called resonant converters or soft switching converters. Actually snubber circuits are used in the conventional converters for the purpose of protection. For high frequency applications hard switching provides high power density and fast transient response but at this frequency the switching stresses and electromagnetic interference effects are increases. These drawbacks are eliminated by using soft switching technique. The soft switching converters are mainly used in high frequency applications. Conventional technique provides switching losses and EMI due to this overall efficiency of the converter will be reduces. In the auxiliary resonant boost converter also used for soft switching here the difference is two switches are present. Both the switches are turned at zero voltage to decrease the losses.

RESONANT BUCK CONVERTER

Fig 1 shows the resonant /soft switching buck converter it consists of resonant capacitor denoted by Cr and resonant inductor Lr and filter elements Lf and Cf. In this converter turn on and turn-off instants of S occurs at zero voltage, it will helps to reduce losses and EMI. In the above fig1 diode D1 is connected across S with appropriate polarity to ensure turn on instant of power switch at zero voltage. The inductor Lr is coupled in series with S to reduce high di/dt of S and Cr is connected across the switch to limit dv/dt of S. Resonant circuit is formed by Lr and Cr, the oscillation of Lr and Cr initiated by turning off of S. diode Dm provides freewheeling path. A low pass filter formed by Lf and Cf is connected at the

* PG Student, VFSTR University, Vadlamudi, Guntur, A.P, India, 522213, Email: k.santhipriya8@gmail.com,
** Assistant Professor, VFSTR university, Vadlamudi, Guntur, A.P, India, 522213, subbarao.mopidevi@gmail.com
*** Associate Professor, VFSTR University, Vadlamudi, Guntur, A.P,522213, pvssobhan@gmail.com

output terminals to provide constant load current. It also filters the high frequency ripple signal. In ZVS buck converter, soft-switching is applied to the power switch. Because of this special feature ZVS buck converter is suitable for high-frequency conversion applications. The circuit analysis can be simplified by, the choosing large value of output filter inductance so that output filter along with load can be considered as an ideal dc current Io, during a high-frequency resonant cycle. The circuit operation of each cycle can be separated into five modes.

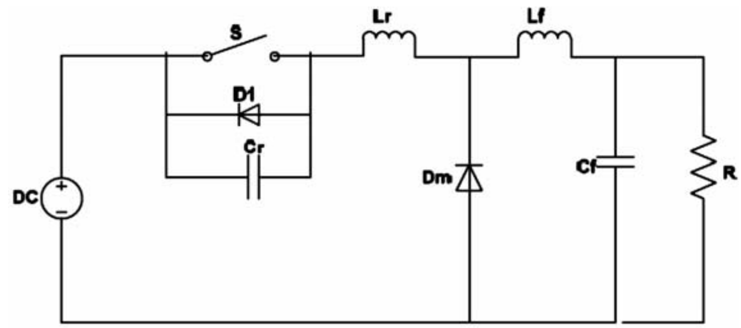

Fig. 1. Schematic diagram of the ZVS resonant converter.

Mode 1:

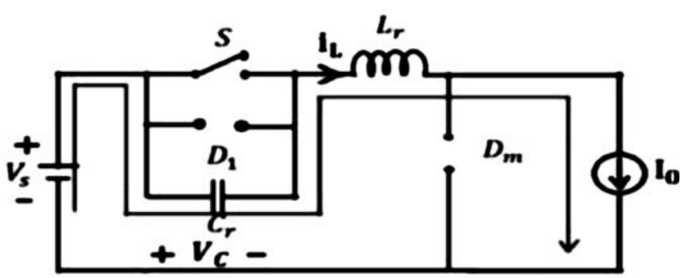

Fig. 2. Schematic diagram of Mode I.

Mode1 starts from 0 and ends at time interval $t1$.In mode1 the power switch S and diode Dm are off. Let us consider initially the resonant Capacitor Cr is uncharged. In this mode Cr charges from 0 to VS at constant Io. Voltage across Cr increases linearly. The expressions are given by

$$Vc = (Io.t)/C \quad (1)$$

this mode completes at $t1$ $$Vc(t = t1) = Vs \quad (2)$$

by sub (2) in (1) we get $$t1 = Vs.C/Io \quad (3)$$

Mode 2:

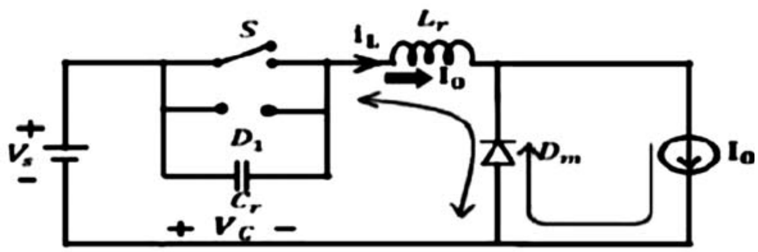

Fig. 3. Equivalent circuit of Mode II.

This mode is starts from 0 and ends at time interval $t2$.. In mode2 S is remains in off , but the Dm turned on. Then voltage across the Cr is given by

$$Vc = V_m \sin w_{ot} + V_s \quad (4)$$

where $$V_m = I_o\sqrt{\frac{L}{C}} \quad (5)$$

We can obtain (6) by by substituting (5) into (4)

The peak switch voltage is $$V_{tp} = V_{cp} = I_o\sqrt{\frac{L}{C}} + V_s \quad (6)$$

Which occurs

$$\text{at } t = \left(\frac{\pi}{2}\right)\sqrt{\frac{L}{C}} \quad (7)$$

where inductor current $$i\text{L} = I_o \cos w_o t \quad (8)$$

mode2 completed at $t = t2$

$$V_c(t = t_2) = V_s \text{ and } i_L(t = t_2) = -I_o \quad (9)$$

$$\therefore \quad t_2 = \pi\sqrt{LC} \quad (10)$$

Mode 3 :

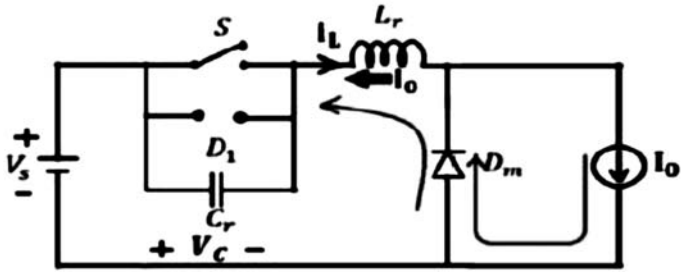

Fig. 4. Equivalent circuit of Mode III.

This mode is starts from 0 and ends at time interval t_3.The capacitor voltage reduces from source voltage V_S to zero voltage is given by

$$V_c = V_s - V_m \sin w_{ot} \quad (11)$$

inductor current $$i_L = -I_o \cos w_{ot} \quad (12)$$

mode 3 completed at $t = t_3$

$$V_c(t = t_3) = 0, \text{ and } i_L(t = t_3) = i_{L3} \quad (13)$$

thus $$t_3 = \sqrt{L/C}\sin^{-1}x \quad (14)$$

where $$x = \frac{V_s}{V_m} = \frac{V_s}{I_o}\sqrt{L/C} \quad (15)$$

Mode 4 :

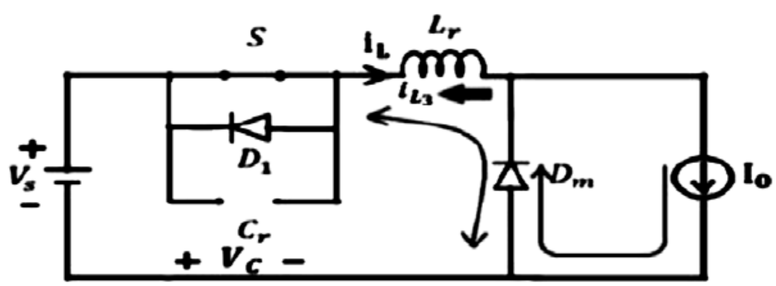

Fig. 5. Equivalent circuit of Mode IV.

Mode 4 starts from 0 and ends at time interval t4. In mode4 S is in ON position and Dm also in ON condition. I_L increases from i_{L3} to Io is given by

$$i_L = i_{L3} + \left(\frac{V_s}{L}\right)t \quad (16)$$

mode 4 completes at time $t = t_4$

$$i_L(t = t_4) = I_o \quad (17)$$

We can obtain (18) by substituting (17) into (16)

$$t_4 = (I_o - i_{L3})\left(\frac{L}{V_s}\right) \quad (18)$$

i_{L3} has a negative value

Mode 5 :

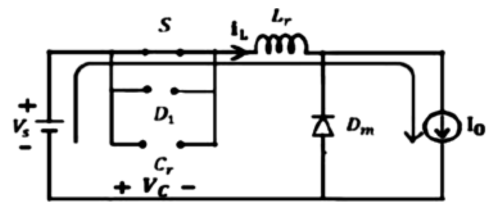

Fig. 6. Schematic diagram of Mode V.

Mode5 starts from 0 and ends at t5. In mode5 S remains in ON condition but Dm is OFF. In this mode S carries the current I_o. at the end of this mode S is turned off and the procedure repeat for every cycle.

$$t_5 = T - (t_1 + t_2 + t_3 + t_4) \quad (19)$$

The peak voltage across the switch is given by

$$V_{tp} = V_{cp} = I_o\sqrt{L/C} + V_s \quad (20)$$

In the above equation the voltage across the switch is function of load current I_o.Therefore the switch voltage depends upon the load current. to maintain the constant load current we have to select the value of inductance is high. For this reason, zero voltage switching converters are applied only for constant-load applications. In this type of converters at the instant of switching the voltage across the switch is zero.

RESONANT BOOST CONVERTER

(I) Configuration Of The Proposed Soft Switching Boost Converter

The soft switching boost converter circuit is shown in fig6.the circuit consists of two switches S1 and S2 where S1 main switch and S2 is auxiliary switch ,resonant inductor ,resonant capacitor and diodes.

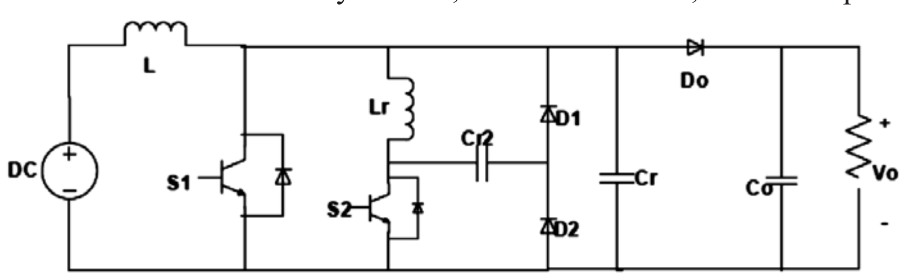

Fig. 7. Schematic diagram of the soft switching boost converter.

(II) Principal of operation of the boost converter

This circuit operation can be divided into nine modes.

Mode 1 ($t0 \leq t < t1$) : In this mode S1 and S2 are in OFF position. The energy stored in L transmitted to load through Do. v_L and i_L are expressed as (22) and (23) from the above 2 equations we get i_L. In this mode Lr is zero and Cr charged to V_o.

$$v_L(t) = V_{in} - V_o \tag{21}$$

$$i_L(t) = \frac{1}{L}\int v_L dt \tag{22}$$

$$i_L(t) = \frac{V_{in} - V_o}{L}(t - t_o) + (t_9) = I(t_9) - \frac{V_o - V_{in}}{L}(t - t_o) \tag{23}$$

$$i_{Lr}(t) = 0,\ V_{cr}(t) = V_0,\ V_{cr}(t_2) = 0 \tag{24}$$

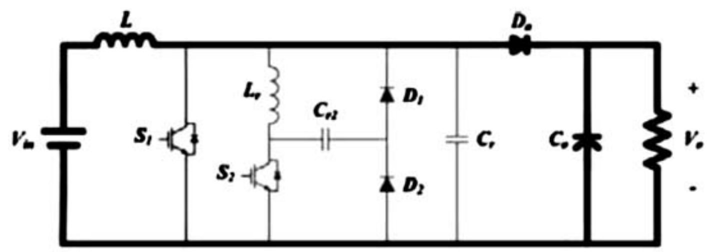

Fig. 8. Equivalent circuit of mode I.

Mode 2 ($t1 \leq t < t2$): Mode 2 begins with the turning ON of S2. After turning on of S2 current flowing through the Lr raises linearly from zero. This mode completes when the i_{Lr} reaches to i_L and voltage across the Lr is equal to Vo. main inductor current will be decreases and it will be minimum at end of this mode. i_{Lr} can be expressed as (25)

$$i_{Lr}(t) = \frac{V_o}{L_r}(t - t_1) \tag{25}$$

$$i_L(t_2) \approx I_{min} \tag{26}$$

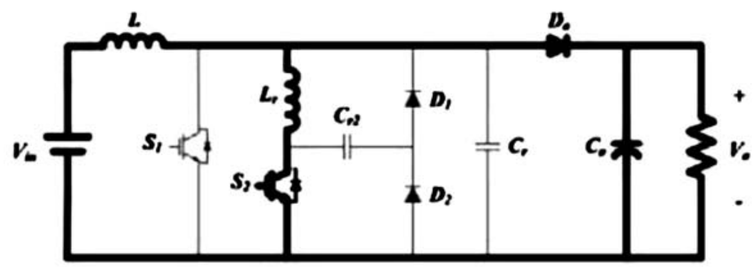

Fig. 9. Equivalent circuit of mode II.

Mode 3 ($t2 \leq t < t3$) : After equalizing the i_{Lr} and i_L the diode Do turned off and Cr is discharged through Lr and Cr upto resonant capacitor Cr is equal to zero. At the time interval of two currents will be equal is expressed in (27). This mode completes at time t_3. In this mode Zr and wr given w_r by

$$t_1 = \frac{i_L}{\left(V_o / L_r\right)} \tag{27}$$

$$i_{Lr}(t) = i_{min}(t) + \frac{V_0}{Z_r}\sin w_r\,(t - t_2) \tag{28}$$

$$V_{cr}(t) = V_o \cos w_r\,(t - t_2) \tag{29}$$

$$Z_r = \sqrt{\frac{L_r}{C_r}} \quad W_r = \frac{1}{\sqrt{L_r C_r}} \tag{30}$$

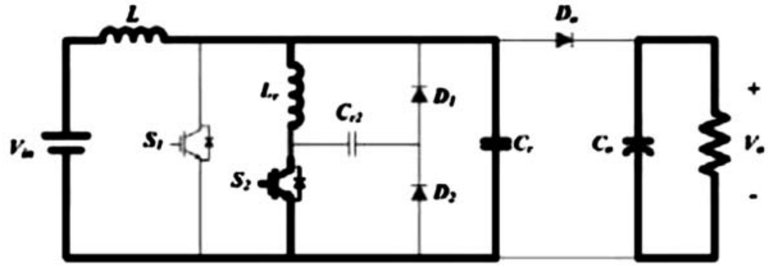

Fig. 10. Equivalent circuit of mode III.

Mode 4 ($t3 \leq t < t4$): The body diode of is S1 is turned on automatically when resonant capacitor voltage reaches to zero. the diode of the main switch is on and short circuited so the voltage across the switch S1 is zero and the turn on signal is given to S1 under zero voltage condition. In this mode voltage across the L is equal to the V_s that can be expressed in (31).

$$i_L(t) = i_{min}(t) + \frac{V_{in}}{L}(t - t_3) \tag{31}$$

$$V_{cr}(t) = 0, \qquad V_{cr2}(t) = 0 \tag{32}$$

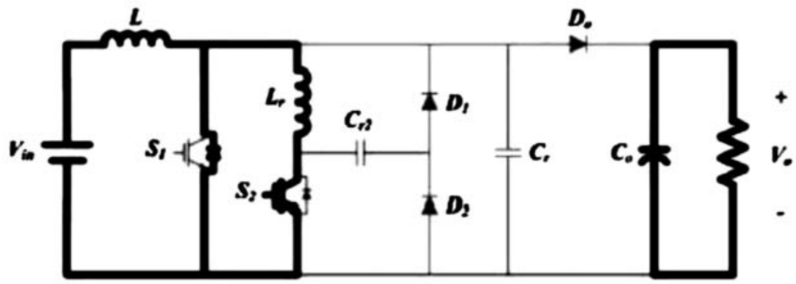

Fig. 11. Equivalent circuit of mode IV.

Mode 5 ($t4 \leq t < t5$) : Mode 4 ends with the turning on of the S1 and at the same time turning off of the S2 at zero voltage condition. In mode5,Lr and C_{r2} start their resonance. After the quarter-wave resonance of Lr and C_{r2}, the current flowing in Lr is zero. This mode concludes with the charging of the resonant capacitor full.

$$i_{Lr}(t) = i_{Lr}(t_3)\cos w_a(t - t_4) \tag{33}$$

$$w_a = \frac{1}{\sqrt{L_r C_{r2}}} \quad Z_a = \sqrt{\frac{L_r}{C_{r2}}}, \tag{33}$$

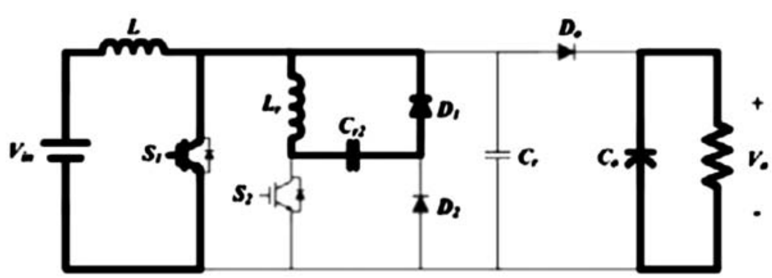

Fig. 12. Equivalent circuit of mode V.

Mode 6 ($t5 \le t < t6$) : After completion of mode 5, the current flow in L_r reverses and in mode 6, a reverse resonance of L and C_{r2} through S1 and D2 occurs. When the voltage across C_{r2} reaches to zero with the resonance, the resonance of Lr and C_{r2} is complete and V_{cr2} is zero. During above two modes V_{cr2} is charges and discharges.

$$v_{Cr2}(t) = Z_a i_{Lr}(t_3) \sin w_a(t - t_4) \quad (34)$$

$$v_{cr2}(t_5) = Z_a i_{Lr}, \qquad v_{cr2}(t_6) = 0 \quad (35)$$

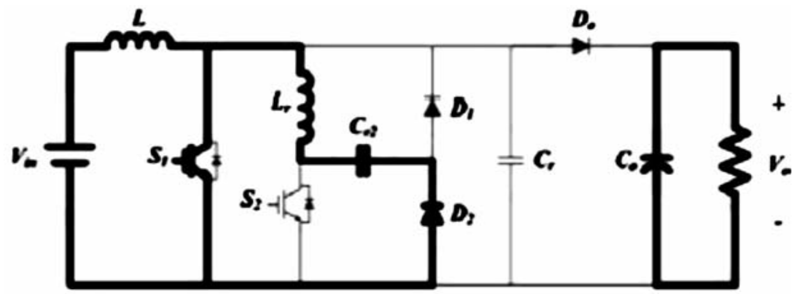

Fig. 13. Equivalent circuit of mode VI.

Mode 7 ($t6 \le t < t7$) : After reaching v_{cr2} to zero, body diode of S2 is turned ON. The current flowing through body diode L_r and S1. By applying PWM technique, at the end of mode7 S1 is turned ON. i_{Lr} and i_L

$$i_L(t) = I_{min} + \frac{V_{in}}{L}(t - t_3) \quad (36)$$

$$i_{Lr}(t_7) = -i_{Lr}(t_3) \quad (37)$$

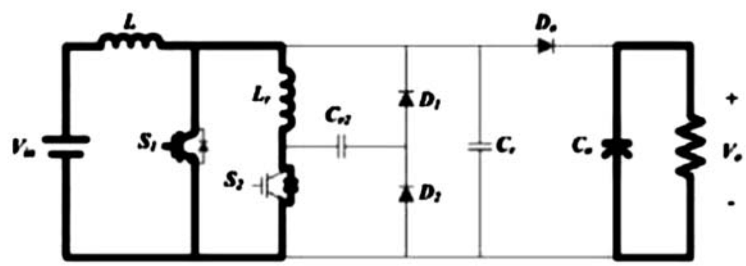

Fig. 14. Equivalent circuit of mode VII.

Mode 8 ($t7 \le t < t8$) : When S_1 turns OFF under ZVS, at this condition mode 8 starts. The charging current of the Cr is equal to the sum of 2 currents.mode8 is concluded with the V_{cr} is equal to the V_o. Because i_{Lr} charges Cr , the i_{Lr} is shown in (38), and (39) under ZVS.

$$i_{Lr}(t) = i_L(t_7) - \{i_L(t_7) + i_{Lr}(t_3)\} \cos w_r t \quad (38)$$

$$Z_r\{i_L(t_7) + i_{Lr}(t_3)\} > V_o \quad (39)$$

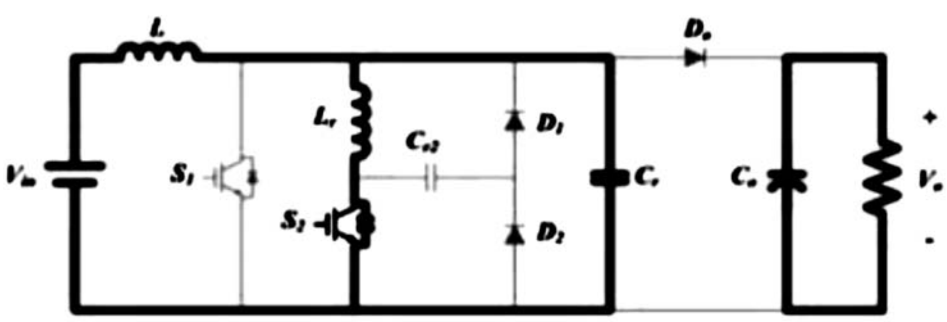

Fig. 15. Equivalent circuit of mode VIII.

Mode 9 ($t8 \le t < t9$) : At the time interval $t8$, Cr charges and the main diode voltage is zero. Therefore, Do turned ON under ZVS and i_Lr reaches to zero. After reaching zero mode 9 concludes and cycle starts. In mode9 i_L and i_{Lr} is given as

$$i_L(t) = i_L(t_7) - \frac{V_o - V_{in}}{L} t \tag{40}$$

$$i_{Lr}(t) = -i_{Lr}(t_3) + \frac{V_o}{L_r} t \tag{41}$$

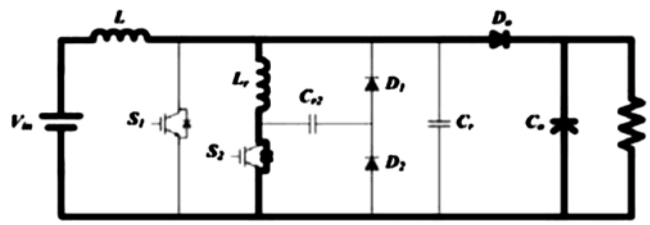

Fig. 16. Equivalent circuit of mode IX.

2. DESIGN OF RESONANT ELEMENTS

(I) BUCK CONVERTER

The condition $Z_o I_o > V_s$ must hold to ensure that the operation is under ZVS.

$$I_o \frac{1}{w_o C_r} > V_{in}$$

$$C_r < I_o / (V_{in} w_o) \tag{42}$$

similarly, because of the condition $Z_o I_o > V_s$ must hold such that

$$C_r = V_{in} / I_o w_o \tag{42}$$

$$I_o w_o L_r > V_{in}$$

$$L_r > V_{in} / I_o w_o \tag{43}$$

Table 1. Parameters that are used in buck converter.

Input voltage	V_{in}	20V
Switching frequency	f_s	105KHZ
Inductor	L	150µH
Capacitor	C	330µF
Resonant inductor	L_r	2.62µH
Resonant capacitor	C_r	0.52µH
Output voltage	V_o	14V
Output current	I_o	7A
Resonant freq	f_r	147KHZ

(II) BOOST CONVERTER

Resonant Capacitor (Cr) :

The Cr is chosen to tolerate ZVS of S_1. In mode 8, the charging time of the Cr must be longer for ZVS of S_1. where ILmax, is the max current of i_{Lr} and the sum of i_{Lr} and i_L is the (Cr) charging current. In this case, the min value of Cr is equal to 20 times the output capacitance of S_1. compared to the mode8 mode3 is small. then the defective duty ratio is lower. Thus, the time is chosen as 0.1Ts .

$$T_r = \frac{\pi}{2}\sqrt{L_r C_r} \quad (44)$$

$$t_{ct\_Cr} = C_r \frac{V_o}{2t_{o\,max}} \quad (45)$$

$$\frac{\pi}{2}\sqrt{L_r C_r} + C_r \frac{V_o}{2I_{o\,max}} \leq 0.1\ \text{Ts} \quad (46)$$

Resonant Inductor (Lr) and Resonant Capacitor (Cr2): In mode5 time for the resonance is chosen as 0.2. Additionally, the capacitor is charges with the current of the inductor and capacitor (Cr2). when higher the capacitor charging voltage then switching stresses are also high. So this voltage is less than the output voltage. These inductor and capacitor voltages are expressed by (47), (48). (51) shows the values.

$$Z_a I_{\text{in max}} \leq V_o \quad (47)$$

$$\pi\sqrt{L_r C_{r2}} \leq 0.1T_s \quad (58)$$

$$w_a \approx 942477.8\,, \quad Z_a \leq 71.8 \quad (49)$$

$$L_r \leq \frac{z_a}{w_a}, \quad C_{r2} \geq \frac{1}{z_a w_a} \quad (50)$$

$$L_r = 20\mu\text{H}, \quad C_{r2} = 30n\text{F} \quad (51)$$

Table 2. Parameters that are used in boost converter.

Input voltage	V_{in}	130V~170V
Output voltage	V_{out}	400V
Switching freq.	F_s	30KHZ
Resonant Cap(C_r)	C_r	3.3nF
Resonant Cap(C_{r2})	C_{r2}	30nF
Resonant inductor	L_r	20µH
Main inductor	L	560µH

3. RESULTS/DISCUSSIONS

Resonant buck converter and the boost converter by using soft switching technique has been designed,modeled and simulated in MATLAB/ Simulink. The simulation parameters are shown in Table I and Table II. The simulation was performed under 105KHZ f_s and 20V Vin for buck converter and 30KHZ f_s and 130~170V Vin for boost converter.

(I) MATLAB MODEL FOR THE BUCK CONVERTER WITH RESONANCE

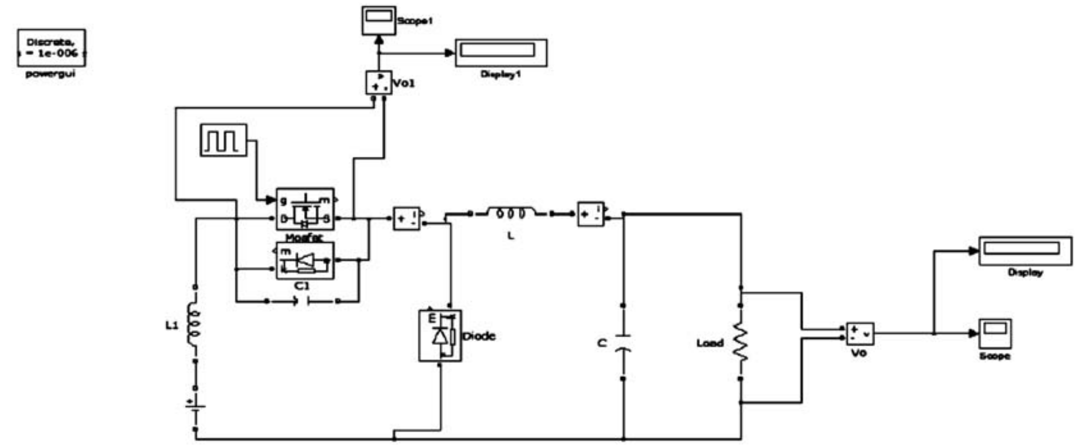

Fig. 17. Simulink diagram of buck converter with resonnce

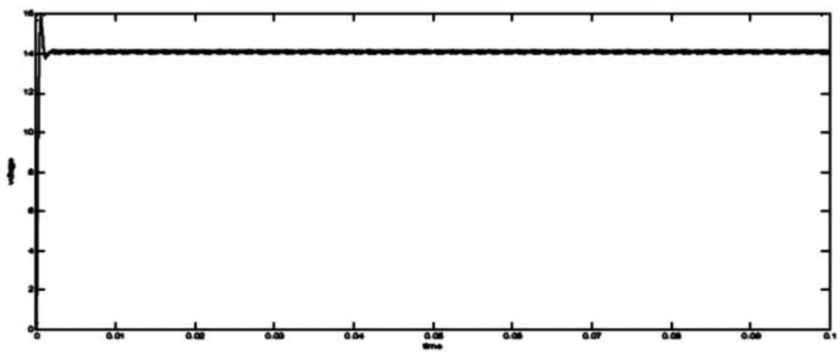

Fig. 18. Output voltage of buck converter without resonance

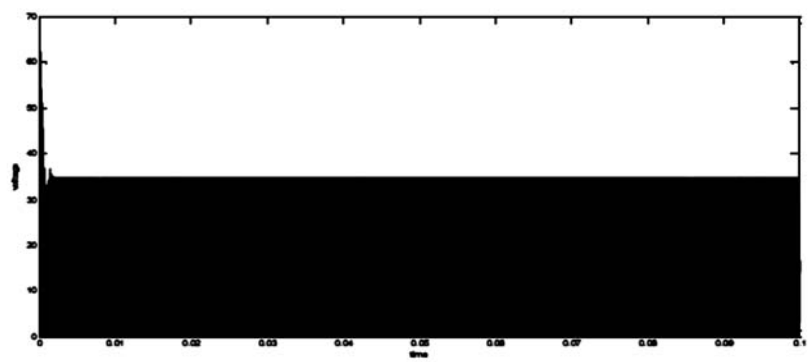

Fig. 19. Switch voltage of buck converter without resonance

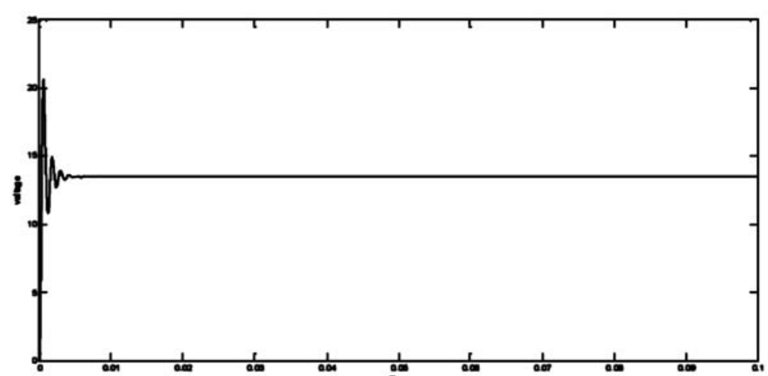

Fig. 20. Output voltage of buck converter with resonance

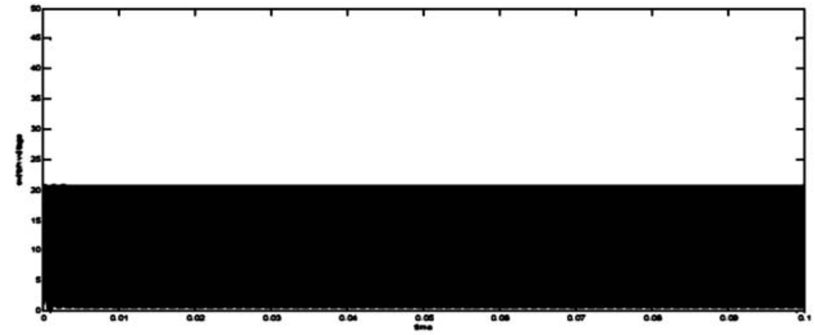

Fig 21. Switching voltage of buck converter with resonance

(II) MATLAB MODEL FOR THE BOOST CONVERTER WITH RESONANCE

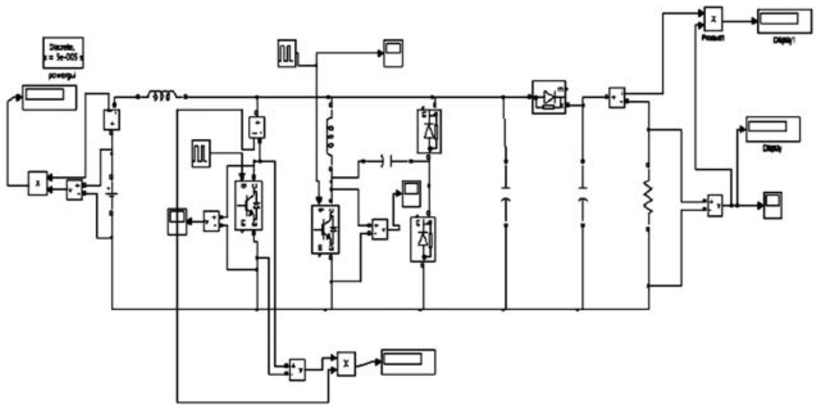

Fig. 22. Simulink diagram of boost converter with resonance

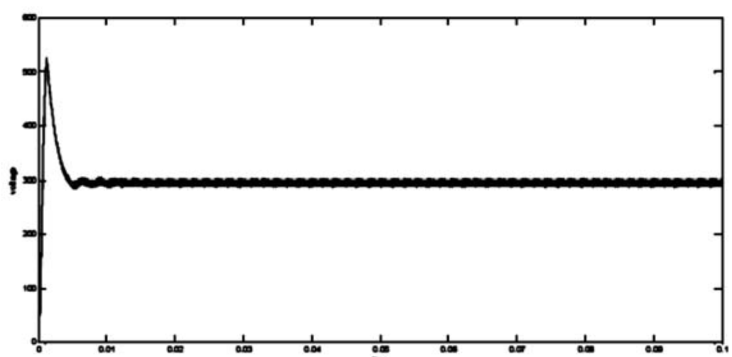

Fig. 23. Output voltage of boost converter without resonance

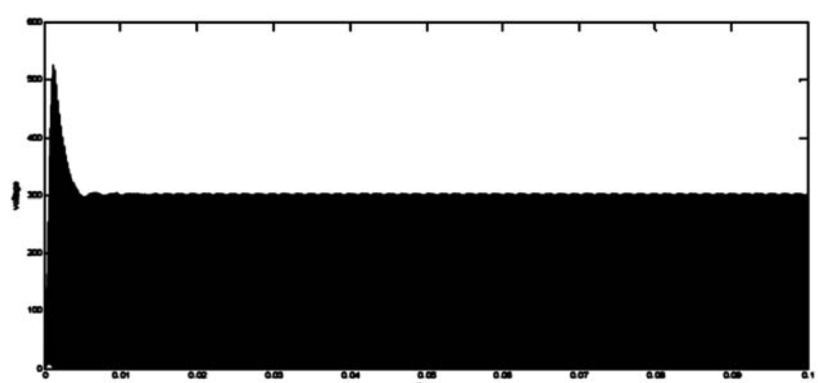

Fig. 24. Switch voltage of boost converter without resonance

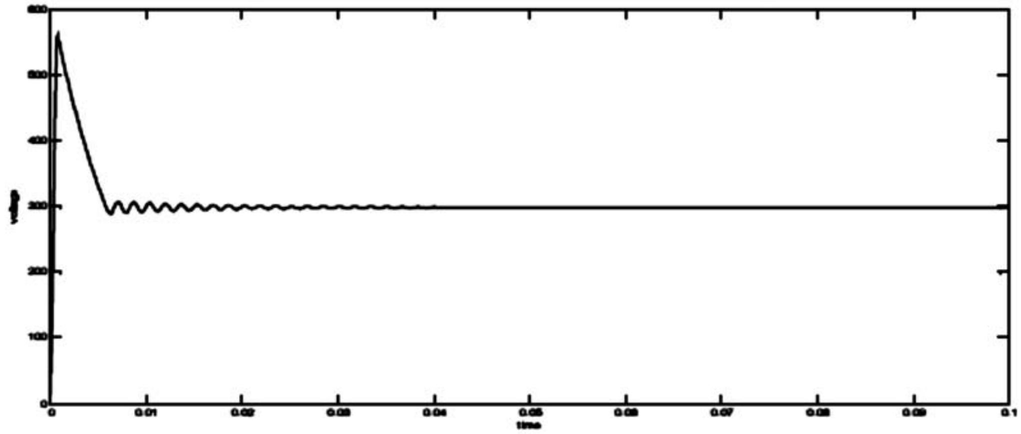

Fig. 25. Output voltage of boost converter with resonance

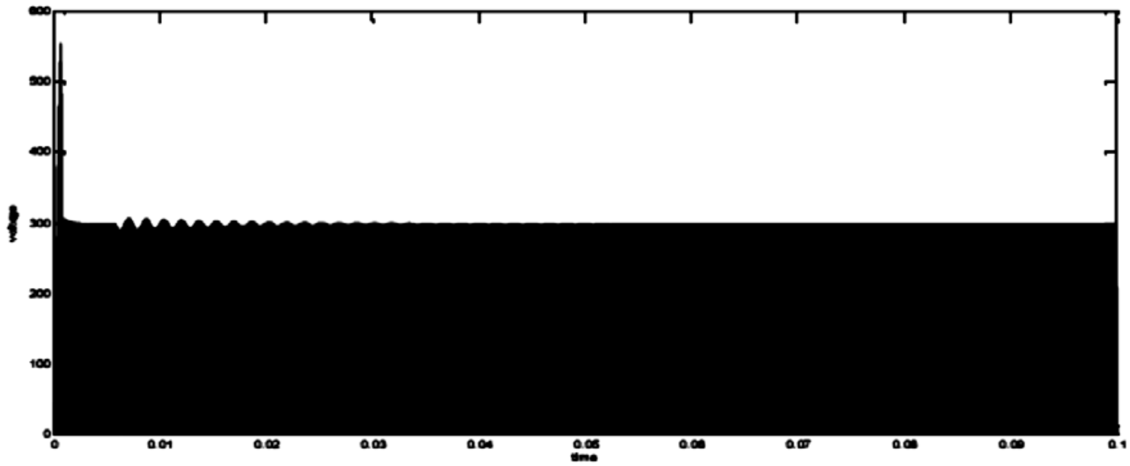

Fig 26. Switch voltage of boost converter with resonance

4. COMPARATIVE ANALYSIS BETWEEN HARD SWITCHING CONVERTER AND HARD SWITCHING CONVERTER :

BUCK CONVERTER

Table 3. Performance of the buck converter with and without switching.

Parameter	*Without resonance*	*With resonance*
Output voltage with ripple	1 V	No ripple
Settling time	0.1 Sec	0.05Sec
Switching Voltage	17 V	12V

BOOST CONVERTER

Table 4. Performance of the boost converter with and without switching.

Parameter	*Without resonance*	*With resonance*
Output voltage with ripple	10 V	No ripple
Settling time	0.1 Sec	0.05 Sec
Switching Voltage	160 V	12 V

5. CONCLUSION

In this paper soft switching technique is applied for both buck and boost converters. Comparison between the performance of conventional technique and soft switching technique using MATLAB/ Simulink has been done in the aspects of output voltage, settling time and switching voltage.It is observed that in soft switching output voltage ripples can be reduced to zero ,settling time can be reduced to 0.1-0.045sec and switching voltage is reduced by 20V from this result soft switching is better compared to hard switching.

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