HIGH FREQUENCY RESONANT DC/DC CONVERTERS

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Abstract

In this paper soft switching technique of a DC/DC converters are anticipated. Hard switching converters produce 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.

I. Introduction

The switching devices are ready to turn ON and OFF the total load current at maximum value of \( \frac{di}{dt} \). Due to the maximum value of \( \frac{di}{dt} \) also experience maximum voltage stresses across the switches[I]. Major drawback of high \( \frac{di}{dt} \) and high \( \frac{dv}{dt} \) 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[II-VI]. 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[VII]. 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.

I.i. Resonant Buck Converter:

Fig1: schematic diagram of the ZVS resonant converter

Fig1. shows the resonant/soft switching buck converter, it consists of resonating
elements capacitor ($C_r$) and inductor ($L_r$) and filter elements $L_f$ and $C_f$. The
circuit operation of each cycle can be separated into five modes.

Mode 1:

Mode 2:

$V_c = V_m \sin \omega_0 t + V_s$  \hspace{1cm} (1)
where

\[ V_m = I_o \sqrt{\frac{L}{C}} \]  \hspace{1cm} (2)

The peak switch voltage is

\[ V_{tp} = V_{cp} = I_o \sqrt{\frac{L}{C}} + V_s \]  \hspace{1cm} (3)

at \( t = \frac{\pi}{2} \sqrt{\frac{L}{C}} \)  \hspace{1cm} (4)

where, inductor current \( i_L = I_o \cos \omega t \)  \hspace{1cm} (5)

Mode 3:

![Fig4: Equivalent circuit of Mode III](image)

The capacitor voltage reduces from source voltage \( V_s \) to zero voltage is given by

\[ V_c = V_s - V_m \sin \omega t \]  \hspace{1cm} (6)

\[ i_L = -I_o \cos \omega t \]  \hspace{1cm} (7)

Mode 4:

![Fig.5: Equivalent circuit of Mode IV](image)

In mode 4 S is in ON position and \( D_m \) also in ON condition. \( I_L \) Increases from \( I_{L3} \) to \( I_o \) is given by
\[ i_L = i_{L3} + \left( \frac{V_s}{L} \right) t \]  \hspace{1cm} (8)

Mode 5:

In mode 5 S remains in ON condition but \( D_m \) 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.

\[ t_5 = T - (t_1 + t_2 + t_3 + t_4) \]  \hspace{1cm} (9)

The peak voltage is,

\[ V_{tp} = V_{cp} = I_o \sqrt{\frac{L}{C}} + V_s \]  \hspace{1cm} (10)

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.

\textbf{I.ii. Resonant Boost Converter:}

The soft switching boost converter circuit is shown in Fig.6, the circuit consists of two switches S1 (Main Switch) and S2 (Auxiliary Switch), resonant inductor, resonant capacitor and diodes.

This circuit operation has 9 modes.
Mode 1 : In this mode S1 and S2 are in OFF position. The energy stored in L transmitted to load through Do. In this mode Lr is zero and Cr charged to $V_o$.

\[ v_L(t) = V_{in} - V_o \]  

\[ i_L(t) = \frac{1}{L} \int v_L \, dt \]  

\[ i_L(t) = \frac{V_{in} - V_o}{L} (t - t_o) + I(t_o) = I(t_o) - \frac{V_o - V_{in}}{L} (t - t_o) \]  

\[ i_{LR}(t) = 0, \quad V_{cr}(t) = V_o, \quad V_{cr}(t_2) = 0 \]  

\[ i_{L1}(t) = \frac{V_o}{L} (t - t_1) \]  

\[ i_L(t_2) \approx I_{min} \]

**Fig.7. Equivalent circuit of mode I**

Mode 2 : 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.

\[ i_{LR}(t) = \frac{V_o}{L_r} (t - t_1) \]  

\[ i_L(t_2) \approx I_{min} \]  

**Fig.8. Equivalent circuit of mode II**

Mode 3 : 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. In this mode Zr and $w_r$ given by

\[ t_1 = \frac{i_L}{(V_o/L_r)} \]  

\[ i_{LR}(t) = i_{min}(t) + \frac{V_o}{x_r} \sin w_r \, (t - t_2) \]  

\[ V_{cr}(t) = V_o \cos w_r (t - t_2) \]  

\[ t_2 = \frac{i_L}{(V_o/L_r)} \]  

\[ i_{LR}(t) = i_{min}(t) + \frac{V_o}{x_r} \sin w_r \, (t - t_2) \]  

\[ V_{cr}(t) = V_o \cos w_r (t - t_2) \]
\[ Z_T = \frac{L_T W_T}{C_T} = \frac{1}{\sqrt{L_T C_T}} \]  

(20)

![Fig.9. Equivalent circuit of mode III](image)

Mode 4: The diode across S1 is turned on automatically when resonant capacitor voltage reaches to zero.

\[ i_L(t) = i_{\text{min}}(t) + \frac{V_{\text{in}}}{L}(t - t_3) \]  

(21)

\[ V_{cT}(t) = 0, \quad V_{cT2}(t) = 0 \]  

(22)

![Fig.10: Equivalent circuit of mode IV](image)

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

\[ i_{Lr}(t) = i_{Lr}(t_3) \cos \omega_a (t - t_4) \]  

(23)

\[ \omega_a = \frac{1}{\sqrt{L_r C_{r2}}}, \quad Z_a = \frac{L_r}{\sqrt{C_{r2}}} \]  

(24)

![Fig.11: Equivalent circuit of mode V](image)
Mode 6: 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 $L_r$ and $C_{r2}$ is complete and $V_{cr2}$ is zero. During above two modes $V_{cr2}$ is charges and discharges.

$$v_{cr2}(t) = Z_a i_{lr}(t_3) \sin \omega_a (t - t_4)$$  \hspace{1cm} (25)

$$v_{cr2}(t_5) = Z_a i_{lr}, \quad v_{cr2}(t_6) = 0$$  \hspace{1cm} (26)

![Fig.12: Equivalent circuit of mode VI](image)

Mode 7: 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 mode 7 $S1$ is turned ON. $i_{lr}$ and $i_l$.

$$i_l(t) = I_{min} + \frac{V_{in}}{L}(t - t_3)$$  \hspace{1cm} (27)

$$i_{lr}(t_7) = -i_{lr}(t_3)$$  \hspace{1cm} (28)

![Fig.13: Equivalent circuit of mode VII](image)

Mode 8: 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. mode 8 is concluded with the $V_{cr}$ is equal to the $V_0$.

$$i_{lr}(t) = i_{L}(t_7) - \{i_{L}(t_7) + i_{lr}(t_3)\} \cos \omega_r t$$  \hspace{1cm} (29)

$$Z_r \{i_{L}(t_7) + i_{lr}(t_3)\} > V_0$$  \hspace{1cm} (30)
Mode 9: At the time interval $t_8$, $C_r$ charges and the main diode voltage is zero. Therefore, $D_o$ turned ON under ZVS and $i_{lr}$ reaches to zero. After reaching zero mode 9 concludes and cycle starts. In mode 9 $i_L$ and $i_{lr}$ is given as

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

$$i_{lr}(t) = -i_{lr}(t_3) + \frac{V_o}{Lr} t$$

II. DESIGN PARAMETERS OF RESONANT ELEMENTS:
II.i. Resonant Buck Converter

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

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

$$C_r < \frac{I_o}{(V_{in} \omega_o)}$$

(33)

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

$$I_o \omega_o L_r > V_{in}$$

$$L_r > \frac{V_{in}}{I_o \omega_o}$$

(34)
Table1: Parameters that are used in buck converter

| $V_{in}$ | 20V |
|----------|-----|
| $f_s$    | 105KHZ |
| $L$      | 150µH |
| $C$      | 330µF |
| $L_r$    | 2.62µH |
| $C_r$    | 0.52µH |
| $V_o$    | 14V |
| $I_o$    | 7A |
| $f_r$    | 147KHZ |

II.i. Resonant Boost Converter

The $C_r$ is chosen to tolerate ZVS of $S_1$. In mode 8, the charging time of the $C_r$ must be longer for ZVS of $S_1$, where $I_{L_{max}}$, is the max current of $i_{Lr}$ and the sum of $i_{Lr}$ and $i_L$ is the ($C_r$) charging current. In this case, the min value of $C_r$ 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.

$$T_r = \frac{\pi}{2} \sqrt{L_r C_r}$$  \hspace{1cm} (35)

$$t_{ct,c_r} = C_r \frac{V_o}{2I_{o_{max}}}$$ \hspace{1cm} (36)

$$\frac{\pi}{2} \sqrt{L_r C_r} + C_r \frac{V_o}{2I_{o_{max}}} \leq 0.1T_s$$ \hspace{1cm} (37)

In mode5 time for the resonance is chosen as 0.2. Additionally, the capacitor is charges with the current of the inductor and capacitor($C_r$). 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.

$$Z_a I_{ln max} \leq V_o$$ \hspace{1cm} (38)

$$\pi \sqrt{L_r C_r^2} \leq 0.1T_s$$ \hspace{1cm} (39)

$$w_a \approx 942477.8, \hspace{1cm} Z_a \leq 71.8$$ \hspace{1cm} (40)

$$L_r \leq \frac{Z_a}{w_a}, C_{r2} \geq \frac{1}{Z_a w_a}$$ \hspace{1cm} (41)

$$L_r = 20\mu H, C_{r2} = 30nF$$ \hspace{1cm} (42)
Table2: Parameters that are used in boost converter

| Parameter | Value |
|-----------|-------|
| $V_{in}$  | 130V~170V |
| $V_{out}$ | 400V |
| $F_s$     | 30KHZ |
| $C_r$     | 3.3nF |
| $C_{r2}$  | 30nF |
| $L_r$     | 20µH |
| $L$       | 560µH |

III. Results / Discussions

Resonant buck converter and the boost converter by using soft switching technique has been designed, modelled 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 $V_{in}$ for buck converter and 30KHZ $f_s$ and 130~170V $V_{in}$ for boost converter.

i. MATLAB MODEL FOR THE BUCK CONVERTER WITH RESONANCE:

fig16: Simulink diagram of buck converter with resonance

fig17: output voltage of buck converter without resonance
fig18: switch voltage of buck converter without resonance

fig19: output voltage of buck converter with resonance

fig20: switching voltage of buck converter with resonance
ii. MATLAB MODEL FOR THE BOOST CONVERTER WITH RESONANCE:

fig21: simulink diagram of boost converter with resonance

fig22: output voltage of boost converter without resonance

fig23: switch voltage of boost converter without resonance
IV. COMPARATIVE ANALYSIS BETWEEN HARD SWITCHING CONVERTER AND HARD SWITCHING CONVERTER

IV.i. Resonant Buck Converter

Table 3: performance of the buck converter with and without switching

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

IV.ii. Resonant Boost Converter

Table 4: performance of the boost converter with and without switching

| Parameter                      | Without resonance | With resonance |
|--------------------------------|-------------------|----------------|
| Output voltage with ripple     | 10V               | No ripple      |
| Settling time                  | 0.1Sec            | 0.045Sec       |
| Switching Voltage              | 160V              | 140V           |
V. 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 0.1-0.045 sec and switching voltage is reduced by 20V from this result soft switching is better compared to hard switching.

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