Passive lossless snubbers for DC/DC converters

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Abstract: A general passive lossless snubber cell is proposed for use in DC/DC converters. The snubber is to suppress the turn-on loss of a MOSFET resulting from the reverse recovery current of the freewheeling diode. Energy recovery is achieved since the energy absorbed by the snubber during turn-on can be delivered to the output during turn-off. The simple structure and the absence of active components and resistors make this snubber a good alternative to a conventional RCD snubber or an active snubber. As an example, a boost converter equipped with the snubber is analysed. A 1kW, 100kHz prototype is implemented in the laboratory, and efficiency of 97% has been measured. Six basic non-isolated DC/DC converters equipped with the proposed snubber cell are also illustrated.

1 Introduction

Pulse width modulated (PWM) DC/DC converters have been widely used as switched mode power supplies in industry. The PWM technique is praised for its high power capability and ease of control. High power density and faster transient response of PWM DC/DC converters can be achieved by increasing the switching frequency. However, as the switching frequency increases, so do the switching losses and EMI noises. High switching losses reduce the power capabilities of PWM DC/DC converters, and serious EMI noises disturb control circuits.

Switching losses and EMI noises are mainly generated during turn-on and turn-off switching transitions of PWM DC/DC converters. According to Pietkiewicz and Tollik [1], there are three different non-ideal commutation phenomena behind this problem. The dominant phenomenon is the turn-on transient caused by the reverse recovery current of the freewheeling diode. During the turn-on process of a MOSFET in a boost circuit, the reverse recovery phenomenon makes the diode conducting reversely discharge itself. The drain current contains input current and the reverse recovery current increases instantaneously, and full output voltage is applied between the drain and source because the diode is still conducting. Multiplication of the drain current and drain-source voltage during the turn-on transient causes serious thermal problems. Fast $\frac{dv}{dt}$ of the drain current also generates serious EMI noises.

Several kinds of snubbers have been presented to reduce switching losses. Active snubbers [2] need auxiliary switches, and hence complex control strategies. RCD snubbers [3] dissipate power through the resistances, and thus reduce efficiency. A passive lossless snubber can effectively restrict switching losses by using no active and no power dissipative components. The circuit structure is simplified, and circuit efficiency is also effectively improved.

In this paper, a passive lossless snubber for boost PFC is investigated in depth. Snubber circuit operations are analysed, and component parameters can be mathematically determined. Experimental results from a 1kW, 100kHz boost PFC are used to verify the analysis. The general snubber cell for the boost converter is generalised to support the common non-isolated DC/DC converters.

2 Boost PFC with a passive lossless snubber

2.1 Principle of operation

Fig. 1 shows a boost PFC with the studied snubber, which is encircled by dotted lines. During the turn-on process, diode $D_1$ conducts reversely to discharge itself. Growth rate of the reverse recovery current is restricted by the snubber inductor $L_1$, which is placed in series with diode $D_1$. After the reverse recovery of $D_1$, it is turned off and the first resonance path is formed by $L_1$, $D_2$ and $C_s$. The energy of $L_1$ in current form is transferred to the snubber capacitor $C_s$ in voltage form through diode $D_2$. After switch $S$ turns off and the first resonance is stopped, the reverse recovery energy is delivered back to the output through the second resonance path $V_r-L_{in}-L_2-C_r-D_3-V_o$. This snubber absorbs the switching loss resulting from the reverse recovery current of diode $D_1$ and delivers it back to the output.

The circuit structure is simplified, and there are fewer components than with other energy recoverable snubbers.
2.2 Equivalent circuit analysis

To analyse the steady-state operations in one switching cycle of the circuit shown in Fig. 1, the following assumptions are made:

(i) the output capacitor \( C \) is large enough to assume that the output voltage \( V_u \) is constant and ripple-free.
(ii) input voltage \( V_i \) rectified from the AC voltage source is approximated to be constant in one switching cycle.
(iii) all semiconductor devices are assumed ideal, except the main diode \( D_1 \).
(iv) the input inductor \( L_i \) is much greater than the snubber inductor \( L_s \).

In addition, the following six time steps are used:

- \( t_0 \) turns on \( t_1 \) = \( D_1 \) is turned off \( t_2 \) = \( L_s \) becomes zero and \( D_3 \) is turned off
- \( t_3 \) = \( V_{CS} \) becomes zero, \( D_1 \) is turned on and \( D_3 \) is turned off

Two cases are analysed according to different duty ratios:

- Case 1 (long duty): \( t_0 - t_1 - t_2 - t_3 - t_4 - t_5 - t_0 \)
- Case 2 (short duty): \( t_0 - t_1 - t_2 - t_3 - t_4 - t_5 - t_0 \)

Based on these assumptions, the circuit operations of two cases in one switching cycle can be divided into six stages and are shown in Figs. 2-4, respectively.

Stage 1 (Fig. 2a; \( t_0 < t < t_1 \))

Switch \( S \) turns on at \( t_0 \). The reverse recovery process makes diode \( D_1 \) conduct reversely to discharge itself. The inductor currents of \( L_i \) and \( L_s \) are given by

\[
I_{L_i}(t) = I_F(t) + \frac{V_i}{L_i}(t - t_0) \\
I_{L_s}(t) = I_F(t) - \frac{V_i}{L_s}(t - t_0)
\]

Stage 2 (Fig. 2b; Case 1: \( t_1 < t < t_2 \); Case 2: \( t_1 < t < t_3 \))

The reverse recovery finishes and diode \( D_1 \) is off at \( t_1 \). Since \( D_1 \) is off, the reverse recovery current in \( L_s \) creates the first resonance path \( L_s - D_2 - C_s \) to charge \( C_s \) through \( D_2 \). The voltage across \( C_s \) is given by

\[
V_{Cs}(t) = \pm \frac{L_s I_{rr}}{C_s} \sin(\omega(t - t_1))
\]

\[
I_{Ls}(t) = I_{rr} \cos(\omega(t - t_1))
\]

\[
I_{rr} = \left( I_F(t_0) - \frac{V_i}{L_s}(t - t_0) \right)
\]

\[
\omega = \frac{1}{\sqrt{L_s C_s}}
\]

Stage 3 (Fig. 3a, Case 1: \( t_2 < t < t_3 \); Fig. 3b, Case 2: \( t_3 < t < t_5 \))

Case 1 (long duty, \( t_2 < t < t_3 \)): the current through \( L_s \) is zero and the voltage across \( C_s \) is constant after the first resonance is stopped by \( D_2 \). The energy absorbed in \( L_s \) is completely delivered to \( C_s \) before switch \( S \) turns off at \( t_3 \). Time \( t_3 \) is given by

\[
t_3 = t_1 + \frac{\pi \sqrt{L_s C_s}}{2}
\]

The energy absorbed in \( L_s \) is completely delivered to \( C_s \).

Case 2 (short duty, \( t_2 < t < t_5 \)) the duty is too short so that switch \( S \) turns off before the resonance stops at \( t_2 \).

\[
V_{Cs}(t_2) = \pm \frac{L_s I_{rr}}{C_s} \sin(\omega(t_2 - t_1)) = \pm \frac{L_s I_{rr}}{C_s}
\]

where \( I_F(t) \) is the forward current through \( L_i \) and \( L_s \).
Case 2 (short duty, $t_3 < t < t_4$): diode $D_3$ is turned on by the input inductor current $I_F(t_3)$ when switch $S$ turns off at $t_3$. $L_s$ and $C_s$ keep resonating through the path $L_s-D_3-C_s$ until the first resonance is stopped by diode $D_1$ at $t_5$. The input inductor current flows through diodes $D_1$ and $D_3$ to the output.

Stage 4 (Fig. 4a; Case 1: $t_3 < t < t_4$. Case 2: $t_2 < t < t_4$)
Case 1 (duty cycle is long, $t_3 < t < t_4$): diodes $D_2$ and $D_1$ are turned on by the input inductor current $I_F(t_3)$ when switch $S$ turns off at $t_3$.
Case 2 (Duty cycle is short, $t_2 < t < t_4$): the first resonance is stopped and $I_{L_s}$ is equal to zero at $t_2$. Time $t_2$ and the voltage $V_{C_s}$ at $t_2$ are also given by eqns. 7 and 8, respectively.

Cases 1 and 2: since diode $D_2$ is on, the voltage across $L_s$ is equal to $V_{C_s}$ and makes $I_{L_s}$ increase reversely to discharge $C_s$ to the output. When $I_{L_s}$ increases to the input inductor current $I_F(t_4)$ at $t_4$, diode $D_2$ is turned off automatically. Assuming that the input inductor current is constant at this stage, time $t_4$ when $D_2$ is automatically turned off and the voltage across $C_s$ at $t_4$ are given by

\[ t_4 = t_n + \sqrt{L_s C_s \sin^{-1} \left( \frac{I_F(t_n)}{I_{FF}} \right)} \]  
\[ V_{C_s}(t_4) = \frac{L_s}{C_s} \left( I_{L_s}^2 - I_F(t_n)^2 \right) \]

where $t_n = t_3$ in Case 1 and $t_n = t_2$ in Case 2.

Stage 5 (Fig. 4b; $t_4 < t < t_5$)
The second resonance is formed by $V_F-L_{in}-L_s-C_s-D_3-V_n$ when diode $D_3$ is turned off at $t_4$. In the second resonance, $L_{in}$, $L_s$, and $C_s$ are discharging to the output. All of the reverse recovery energy is completely transferred back to the output when $V_{C_s}$ is discharged to zero through diode $D_3$ at $t_5$. Assuming that the input inductor current is constant at this stage, time $t_5$ when $V_{C_s}$ becomes zero is given by

\[ t_5 = t_4 + \frac{\sqrt{L_s C_s (I_{L_s}^2 - I_F(t_4)^2)}}{I_F(t_4)} \]

Stage 6 (Fig. 4c; $t_5 < t < t_0$)
The energy recovery of the snubber finishes when diode $D_1$ is turned on at $t_5$. After that, the current $I_F(t_5)$ flows through diode $D_1$ instead of diode $D_3$ to prevent $C_s$ from being charged reversely. Diode $D_1$ is turned on and $D_3$ is turned off at $t_5$. The input voltage source and the input inductor keep discharging to the output through diode $D_1$. The circuit operation is the same as in Stage 1 when switch $S$ turns on again at $t_0$ in the next switching cycle.

3 General snubber cell for DC/DC converters

The general passive lossless snubber cell is designed to suppress the turn-on switching loss resulting from the reverse recovery process of the freewheeling diode. It
follows that the proposed snubber can be generalised to support other basic DC/DC converters which suffer from the same switching loss. A general snubber cell is defined and shown in Fig. 7. Nodes $A$ and $K$ are connected to the anode and the cathode of the converter freewheeling diode $D_1$, respectively. Node $A'$ is connected to the component that was connected to the anode of $D_1$ in the original circuit.

The general snubber cell consists of one inductor $L_s$, one capacitor $C_s$, and two diodes $D_2$ and $D_3$. The snubber inductor $L_s$ is placed in series with the freewheeling diode $D_1$ to restrict the growth rate of the reverse recovery current when the switch turns on. After the turn-on transient, $I_{ss}, D_3$ and $C_s$ form a resonance path to transfer the absorbed energy from $L_s$ to $C_s$. Energy stored in $C_s$ is delivered to the output through $D_3$ after the switch turns off. $D_3$ is turned off and $D_2$ is turned on after $V_{CS}$ is discharged to zero.

Snubber operation principles discussed in the boost converter example can be extended to other topologies. Six basic DC/DC converters are shown in Figs. 8–10 with the proposed snubber cells embedded.

4 Experimental results

4.1 Design example

The snubber inductor $L_s$ and snubber capacitor $C_s$ are the two main elements to be designed. In Stage 4, diode $D_2$ should be automatically turned off before the voltage of $C_s$ is discharged to zero, or the residual current through $D_2$ will turn on $D_1$ and $D_3$ for the whole switching period. In other words, $I_{ss}$ should be greater than $I_F$ according to eqn. 9. Snubber inductor $L_s$ should be as large as possible to decrease the reverse recovery loss, but $I_s$ should be kept larger than $I_F$. $L_s$ can be determined by the following procedures.

Step 1: determine reverse recovery current peak value $I_{ss}$

The drain current of the MOSFET will have a transitional peak value equal to $I_F + I_{ss}$. $I_{ss}$ can be determined by setting the peak value of the drain current and then subtracting $I_F$.

Step 2: calculate reverse current slope $dI_R/dt$

$I_{ss}$ has the following relationship [4]:

$$I_{ss} \propto \sqrt{I_F \frac{dI_R}{dt}}$$

(12)

$I_{ss}$ for specified $I_F$ and $dI_R/dt$ can be found in a data book. The reverse current slope $dI_R/dt$ can be obtained by using $I_F$ and $I_{ss}$ calculated in Step 1 in eqn. 12.

Step 3: determine snubber inductor $L_s$

The equation $V = L_s (dI_R/dt)$ is used to determine $L_s$, where $V$ is the output voltage and $I_R$ is the current through $D_1$ as well as $L_s$, $L_s$ can be determined by

$$L_s = \frac{V}{\frac{dI_R}{dt}}$$

(13)
The voltage rating of $D_1$ is equal to the output voltage plus $V_{CS}$. The snubber capacitor $C_s$ should be as small as possible to reduce the resonant period and to prevent an excessively high voltage rating of $D_1$. The recommended value of $V_{CS}$ is $50 \sim 100$V and $C_s$ can be determined by eqn. 8.

Table 1: Part list of the implemented prototype power circuit

<table>
<thead>
<tr>
<th>Part</th>
<th>Type</th>
<th>Part</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>IRFP460</td>
<td>$L_p$</td>
<td>2$\mu$H</td>
</tr>
<tr>
<td>$D_1$</td>
<td>HFA15TB60</td>
<td>$C_s$</td>
<td>100nF</td>
</tr>
<tr>
<td>$D_2$</td>
<td>HFA15TB60</td>
<td>$L$</td>
<td>180$\mu$H</td>
</tr>
<tr>
<td>$D_3$</td>
<td>HFA15TB60</td>
<td>$C$</td>
<td>940$\mu$F</td>
</tr>
</tbody>
</table>

Fig. 11  Simplified circuit of implemented prototype

Fig. 12  Waveforms of snubber inductor current and snubber capacitor voltage
\[ a \] Experimental results
\[ b \] Simulation results

4.2 Experimental waveforms

To experimentally verify the principle of operation and the theoretical analysis, a prototype of 1kW, 100kHz boost converter with the passive lossless snubber is implemented. Control strategy is implemented with a L4981A. This prototype is regulated at 400V DC output with 220V AC input. A simplified circuit of the implemented prototype is shown in Fig. 11, with the components specifications listed in Table 1.

The snubber inductor current and snubber capacitor voltage waveforms are shown in Fig. 12a, and PSPICE simulation results are shown in Fig. 12b. The waveforms in Fig. 12 can be collated with those of $V_{CS}$ and $I_{Lp}$ in Fig. 6a.

Fig. 13  Waveforms of MOSFET commutation with the proposed snubber
\[ a \] Experimental results
\[ b \] Simulation results

Fig. 14  Waveforms of MOSFET commutation without snubber
\[ a \] Experimental results
\[ b \] Simulation results

The commutation waveforms of the MOSFET with the proposed snubber are shown in Fig. 13a, and PSPICE simulation results are shown in Fig. 13b. Counterparts without the snubber are shown in Fig. 14a and b, respectively, to contrast with Fig. 13. It is easily seen that the turn-on loss is apparently reduced and the MOSFET commutates near the ZCS (zero-current-switch). The reason for the ZCS is the discharge of the parasitic drain-source capacitance of the MOSFET during the turn-on process. This switching loss can only be removed by resonant converter techniques or active snubbers. It can also be seen that the growth rate of the drain current is effectively eliminated. EMI noises are reduced due to the slower $\frac{\text{di}}{\text{dt}}$ of drain current. Efficiency of 97% at 1kW loading has been measured by the Volttech PM3000A.

5 Conclusion

A general passive lossless snubber cell for DC/DC converters has been proposed. The general snubber cell is composed of only one inductor, one capacitor and two diodes. The cell is designed to suppress turn-on switching losses caused by the reverse recovery current of the freewheeling diode. Steady-state circuit operations of a boost circuit with the proposed snubber have been analysed. Experimental waveforms of the MOSFET commutation show that the snubber can effectively suppress the reverse recovery loss and eliminate the $\frac{\text{di}}{\text{dt}}$ of the drain current. The snubber inductor and capacitor for the boost topology can be precisely determined by the presented design. The circuit operation analysis and design rules are also valid when applying the snubber to other topologies.

6 References

1 PIETKIEWICZ, A., and TOLLIK, D.: 'Snubber circuit and Mosfet paralleling considerations for high power boost-based power-factor correctors'. INTELEC '95, pp. 41-45