A Lossless Snubber for DC/DC Converters and Its Application in PFC

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Abstract-*A passive lossless snubber is proposed in this paper to reduce switching losses and EMI noise by restricting di/dt and dv/dt of the switching device . As an example, a boost convertor with the lossless snubber is presented to illustrate the operation principle and theoretical analysis in details. Six basic DC/DC convertor topologies equipped with the proposed snubber are also shown in this paper. A 5kW power factor correction (PFC) prototype with the snubber is designed to show the advantage of the snubber. Both of simulative and experimental results are given .*

Key word: DC/DC convertor, passive lossless snubber, power factor correction (PFC)

1. Introduction

Pulsed width modulated (PWM) DC/DC convertor has been widely used for its high power capability and ease of control. Smaller boost inductor and filter capacitor could be achieved by increasing the switching frequency. However, with the increase of the switching frequency, so do the switching loss and EMI noise [1,2].

Switching losses and EMI noise are mainly generated in the turn-on and turn-off moment. Turn-on loss is mainly caused by reverse-recovery current of the freewheeling diode and large di/dt noise is also brought about. On the other hand, the turn-off loss is mainly caused by the fast increase of the voltage of the switching device and large dv/dt noise is brought about too.

Several methods were proposed to deal with the problem mentioned above. But most of them had to use an auxiliary switch to make the main switching device working in resonant switching mode. It may bring about other problems such as complicated circuit configuration, complex controlling method, higher current or voltage stress and lower reliability.

In this paper a passive snubber, which is as simple as a RCD snubber, is used in a boost convertor (shown in Fig.1). With this snubber, the turn-on di/dt was restrained by the small inductor in series with T and the turn-off dv/dt was restrained by the capacitor in parallel with T. Simple configuration, high performance, low cost and high reliability are the distinct advantages of this passive lossless snubber.

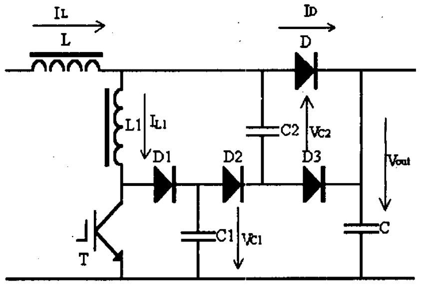


Fig.1 The boost convertor with lossless snubber

2. Principle of Operation

The boost DC/DC convertor is shown in Fig.1. L, T, D and C built up the main circuit, and C1, C2, L1, D1, D2 and D3 composed of the snubber circuit. T is working in high-frequency PWM mode.

Because the output capacitor and the inductor are very large and transferring time is very short, we can assume that the current of L1 and the output voltage are constant in the transferring process. The working principle and working circuit are shown in Fig.2 and Fig.3 respectively. In order to show the turn-on and turn-off moment more distinct, it was magnified compared to the really working time.

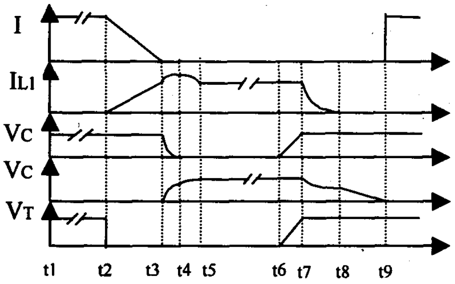


Fig.2 The working principle

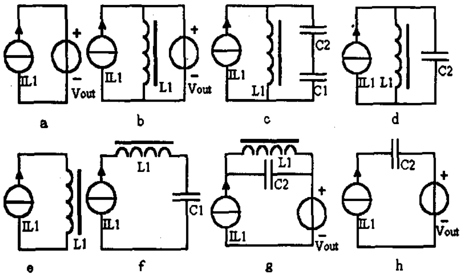


Fig.3 The working circuit

At stage 1($t1 \leq t \leq t2$), D conducts and T is turnoff (shown in Fig.3.a). The current of inductor L(I_L) flows through D. The voltage of C1(V_{C1}) and the voltage of C2(V_{C2}) equal to Vout and 0 respectively.

At stage 2($t2 \leq t \leq t3$), T is turned on and the current of the inductor L1(i_{L1}) increases linearly (shown in Fig.3.b). V_{C1} and V_{C2} keep constant.

At stage 3($t3 \leq t \leq t4$), D ends conducting and recovered its blocking characteristic(shown in Fig.3.c). D2 begins to conduct, so C1, C2 and L1 resonate through T and D2. V_{C1} decreases and V_{C2} increases.

At stage 4($t4 \leq t \leq t5$), when V_{C1} is equal to 0, D1 begins to conducts, so L1 and C2 resonate through D1, D2 (shown in Fig.3.d). V_{C2} still increases with the decrease of i_{L1}.

At stage 5($t5 \leq t \leq t6$), when I_{L1} is equal to I_L again, the turn-on transferring process is ended and V_{C1} and V_{C2} keep constant(shown in Fig.3.e). The circuit works as a common boost circuit.

At stage 6($t6 \leq t \leq t7$), T is turned off and D1 begins to conduct (shown in Fig.3.f), and the voltage of C1 increases linearly.

At stage 7($t7 \leq t \leq t8$), when Vc1 is equal to Vout, D2 and D3 begin to conduct, so L1 and C2 resonate through D1 (shown in Fig.3.g). V_{C1} and i_{L1} decrease simultaneously.

At stage 8($t8 \leq t \leq t9$), when i_{L1} is equal to 0, both of D1 and D2 end conducting and C2 discharged linearly (shown in Fig.3.h). Until V_{C2} equals to 0, D begins to conduct.

The turn-on di/dt stress and turn-off dv/dt stress are restrained by L1 and C1 respectively, so the switching loss and EMI noise are greatly reduced. At the turn-on process, the energy of C1 transferred to C2, and at the turn-off process the energy of C2 and L1 transferred to the load. So this kind of snubber circuit is lossless, and the efficiency is very high.

3. Parameter Selection of Snubber Circuit

To prevent the reverse-recovery current, the current increasing time of L1 should be longer than the diode reverse-recovery time, so the value of L1 is determined by equation below.

$$L1 \geq Vout / trr \qquad (1)$$

And with the inductance increasing, the turn-on loss decreased, but it may lead to the duty loss problem of booster. According to the custom, the resonant perimeter should be less than one tenth of the working perimeter. Because the value of C2 is much larger than that of C1, the resonant premeter is mainly deterimated by L1 and C2.

$$2\pi\sqrt{L1\bullet C2}\le T/10 \qquad (2)$$

In the stage (g), the current of L1 should decrease to 0 before the voltage of C2 does. In that situation, the current of L1:

$$i = I_L - V_{C2}\sin\omega t/\omega L1 \qquad (3)$$

So $$V_{C2}\ge I_L\bullet\omega L_1 \qquad (4)$$

The value of C2 should be much larger than that of C1.In the process of T turning on, the energy of C1 transferred to C2,

$$v_{c2} = v_{c1}\sqrt{C_1/C_2} \qquad (5)$$

and in the stage (d), the voltage added to D equivalent to the sum of output voltage and the voltage of C2. Therefore, the larger value of C2 is, the less voltage stress of D is. But it may lead to the problem such as long switching transient time and large transient current of T.

The larger C1 can decrease the turned-off loss of T. But too large capacitance can decrease the ratio between C1 and C2, and the voltage of C2 maybe too high.

The parameter of the snubber can be caculated from those equation. The parameter of the D1, D2, D3 is selected mainly concerning with the dynamic performance and the capability of surge current . Because they only conduct in the short turn-on and turn-off process, and the avergy current is very low, we can choose the diode in low rated voltage and current.

4. Simulative Results

We use the Pspice to simulate the circuit proposed above, and the simulative results were shown below.

The waveform, which is shown in Fig.4, is the turn-on process of T without snubber. Because of the diode reverse recovery, a large peak current (in the bottom) flows through T before the voltage (in the top) drops to 0. So the switching loss is very high and the large di/dt can bring about serious EMI noise.

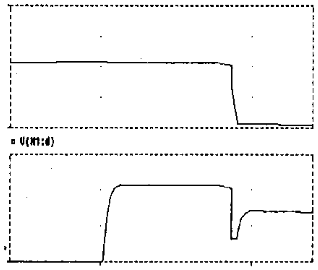


Fig.4 The turn-on process of T
(without snubber)
(Top: the voltage of T, bottom: the current of T)
(u: 500V/div, i: 50A/div, t:100ns/div)

Fig.5 shows the turn-on process of T using the lossless snubber. The voltage (in the bottom) of T drops quickly when the triggering pulse added to T (in the middle), but the current (in the top) of T rises slowly, so the turn-on loss is very low and di/dt noise is small. T is working in the zero-current turn-on mode, and D is working in the zero-current turn-off mode.

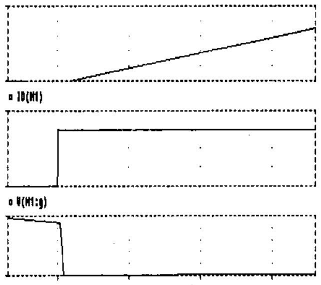


Fig.5 The turn-on process of T
(using the lossless snubber)
(Top: the current of T, middle: the trigger pulse of T,
bottom: the voltage of T)
(i: 50A/div, u1: 20V/div,u2: 500V/div,t:100ns/div)

Fig.6 shows the turn-off process of T. When T is turned off, the voltage of T (in the bottom) rises slowly, but the current of T (in the top) is removed quickly, so the turn-off loss is very low and dv/dt noise is small. T is working near the zero-voltage turn-off mode, and D is working in the zero-voltage turn-on mode.

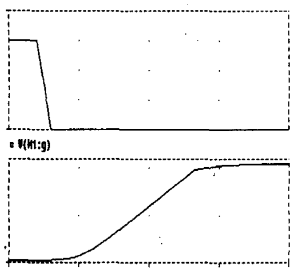


Fig.6 The turn-off process of T

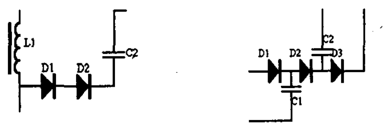
(Top: the voltage of T, bottom: the current of T)

(u1: 500V/div,i: 50A/div, t:100ns/div)

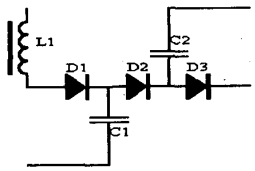
5.Generic Snubber for six kinds of basic DC/DC Convertors

The lossless snubber circuit can be divided to two parts, turn-on and turn-off snubber (showing in Fig.7(a) and Fig.7(b) respectively). Both of them have a capacitor and a current loop to transfer the energy stored in the inductor or capacitor of the snubber.

In the turn-on moment, an inductor in series with switching device to restrain the turn-on di/dt stress and a capacitor in parallel with the inductor to transfer the energy. In the turn-off moment, a capacitor in parallel with switching device to restrain the turn-off du/dt stress and a capacitor in series with the capacitor to transfer the energy. So a whole snubber is shown in Fig.7(c).



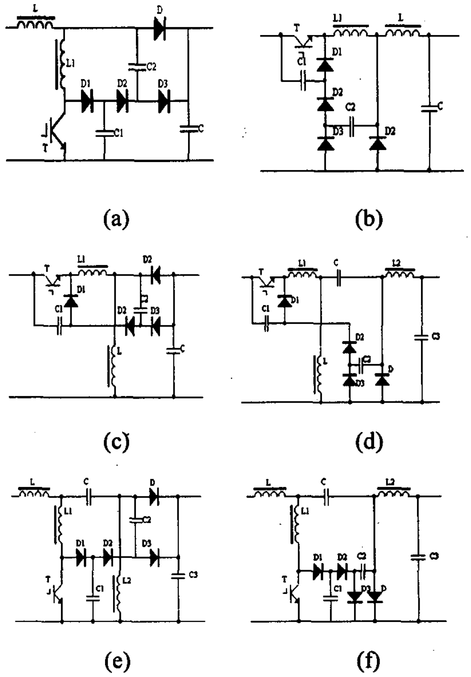
(a)Turn-on snubber (b) Turn-off snubber



(c) Turn-on and turn-off snubber

Fig.7 The lossless snubber cell

Using the general principle mentioned above, we can generalize the lossless snubber circuit of the boost convertor to other five kinds of basic DC/DC convertor. The topologies are shown in Fig.8, and the principle of operation is alike to the principle of the boost convertor analyzed above.



(a) (b)

(c) (d)

(e) (f)

Fig.8 Six basic DC/DC convertor topologies with the lossless snubber

(a) Boost (b) Buck (c) Boost-buck

(d) Zeta (e) Cuk (f) Sepic

6. Application in PFC and Experimental Results

In order to fit the standard of IEC552-2, high power rating switching power supply (SPS), uninterruptable power supply (UPS) must have PFC (power factor correction) circuit to improve their power factor [4]. A 5kW single-phase PFC AC-DC prototype using the snubber circuit mentioned above is designed, and its main circuit is shown in Fig 9.

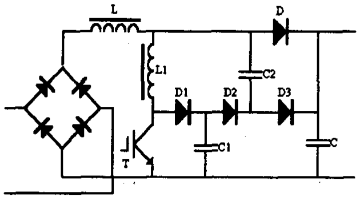


Fig.9 The PFC circuit with lossless snubber

Fig.10 shows the input current and voltage waveform of the prototype. In this prototype, the input current waveform is traced the input voltage waveform, so the PF is very high.

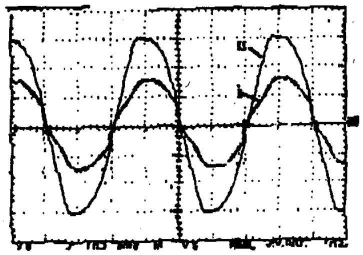


Fig.10 The input voltage and current (u: 100V/div, i: 20A/div, t:5ms/div)

Fig.11 shows the voltage waveform of the T and its triggering pulse waveform. When triggering pulse of T is removed, the voltage spike of T is very low. It is profitable for the IGBT to reduce the turn-off loss and to work in the safe operating area.

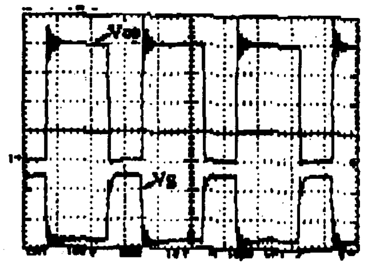


Fig.11 The voltage and the trigger of T (Vce:100V/div,Vg:10V/div,t:10 μ s/div)

Fig.12 shows the voltage and current waveform of T when it is triggered. Because the voltage of T is dropping steeply and the current rises slowly, the turn-on loss and di/dt noise are very low.

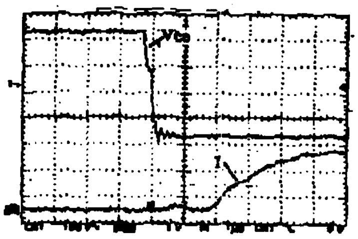


Fig.12 The voltage and current of T (Vce:100V/div,I:10A/div,t:1 μ s/div) (When T is turned on).

The efficiency of this set of AC/DC convertor was measured more than 94%. The experimental results testified the advantage of the lossless snubber such as high efficiency, low du/dt and di/dt noise and low turn-off voltage spike.

7. Conclusion

Both the simulative and the experimental results proved that the lossless snubber could lower the turn-on transient current stress of T, and reduce the switching loss effectively. So the efficiency of the equipment is very high and the switching frequency can be increased greatly, this would decrease the size of inductor and capacitance significantly. On the other hand, because the switching device operates at ZCS turn-on and close to ZVS turn-off, the EMI noise is greatly lowered.

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