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Enhanced switching characteristics of DC-DC boost converter systems

S. M. El-Ghanam[1], W. Abdel Basit[1]*, M. Ismail[1], S. A. Kamh[1], H. A. Ashry[2] and F. A. S. Soliman[3]

[1]Electronics Research Laboratory, Physics Department, Faculty of Women for Arts, Science and Education, Ain-Shams University, Heliopolis, Cairo, Egypt.
[2]National Center for Radiation Research and Technology, Atomic Energy Authority, Nasr City, Cairo, Egypt.
[3]Nuclear Materials Authority, P. O. Box 530, Maadi-11728, Cairo, Egypt.

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ABSTRACT

In this paper, improvement of the switching characteristics of DC-DC boost converters based on power bipolar junction transistor (BJT) against excessive rise rates of voltage (dv/dt) or current (di/dt) was investigated. Here, it was proven that, in the normal operation of the boost converter (for free running devices), signal voltage across the switch resonates at parasitic ringing frequency of 1.14 MHz during turn-off. Also, ringing signal frequency of 89.0 kHz superimposed the output current waveform was noticed during turn-on mode of operation. Thus, the paper was devoted in the design, analysis and applications of dissipative voltage and current – snubber circuits, as a trial to improve such systems. From which, it is shown that the snubber circuits successfully improve the noticed problems, where for the first case (dv/dt), the ringing frequency was decreased down to 0.20 MHz, while for the second case (di/dt), the ringing frequency was completely damped.

Keywords: DC-DC boost converter, dissipative voltage and current – snubber circuits.

*Corresponding author. E-mail: wafaazekri2006@yahoo.com. Tel: 002448083214, 0201226045431.

INTRODUCTION

Switch mode power supplies (SMPS) are popular because of higher efficiency, smaller size and lighter weight. It is one of the most popular power supplies used to supply various electronic and electrical devices. However, they also generate and emit unwanted electrical signal, electromagnetic interference (EMI noise), that can lead to performance degradation of SMPS and other nearby electrical/electronic equipments (Zare, 2011; Singh et al., 2012). High rates of dv/dt and parasitic capacitors are the reasons for common mode interference. The interference sources are coupled onto the power cable to the equipment. In addition, the interference may be coupled inductively or capacitive from another cable to the power cable (Lee, 2008).

The applications of DC-DC converters appear in a large number of modern electronic circuits and systems. But, switching losses are high due to operation of the converters in hard switching mode. For the advanced technologies, the power losses must be properly evaluated and measurements should be taken to reduce the losses effectively (Kumar et al., 2010).

Semiconductor power devices need snubber circuits because they have a limited safe operating area at turn-on and turn-off. The objective of a snubber circuit is to help the device during the switching transitions to survive the voltage and the current stresses. These stresses are due to the interruption of the current at turn-off and to the collapse of the voltage at turn-on (Al Hassan and Lanin, 2012). In this concern, snubber circuits are usually placed in the converter structure to adjust the turn-off and turn-on losses. Where, the turn-off snubber circuit (RC) is connected in parallel to limit the (dv/dt) at turn-off. The turn-on snubber circuit (RL) is connected in series to limit the di/dt at turn-on. The purpose of using snubber circuits is to (Kumar et al., 2010; U-Yaisom et al., 2002):

1) Limit rate of voltage rise across a switching device.
2) Limit rate of current rise through a switching device.

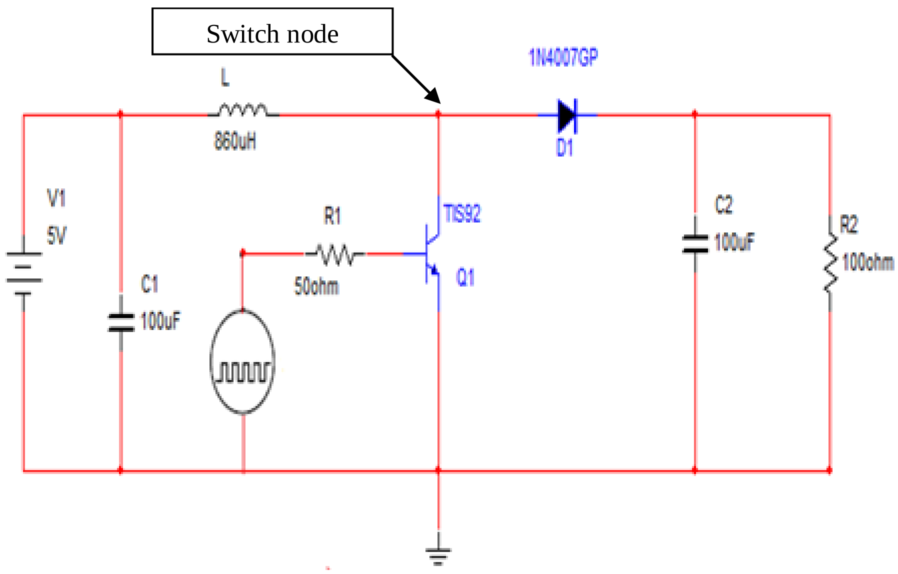

Figure 1. Boost converter circuit in normal operation.

3) Modify the switching trajectory.
4) Reduce EMI.

In this paper, the performance of one of the basic converter topologies, the boost converter, is investigated and analyzed in normal operation. Then, as a trial to improve their characteristics, turn-off (RC) snubber, and turn-on (RL) snubber circuits were designed, analyzed and introduced to the proposed circuits.

MULTI-SIM SIMULATION CIRCUIT

The simulation circuit of boost converter operated in discontinuous mode shown in Figure 1 was investigated. The circuit is commonly used for the conversion of an unregulated DC input into a controlled DC output, at a desired voltage. One of the methods for controlling the output voltage employs adjusting the switching frequency and the on-duration of the switch (Mohan et al., 2003). In this concern, a square wave pulse with amplitude of 20.0 V, duty cycle 50% and frequency 2.0 kHz was used as control signal to obtain desired DC output. The electrical stresses placed on power transistor switch in boost converter during turn-off and-on modes of operations were reduced by using voltage-and current-snubber circuits. Finally, the design procedures of the snubber circuits will be described in details.

RESULTS AND DISCUSSION

Dissipative voltage snubber

At the end of the switching period, when the current through the boost inductor (L) drops to zero (turn-off), the parasitic capacitance, dominated by the junction diode capacitance and the output capacitance (C_{oss}) of the boost BJT switch, resonates with the boost inductor (Zumbahlen, 2011; Application Report, 2006). In this concern, the scope trace of voltage waveform at switch node, with 10 µs/div time scale, is shown in Figure 2, where the voltage across the switch resonates at ringing frequency of 1.14 MHz. This ringing frequency can be minimized with the aid of a properly designed RC snubber circuit placed between the collector and the emitter of the switching transistor (Godse and Bakshi, 2009; Zhao and Chengbiao, 2011).

Design of dissipative voltage snubber circuit

In order to minimize the ringing frequency at the switch node, the following steps are followed (Application Report, 2006):

1. A shunt capacitor (C_{ADD}) is added across the collector-emitter terminals of BJT. Then, its value is to be adjusted until the frequency of the parasitic resonance is reduced to half its initial value, that is, 0.57 MHz (Figure 3), measured at C_{ADD} = 50 pF. From which, it could be concluded that adding a shunt capacitor having a value that equals three times the parasitic capacitance (C_{PAR}) reduces the ringing frequency to half its initial value (Chen, 2005).

Because the resonant frequency (f_{PAR}) of a parasitic LC circuit is inversely proportional to the square root of the LC product, the total circuit capacitance [C_{PAR} + C_{ADD}] is now 4 times its original value of parasitic capacitance. This is the minimum value for the capacitance that should

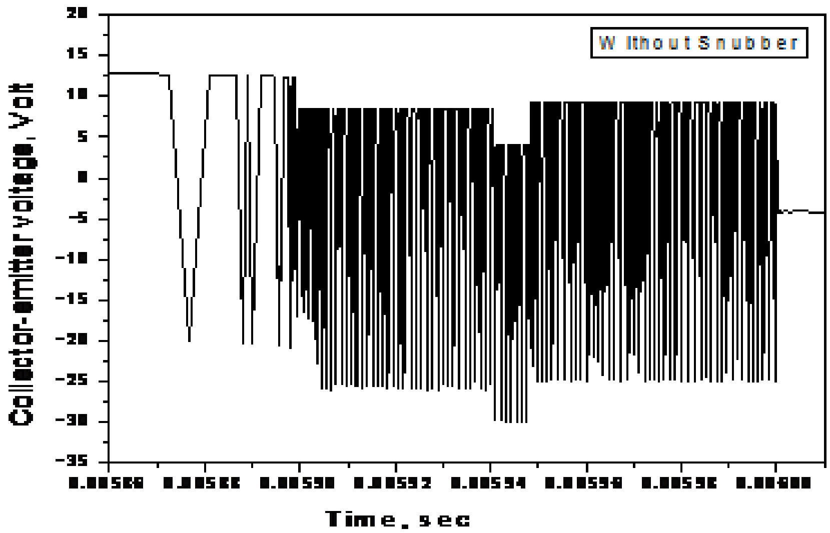

Figure 2. Traced waveform of the output voltage signal at switch node of boost converter without snubber.

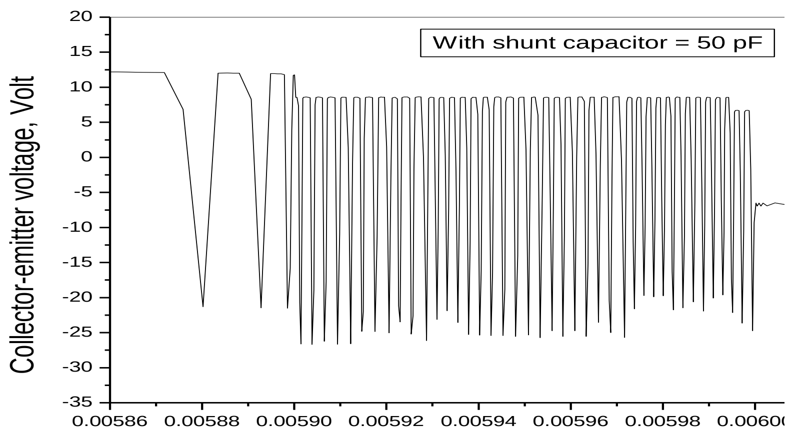

Figure 3. Traced output voltage signal at switch node of boost converter with 50 pF shunt capacitor.

be used for snubber capacitor (Brown, 1990).
Where, C_{ADD}= 50 pF

Then, $C_{PAR} = \frac{C_{ADD}}{3}$ = 16.6 pF (1)

2. The computed parasitic inductance (L_{PAR}) value, causing the ringing frequency equals 1.3 mH, is from the following formula:

$$L_{PAR} = \frac{1}{(2\pi\ f_{PAR})^{1/2} * C_{PAR}} \quad (2)$$

3. The optimal snubber resistor (R_{SNUB}) value is computed to be 9.4 kΩ using the formula:

$$R_{SNUB} = Z = \sqrt{\frac{L_{PAR}}{C_{PAR}}} \quad (3)$$

It is considered as the characteristic impedance of the original parasitic capacitance and inductance.

4. Snubber capacitor could be adjusted to be 50 times the value of the parasitic capacitance (C_{PAR}), that is, 800 pF to improve the ringing damping.

Finally, the boost converter circuit with RC snubber and scope trace of output voltage (at switch node), were illustrated in Figures 4 and 5. From which, it is clearly shown that parasitic ringing frequency was only greatly

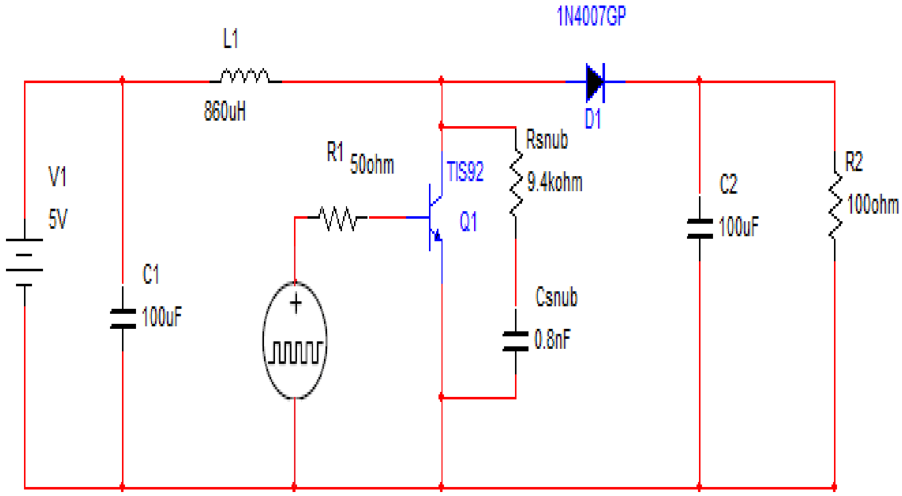

Figure 4. Boost converter circuit with parallel RC snubber circuit.

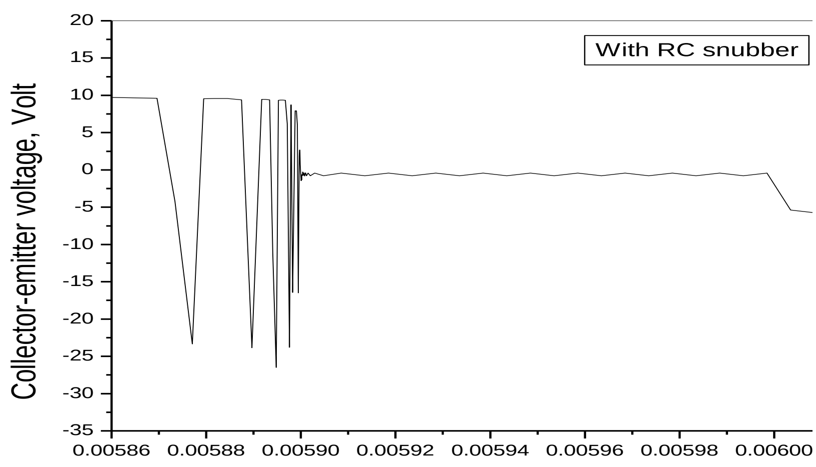

Figure 5. Traced output voltage signal at switch node with RC snubber.

damped from 1.14 MHz down to 0.2 MHz, while the voltage overshoot was not affected.

The input- and output–voltage signal traces of BJT switch were plotted as a function of time using 100 µs/div time scales without and with RC snubber as shown in Figures 6 and 7, respectively.

At this step, it is fairly to mention that a higher value of snubber resistor and a smaller value of snubber capacitor will decrease the power dissipation within the snubber, but the damping factor will worsen and the peak voltage of the spike will grow (Brown, 1990). Therefore, in the next section, a trail was carried out in order to introduce more improvement on the shape of output voltage waveform. This was carried out by means of decreasing R_{SNUB} value from 9.4 kΩ down to 100 Ω and by increasing C_{SNUB} value from 0.8 nF up to 3.0 µF.

The input- and output–voltage waveform traces of BJT switch with RC snubber circuit (R_{SNUB} = 100 Ω, C_{SNUB} =

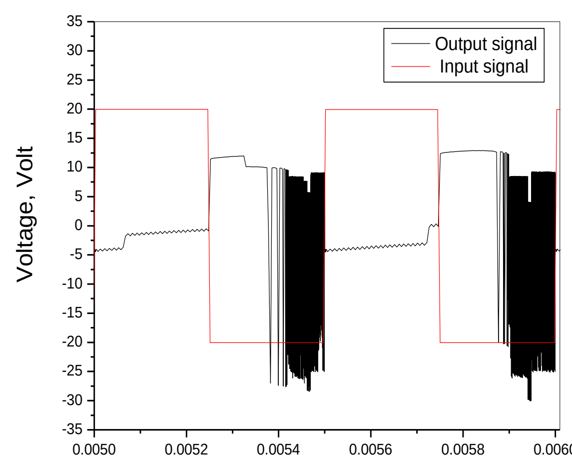

Figure 6. Traced input- and output-voltage signals of BJT switch without RC snubber.

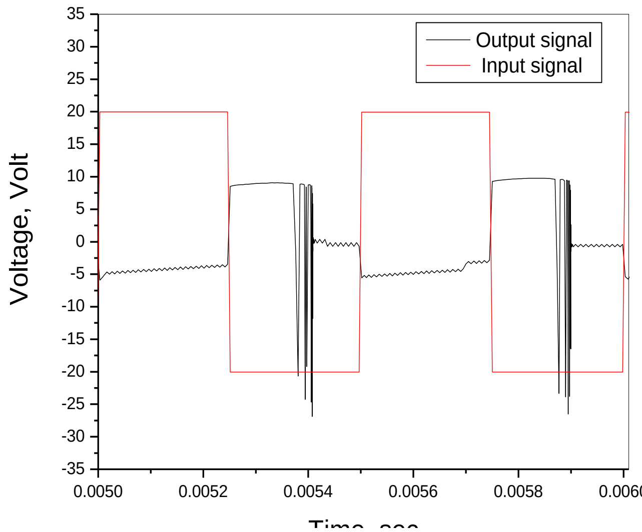

Figure 7. Traced input- and output- voltage signals of BJT switch with RC snubber.

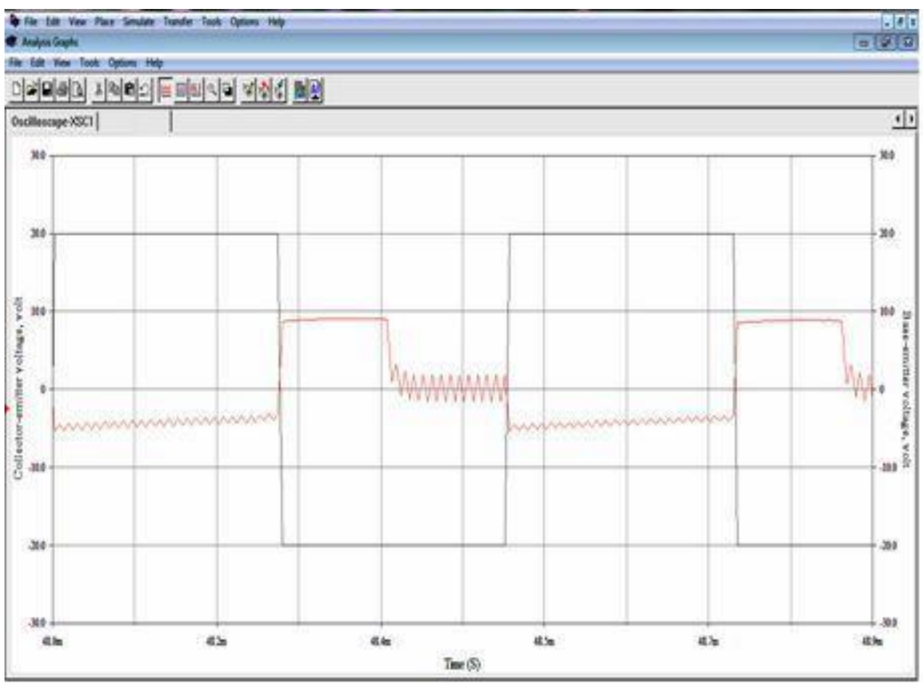

Figure 8. Traced input- and output- voltage signals of BJT switch with RC snubber.

3.0 µF) is shown in Figure 8. It is clearly shown that, peak voltage of spike was damped.

The power dissipation of the snubber resistor was calculated applying Equation 4. It is found that power dissipation increases from 1.30 mW up to 4.80 Watts due to the increase of C_{SNUB} value from 0.80 nF up to 3.0 µF.

$$P = f\,CV^2 \qquad (4)$$

where:
P: power dissipation; f: switch frequency; C: value of the snubber capacitor; V: voltage that the capacitor charges on each switching transition.

Dissipative current snubber

The purpose of the current snubber is to control the rate

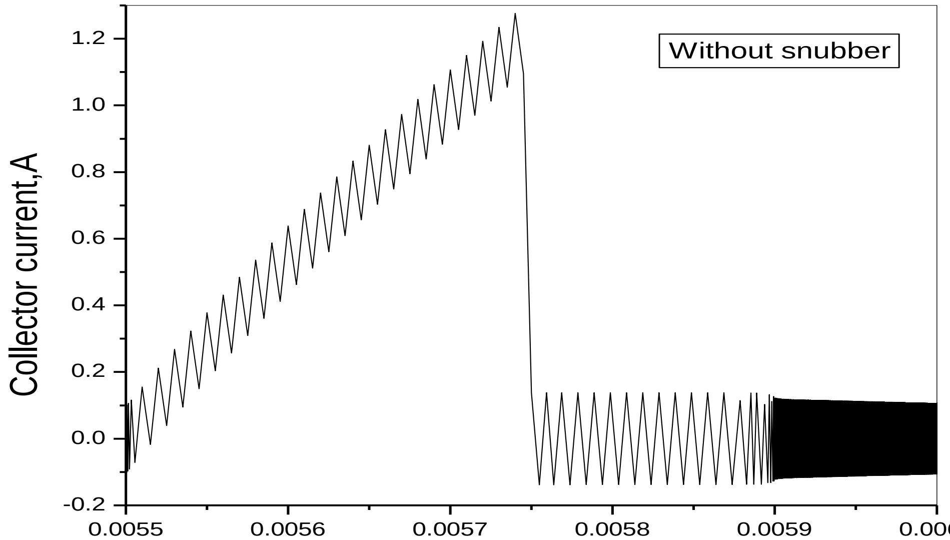

Figure 9. Ringing in current waveform, plotted at time scale of 50 µs/div.

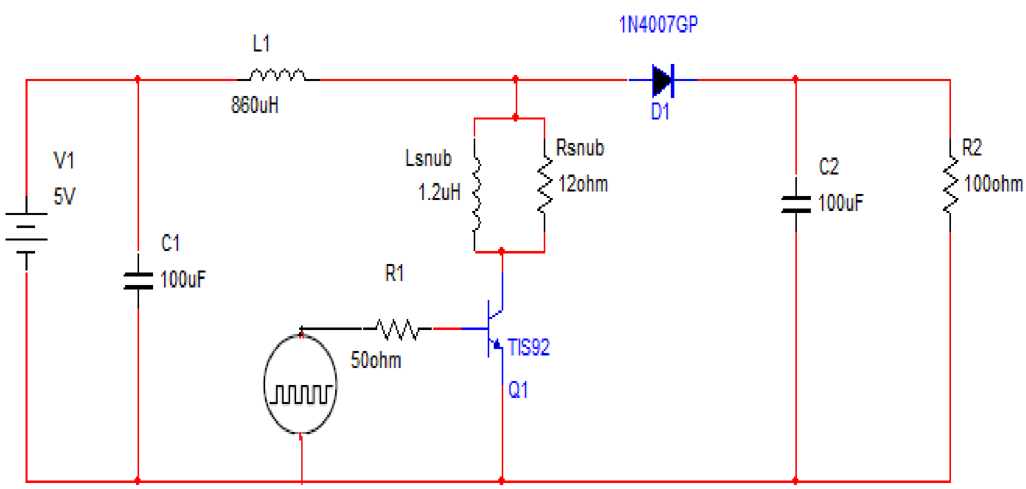

Figure 10. Boost converter circuit with series RL snubber circuit.

of current rise and the rate of current decrease (di/dt), as well as the over current. The inductance of RL snubber circuit allows the switch to be fully turned-on and the current reaches its operating value. This greatly reduces the peak power dissipation and the average dissipation in the switch and consequently increases its reliability (Todd, 2001).

In boost converter system, during turn-on a parasitic ringing with frequency of 89.0 kHz super imposed the collector current waveform is noticed (Figure 9). The matter is mainly due to the parasitic LC resonance in the switching loop. This ringing could be reduced by applying the current snubber circuit (R_{SNUB} – L_{SNUB}) as an inductive load of switch as shown in Figure 10.

The current snubber circuit elements could be calculated using the following equations (Alnasseir, 2007):

$$R_{SNUB} = \frac{\Delta V_{CE}}{I_o} \quad (5)$$

$$L_{SNUB} = \frac{\Delta V_{CE} t_{ri}}{I_o} \quad (6)$$

where V_{CE} is the collector-emitter voltage; t_{ri} is the current rise time; and I_o is the output current.

The values of V_{CE} and I_o could be measured using Figure 11 as follows: 5.0 V and 0.414 mA, respectively.

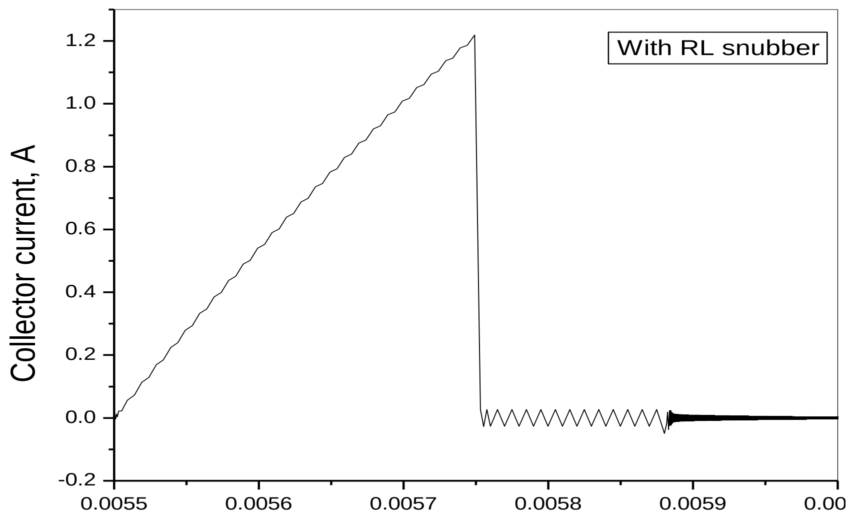

Figure 11. Current waveform with RL snubber, plotted at time scale 50 µs/div.

The current rise time (t_{ri}), taken from power BJT data sheet equals 0.10 µs. Therefore, the current snubber circuit elements (R_{SNUB} and L_{SNUB}) are determined using Equations 5 and 6 as follows: 12 Ω and 1.20 µH, respectively. The output current waveform of switch after applying current snubber is shown in Figure 11. It is clearly shown that parasitic ringing frequency in current waveform was greatly damped.

CONCLUSION

Protection and improvement of DC-DC boost converters were proved within the text, where excessive rates of either the voltage (dv/dt) or the current (di/dt) was successfully damped applying dissipative snubbers. Finally, the paper presents a simple design method of the proposed two snubbers.

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