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A new lossless snubber for DC-DC converters with energy transfer capability

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Abstract. In this paper, a new passive lossless snubber circuit with energy transfer capability is proposed. The proposed lossless snubber circuit provides Zero-Current Switching (ZCS) condition for turn-on instants and Zero-Voltage Switching (ZVS) condition for turn-off instants. In addition, its diodes operate under soft switching condition. Therefore, no significant switching losses occur in the converter. Since the energy of the snubber circuit is transferred to the output, there are no significant conduction losses. The proposed snubber circuit can be applied on isolated and non-isolated converters. To verify the operation of the snubber circuit, a boost converter using the proposed snubber is implemented at 70W. Also, the measured conducted Efficiency Electromagnetic Interference (EMI) of the proposed boost converter and conventional ones are presented which show the effects of proposed snubber on EMI reduction. The experimental results confirm the presented theoretical analysis.

Keywords: lossless passive snubber; proposed converter; soft switching; zero-current switching (ZCS); zero-voltage switching (ZVS); Efficiency electromagnetic interference (EMI)

1. Introduction

Today, power electronic circuits have been used vastly in industries. One of the great challenges of these circuits is to increase their power density which is achieved by increasing the switching frequency. However, increasing the switching frequency leads to an increase in the switching losses and consequently results in a reduction in the efficiency and reliability. To this end, the use of soft switching techniques has been more considered (Bilgin *et al*. 2003, Amini and Farzanehfard 2009, Maghareh *et al*. 2018, Salehi *et al*. 2015, Mahendran and Ramabadran 2017). One of the techniques is to apply the lossless nubber circuits (Li and Chung 2010, Khalilian *et al*. 2014, Mohammadi *et al*. 2015, Mohammadi and Ordonez 2015). The lossless snubber circuits are divided into two main active and passive categories. The active snubbers have an additional switch in their circuit. Active clamp circuit is an active snubber which has low count elements and provides ZVS conditions for all switches. Hence, the main disadvantages of this circuit increases duty cycle loss that causes to increase conduction losses (Acik and Çadirci 2002, Wu *et al*. 2008, Igarashi 2018).

Li and Ho (2015) proposed a new active snubber in which the main switch operates under ZVS conditions and the auxiliary switch is turned on and off under ZCS conditions. The snubber circuit can be applied to the interleaved structure, but the circuit has high duty cycle loss and complex operation.

In the present paper, a new passive lossless snubber is proposed in which the energy is transferred to the output. The proposed snubber provides ZCS condition for turn-on and ZVS condition for turn-off instants of the switch. It should be noted that its diodes operate under soft switching condition. Therefore, no significant switching losses occur in the converter leads to an increase in the efficiency. In addition, the proposed snubber decrease conducted EMI. EMI peak for the proposed boost converter shows a decrease of 13 dBμVin comparison with the conventional ones.

2. Principles of proposed converter operation

2.1 Circuit description

The proposed snubber consists of two resonant capacitors (C_1,C_2), one resonant inductor (L_r), four diodes (D_1-D_4) and three coupled inductors(L_1-L_3).The schematic of the boost converter with the proposed snubber is shown in Fig. 1.

At turn-off instant, the snubber capacitors (C_1,C_2) create ZVS conditions for the switch and are charged to $V_O/2$. Due to the leakage of L_r, the capacitors C_1 and C_2 must be discharged at ZVS conditions. The switch S is turned on when the capacitors C_1 and C_2 transfer their energy to L_1 and L_2 inductors. This energy remains in inductors as long as the S-switch is off. For simplicity of the converter analysis, the following assumptions are considered:

(1) All elements are ideal.
(2) L_1 and L_2 are equal ($L_1 = L_2 = L$).
(3) C_1 and C_2 are equal ($C_1 = C_2 = C$).

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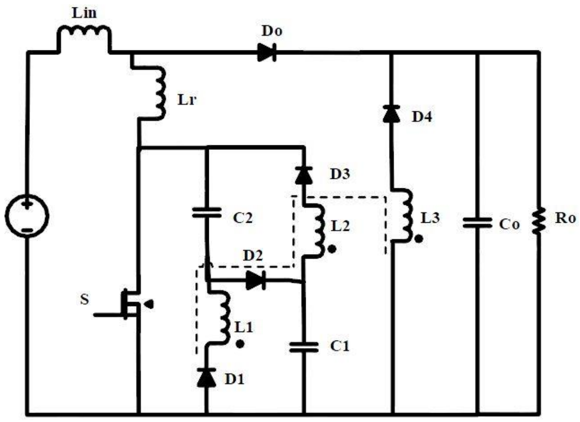


Fig. 1 The boost converter with proposed snubber

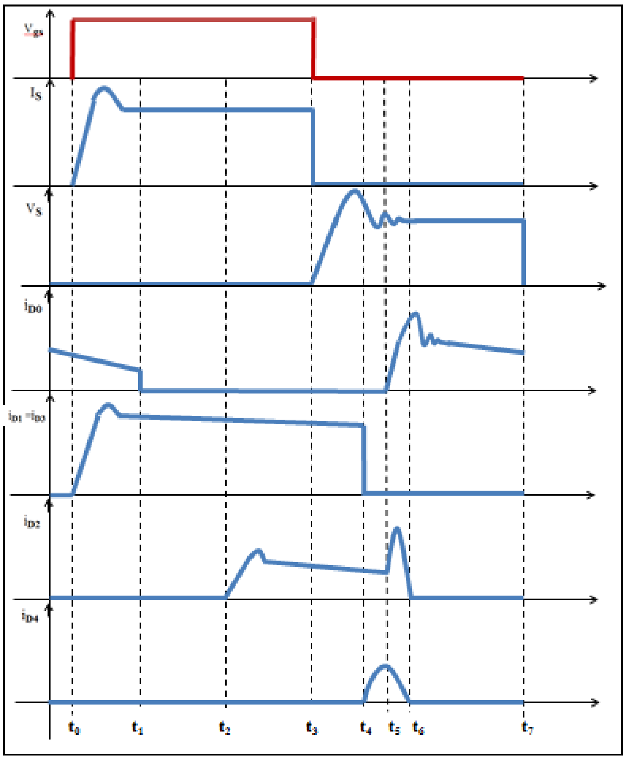


Fig. 2 Key waveforms of the proposed converter

(4) The turn ratio between L and L_3 is $n = \sqrt{L/L_3}$.

(5) L_{in} and C_o are large and therefore, the input current and output voltage are constant in the cycle.

The proposed boost converter has seven modes in the switching cycle. The key waveforms of the proposed converter are shown in Fig. 2. D_o is on before mode 1 and the other semiconductor elements are off.

2.2 The proposed circuit operation

Mode 1: $t_0 < t < t_1$

In this mode, the switch is turned on under the ZCS conditions because of series inductor L_r. Since the output voltage is placed across the L_r, its current increases linearly and D_o current decreases with the same slope simultaneously. Also, D_1 and D_2 turn on under ZCS conditions and a resonance occurs between C_1, C_2, L_1 and L_2. Therefore, C_1 and C_2 voltages reduce resonantly and L_1 and L_2 current increase according to the following equations

$$i_{L_r}(t) = \frac{V_O}{L_r}(t - t_0) \tag{1}$$

$$i_{L1}(t) = i_{L2}(t) = \frac{V_O}{2Z_0}\sin(\omega_0(t - t_0)) \tag{2}$$

$$V_{C1}(t) = V_{C2}(t) = \frac{V_O}{2}(1 - \cos(\omega_0(t - t_0))) \tag{3}$$

$$Z_0 = \sqrt{\frac{2L}{C}} \tag{4}$$

$$\omega_0 = \frac{1}{\sqrt{2LC}} \tag{5}$$

Mode 2: $t_1 < t < t_2$

This mode begins when L_r current reaches input current and D_o turns off under ZCS conditions. The resonance of

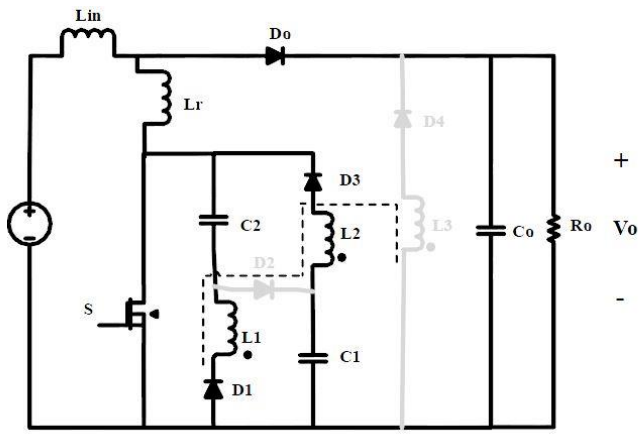


Fig. 3 The operation of the proposed circuit in the first Mode

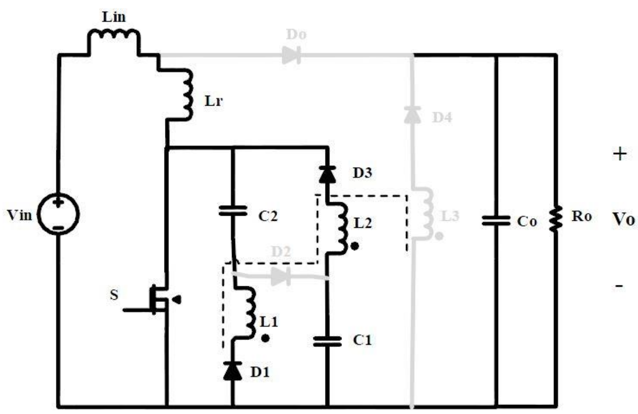


Fig. 4 The operation of the proposed circuit in the second Mode

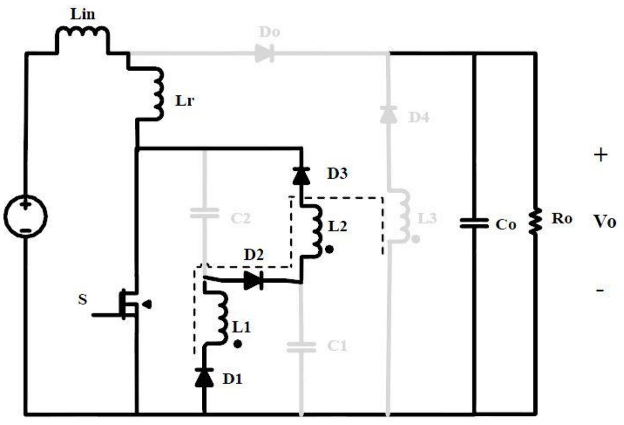


Fig. 5 The operation of the proposed circuit in the third Mode

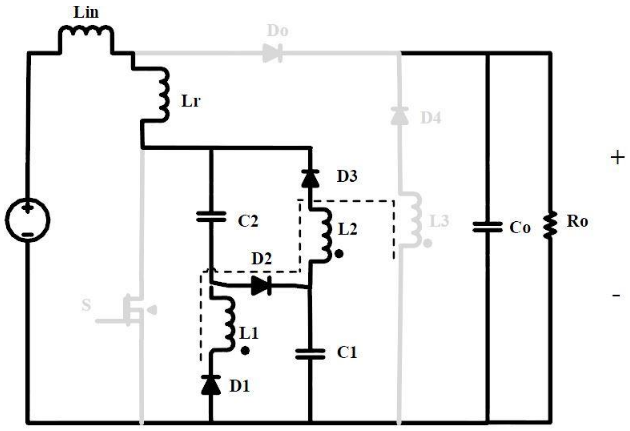


Fig. 6 The operation of the proposed circuit in the fourth Mode

the previous mode continues until capacitors C_1 and C_2 discharge. Eqs. (2) and (3) are also established in this mode.

Mode 3: $t_2 < t < t_3$

This mode begins when C_1 and C_2 are completely discharged and D_2 turns on. Therefore, L_1 and L_2 freewheel through D_1, D_2, D_3 and S. In addition, input inductor is charged linearly, similar to mode 2. This mode ends when switch is turned off.

$$i_{Lr}(t) = i_{Lin}(t) = i_{Lin}(t_I) + \frac{V_{in}}{L_{in} + L_r}(t - t_I) \tag{6}$$

$$i_S(t) = i_{Lr}(t - t_I) + \frac{V_0}{2Z_0}\sin\left(\omega_0(t - t_I)\right) \tag{7}$$

Mode 4: $t_3 < t < t_4$

In this mode, switch is turned off under ZVS conditions and C_1 and C_2 are charged. According to Eq. (8), the voltage relation of C_1 and C_2 consists oft wo terms. The first term is linear and the second one is resonance between L_1, L_2 and snubber capacitor. Since the input current is large and snubber capacitors are too small, the duration of this mode is very short. At the end of this mode, D_1 and D_3 turn off under ZVS conditions.

$$\begin{aligned} V_{C1}(t) &= V_{C2}(t) \\ &= \frac{I_{in}(t_3)}{C}(t - t_3) + i_L(t_3) Z_1 \sin(\omega_0\,(t - t_3)) \end{aligned} \tag{8}$$

$$Z_1 = \sqrt{\frac{2L}{C}} \tag{9}$$

Mode 5: $t_4 < t < t_5$

At the beginning of this mode, the voltages of capacitors (C_1 and C_2) reach n_1V_o. Therefore, D_4 conducts andD_1 and D_3 turn off under ZVS conditions and the storage energy in L_1 and L_2 is transferred to the output through the path L_3,D_4. Moreover, snubber capacitors continue to be charged by the input current. The following equation is true for snubber capacitor voltage.

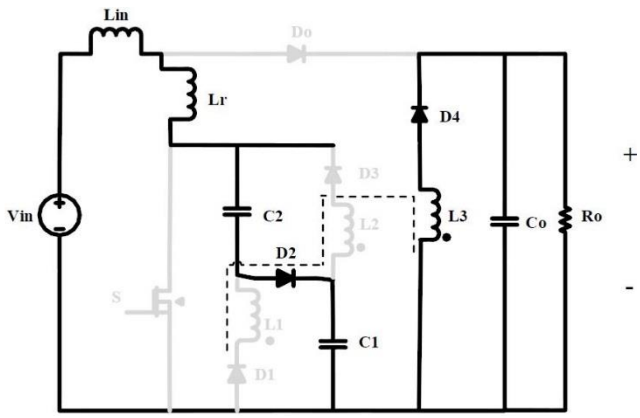


Fig. 7 The operation of the proposed circuit in the fifth Mode

$$V_{C1}(t) = V_{C2}(t) = V_C(t_4) + \frac{I_{in}}{C}(t - t_4) \tag{10}$$

Mode 6: $t_5 < t < t_6$

When the sum of the voltages of snubber capacitors reaches $V_0(1 + L_r/L_{in})$, output diode conducts and this mode begins. In this mode, L_{in} discharges linearly to the output and L_3 discharges to the output linearly with slope $-V_O/L_3$. Since L_r still has energy leads to aresonance between snubber capacitors and L_r. The important equations of this mode are presented as follows

$$i_{Lin}(t) = i_{Lin}(t_5) + \frac{V_{in} - V_O}{L_{in}}(t - t_5) \tag{11}$$

$$\begin{aligned} V_C(t) = V_O \cos(\omega_2(t - t_5)) \\ + i_{L_r}(t_5) Z_2 \sin(\omega_2\,(t - t_5)) \end{aligned} \tag{12}$$

$$Z_2 = \sqrt{\frac{2L_r}{C}} \tag{13}$$

$$\omega_2 = \sqrt{\frac{2}{C.L_r}} \tag{14}$$

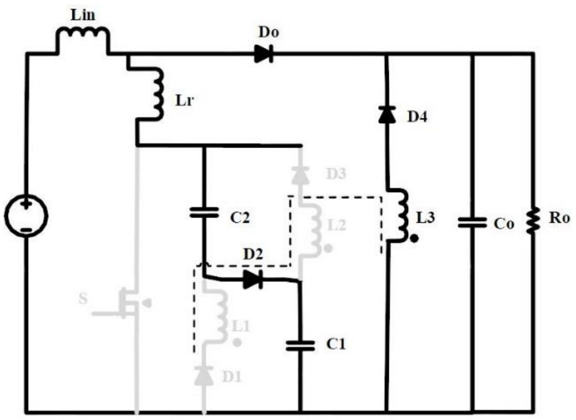


Fig. 8 The operation of the proposed circuit in the sixth Mode

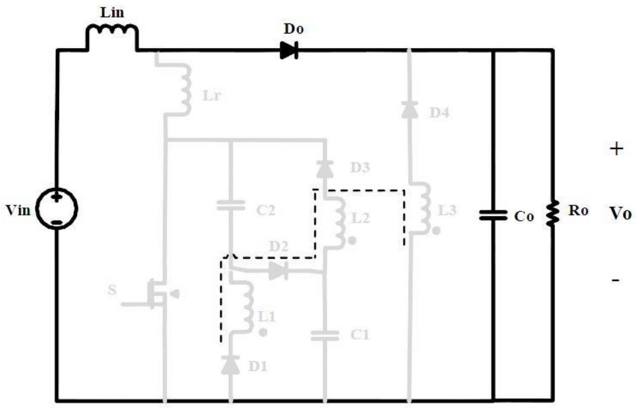


Fig. 9 The operation of the proposed circuit in the seventh Mode

Mode 7: $t_6 < t < t_7$

This mode begins when the current of L_r reaches zero and diode D_2 turns off under ZVS conditions. Moreover, L_3 discharges completely and D_4 turns off under ZCS conditions. Therefore, the proposed snubber circuit is removed from the converter and the proposed converter operates like conventional boost converters when the switch is off.

$$i_{Lin}(t) = i_{Lin}(t_6) + \frac{V_{in} - V_O}{L_{in}}(t - t_6) \tag{15}$$

$$i_{L_3}(t) = i_{L_3}(t_6) + \frac{-V_O}{L_3}(t - t_6) \tag{16}$$

Design procedure

Since the design of the proposed converter is the same as the conventional boost converters, the proposed lossless snubber should be designed only. At the first step, the snubber capacitor must be calculated. In order to create ZVS conditions for the switch, the snubber capacitors are chosen by using the following equation (Mohan *et al*. 2003)

$$C_1 = C_2 = C = \frac{i_{Lin}.t_f}{2V_{SW}} \tag{17}$$

Where t_f is the fall time of the switch and V_{SW} is the voltage of switch after it turns off.

To create ZCS conditions when the switch turn on, L_r should be designed according to the snubber inductors (Mohan *et al*. 2003)

$$L_r = \frac{V_{SW}.t_r}{I_{SW}} = \frac{V_O.t_r}{I_{in}} \tag{18}$$

where t_r is the rise time of the switch, I_{SW} is the current of switch after it turns on and V_{SW} is the voltage of the switch before it turns off. Under this condition, snubber capacitors must be discharged completely as long as the switch is on. Therefore, the occurrence time of the resonance in the first state is important.

As mentioned in the previous section, the voltages of snubber capacitors is zero after half cycle of resonant period between capacitors C_1 and C_2 and inductors L_1 and L_2. Therefore, this time should be less than the minimum of the switch on time ($D_{min}T_{sw}$), thus

$$\begin{gathered} C_1 = C_2 = C \\ L_{1,2} < \frac{D_{min}^2}{2\pi^2.C.f_{SW}{}^2} \end{gathered} \tag{19}$$

where D_{min} is the minimum value of the duty cycle.

The inductor L_3 delivers the storage energy in the core of the snubber windings to the output when the switch is off. According to the minimum time for discharging L_3 energy to the output, L_3 can be calculated using the following equation and inductor carries out this energy transfer and evacuates the energy in the core. Its amount is expressed as follows

$$L_3 < \frac{4}{f_{SW}{}^2.C} \tag{20}$$

3. Experimental results

In this section, the proposed converter is designed and made according to Table 1. Measured waveforms of the switch and diodes verify the theoretical analysis.

Table 1 Parameters of implemented converter

Element	Specification
L_{in}	400 µH
L_r	5 µH
$L_1 = L_2 = L$	10 µH
L_3	20 µH
$C_1 = C_2 = C$	4 nF
C_O	47 µF
All diodes	MUR 860
Switch	IRF 640
f_{SW}	100kHz
V_{in}	24V
V_{out}	44V

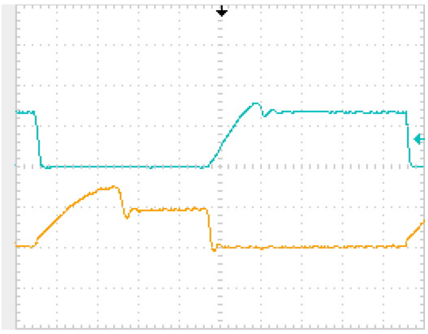


Fig. 10 Top: voltage wave form of converter switch (40 V/div); Bottom: current wave form of converter switch (2.5 A/div), (Time: 1 μs/div)

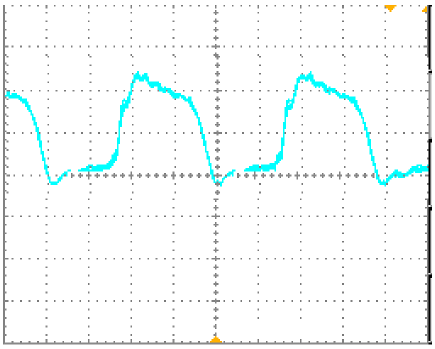


Fig. 11 Current wave form of diodeD1 in the proposed boost converter (250 mA/div), (Time: 2.5 μs/div)

Fig. 12 Current wave form of diode D_2 in the proposed boost converter (1 A/div), (Time: 2.5 μs/div)

The waveforms of the voltage and current of the switch are illustrated in Fig. 10.

As can be seen, the switch is turned on under ZCS condition due to the slope of the switch current. Also, the slope of the switch voltage when the switch turns off shows that it is turned off under ZVS condition. The current stress of the switch can be controlled by varying the resonant tank impedance according to Eq. (7). Thus, the switch current stress decreases by increasing Z_0. However, the leakage inductance of coupled inductance increases and causes to undesirable ringing across the switch and auxiliary diodes because of increasing snubber inductors (L_1, L_2).

The current waveforms of D1, D_2, and D_3 are presented in Figs. 11 to 13, respectively.

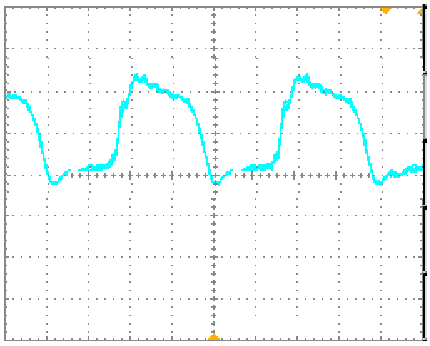


Fig. 13 Current waveform of diode D3 in proposed boost converter (250 mA/div), (Time: 2.5 μs/div)

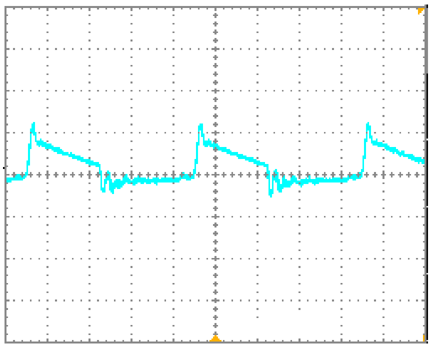


Fig. 14 Current waveform of diode DO in proposed boost converter (5 A/div), (Time: 2.5 μs/div)

As shown in these waveforms, the diodes current increases and then decreases with the slope and therefore ZCS conditions are provided for turn-on and turn-off states of diodes. So, reverse recovery problem does not exist in these diodes. Fig. 14 shows the current waveform of the output diode.

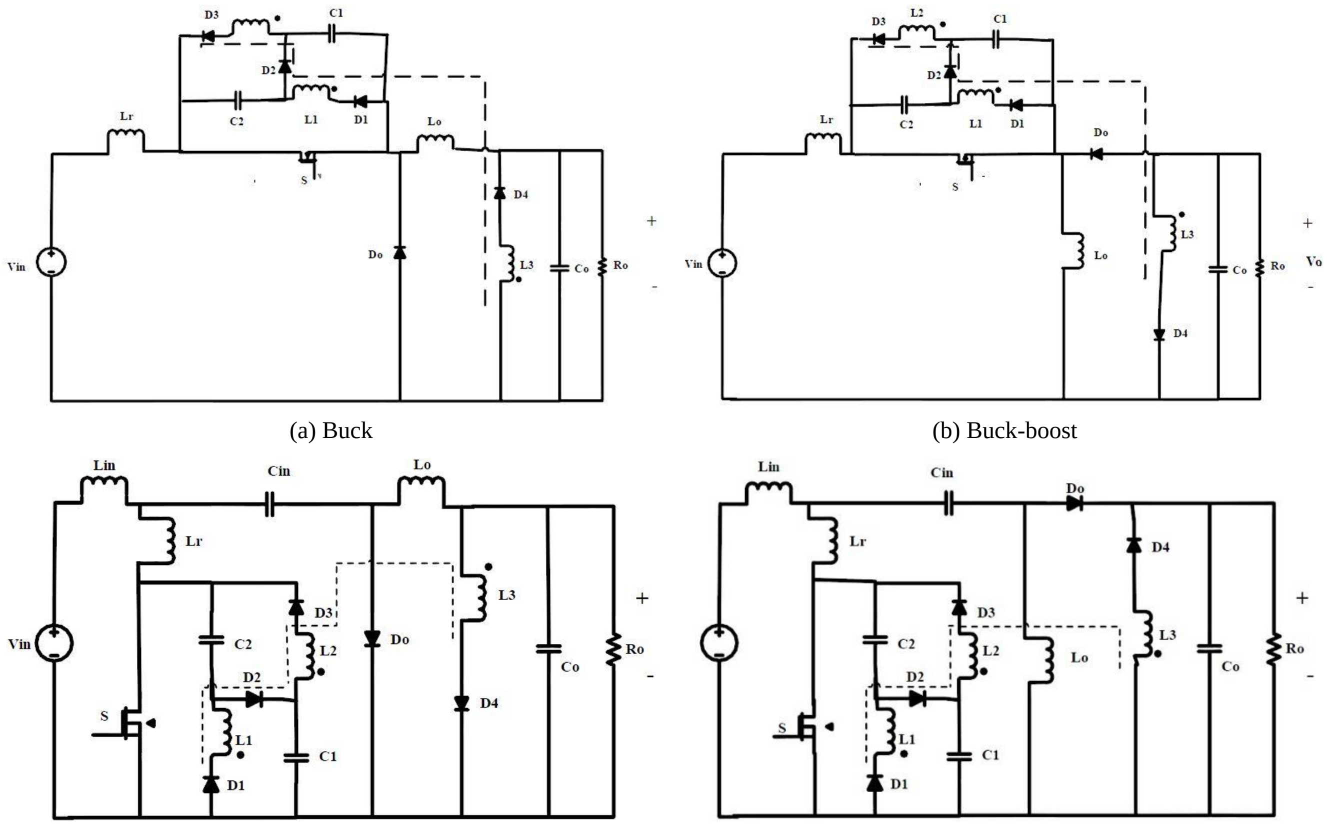
As can be seen in this figure, the output diode turns on and turns off under ZC Scondition due to the presence of L_r. Therefore, not only there are no switching losses in diodes, but also there is no reverse recovery problem.

4. The other soft switching converters with the proposed lossless snubber

Fig. 15 shows the buck, buck-boost, cuk, and sepic converter with proposed lossless snubber. The operation of these converters is the same as the proposed boost converter, which is analyzed in the previous section. The proposed lossless snubber can also be applied on isolated converter and the snubber can be absorbed the leakage inductances of transformer.

5. Comparison of proposed conveter conducted EMI with conventional ones

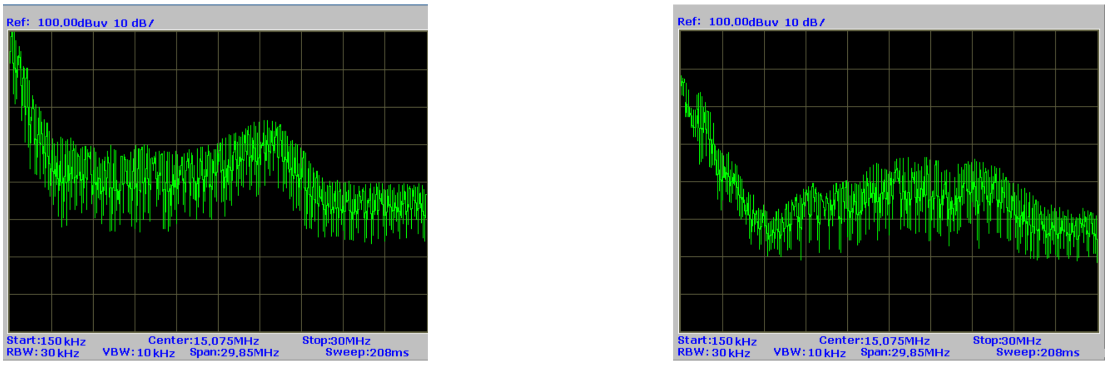
In this section, the measured conducted EMI of the proposed converter is compared to the conventional boost converter without snubber conducted EMI measured



(a) Buck (b) Buck-boost

(c) Cuk (d) Sepic

Fig. 15 The other soft switching converters with the proposed lossless snubber



(a) (b)

Fig. 16 Conducted EMI measurement. (a) hard-switching boost converter; (b) proposed boost converter; (Ver. axis: 20–100 dBμV; Hor.axis: 0.15–30 MHz)

according to the CISPR 22 standard. The line impedance stabilization network (LISN) is located between the input line and the converter and for displaying conducted EMI a Gw-Instek GSP380 spectrum analyzer is used (Yazdani *et al*. 2015, Ariyan and Yazdani 2017). The measured conducted EMI of the proposed converter and conventional boost converter is shown in Figs. 16(a) and (b), respectively. These figures show that the peak of conducted EMI for proposed boost converteris approximately 87 dBμV. In comparison with the conventional boost converter, a decrease of 13 dBμ Vindicates a better performance of the proposed converter.

6. Conclusions

In this paper, a new passive lossless snubber with energy transfer capability is proposed. The proposed snubber can be applied on isolated and non isolated single switch DC-DC converters and their switch operates under ZCS condition for turn-on instant and ZVS condition for turn-off one. The energy of the snubber is transferred to the output. Therefore, the efficiency of the converter increases. Since the proposed snubber does not have any extra switch, the implementation of control circuits is simple. Also, all diodes turn off under ZCS conditions and don’t exist reverse recovery problem subsequently. In addition, the proposed snubber decreases the conduction EMI. A 70W prototype of the boost converter is used to verify the proposed snubber with the theoretical analysis.

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