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에너지재생 수동스너버를 갖는 고역율 부스트 정류기

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High-Power-Factor Boost Rectifier with a Passive Energy Recovery Snubber

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Abstract

A passive energy recovery snubber for high-power-factor boost rectifier, in which the main switch is implemented with a MOSFET, is described in terms of the equivalent circuits that are operational during turn-on and turn-off sequences.

The main switch combined with proposed snubber can be turned on with zero current and turned off at limited voltage stress. The high-power-factor boost rectifier with proposed snubber is implemented, and the experimental results are presented to confirm the validity of proposed snubber.

I. Introduction

Snubbers are required to limit di/dt and dv/dt in the power semiconductor device, keep the device within its safe operating areas, and to reduce the switching power losses in the device. Conventional snubbers, which discharge via resistors, are simple to design and use, but the energy dissipated in the resistors is proportional to the switching frequency. Therefore, resistive snubbers are not practical at the high switching frequencies encountered in the modern power electronics system. In high frequency applications, it is necessary to use an energy recovery snubber to keep losses to a minimum, by regenerating the energy trapped in the snubber circuit back into the DC rail.

For the pulse-width-modulated(PWM) boost converter, several methods have been described to recover the trapped energy in the snubber circuit [1]-[4]. An active auxiliary switch is used in [1]-[2] to regenerate the trapped energy to DC output. The auxiliary switch also provides a soft switching for the main semiconductor switch. But, an additional control circuit is needed to drive the auxiliary switch. In [3], the trapped energy is transferred into the load through a DC/DC converter. This method could be expensive due to the energy recovery converter, as well as being more complex than other methods. A transformer may also be used as a passive element in an energy recovery circuit[4]. The turn-on snubber inductor is replaced with a transformer, so that the energy in the inductor is recovered into the output via the secondary winding of the transformer. The control circuit of this method is the same as that of the basic boost converter. However, the transformer for this snubber may be difficult to construct and the voltage on the main switching device may exceed the output voltage.

In this paper, the passive energy recovery snubber proposed in [5] is more elaborately described. The high-power-factor boost rectifier in combination with this snubber is implemented, and the experimental resuls are provided.

II. Operation Analysis of Boost Converter with Proposed Snubber

Fig. 1 shows the circuit diagram of proposed energy recovery snubber circuit for boost converter. Since the circuit uses a MOSFET for main switch, the purpose of turn-off snubber consisting of Cr and D2 is to clamp the voltage across this MOSFET [6]. When Q is turned on, the rate of rise of the forward current of Q is limited by the current limiting inductor Ls. When Q is turned off, the flow of current to the load is gradually changed from D2 to D1, and the snubber capacitor Cr is charged to its positive peak value. If Q is turned on again, the trapped energy in Cr is discharged through D3 and Lr, and the polarity of the capacitor energy is reversed. During the next turn-off transition period of Q, the snubber energy is recovered into the load through Cr-D2 path or D3-Lr-D2 path.

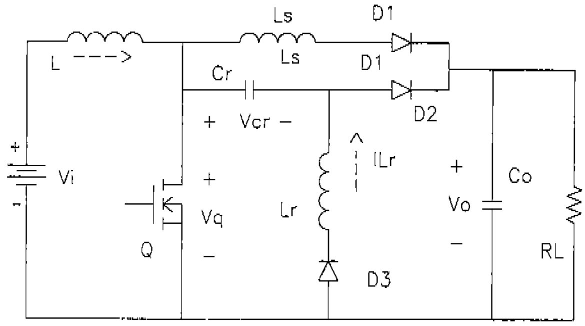


Fig. 1. Proposed boost converter circuit.

To simplify the analysis, the following assumptions are made :

1) input filter inductance is large so that I_L is constant,

2) output filter capacitance is large so that Vo is constant,

3) all semiconductor devices are ideal.

Furthermore, the following symbols are also defined :

$w_1 = 1/\sqrt{L_s C_r}$, $Z_1 = \sqrt{L_s/C_r}$,

T_{on} = turn-on period of Q, $w_2 = 1/\sqrt{L_r C_r}$,

$Z_2 = \sqrt{L_r/C_r}$.

Depending on the operating conditions, the proposed snubber circuit can be in Region-1 operation in which the variation of $w_2 T_{on}$ is in the range of above π, or in Region-2 opearation in which the variation of $w_2 T_{on}$ is in the range of between 0 and π. The theoretical waveforms of Fig. 1 for Region 1 and 2 are shown in Fig. 2 and Fig 3, respectively. The converter goes through different topological modes(M1, M2, ..., M7) in a steady-state cycle. The corresponding equivalent circuits of the converter in each of the topological modes are given in Fig. 4. Since the voltage across output capacitor and the current on input inductor are both constant, they are replaced by the dc sources Vo and I_L, respectively.

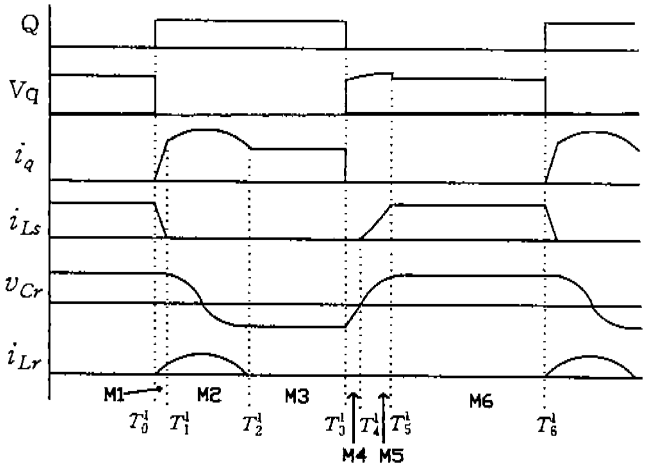


Fig. 2. Typical Region-1 waveforms.

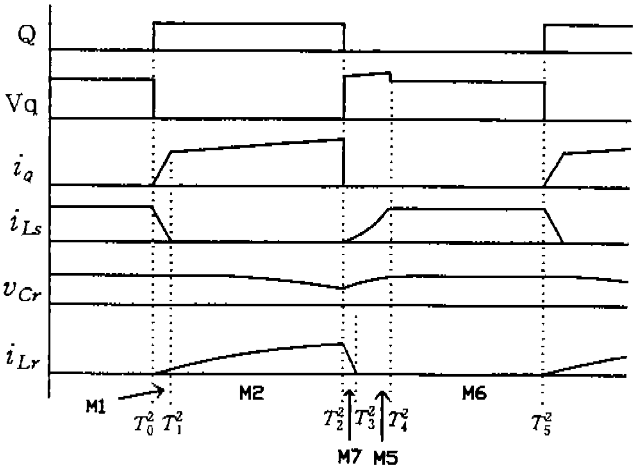


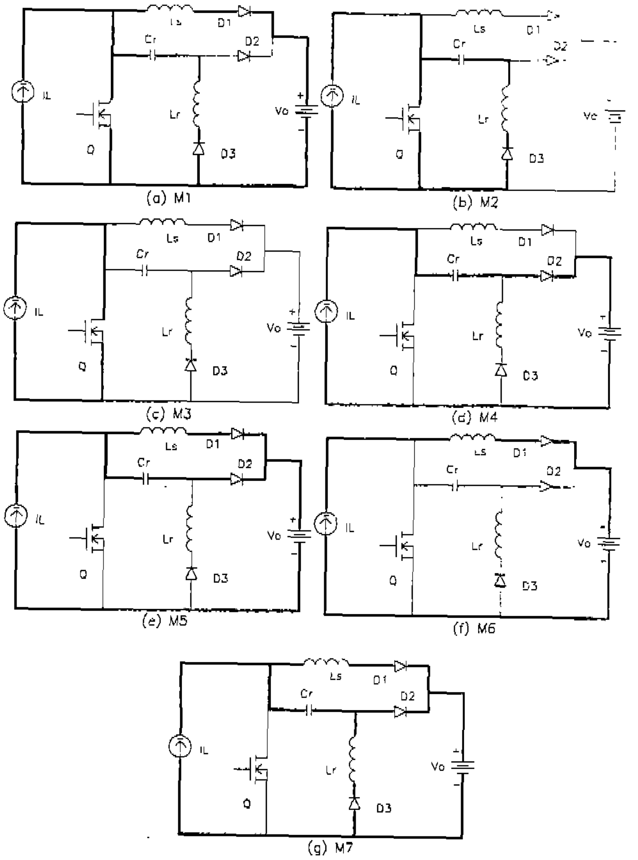
Fig. 3. Typical Region-2 waveforms.

A. Region-1 Operation ($w_2 T_{on} > \pi$)

The sequence of topological modes in Region-1 operation are M1, M2, M3, M4, M5, and M6. This operation occurs for $w_2 T_{on} > \pi$.

a) $T_0^1 - T_1^1$ (M1) : Prior to T_0^1, the MOSFET Q is off, and the rectifier diode D1 is conducting. At T_0^1, Q is turned on. The Ls current linearly falls until it reaches 0, where D1 is turned off. The Lr current starts to increase due to the resonance between Lr and Cr. Because of controlled di/dt at turn-on, the turn-on loss of Q is negligible and the peak reverse current of D1 can be limited.

b) $T_1^1 - T_2^1$ (M2) : Lr current continues to make a resonance until the resonance brings its



(a) M1 (b) M2 (c) M3 (d) M4 (e) M5 (f) M6 (g) M7

Fig. 4. Equivalent circuits for different topological modes.

current to zero at T_2^1 . Cr voltage is decreased until its voltage becomes reversed peak value. Using the initial Cr voltage of V_p and Lr current of zero at T_0^1 , the resonant current and the resonant voltage equations during M1 and M2 can be written as

$$i_{Lr}(t) = \frac{V_p}{Z_2}\sin w_2 t$$

$$v_{Cr}(t) = V_p \cos w_2 t \qquad (1)$$

c) $T_2^1 - T_3^1$ (M3) : D3 is turned off when the Lr current attempts to reverse. The operation of the circuit of this stage is identical to that of the basic boost converter.

d) $T_3^1 - T_4^1$ (M4) : At T_3^1 , Q is turned off. Cr is linearly charged by I_L to zero voltage. The energy trapped in Cr is transferred into the load during this mode.

e) $T_4^1 - T_5^1$ (M5) : When the capacitor Cr voltage becomes zero, diode D1 is turned on. The voltage across Q is limited by $V_o + V_{Cr}$. The Ls current builds up and the charging current into Cr goes down to zero. The induced voltage on Ls is absorbed in the snubber capacitor Cr. This stage finishes when the Ls current becomes I_L and Cr voltage is charged to its peak value at T_5^1 . The stress energy charge into Cr and the energy recovery into the load occur simultaneously during this mode.

Considering that the initial Ls current and Cr voltage are zeros at T_4^1 , the state equations during M5 are given :

$$i_{Ls}(t) = I_L(1 - \cos w_1 t)$$

$$v_{Cr}(t) = Z_1 I_L \sin w_1 t . \qquad (2)$$

f) $T_5^1 - T_6^1$ (M6) : This interval is identical to the freewheeling stage of the basic boost converter. During this stage, energy transfer from source to load occurs. At T_0^1 , Q is turned on again, starting another switching cycle.

B. Region-2 Operation($0 < w_2 T_{on} \leq \pi$)

The sequence of topological modes in Region-2 operation are M1, M2, M7, M5, and M6. M1 and M6 of Region-2 operation are similiar to those of Region-1 operation.

a) $T_1^2 - T_2^2$ (M2) : Lr current continues to make a resonance until Q is turned off. The Cr voltage is reduced to negative value at T_2^2 when $w_2 T_{on}$ varies from $\pi/2$ to π . For $w_2 T_{on} \leq \pi/2$, the Cr voltage is reduced to positive value at T_2^2 .

For the interval $T_0^2 - T_2^2$, the state equations of LrCr tank in Region-2 operation can be expressed as (1) of Region-1 operation.

b) $T_2^2 - T_3^2$ (M7) : At T_2^2 , Q is turned off, and its voltage is limited by Vo+ V_{Cr} due to the conduction of D2. The energy stored in the inductor Lr is directly transferred into the load. Lr current goes down to zero at T_3^2 . The input current goes into the load through Ls-D1 or Cr-D2. For $\pi/2 < w_2 T_{on} \leq \pi$, the input current flowes entirely via Cr-D2 path until the Cr voltage is charged by I_L to zero. When the value of Cr voltage is greater than zero, D1 is turned on.

c) $T_3^2 - T_4^2$ (M5) : The Ls current builds up until it reaches I_L at T_4^2. The charging current into Cr gradually goes down to zero and the Cr voltage reaches V_p .

During the conduction of both D1 and D2, the Ls current and the Cr voltage can be expressed as the following :

$$i_{Ls} = \frac{V_{Cr}(0)}{Z_1} \sin w_1 t + I_L(1 - \cos w_1 t)$$

$$v_{Cr}(t) = V_{Cr}(0) \cos w_1 t + Z_1 I_L \sin w_1 t \quad (3)$$

where the initial Ls current is zero and $V_{Cr}(0)$ is the Cr voltage at the start of D1 conduction. Since $V_{Cr}(0)$ is not less than zero, $V_{Cr}(0)$ can be derived from (1) as

$$V_{Cr}(0) = 0 \text{ , for } \pi/2 < w_2 T_{on} \leq \pi$$

and

$$V_{Cr}(0) = V_p \cos w_2 T_{on} \text{ , for } 0 < w_2 T_{on} \leq \pi/2 \quad (4)$$

When $w_2 T_{on}$ varies from $\pi/2$ to π , the equation (3) is equal to (2).

III. Experimental Results

A 100-kHz, 500W high-power-factor boost rectifier with the proposed energy recovery snubber has been implemented to demonstrate the operation. It is regulated at 375-V output with a 110-220 VAC input range. The experimental power circuit is given in Fig. 5.

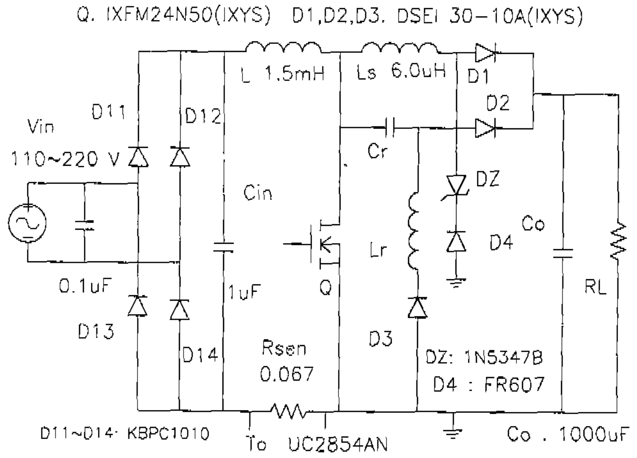


Fig. 5. Experimental boost rectifier circuit.

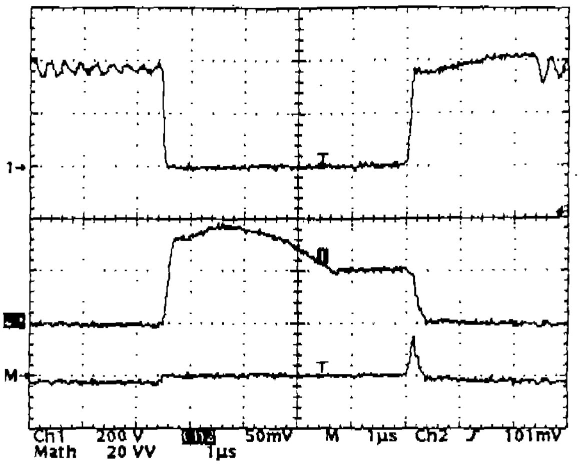


Fig. 6. Measured voltage(upper trace-200 V/div), current(middle trace-5 A/div), and loss(lower trace-2 kW/div) waveforms of Q operating in Region-1 (time scale: 1 μs/div).

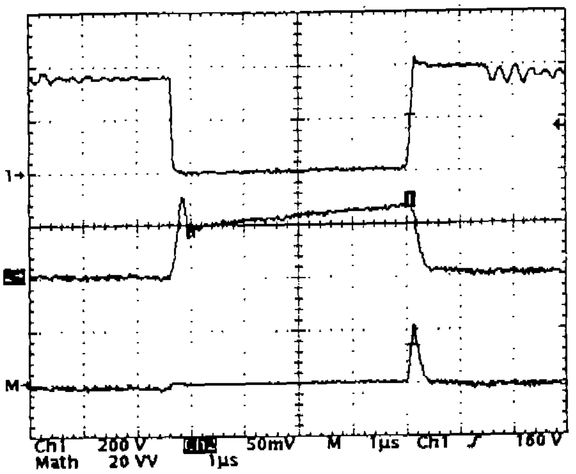


Fig. 7. Measured voltage(upper trace-200 V/div), current(middle trace-5 A/div), and loss(lower trace-2 kW/div) waveforms of Q operating in Region-2 (time scale: 1 μs/div).

Fig. 6 shows the measured voltage, current, and loss waveforms of Q operating in Region-1. The snubber components are chosen as : Ls = 6.0 μH, Cr = 0.1 μF, and Lr = 10 μH. It can be seen that the turn-on loss of the main switch Q is negligible due to the action of the current limiting inductor Ls, and the turn-off loss of this switch is smaller compared to that of the conventional boost converter due to the reduced turn-off voltage stress of Q.

Fig. 7 shows the measured voltage, current, and loss waveforms of Q operating in Region-2. The snubber components are chosen as : Ls = 6.0 μH, Cr = 0.47 μF, and Lr = 110 μH. It can be seen that the turn-on loss of Q is negligible and the turn-off loss is still significant due to high turn-off current.

The input ac voltage and current for both Region-1 and Region-2, which demonstrates the high power factor of proposed boost rectifier, are shown in Fig. 8. The measured power factor is 0.99.

The measured efficiency of the implemented converter shows 97.5 % at high-line-input voltage and 94.5 % at low-line-input voltage in Region-1 operation. The efficiency for Region-2 operation is measured as 96.5 % at high-line-input voltage and 91.5 % at low-line-input voltage. The measured efficiency of boost rectifier operating in Region-1 is 1-3% higher than that of the rectifier operating in Region-2.

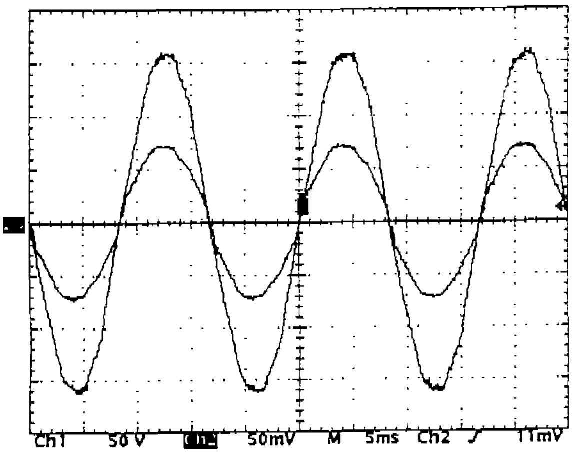


Fig. 8. Measured input voltage (outer trace-50 V/div) and current (inner trace-5 A/div) waveforms (time scale: 5 ms/div).

IV. Conclusion

A passive energy recovery snubber for boost converter has been presented. The main switch Q of the boost converter, which is implemented with a MOSFET in this paper, is turned on with zero current and turned off with a limited voltage clamp. When the snubber is designed to be operated in Region-1, the turn-on loss of Q is negligible and the turn-off loss of the switch become smaller compared to that of the conventional boost converter. In Region-2 operation of the snubber, the turn-on loss of Q is negligible and the turn-off loss of the switch is still significant due to high turn-off current.

The high-power-factor boost rectifier with a passive energy recovery snubber is implemented to confirm the operation. The experimental results show good agreement with the theoretical ones. The measured efficiency of the boost rectifier operating in Region-1 is 1-3% higher than that of the rectifier operating in Region-2. The measured power factor is 0.99.

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