Output inductor-less active clamp forward converter employing current boost-up circuit for high power density adaptor

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Abstract

This paper proposes an output inductor-less active clamp forward converter employing current boost-up circuit for high power density adaptor. By applying the proposed current boost-up circuit, the proposed converter has low conduction loss and low voltage ringing of the secondary rectifier. This paper presents the analysis of the proposed converter and a comparison between the proposed converter and the conventional converter through experiment.

1. INTRODUCTION

Recently, many isolated DC-DC converter topologies suitable for high power density and high current applications have been presented [1]-[3]. All of them try to reduce size and cost by optimizing the magnetic component and minimizing the number of passive components. The conventional active clamp forward converter without output inductor can be considered for high power density [3]. However the conventional converter has high peak current, which causes the serious heat problem at the secondary side due to high conduction loss. Therefore the conventional converter is undesirable for high current applications. To overcome this problem, the proposed converter adopts a current boost up circuit across the output diode. A current boost up circuit decreases rms value of the transformer secondary current and clamps the rectifier voltage ringing. These features make the proposed converter suitable for high power density, and high current applications.

In the following sections, the detailed analysis of the proposed converter will be presented. Experiment results demonstrate that merits and demerits of the proposed circuit.

2. OPERATION PRINCIPLE

Fig.1 shows the proposed current boost up active-clamped forward without output filter is shown in Fig.1.

According to the characteristics of the forward converter, step-down operation, the output voltage \( V_O \) reflected to the transformer primary side, \( V_{pri} \), should be lower than the input voltage \( V_i \).

Key waveforms of the proposed converter in a switching period are shown in Fig.2. As can be seen, each switching period can be subdivided into eight modes described in the following.

Mode 1 \((t_0 – t_1)\): This mode begins at \( t_0 \) when \( Q_1 \) is turned-on. This interval represents the powering mode, the energy is transferred to the output from the source. \( V_i \) is applied to the primary winding of transformer \( T_1 \), it makes \( I_{lkg} \) linearly increase. \( I_4 \) is the maximum value of \( I_{lkg} = I_3 \).

Mode 2 \((t_1 – t_2)\): Mode 2 begins at \( t_1 \) when \( Q_1 \) is turned-off. At the same time, a resonance between \( L_{lkg} \), \( C_{oss1} \), and \( C_{oss2} \) is started. In this mode, \( D_{b1} \) is reverse biased, and \( D_{b2} \) is forward biased. At the end of this mode, the value of \( I_{Lm} \) equals that of \( I_{lkg} = I_3 \).

Mode 3 \((t_2 – t_3)\): Mode 3 begins at \( t_3 \) when \( Q_3 \) is turned-on. This interval represents the recovery mode. The current \( I_{lkg} \) from the source is clamped by \( D_{b2} \). At the end of this mode, the value of \( I_{lkg} \) equals that of \( I_{Lm} = I_3 \).
\[ I_{\text{lkg}}(t) = I_{\text{Q}} \cos \left( \frac{1}{2 L_{\text{lkg}} C_{\text{OSS}}} t \right) \]  

(4)

Where \( C_{\text{OSS}} = C_{\text{OSS1}} = C_{\text{OSS2}} \).

Mode 3 \((t_5 - t_6)\): At \( t_5 \), \( D_2 \) is reverse biased. During this mode \( L_m \) and \( L_{\text{lkg}} \) resonate with \( C_{\text{OSS1}}, C_{\text{OSS2}}, C_1 \) and \( C_b \). At the end of this mode, the voltage across \( Q_2 \) is 0 and the body diode of \( Q_2 \), \( D_{Q2} \), is forward biased.

\[ I_{\text{lkg}}(t) = \sqrt{\left( I_{\text{in}} + V_C \right)^2 + \frac{1}{2} C_b \left( \frac{V_C}{n} \right)^2} \]  

(8)

Mode 8 \((t_7 - t_8)\): This mode is similar to mode 4, except \( D_{Q1} \) is forward biased. By turning on \( Q_1 \) during the value of \( I_{\text{lkg}} \) is negative, \( Q_1 \) can achieve ZVS.

\[ I_{\text{lkg}} \left( t \right) = \left( I_{\text{in}} + I_1 \right) \sin \left( \frac{1}{2 L_{\text{lkg}} \left( 2 C_{\text{OSS}} + C_b \right)} \right) \]  

(9)

3. Design considerations

In this section, the large signal modeling is presented to obtain DC conversion ratio.

For the convenience of the analysis of the steady state operation, several assumptions are made as follows:

a) Interval from \( t_1 \) to \( t_4 \) and interval from \( t_5 \) to \( t_8 \) are neglected.

b) \( V_C, V_0 \) is constant.

c) The secondary leakage inductance: \( L_{\text{lkg}} \).

d) \( C_b \gg C_{\text{OSS}} \).

According to these assumptions, the switching period can be divided into only two modes. The average current of \( I_{\text{sec}} \), the difference between \( I_{\text{in}} \) and \( I_{\text{in}} \), is equal to \( I_0 \). In Fig. 2, we can analyze boosting current, \( I_2 - I_1 \), by calculating following equation (8), and (9)

\[ L_{\text{lkg}} \left( I_2 - I_1 \right)^2 = \frac{1}{2} C_b \left( \frac{V_C}{2} \right)^2 + \frac{1}{2} C_{\text{OSS}} \left( \frac{V_{\text{in}} + V_C}{2} \right)^2 \]  

(10)
\[ V_C = \frac{D}{1 - D} V_{in} \quad (11) \]

Substituting (3) into (2) gives the following expression for \( I_2 - I_1 \):

\[ I_2 - I_1 = \frac{V_{in}}{2[(1 - D) D_C + 2 C_{OSS}]} \quad (12) \]

From (2) and (3), \( I_4 - I_3 \) can be expressed as follows:

\[ I_4 - I_3 = \frac{V_{in} - n_x V_O}{L_{ikg}} DT_S - \left( I_1 + n_x V_O \right) DT_S \quad (13) \]

From (4), (5) and (6), an expression for the voltage conversion ratio can be derived as follows:

\[ G = \frac{R_O L_{in} D_N \left[ \frac{2 L_{ikg} C_b}{2 - (1 - D) T_S} \right]}{2(1 - D) \left( 2 L_{ikg} L_{m} + R_O L_{in} n DT_S + R_O L_{ikg} n DT_S \right)} \quad (15) \]

Fig. 4 shows the voltage conversion ratio according to the load variation. Since the proposed converter has active clamp circuit, the voltage stress of switches gets higher as the duty ratio gets larger. Therefore the ZVS condition of the switch is poor. In case of the small duty ratio, although the variation of the duty ratio is small by load condition, rms value of the secondary current of the transformer is high. Therefore the duty ratio can be designed by considering the ZVS condition, the secondary conduction loss of the transformer and the variation of the duty ratio.

4. Experiment Results

Based on the analysis of the proposed converter, a prototype circuit has been built. The specification of the prototype follows:

- Input voltage \( V_{in} \): 90V
- Output voltage \( V_o \): 14.5V
- Maximum output power \( P_o \): 45W
- Switching frequency \( f_s \): 100kHz
- Turn ratio of the transformer \( n \): 8.4

Table 1 shows components are used for the prototype of the 14.5V, 45W converter operated at 100kHz has been built. The transformer was built on a PC44PQ2016 core (\( N_p = 42, N_s = 5 \)).

<table>
<thead>
<tr>
<th>Switching frequency ( f_s )</th>
<th>100kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switches (Q1,Q2)</td>
<td>FQP20N60C3</td>
</tr>
<tr>
<td>Diode (D)</td>
<td>V60100C</td>
</tr>
<tr>
<td>Turn ratio ( (N_p/N_s) )</td>
<td>42 : 5</td>
</tr>
<tr>
<td>Leakage inductance ( L_{ikg} )</td>
<td>12uH</td>
</tr>
<tr>
<td>Magnetizing inductance ( L_m )</td>
<td>1.5mH</td>
</tr>
<tr>
<td>Boost capacitor ( C_b )</td>
<td>80nF</td>
</tr>
</tbody>
</table>

Table 1 Component lists for the prototype converter

Fig. 5 shows key waveforms of the proposed converter. The primary current \( I_{lg} \) and the voltage across the primary side of the transformer, \( V_{pri} \), are well agreed with the theoretical analysis. We can see the primary current \( I_{lg} \) is boosted.

Fig. 6 shows the efficiency of the proposed converter and that of the conventional active-clamped forward converter without output filter, by changing load current. As shown in this figure, the efficiency of the proposed converter is about 0.7% higher than that of the conventional one at heavy load range.

5. Conclusion

In this paper, an output inductor-less active clamp forward converter employing current boost-up circuit for high power density is presented. The proposed converter has low conduction loss by applying boost up circuit. An operation principle and a simplified analysis of the proposed converter are given. The experimental result shows that the efficiency of the proposed converter is 0.7% higher than that of the conventional one. Therefore, the proposed converter is suitable for high power density and high current applications.

Reference