RCD Snubber Design and Analysis using Resonance Coordinate

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Abstract

An approach to design and analyze an RCD snubber for flyback converters will be introduced. The resonance coordinate provides an easy way to understand the transient period of the switch turn-off and helps to design and analyze the RCD snubber easily. An example of analyzing RCD snubber losses for 40W prototype will be given and experimented to show the effectiveness of the suggested method.

1. Introduction

Commercially, the flyback converter is widely used due to its light weight and low cost. However it has a serious problem: hard switching operation of the main switch, which results in a high voltage surge and oscillation across the switch. The voltage stress of the main switch is the sum of input voltage $V_{in}$, reflected output voltage $nV_{out}$ and voltage spike caused by the leakage inductance. The most widely used method for reducing voltage spike is using an RCD snubber network. If the snubber resistor $R_{sn}$ is decreased, the snubber capacitor voltage $V_{sn}$ is also decreased; however, the power loss caused by $R_{sn}$ is increased. So using the RCD snubber, a trade-off is needed between voltage stress (the sum of $V_{in}$ and $V_{sn}$) and efficiency. So an optimal RCD snubber design is necessary.

This paper deals with the conventional analysis of the voltage spike caused by the leakage inductance. Then an easy analyzing method in resonance coordinate will be introduced for further analysis. For optimal design, snubber current will be analyzed in resonance coordinate. The validity of the introduced analysis method using resonance coordinate will be evaluated with an example of analyzing RCD snubber losses for 40 W prototypes.

2. RCD snubber design and analysis

2.1 General method of RCD snubber design

The RCD snubber circuit is used to clamp the voltage spike caused by the resonance between leakage inductance and output capacitance of the switch MOSFET to protect MOSFET with a limited breakdown voltage rating. To describe the operational principles to design the RCD snubber, there are a couple of assumptions:

1. $V_{in} > nV_{out}$, and $V_{in}$ is almost constant due to the large $C_{in}$;
2. $C_{DS} = C_{oss} + C_{trans}$, and is constant regardless of $V_{DS}(t)$;
3. No secondary side leakage inductance, thus $I_{bak}(t)$ can be changed into the secondary side diode current instantaneously when primary switch Q1 turns off, where $C_{bak}$ is the snubber capacitance, $C_{oss}$ is the effective capacitance between drain and source of the main switch, $C_{trans}$ is the output capacitance of the switch MOSFET,

$$V_{DS}(t) = \frac{L_{L}}{V_{in}} \times I_{peak}$$

where $I_{peak}$ is the peak drain current just before the switch Q1 turns off. The power dissipation in the snubber network ($P_{sn}$) is

$$P_{sn} = \frac{1}{2} \times L_{L} \times I_{peak}^{2} \times f_{sw} \times \frac{V_{in}}{V_{in} - nV_{out}} = \frac{V_{in}^{2}}{R_{sn}} \times \frac{1}{2} \times L_{L} \times I_{peak}^{2} \times f_{sw} \times \frac{V_{in}}{V_{in} - nV_{out}}$$

Therefore, the snubber resistor $R_{sn}$ can be obtained as:

$$R_{sn} = \frac{V_{in}^{2}}{L_{L} \times I_{peak}^{2} \times f_{sw} \times \frac{V_{in}}{V_{in} - nV_{out}}}$$

However, the peak drain current is reduced somewhat after stepping a couple of stages of L-C resonance. Therefore, the above equation might mislead an over-designed system. So $I_{peak}$ of Eq. (1) should be changed with the peak current of snubber ($I_{pk,sn}$).

Let’s find out $I_{pk,sn}$ using resonance coordinate to avoid an over design of the RCD snubber in the following section.

2.2 RCD snubber design and analysis in resonance coordinate

An RCD snubber design will be done in resonance coordinate in this chapter. To design the snubber only, there is no need to analyze the whole flyback operational modes. Figure 1 shows the typical $V_{DS}(t)$ of the switching MOSFET in flyback converters.

![Figure 1. $V_{DS}(t)$ after switch turns off](image-url)
In Mode 1, the current in the inductors (Lsn and Lmk) charges Csn until its voltage reaches Vastn+Voutn, where Lmk is the magnetizing inductance of the transformer. In Mode 2, by the resonance between Cds and Lmk, the voltage on Cds increases up to Vastn+Vsn at the end of this mode.

2.2.1 Equations for the Peak Drain Current

\( i_{\text{pk,sn}}(t) \) and \( v_{\text{os}}(t) \) can be plotted in the resonance coordinate as shown in Figure 2 during Modes 1–4.

\[
V_{m} = \sqrt{\left(\frac{L_m}{L_k} + L_k\right) y^2 - \frac{L_k}{L_k + L_m} B^2}
\]

Figure 2. Mode analysis in resonance coordinates

Mode 1. It is a circle with the origin at \((V_{in}, 0)\) and the kick-off point at \((0, V_{in,peak})\). From Mode 1 of Figure 2,

\[
(x - V_{in})^2 + y^2 = V_{in,peak}^2 + (Z_m I_{peak})^2
\]

where \( Z_m \) is the characteristic impedance of \( L_m \) and Cds, \( \sqrt{L_m/Cds} \).

Mode 2. It is an ellipse with the origin at \((V_{in}+nV_{out}, 0)\) and the kick-off point at \((A, B)\). And the circle is changed into an ellipse by coordinate mapping. From Mode 2 of Figure 2,

\[
(x - (V_{in} + nV_{out}))^2 + \left(\frac{L_k}{L_k + L_m}\right) y^2 = \left(\frac{L_k}{L_k + L_m}\right) B^2
\]

From Eqs. (4) and (5), \( I_{pk,sn}(\text{point D}) \) is obtained as

\[
I_{pk,sn} = \frac{C_{sn}}{L_k + L_m} \left[ V_{in}^2 + (Z_m I_{peak})^2 - nV_{out}^2 - \frac{L_k}{L_k + L_m} (V_{in}^2 - nV_{out}^2) \right]^{1/2}
\]

The Eq. (6) is calculated with an assumption that there is no leakage inductance in snubber network that isos(t) is right the same as the \( I_{pk,sn} \) when snubber conducts. \( i_{pk,sn}(t) \) increases with a slope determined by parasitic inductance(Lpk,sn) which exists in the snubber network for a really short time when \( v_{os}(t) \) reaches \( V_{in}+V_{sn} \). So real snubber peak current \( I_{pk,sn,real} \) is smaller than \( I_{pk,sn} \) of Eq. (6). Considering \( I_{pk,sn}, I_{pk,sn,real} \) is calculated as

\[
I_{pk,sn,real} = \frac{I_{pk,sn}}{1 + \frac{L_{pk,sn}}{L_k}}
\]

To obtain the correct equations for the power loss and \( R_{loss} \) in the snubber network, \( I_{pk,sn} \) of Eqs. (2) and (3) should be replaced by \( I_{pk,sn,real} \) of Eq. (7).

According to Eqs. (2), (6), and (7), for reducing snubber loss, \( L_k, I_{pk,sn} \), and \( f_{os} \) should be reduced, and \( C_{sn} \) should be increased.

2.2.2 Evaluation of the optimized snubber by experimental results

When a system operates with the calculated \( R_{sn} \) \((23.5 \text{ k} \Omega)\) using the conventional method, key waveforms of \( i_{pk,sn}(t) \) and \( v_{os}(t) \) are obtained as shown in Figure 3.

![Figure 3. Key waveforms (Test conditions: \( V_{in}=300 \text{ Vdc}, P_{out}=40 \text{ W}, V_{out}=15 \text{ V}, I_{pk,sn}=2 \text{ A}, V_{osc}=5 \text{ V}, I_{os}=2 \text{ A}, L_{sn}=5 \text{ uH}, L_{mk}=600 \text{ uH}, C_{in}=170 \text{ pF}, L_{pk,sn}=0.6 \text{ uH})\)](image)

The measured values for the current, voltage, and switching frequency are as follows: \( I_{pk,sn}=1.058 \text{ A}, I_{pk,sn,real}=0.916 \text{ A}, f_{os}=64 \text{ kHz}, V_{in}=101 \text{ V}, V_{out}=70 \text{ V}. \) The calculated \( I_{pk,sn,real} \) is 0.941 A using Eqs. (6) and (7), which is a little bit higher than the measured \( I_{pk,sn,real} \). But the calculated \( I_{pk,sn,real} \) is close to the measured \( I_{pk,sn,real} \) compared to \( I_{pk,sn} \). Accordingly, the power losses \( P_{sn} \) calculated based on \( R_{sn} \) and \( I_{pk,sn} \) are closer than the case of \( I_{pk,sn,real} \). They are \( P_{sn,real}=0.434 \text{ W} \) and \( P_{sn,I_{pk,sn,real}}=0.462 \text{ W} \) respectively, while \( P_{sn,I_{pk,sn,real}}=0.584 \text{ W} \), which is much larger than real \( P_{sn} \). The difference of \( P_{sn} \) calculated based on \( I_{pk,sn} \) and \( I_{pk,sn,real} \) is determined as Eq. (8).

\[
\Delta P_{sn} = \frac{1}{2} L_k \times f_{os} \times \frac{V_{in}}{V_{out}} \times (I_{pk,sn}^2 - I_{pk,sn,real}^2)
\]

If \( P_{sn} \) is over estimated using \( I_{pk,sn} \), \( R_{sn} \) will be over designed. For more optimal design, \( R_{sn} \) should be chosen based on \( I_{pk,sn,real} \) instead of \( I_{pk,sn} \), and \( P_{sn} \) will decrease and \( R_{sn} \) will increase.

3. Conclusion

We can find out the exact snubber peak current using the resonance coordinate. Normally, \( R_{sn} \) is chosen based on \( I_{pk,sn} \) for approximation and accordingly the \( R_{sn} \) is an over-designed value, because \( P_{sn} \) is over estimated. Using \( I_{pk,sn,real} \) we can get a more exact and smaller estimated \( P_{sn} \) and larger \( R_{sn} \) consequently.

However, the modified \( I_{pk,sn,real} \) is almost same as the original \( I_{pk,sn} \), if the characteristic impedance of \( Z_{sn} \) is very large. The smaller the original \( I_{pk,sn} \), the more gap between \( I_{pk,sn} \) and \( I_{pk,sn,real} \). As a result, the modified method is useful in low power level power supply unit.

Reference