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1. Introduction

This document describes the design of a simple “RC snubber circuit”. The snubber is used to suppress high-frequency oscillations associated with reverse recovery effects in power semiconductor applications.

2. Test circuit

The basic circuit is a half-bridge and shown in Figure 1.

Q1 and Q2 are BUK761R6-40E devices. The inductor could also be connected to 0 V rather than $V_{DD}$.

Inductor current is established in the red loop; Q2 is off and current is flowing through Q1 body diode. When Q2 is turned on, current “commutates” to the blue loop and the reverse recovery effect occurs in Q1. We observe the effect of Q1 reverse recovery on the $V_{DS}$ waveform of Q2; see Figure 2.
We are primarily interested in the parasitic elements in the circuit:

- \( L_{LK} \) is the total stray or “leakage” inductance comprised of PCB trace inductance, device package inductance, etc.
- The parasitic capacitance \( C_{LK} \) is mainly due to \( C_{oss} \) of the upper (Q1) device.

Q2 is treated as a simple switch. The oscillation can be eliminated (snubbed) by placing an RC circuit across Q1 drain-source; see Figure 4.
3. Determining $C_{LK}$ and $L_{LK}$

Before we can design the snubber, we must first determine $C_{LK}$ and $L_{LK}$. We could attempt to measure $C_{LK}$ and $L_{LK}$ directly, but a more elegant method can be used. For this LC circuit, we know that:

$$f_{RING0} = \frac{1}{2\pi\sqrt{L_{LK}C_{LK}}}$$  \hspace{1cm} (1)

where $f_{RING0}$ is the frequency of oscillation without a snubber in place; see Figure 2. If we add an extra additional capacitor across Q1 ($C_{add}$), the initial oscillation frequency from $f_{RING0}$ to $f_{RING1}$ ($f_{RING1} < f_{RING0}$) will change. It can be shown that (see Section 7 “Appendix A; determining $C_{LK}$ from $C_{add}$, $f_{RING0}$ and $f_{RING1}$”):

$$C_{LK} = \frac{C_{add}}{x^2 - 1}$$  \hspace{1cm} (2)

where:

$$x = \frac{f_{RING0}}{f_{RING1}}$$  \hspace{1cm} (3)

So if we measure $f_{RING0}$ (without $C_{add}$), then add a known $C_{add}$ and measure $f_{RING1}$, we can determine $C_{LK}$ and $L_{LK}$ (two equations, two unknowns).

$C_{add} = 3200$ pF was added in circuit, and $f_{RING1}$ found to be $22.2$ MHz ($f_{RING0}$ previously found to be $31.25$ MHz; see Figure 2).

from Equation 3:

$$x = \frac{31.25}{22.2} = 1.41$$  \hspace{1cm} (4)

and from Equation 2:

$$C_{LK} = \frac{3200 \text{ pF}}{1.41^2 - 1} = 3239 \text{ pF}$$  \hspace{1cm} (5)
Rearranging Equation 1:

\[ L_{LK} = \frac{I}{(2\pi f_{RING0})^2 C_{LK}} \]  \hspace{1cm} (6)

So with \( f_{RING0} = 31.25 \text{ MHz} \) and \( C_{LK} = 3239 \text{ pF} \):

\[ L_{LK} = \frac{I}{(2 \times \pi \times 3.125 \times 10^7)^2 \times 3.239 \times 10^{-9}} = 8.01 \times 10^{-9} \text{ H} = 8.0nH \]  \hspace{1cm} (7)

and with \( f_{RING1} = 22.2 \text{ MHz} \) and \( (C_{LK} + C_{add}) = 3239 \text{ pF} + 3200 \text{ pF} = 6439 \text{ pF} \):

\[ L_{LK} = \frac{I}{(2 \times \pi \times 2.22 \times 10^7)^2 \times 6.439 \times 10^{-9}} = 7.98 \times 10^{-9} \text{ H} = 8.0nH \]  \hspace{1cm} (8)

In other words, the calculated value of \( L_{LK} \) remains almost unchanged when we add the additional 3200 pF capacitance. This is a good sanity check of the method for determining \( C_{LK} \) and \( L_{LK} \).

### 4. Designing the snubber - theory

If we replace \( C_S \) in Figure 4 with a short-circuit, then we simply have the classic RLC circuit found in text books. The response of this circuit to a step change in voltage (that is \( Q_2 \) turning on) depends on the degree of damping (\( \zeta \) or zeta) in the circuit; see Figure 5.
In theory the circuit oscillates indefinitely if \( \zeta = 0 \), although this is a practical impossibility as there is always some resistance in a real circuit. As \( \zeta \) increases towards one, the oscillation becomes more damped that is, tends to decrease over time with an exponential decay envelope. This is an “underdamped” response. The case \( \zeta = 1 \) is known as “critically damped” and is the point at which oscillation just ceases. For values of greater than one (overdamped), the response of the circuit becomes more sluggish with the waveform taking longer to reach its final value. There is therefore more than one possible degree of damping which we could build into a snubber, and choice of damping is therefore part of the snubber design process.

For this configuration of RLC circuit, the relationship between \( \zeta \), \( R_S \), \( L_{LK} \) and \( C_{LK} \) is:

\[
\zeta = \left( \frac{L}{2R_S} \right) \sqrt{\frac{L_{LK}}{C_{LK}}} \quad (9)
\]

The snubber capacitor \( C_S \) does not appear in Equation 9.

In some circuits, it is possible to damp the oscillations with \( R_S \) alone. However, in typical half-bridge circuits we cannot have a resistor mounted directly across Q1 drain source. If we did, then Q1 is permanently shorted by the resistor and the circuit as a whole would not function as required. The solution is therefore to put \( C_S \) in series with \( R_S \), with the value of \( C_S \) chosen so as not to interfere with normal operation.

The snubber is a straightforward RC circuit whose cut-off frequency \( f_C \) is:

\[
F_C = \frac{f}{2\pi R_S C_S} \quad (10)
\]

Again, we must choose which value of \( f_C \) to be used, and there is no single correct answer to this question. The cut-off frequency of the snubber must be low enough to effectively short-circuit the undamped oscillation frequency \( f_{RING0} \), but not so low as to present a significant conduction path at the operating frequency of the circuit (for example 100 kHz or whatever). A good starting point has been found to be \( f_C = f_{RING0} \).

5. Designing the snubber - in practice

We now have sufficient information to design a snubber for the waveform shown in Figure 2. To recap:

\[
C_{LK} = 3239 \text{ pF} \\
L_{LK} = 8.0 \text{ nH} \\
f_{RING0} = 31.25 \text{ MHz}
\]

\[
\zeta = \left( \frac{L}{2R_S} \right) \sqrt{\frac{L_{LK}}{C_{LK}}} \quad (11)
\]

\[
F_C = \frac{f}{2\pi R_S C_S} = f_{RING0} \quad (12)
\]

The first task is to choose a value of damping (Figure 5). We have chosen \( \zeta = 1 \), that is, critical damping. Rearranging Equation 11 we have:
designing RC snubbers

\[ R_S = \left( \frac{1}{2\zeta} \right) \frac{L_{KL}}{C_{KL}} = \left( \frac{1}{2} \right) \frac{8.0 \times 10^{-9}}{3.239 \times 10^{-9}} = 0.78\Omega \]  

(13)

use \(2 \times 1.5\ \Omega\) in parallel to give 0.75 \(\Omega\).

Rearranging Equation 12 we have:

\[ C_S = \frac{1}{2\pi R_S f_{RINGO}} = \frac{1}{2\pi \times 0.75 \times 3.125 \times 10^7} = 6.79\text{nF} \]  

(14)

use 4.7 nF + 2.2 nF to give 6.9 nF.

The snubber was fitted across Q1 drain source. The resulting waveform is shown in Figure 6 together with the original (non-snubbed) waveform from Figure 2.

As seen in Figure 6, the snubber has almost eliminated the ringing in the VDS waveform. This technique could also be applied to the MOSFET in the Q2 position.

6. Summary

- Reverse recovery effects in power devices can induce high frequency oscillations in devices connected to them.
- A common technique for suppressing the oscillations is the use of an RC snubber.
- Design of an effective snubber requires the extraction of the circuit parasitic capacitance and inductance. A method has been demonstrated for doing this.
- The snubbed circuit has been shown to be a variation on the classic RLC circuit.
A method of determining values of snubber components has been demonstrated. The method has been shown to work well, using the example of BUK761R6-40E MOSFETs.

7. Appendix A; determining $C_{LK}$ from $C_{add}$, $f_{RING0}$ and $f_{RING1}$

We know that:

$$f_{RING0} = \frac{1}{2\pi \sqrt{L_{LK} C_{LK}}} \quad (15)$$

where $f_{RING0}$ is the frequency of oscillation without a snubber in place and $L_{LK}$ and $C_{LK}$ are the parasitic inductances and capacitances respectively.

If we add capacitor $C_{add}$ across Q1 drain-source, $f_{RING0}$ is reduced by an amount “x” where:

$$\frac{f_{RING0}}{x} = \frac{1}{2\pi \sqrt{L_{LK} (C_{LK} + C_{add})}} \quad (16)$$

therefore

$$\frac{1}{2\pi \sqrt{L_{LK} C_{LK}}} = \frac{x}{2\pi \sqrt{L_{LK} (C_{LK} + C_{add})}} \quad (17)$$

$$\frac{1}{\sqrt{L_{LK} C_{LK}}} = \frac{x}{\sqrt{L_{LK} (C_{LK} + C_{add})}} \quad (18)$$

$$\sqrt{L_{LK} C_{LK}} = \sqrt{\frac{L_{LK} (C_{LK} + C_{add})}{x}} \quad (19)$$

$$C_{LK} = \frac{C_{LK} + C_{add}}{x^2} \quad (20)$$

$$C_{LK} x^2 - C_{LK} = C_{add} \quad (21)$$

$$C_{LK} (x^2 - 1) = C_{add} \quad (22)$$

$$C_{LK} = \frac{C_{add}}{x^2 - 1} \quad (23)$$

where:

$$x = \frac{f_{RING0}}{f_{RING1}} \quad (24)$$
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