AN11160

Designing RC snubbers

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Document information

Information	Content
Keywords	RC snubber, commutation, reverse recovery, leakage inductance, parasitic capacitance, RLC circuit and damping, MOSFET
Abstract	This document describes the design of a simple RC snubber circuit.

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 Fig. 1.

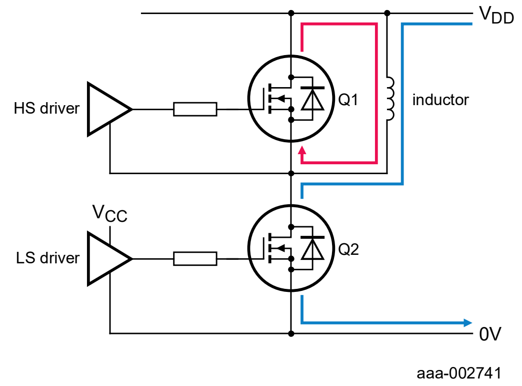

Fig. 1. The half-bridge circuit

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 Fig. 2.

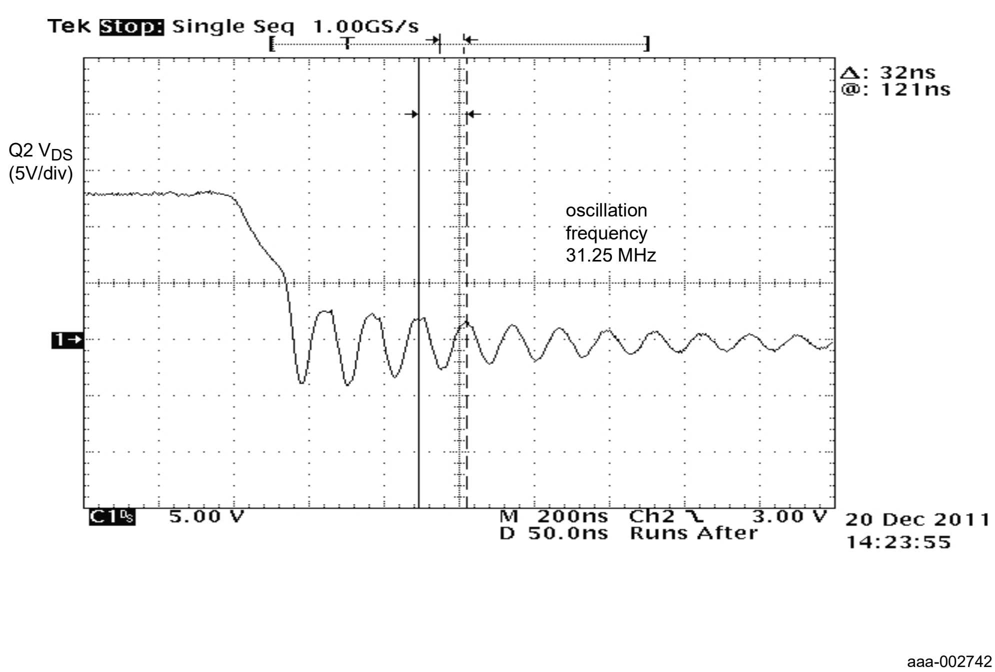

Fig. 2. Reverse recovery-induced oscillation in Q2 V_{DS}

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The equivalent circuit is shown in Fig. 3.

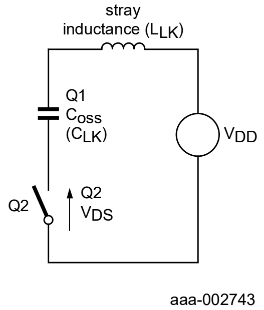

Fig. 3. Equivalent circuit

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 Fig. 4.

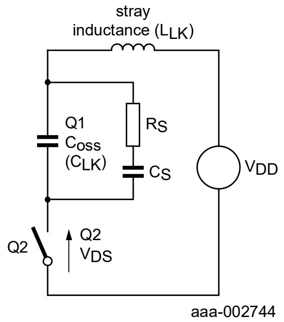

Fig. 4. Equivalent circuit with snubber components R_S and C_S

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:

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

Where f_{RING0} is the frequency of oscillation without a snubber in place; see Fig. 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):

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

where:

$$x = \frac{f_{RING0}}{f_{RING1}} \quad (3)$$

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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 Fig. 2).

From Equation 3:

$$x = \frac{31.25}{22.2} = 1.41 \quad (4)$$

and from Equation 2:

$$C_{LK} = \frac{3200\,pF}{1.41^2 - 1} = 3239\,pF \quad (5)$$

Rearranging Equation 1:

$$L_{LK} = \frac{1}{(2\pi f_{RING0})^2\ C_{LK}} \quad (6)$$

So with f_{RING0} = 31.25 MHz and C_{LK} = 3239 pF:

$$L_{LK} = \frac{1}{(2 \times \pi \times 3.125 \times 10^7)^2 \times 3.239 \times 10^{-9}} = 8.01 \times 10^{-9} H = 8.0\ nH \quad (7)$$

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

$$L_{LK} = \frac{1}{(2 \times \pi \times 2.22 \times 10^7)^2 \times 6.439 \times 10^{-9}} = 7.98 \times 10^{-9} H = 8.0\ nH \quad (8)$$

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}.

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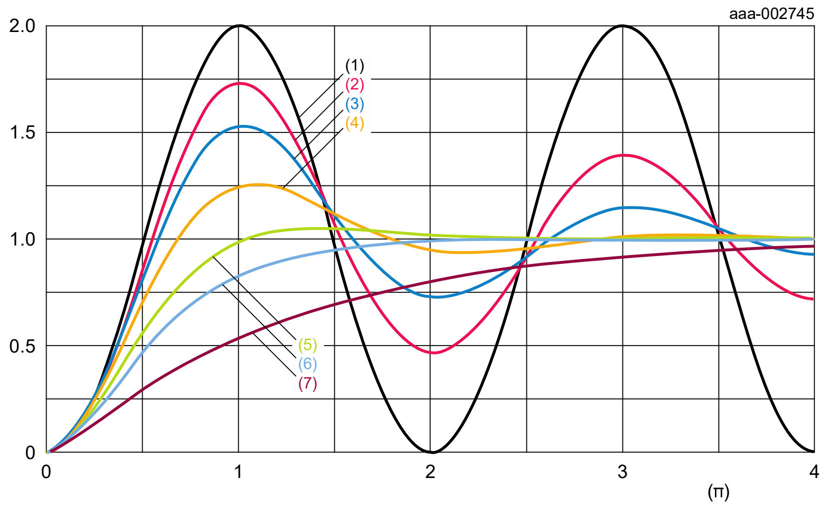
4. Designing the snubber - theory

If we replace C_S in Fig. 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 Q2 turning on) depends on the degree of damping (ζ or zeta) in the circuit; see Fig. 5.



(1) ζ = 0.
(2) ζ = 0.1.
(3) ζ = 0.2.
(4) ζ = 0.4.
(5) ζ = 0.7.
(6) ζ = 1.
(7) ζ = 2.

Fig. 5. Step response of an RLC circuit for various values of zeta (ζ)

In theory the circuit oscillates indefinitely if ζ = zero, although this is a practical impossibility as there is always some resistance in a real circuit. As ζ increases towards one, the oscillation becomes more damped that is, tends to decrease over time with an exponential decay envelope. This is an “under-damped” response. The case ζ = one is known as “critically damped” and is the point at which oscillation just ceases. For values of greater than one (over-damped), 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 ζ, R_S, L_{LK} and C_{LK} is:

$$\zeta = \left(\frac{1}{2R_S}\right)\sqrt{\frac{L_{LK}}{C_{LK}}} \quad (9)$$

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:

$$F_C = \frac{1}{2\pi \ R_S \ C_S} \quad (10)$$

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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 Fig. 2. To recap:

C_{LK} = 3239 pF
L_{LK} = 8.0 nH
f_{RING0} = 31.25 MHz

$$\zeta = \left(\frac{1}{2R_S}\right)\sqrt{\frac{L_{LK}}{C_{LK}}} \tag{11}$$

$$F_C = \frac{1}{2\pi\, R_S\, C_S} = f_{\mathrm{RING0}} \tag{12}$$

The first task is to choose a value of damping (Fig. 5). We have chosen ζ = 1, that is, critical damping. Rearranging Equation 11 we have:

$$R_S = \left(\frac{1}{2\zeta}\right)\sqrt{\frac{L_{LK}}{C_{LK}}} = \left(\frac{1}{2}\right)\sqrt{\frac{8.0\times10^{-9}}{3.239\times10^{-9}}} = 0.78\ \Omega \tag{13}$$

use 2 × 1.5 Ω in parallel to give 0.75 Ω.

Rearranging Equation 12 we have:

$$C_S = \frac{1}{2\pi\, R_S\, f_{\mathrm{RING0}}} = \frac{1}{2\times\pi\times0.75\times3.125\times10^{7}} = 6.79\ nF \tag{14}$$

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 Fig. 6 together with the original (non-snubbed) waveform from Fig. 2.

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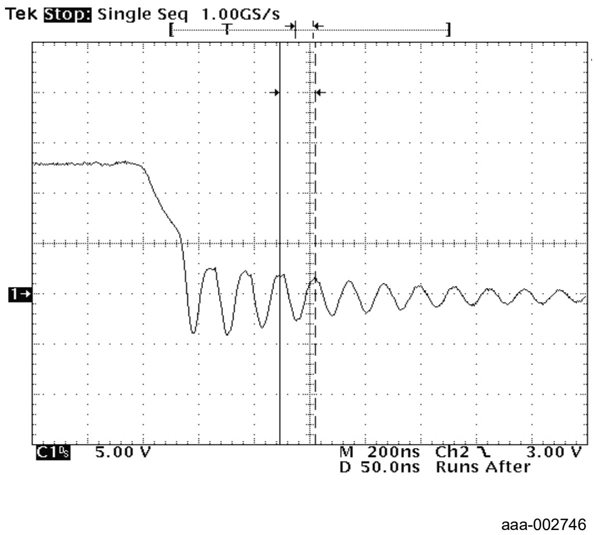
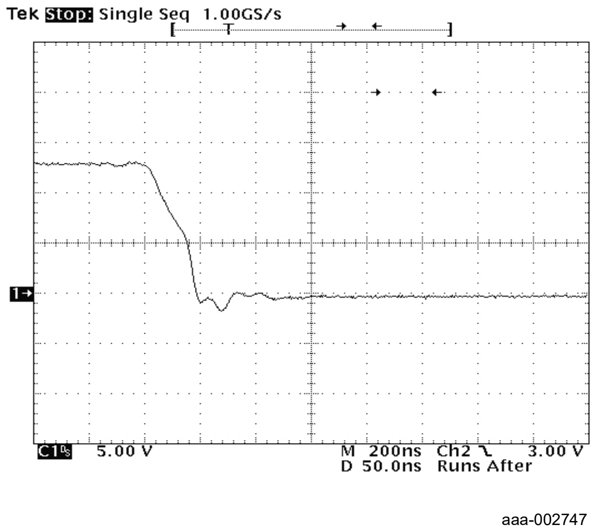


a. Without snubber
Vertical scale is 2 V/div.



b. With snubber

Fig. 6. Q2 V_{DS} waveform with and without snubber

As seen in Fig. 6 the snubber has almost eliminated the ringing in the V_{DS} 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:

$$f_{RING0} = \frac{1}{2\pi\sqrt{L_{LK}\,C_{LK}}} \tag{15}$$

where fRING0 is the frequency of oscillation without a snubber in place and LLK and CLK are the parasitic inductances and capacitances respectively.

If we add capacitor Cadd across Q1 drain-source, fRING0 is reduced by an amount “x” where:

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

therefore

$$\frac{1}{2\pi\sqrt{L_{LK}\,C_{LK}}} = \frac{x}{2\pi\sqrt{L_{LK}\left(C_{LK} + C_{add}\right)}} \tag{17}$$

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

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

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

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

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

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

where:

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

8. Revision history

Table 1. Revision history

Revision number	Date	Description
2.0	2021-05-18	Document revised to use latest Nexperia branding and legal information.
1.0	2012-04-25	Initial version.

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