Important notice

Dear Customer,

On 7 February 2017 the former NXP Standard Product business became a new company with the tradename Nexperia. Nexperia is an industry leading supplier of Discrete, Logic and PowerMOS semiconductors with its focus on the automotive, industrial, computing, consumer and wearable application markets.

In data sheets and application notes which still contain NXP or Philips Semiconductors references, use the references to Nexperia, as shown below.


Instead of sales.addresses@www.nxp.com or sales.addresses@www.semiconductors.philips.com, use salesaddresses@nexperia.com (email)

Replace the copyright notice at the bottom of each page or elsewhere in the document, depending on the version, as shown below:
- © NXP N.V. (year). All rights reserved or © Koninklijke Philips Electronics N.V. (year). All rights reserved
Should be replaced with:
- © Nexperia B.V. (year). All rights reserved.

If you have any questions related to the data sheet, please contact our nearest sales office via e-mail or telephone (details via salesaddresses@nexperia.com). Thank you for your cooperation and understanding,

Kind regards,

Team Nexperia
An1160
Designing RC snubbers
Rev. 1 — 25 April 2012
Application note

Document information

<table>
<thead>
<tr>
<th>Info</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keywords</td>
<td>RC snubber, commutation, reverse recovery, leakage inductance, parasitic capacitance, RLC circuit and damping, MOSFET</td>
</tr>
<tr>
<td>Abstract</td>
<td>This document describes the design of a simple RC snubber circuit</td>
</tr>
</tbody>
</table>
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.

![Fig 1. The half-bridge circuit](image)

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.

The equivalent circuit is shown in Figure 3.

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

Fig 3. Equivalent circuit
Designing RC snubbers

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:

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

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 $f_{RING1}$”):

$$C_{LK} = \frac{C_{add}}{x^2 - 1} \tag{2}$$

where:

$$x = \frac{f_{RING0}}{f_{RING1}} \tag{3}$$

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:

$$x = \frac{31.25}{22.2} = 1.41 \tag{4}$$

and from Equation 2:

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

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

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

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

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

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

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  \( Q2 \) 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:

$$\zeta = \left( \frac{L}{2R_S} \right) \left( \frac{L_{LK}}{C_{LK}} \right)$$  \hspace{1cm} (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:

$$f_C = \frac{f}{2\pi R_S C_S}$$  \hspace{1cm} (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:

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

$$\zeta = \left( \frac{L}{2R_S} \right) \left( \frac{L_{LK}}{C_{LK}} \right)$$  \hspace{1cm} (11)

$$f_C = \frac{f}{2\pi R_S C_S} = f_{RING0}$$  \hspace{1cm} (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

\[ R_S = \left( \frac{1}{2\pi f} \right) \sqrt{\frac{L_{LK}}{C_{LK}}} = \left( \frac{1}{2} \right) \sqrt{\frac{8.0 \times 10^{-9}}{3.239 \times 10^{-9}}} = 0.78\Omega \]  \hspace{1cm} (13)

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

Rearranging Equation 12 we have:

\[ C_S = \frac{1}{2\pi R_S f_{RING0}} = \frac{1}{2\pi \times 0.75 \times 3.125 \times 10^{-7}} = 6.79\,nF \]  \hspace{1cm} (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 \( V_{DS} \) 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:

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

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

therefore

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

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

$$C_{LK} = \frac{C_{LK} + C_{add}}{x^2}$$  \hspace{1cm} (20)

$$C_{LK}x^2 - C_{LK} = C_{add}$$  \hspace{1cm} (21)

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

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

where:

$$x = \frac{f_{RING0}}{f_{RING1}}$$  \hspace{1cm} (24)
8. Legal information

8.1 Definitions

Draft — The document is a draft version only. The content is still under internal review and subject to formal approval, which may result in modifications or additions. NXP Semiconductors does not give any representations or warranties as to the accuracy or completeness of information included herein and shall have no liability for the consequences of use of such information.

8.2 Disclaimers

Limited warranty and liability — Information in this document is believed to be accurate and reliable. However, NXP Semiconductors does not give any representations or warranties, expressed or implied, as to the accuracy or completeness of such information and shall have no liability for the consequences of use of such information. NXP Semiconductors takes no responsibility for the content in this document if provided by an information source outside of NXP Semiconductors. In no event shall NXP Semiconductors be liable for any indirect, incidental, punitive, special or consequential damages (including without limitation - lost profits, lost savings, business interruption, costs related to the removal or replacement of any products or rework charges) whether or not such damages are based on tort (including negligence), warranty, breach of contract or any other legal theory.

Notwithstanding any damages that customer might incur for any reason whatsoever, NXP Semiconductors’ aggregate and cumulative liability towards customer for the products described herein shall be limited in accordance with the Terms and conditions of commercial sale of NXP Semiconductors.

Right to make changes — NXP Semiconductors reserves the right to make changes to information published in this document, including without limitation specifications and product descriptions, at any time and without notice. This document supersedes and replaces all information supplied prior to the publication hereof.

Suitability for use — NXP Semiconductors products are not designed, authorized or warranted to be suitable for use in life support, life-critical or safety-critical systems or equipment, nor in applications where failure or malfunction of an NXP Semiconductors product can reasonably be expected to result in personal injury, death or severe property or environmental damage. NXP Semiconductors and its suppliers accept no liability for inclusion and/or use of NXP Semiconductors products in such equipment or applications and therefore such inclusion and/or use is at the customer’s own risk.

Applications — Applications that are described herein for any of these products are for illustrative purposes only. NXP Semiconductors makes no representation or warranty that such applications will be suitable for the specified use without further testing or modification. Customers are responsible for the design and operation of their applications and products using NXP Semiconductors products, and NXP Semiconductors accepts no liability for any assistance with applications or customer product design. It is customer’s sole responsibility to determine whether the NXP Semiconductors product is suitable and fit for the customer’s applications and products planned, as well as for the planned application and use of customer’s third party customer(s). Customers should provide appropriate design and operating safeguards to minimize the risks associated with their applications and products. NXP Semiconductors does not accept any liability related to any default, damage, costs or problem which is based on any weakness or default in the customer’s applications or products, or the application or use by customer’s third party customer(s). Customer is responsible for doing all necessary testing for the customer’s applications and products using NXP Semiconductors products in order to avoid a default of the applications and the products or of the application or use by customer’s third party customer(s). NXP does not accept any liability in this respect.

Export control — This document as well as the item(s) described herein may be subject to export control regulations. Export might require a prior authorization from competent authorities.

Evaluation products — This product is provided on an “as is” and “with all faults” basis for evaluation purposes only. NXP Semiconductors, its affiliates and their suppliers expressly disclaim all warranties, whether expressed or implied, statutory, including but not limited to the implied warranties of non-infringement, merchantability and fitness for a particular purpose. The entire risk as to the quality, or arising out of the use or performance, of this product remains with customer.

In no event shall NXP Semiconductors, its affiliates or their suppliers be liable to customer for any special, indirect, consequential, punitive or incidental damages (including without limitation damages for loss of business, business interruption, loss of use, loss of data or information, and the like) arising out of or inability to use the product, whether or not based on tort (including negligence), strict liability, breach of contract, breach of warranty or any other theory, even if advised of the possibility of such damages.

Notwithstanding any damages that customer might incur for any reason whatsoever (including without limitation, all damages referenced above and all direct or general damages), the entire liability of NXP Semiconductors, its affiliates and their suppliers and customer’s exclusive remedy for all of the foregoing shall be limited to actual damages incurred by customer based on reasonable reliance up to the greater of the amount actually paid by customer for the product or five dollars (US$5.00). The foregoing limitations, exclusions and disclaimers shall apply to the maximum extent permitted by applicable law, even if any remedy fails of its essential purpose.

Translations — A non-English (translated) version of a document is for reference only. The English version shall prevail in case of any discrepancy between the translated and English versions.

8.3 Trademarks

Notice: All referenced brands, product names, service names and trademarks are the property of their respective owners.
9. Contents

1 Introduction ............................................. 3
2 Test circuit ............................................. 3
3 Determining $C_{\text{LK}}$ and $L_{\text{LK}}$ .................. 5
4 Designing the snubber - theory ..................... 6
5 Designing the snubber - in practice ............ 7
6 Summary .................................................. 8
7 Appendix A; determining $C_{\text{LK}}$ from $C_{\text{add}}$, $f_{\text{RING0}}$ and $f_{\text{RING1}}$ ........................................ 9
8 Legal information ....................................... 10
  8.1 Definitions .......................................... 10
  8.2 Disclaimers .......................................... 10
  8.3 Trademarks .......................................... 10
9 Contents .................................................. 11