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A Methodical Approach To Snubber Design

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Even in a correctly designed switching power supply, stray capacitance and inductance in the traces and leads can cause oscillation in switching currents at turn-off due to the energy stored in these parasitic components. Since the oscillation may occur at many megahertz, satisfying requirements for the electromagnetic compatibility (EMC) of the switching power supply may be challenging.

Properly designed snubbers may absorb the energy stored in the stray components and make the switching process smooth and oscillation-free. Unfortunately, many designers overlook the physical processes in switching circuits and just pick values for snubber components using trial and error, leading to poor results. This article explains the underlying process that leads to oscillation in switching power supplies and describes an analytical approach to designing an RC snubber that will effectively dampen the oscillation.

Very often the parasitic turn-off oscillation occurs when a MOSFET comprising the power switch in a switching power supply or solenoid driver turns off quickly. The energy stored in the MOSFET output capacitance causes a resonant situation with the stray inductance of traces and parts' leads. A properly designed simple RC snubber can convert the resonant (oscillating) process into an aperiodic one, thus mitigating the EMC issues.

Fig. 1 shows a regular circuit, consisting of the output capacitance of a MOSFET C_D, a stray inductance L_{st} and a snubber R_{sn}-C_{sn}, connected in parallel with the drain and source output terminals of the MOSFET. This snubber should damp oscillations, which *always* occur in the drain circuit during MOSFET turn-off, by removing the conditions that may support the oscillation.

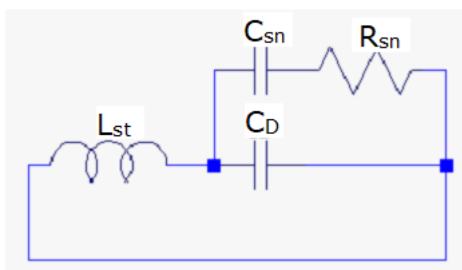


Fig. 1. RC snubber installed from drain to ground of a MOSFET with output capacitance C_D.

However, parasitic oscillations may be generated in other parts of a switching power supply such as in the gates of MOSFETs or in rectifiers. But in these cases, these oscillations are always associated with the release of energy stored in stray components in the circuit. Therefore, the analysis that will be presented in this article is good for any electronic circuit, subject to the energy exchange between its components.

We will consider an equivalent oscillating circuit, which usually occurs when a MOSFET turns off, and the output capacitance C_D exchanges energy with a stray inductor L_{st} through a blocking capacitance of the input power supply.

This circuit behavior at the MOSFET turn-off is the same as that when a rail voltage V_{rail} hits this circuit. We will analyze the transfer function of this circuit for the rail voltage reaching C_D, and define the snubber capacitor C_{sn} and resistor R_{sn} values that destroy the oscillation and convert it into an aperiodic process.

How A Snubber Works At Switch Turn-Off

We start by defining the snubber impedance this way:

$$Z_{sn}(s) = R_{sn} + \frac{1}{s \cdot C_{sn}}$$

which simplifies to this:

$$Z_{sn}(s) = \frac{C_{sn} \cdot R_{sn} + 1}{C_{sn} \cdot s} \qquad (1)$$

The impedance of the circuit, composed of the snubber in parallel with C_D can be expressed by this simplified formula:

$$Z_0(s) = \frac{C_{sn} \cdot R_{sn} \cdot s + 1}{s(C_D + C_{sn} + C_D \cdot C_{sn} \cdot R_{sn} \cdot s)} \qquad (2)$$

The total impedance of the circuit is therefore

$$Z_{tot}(s) = \frac{C_D \cdot L_{st} \cdot s^2 + C_{sn} \cdot L_{st} \cdot s^2 + C_{sn} \cdot R_{sn} \cdot s + C_D \cdot C_{sn} \cdot L_{st} \cdot R_{sn} \cdot s^3 + 1}{s(C_D + C_{sn} + C_D \cdot C_{sn} \cdot R_{sn} \cdot s)} \qquad (3)$$

Then, the voltage across the snubber when V_{rail} hits the circuit during MOSFET turn-off is

$$V_D(s) = \frac{V_{rail}(s)}{\frac{C_D \cdot L_{st} \cdot s^2 + C_{sn} \cdot L_{st} \cdot s^2 + C_{sn} \cdot R_{sn} \cdot s + C_D \cdot C_{sn} \cdot L_{st} \cdot R_{sn} \cdot s^3 + 1}{s(C_D + C_{sn} + C_D \cdot C_{sn} \cdot R_{sn} \cdot s)}} \cdot \frac{C_{sn} \cdot R_{sn} + 1}{s \cdot (C_D + C_{sn} + C_D \cdot C_{sn} \cdot R_{sn} \cdot s)}$$

This expression simplifies to

$$V_D(s) = \frac{V_{rail}(s) \cdot (C_{sn} \cdot R_{sn} \cdot s + 1)}{C_D \cdot L_{st} \cdot s^2 + C_{sn} \cdot L_{st} \cdot s^2 + C_{sn} \cdot R_{sn} \cdot s + C_D \cdot C_{sn} \cdot L_{st} \cdot R_{sn} \cdot s^3 + 1} \qquad (4)$$

Now we are ready to define the transfer function:

$$G(s) = \frac{V_D(s)}{V_{rail}(s)} \qquad (5)$$

Then, substituting equation (4) into (5) we obtain:

$$G(s) = \frac{(C_{sn} \cdot R_{sn} \cdot s + 1)}{C_D \cdot L_{st} \cdot s^2 + C_{sn} \cdot L_{st} \cdot s^2 + C_{sn} \cdot R_{sn} \cdot s + C_D \cdot C_{sn} \cdot L_{st} \cdot R_{sn} \cdot s^3 + 1} \qquad (6)$$

For simplicity, we can express several of the terms in equation (6) as time constants:

$$\tau_1 = C_{sn} \cdot R_{sn}$$
$$\tau_2 = \sqrt{L_{st} \cdot (C_D + C_{sn})} \qquad (7)$$
$$\tau_3 = C_{sn} \cdot R_{sn}$$
$$\tau_4 = \sqrt[3]{C_D \cdot C_{sn} \cdot L_{st} \cdot R_{sn}}$$

Now it is time to re-write (6) in a simpler form:

$$G(s) = \frac{(\tau_1 \cdot s + 1)}{1 + s \cdot \tau_3 + s^2 \cdot {\tau_2}^2 + s^3 \cdot {\tau_4}^3} \qquad (8)$$

To make this expression suitable for the Inverse LaPlace transform, we convert the denominator into the factored form:

$$1 + s \cdot \tau_3 + s^2 \cdot {\tau_2}^2 + s^3 \cdot {\tau_4}^3 = (1 + s \cdot T_1) \cdot (1 + s \cdot T_2) \cdot (1 + s \cdot T_3) \qquad (9)$$

Here T_1, T_2 and T_3 are new time constants, and solve the system of equations. We will do that in the MathCAD 15 hidden area for simplicity. The values for these new time constants are obtained in the hidden area.

To do this, we begin by finding the original of the LaPlace transform (8) in the time domain:

$$\frac{(\tau_1 \cdot s + 1)}{s \cdot (1 + s \cdot T_1) \cdot (1 + s \cdot T_2) \cdot (1 + s \cdot T_3)} \Bigg|_{assume,\, s>0,\, \tau_1>0,\, T_1>0,\, T_2>0,\, T_3>0}^{inverse\ Laplace}$$

$$\Rightarrow 1 - \frac{T_2 \cdot e^{-\frac{t}{T_2}} \cdot (T_2 - \tau_1)}{{T_2}^2 - T_1 \cdot T_2 + T_1 \cdot T_3 - T_2 \cdot T_3} - \frac{T_3 \cdot e^{-\frac{t}{T_3}} \cdot (T_3 - \tau_1)}{{T_3}^2 + T_1 \cdot T_2 - T_1 \cdot T_3 - T_2 \cdot T_3} - \frac{T_1 \cdot e^{-\frac{t}{T_1}} \cdot (T_1 - \tau_1)}{{T_1}^2 - T_1 \cdot T_2 - T_1 \cdot T_3 + T_2 \cdot T_3}$$

Next, we analyze expressions for T_1, T_2 and T_3 from the hidden area and pay attention to the expressions under the radical sign. These expressions should be positive unless we want to have ringing in the circuit. This requirement evokes the equation:

$$\frac{{\tau_2}^6}{27} - \frac{{\tau_2}^4 \cdot {\tau_3}^2}{108} - \frac{{\tau_2}^2 \cdot \tau_3 \cdot {\tau_4}^3}{6} + \frac{{\tau_3}^3 \cdot {\tau_4}^3}{27} + \frac{{\tau_4}^6}{4} = 0 \qquad (10)$$

Substituting expressions for the time constants from (7), we get:

$$\frac{\lfloor L_{st}\cdot(C_D+C_{sn})\rfloor^3}{27}-\frac{\lfloor L_{st}\cdot(C_D+C_{sn})\rfloor^2\cdot(C_{sn}\cdot R_{sn})^2}{108}-\frac{\lfloor L_{st}\cdot(C_D+C_{sn})\rfloor^1\cdot(C_{sn}\cdot R_{sn})\cdot(C_D\cdot C_{sn}\cdot L_{st}\cdot R_{sn})^1}{6}$$

$$+\frac{(C_{sn}\cdot R_{sn})^3\cdot(C_D\cdot C_{sn}\cdot L_{st}\cdot R_{sn})^1}{27}+\frac{(C_D\cdot C_{sn}\cdot L_{st}\cdot R_{sn})^2}{4}=0 \qquad (11)$$

Equation (11) describes the borderline condition that holds true for keeping the parasitic oscillation close to extinction.

Solving for R_S, we can obtain a value of the snubber resistor that satisfies the borderline condition.

$$R_{sn}=\left|\begin{matrix}
\sqrt{\dfrac{27\cdot\left[\dfrac{L_{st}\cdot\sqrt{\dfrac{C_{sn}^{\ 5}\cdot(C_{sn}-8\cdot C_D)^3}{11664}}}{2}+\dfrac{C_{sn}^{\ 4}\cdot L_{st}}{216}+\dfrac{5\cdot C_D\cdot C_{sn}^{\ 3}\cdot L_{st}}{54}-\dfrac{C_D^{\ 2}\cdot C_{sn}^{\ 4}\cdot L_{st}}{27}\right]}{C_D C_{sn}^{\ 4}}} \\
-\sqrt{\dfrac{\frac{1}{C_D}}{C_{sn}^{\ 4}}\cdot\left[\dfrac{27}{2}\cdot L_{sn}\cdot\sqrt{\dfrac{1}{11664}}\cdot C_{sn}^{\ 5}\cdot(C_{sn}-8\cdot C_D)^3+\dfrac{1}{8}\cdot C_{sn}^{\ 4}\cdot L_{sn}+\dfrac{5}{2}\cdot C_D\cdot C_{sn}^{\ 3}\cdot L_{sn}-C_D^{\ 2}\cdot C_{sn}^{\ 2}\cdot L_{sn}\right]} \\
\sqrt{\dfrac{-27\cdot\left[\dfrac{L_{sn}\cdot\sqrt{\dfrac{C_{sn}^{\ 5}\cdot(C_{sn}-8\cdot C_D)^3}{11664}}}{2}-\dfrac{C_{sn}^{\ 4}\cdot L_{st}}{216}-\dfrac{5\cdot C_D\cdot C_{sn}^{\ 3}\cdot L_{st}}{54}+\dfrac{C_D^{\ 2}\cdot C_{sn}^{\ 2}\cdot L_{st}}{27}\right]}{C_D C_{sn}^{\ 4}}} \\
-\sqrt{-\dfrac{\frac{1}{C_D}}{C_{sn}^{\ 4}}\cdot\left[\dfrac{27}{2}\cdot L_{sn}\cdot\sqrt{\dfrac{1}{11664}}\cdot C_{sn}^{\ 5}\cdot(C_{sn}-8\cdot C_D)^3-\dfrac{1}{8}\cdot C_{sn}^{\ 4}\cdot L_{sn}-\dfrac{5}{2}\cdot C_D\cdot C_{sn}^{\ 3}\cdot L_{sn}+C_D^{\ 2}\cdot C_{sn}^{\ 2}\cdot L_{sn}\right]}
\end{matrix}\right| \qquad (12)$$

The acceptable value for R_{sn} is the very first term in (12). Luckily, this system of equations also defines the limitation on the value for the snubber capacitor that helps in designing the snubber. It is:

$$C_{sn} > 8\cdot C_D \qquad (13)$$

This is a very important result since it removes the guess work that is often present in snubber capacitor selection.

Therefore, after selecting the snubber capacitor value, which should be close to $8\bullet C_D$, one can find the snubber resistor value from

$$R_{sn} = \sqrt{\frac{27 \cdot \left[\frac{L_{st} \cdot \sqrt{\frac{C_{sn}^{5} \cdot (C_{sn} - 8 \cdot C_D)^3}{11664}}}{2} + \frac{C_{sn}^{4} \cdot L_{st}}{216} + \frac{5 \cdot C_D \cdot C_{sn}^{3} \cdot L_{st}}{54} - \frac{C_D^{2} \cdot C_{sn}^{4} \cdot L_{st}}{27} \right]}{C_D C_{sn}^{4}}} \quad (14)$$

Since the C_D value may strongly depend on the voltage applied, which is the case in MOSFETs, it is necessary to use an averaged value, using the following formula:

$$C_D = -\frac{C_{DS0} \cdot V_{DS0} \left(e^{-\frac{0.37 \cdot V_{DS\_span}}{V_{DS0}}} - 1.0 \right)}{V_{DS\_span}} \quad (15)$$

Here V_{DSO} is defined at the crossing of the tangential line at $V_{ds} = 0$ and the V_{ds} axis since V_{ds} decays exponentially. V_{DS_span} is the span of the drain-source voltage during operation and C_{DSO} is the initial drain-source capacitance at zero drain-source voltage.

A Snubber Design Example

Let's start by assuming we have a circuit like that shown in Fig. 1 with values of L_{St} = 10 nH and C_D = 20 pF. Let's also assume V_{rail} = 180 V and f_{SW} = 150 kHz for our operating conditions.

Per equation 13, we can begin by determining a value for C_{sn} of 8.5 x C_D = 170 pF.

Then applying equation (14) we can determine a value of R_{sn}.

$$R_{sn} = \sqrt{\frac{27 \cdot \left[\frac{L_{st} \cdot \sqrt{\frac{C_{sn}^{5} \cdot (C_{sn} - 8 \cdot C_D)^3}{11664}}}{2} + \frac{C_{sn}^{4} \cdot L_{st}}{216} + \frac{5 \cdot C_D \cdot C_{sn}^{3} \cdot L_{st}}{54} - \frac{C_D^{2} \cdot C_{sn}^{4} \cdot L_{st}}{27} \right]}{C_D C_{sn}^{4}}} = 14.266\ \Omega$$

To simplify component selection and to provide some design margin with respect to the inequality in (13), we can choose a standard value of 200 pF for C_{sn}, which leads to a slightly lower value for R_{sn} of

$$R_{sn} = round\left(\frac{R_{sn} \cdot 0.9}{\Omega}\right) \cdot \Omega = 13\ \Omega$$

Now that we have our values for the snubber components, we can calculate the time constants, which we will use later when writing the expression for the voltage across the MOSFET, $V_D(t)$:

$$\tau_1 = C_{sn} \cdot R_{sn}$$

$$\tau_2 = \sqrt{L_{st} \cdot (C_D + C_{sn})}$$

$$\tau_3 = C_{sn} \cdot R_{sn}$$

$$\tau_4 = \sqrt[3]{C_D \cdot C_{sn} \cdot L_{st} \cdot R_{sn}}$$

To specify the snubber resistor's rated power, we will need to know its power dissipation. The voltage across the snubber resistor is

$$V_{Rsn}(t) = V_{rail} \cdot \left(1 - e^{\frac{-t}{R_{sn} \cdot C_{sn}}}\right)$$

which leads to an expression for the resistor's power dissipation and the following result:

$$P_{R_{sn}} = 2f_{SW} \cdot \int_0^{3 \cdot R_{sn} \cdot C_{sn}} \frac{\left[V_{rail} \cdot \left(1 - e^{\frac{-t}{R_{sn} \cdot C_{sn}}}\right)\right]^2}{R_{sn}} dt = 3.107\ W$$

Now that we have our snubber components, we would like to see how they perform. Equation (4) gives us an expression for the voltage across the snubber when the MOSFET turns off:

$$V_D(s) = \frac{V_{rail}(s) \cdot (C_{sn} \cdot R_{sn} \cdot s + 1)}{C_D \cdot L_{st} \cdot s^2 + C_{sn} \cdot L_{st} \cdot s^2 + C_{sn} \cdot R_{sn} \cdot s + C_D \cdot C_{sn} \cdot L_{st} \cdot R_{sn} \cdot s^3 + 1}$$

which can be rewritten in the time domain as follows by substituting the time constants for the circuit values:

$$V_D(t) = V_{rail}\left[1 - V\frac{T_2 \cdot e^{-\frac{t}{T_2}} \cdot (T_2 - \tau_1)}{{T_2}^2 - T_1 \cdot T_2 + T_1 \cdot T_3 - T_2 \cdot T_3} - \frac{T_3 \cdot e^{-\frac{t}{T_3}} \cdot (T_3 - \tau_1)}{{T_3}^2 + T_1 \cdot T_2 - T_1 \cdot T_3 - T_2 \cdot T_3} - \frac{T_1 \cdot e^{-\frac{t}{T_1}} \cdot (T_1 - \tau_1)}{{T_1}^2 - T_1 \cdot T_2 - T_1 \cdot T_3 + T_2 \cdot T_3}\right]$$

Graphing this expression yields the result shown in Fig. 2.

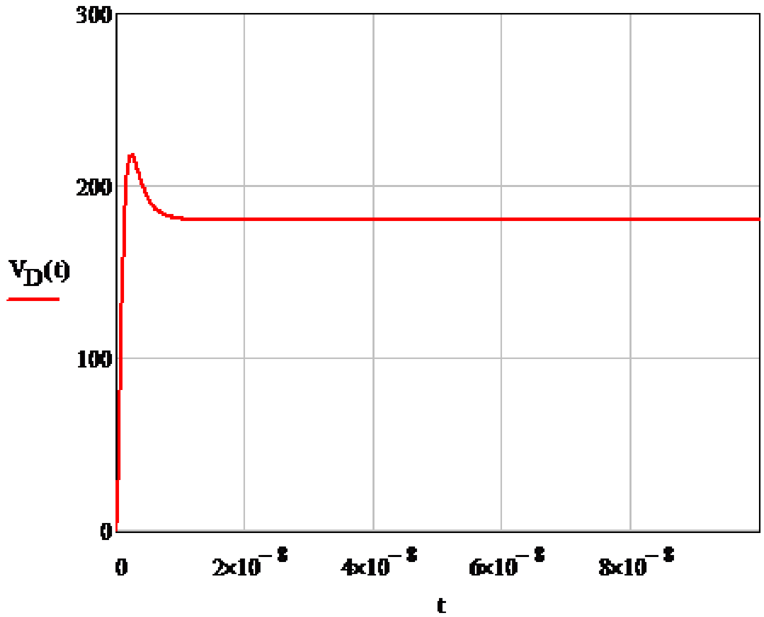
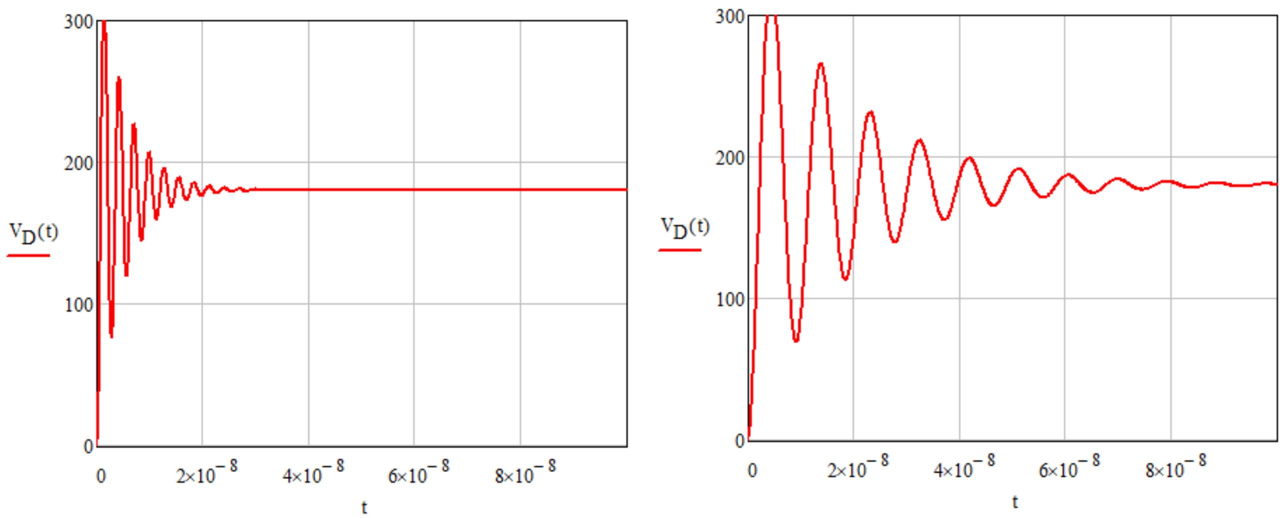


Fig. 2. With the snubber values calculated in our design example (C_{sn} = 200 pF and R_{sn} = 13 Ω), the voltage across the snubber (at the switching node) exhibits only slight overshoot and no oscillation with fast switching.

The above design example demonstrates how properly calculating the snubber component values leads to oscillation-free operation even with fast switching. But to put this result in perspective, let's consider what happens if the snubber values are selected arbitrarily and then adjusted experimentally as illustrated in Fig. 3. Typically, engineers will adjust the value of the snubber resistor, which causes problems with switching operation. As the results in Fig. 3 demonstrate, random selection of the R_{sn} and C_{sn} values leads either to oscillations or excessive power dissipation as shown in (c).

C_{sn} = 200 pF and R_{sn} = 130 Ω

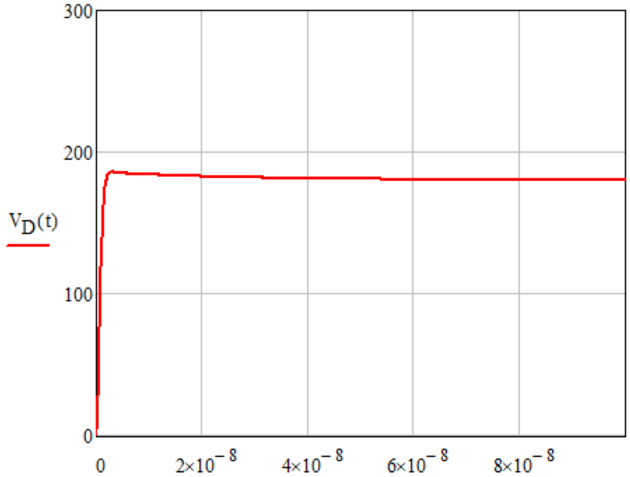
C_{sn} = 200 pF and R_{sn} = 1.3 Ω



(a)

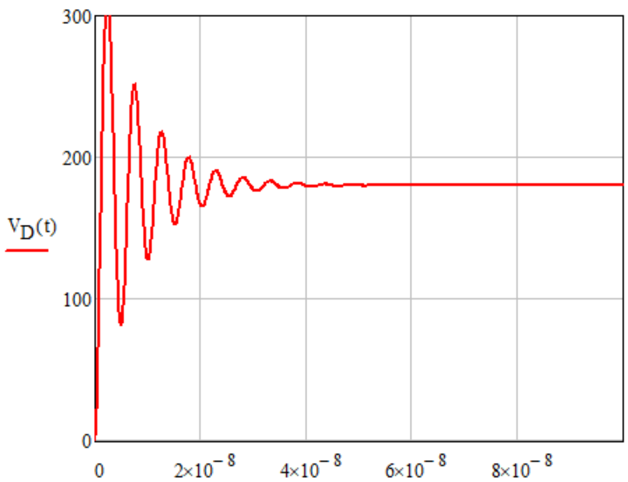
(b)

C_{sn} = 2000 pF, R_{sn} = 13 Ω and P_{Rsn} = 31 W



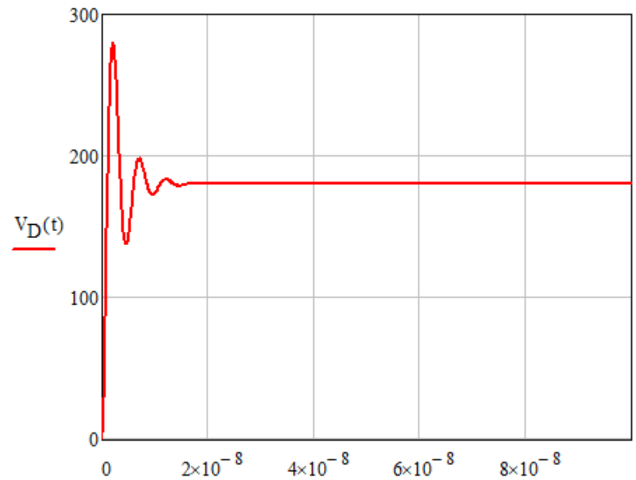
(c)

C_{sn} = 47 pF and R_{sn} = 5 Ω



(d)

C_{sn} = 47 pF and R_{sn} = 13 Ω



(e)

Fig. 3. Randomly selecting snubber component values and adjusting them experimentally leads either to oscillations on the switching waveform, or excessive power dissipation. Part (c) shows the case where oscillation has been eliminated but at the cost of excessive power dissipation in the snubber resistor. The results shown here were obtained by plugging in the R_{sn} and C_{sn} values shown into our expression for $V_D(t)$.

About The Author

Gregory Mirsky is a senior electrical engineer with Continental Automotive Systems in Deer Park, Ill., which he joined in March 2015. In his current role, Gregory performs design verification on various projects, designs and implements new methods of electronic circuit analysis, and runs workshops on MathCAD 15 usage for circuit design and verification.

He obtained a Ph.D. degree in physics and mathematics from the Moscow State Pedagogical University, Russia. During his graduate work, Gregory designed hardware for the high-resolution spectrometer for research of highly compensated semiconductors and high-temperature superconductors. He also holds an MS degree from the Baltic State Technical University, St. Petersburg, Russia where he majored in missile and aircraft electronic systems.

Gregory holds numerous patents and publications in technical and scientific magazines in Great Britain, Russia and the United States. Outside of work, Gregory's hobby is traveling, which is associated with his wife's business as a tour operator, and he publishes movies and pictures about his travels online.

For more information on snubber design, see How2Power's Design Guide, locate the Power Supply Function category and select "Filters and Snubbers".