

Designing RC Snubber Networks

Snubbers are any of several simple energy absorbing circuits used to eliminate voltage spikes caused by circuit inductance when a switch — either mechanical or semi-conductor—opens. The object of the snubber is to eliminate the voltage transient and ringing that occurs when the switch opens by providing an alternate path for the current flowing through the circuit's intrinsic leakage inductance. Snubbers in switchmode power supplies provide one or more of these three valuable functions:

- Shape the load line of a bipolar switching transistor to keep it in its safe operating area.
- Remove energy from a switching transistor and dissipate the energy in a resistor to reduce junction temperature.
- Reduce ringing to limit the peak voltage on a switching transistor or rectifying diode and to reduce EMI by reducing emissions and lowering their frequency.

The most popular snubber circuit is a capacitor and a series resistor connected across a switch. Here's how to design that ubiquitous RC Snubber:

Component Selection: Choose a resistor that's noninductive. A good choice is a carbon composition resistor. A carbon film resistor is satisfactory unless it's trimmed to value with a spiral abrasion pattern. Avoid wirewound because it is inductive.

Choose a capacitor to withstand the stratospherically high peak currents in snubbers. For capacitance values up to 0.01 μF , look first at dipped mica capacitors. For higher capacitance values, look at the Type DPP radial-leaded polypropylene, film/foil capacitors. Axial-leaded Type WPP is as good except for the higher inductance intrinsic to axial-leaded devices.

The highest Type DPP rated voltage is 630 Vdc and the highest Type WPP voltage is 1000 Vdc. For higher voltages and capacitances, stay with polypropylene film/foil capacitors, choosing the case size you prefer from Types DPFF and DPSS selections. For the smallest case size, choose Type DPPM or DPMF, but realize that these types include floating metallized film as common foils to achieve small size. The use of metallized film reduces the peak current capability to from a third to a fifth of the other high-voltage choices.

The selection process is easy in this catalog — peak current and rms current capability is provided with the capacitance ratings. The peak current capability is the dV/dt capability times the nominal capacitance. The rms current capability is the lower of the current which causes the capacitor to heat up 15°C or the current which causes the capacitor to reach its AC voltage.

We've included dV/dt capability tables to allow you to compare CDE snubber capacitors to other brands. Dipped mica capacitors can withstand dV/dts of more than 100,000 $\text{V}/\mu\text{s}$ for all ratings and Type DPPs can withstand more than 2000 $\text{V}/\mu\text{s}$. For high-voltage snubbers, Types DPFF and DPSS handle more than 3000 $\text{V}/\mu\text{s}$, and Types DPMF and DPPM, more than 1000 $\text{V}/\mu\text{s}$. See the table for values according to case length.

Assuming that the source impedance is negligible—the worst case assumption—the peak current for your RC Snubber is:

$$I_{pk} = \frac{V_0}{R_s} \quad \begin{array}{l} V_0 = \text{open circuit voltage} \\ R_s = \text{snubber resistance} \\ C_s = \text{snubber capacitance} \end{array}$$

And the peak dV/dt is:

$$dV/dt_{pk} = \frac{V_0}{R_s C_s}$$

While for a sinewave excitation voltage, rms current in amps is the familiar:

$$I_{rms} = 2\pi f C V_{rms} \times 10^{-6} \quad \begin{array}{l} f = \text{frequency in Hz} \\ C = \text{capacitance in } \mu\text{F} \\ V = \text{voltage in } V_{rms} \end{array}$$

For a squarewave you can approximate rms and peak current as:

$$I_{rms} = \frac{C V_{pp}}{.64 \sqrt{tT}} \quad \begin{array}{l} V_{pp} = \text{peak-peak volts} \\ t = \text{pulse width in } \mu\text{s} \\ V = \text{voltage in } V_{rms} \\ T = \text{Pulse periods in } \mu\text{s} \end{array}$$

and

$$I_{peak} = \frac{C V_{pp}}{.64 tT}$$

Other Capacitor Types: Here's a last word on capacitor choice to help you venture out on your own into the uncharted territory of capacitors not specified for use in snubbers and are not in this section.

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Realize that metallized film types and high-K ceramic types have limited peak-current and transient withstanding capability, on the order of 50 to 200 V/ μ s. Polyester has 15 times the loss of polypropylene and is fit only for low rms currents or duty cycles. And, be sure to take voltage and temperature coefficients into account. While a mica's or a Type DPP's capacitance is nearly independent of voltage and temperature, by comparison, a high-K ceramic dielectric like Y5V can lose $\frac{1}{4}$ of its capacitance from room temperature to 50°C (122°F) and lose another $\frac{1}{4}$ from zero volts to 50% rated voltage.

Quick Snubber Design: Where power dissipation is not critical, there is a quick way to design a snubber. Plan on using a 2-watt carbon composition resistor. Choose the resistor value so that the same current can continue to flow without voltage overshoot after the switch opens and the current is diverted into the snubber. Measure or calculate the voltage across the switch after it opens and the current through it at the instant before the switch opens. For the current to flow through the resistor without requiring a voltage overshoot, Ohm's Law says the resistance must be:

$$R \leq \frac{V_o}{I} \quad \begin{array}{l} V_o = \text{off voltage} \\ I = \text{on current} \end{array}$$

The resistor's power dissipation is independent of the resistance R because the resistor dissipates the energy stored in the snubber capacitor, $\frac{1}{2}C_s V_o^2$, for each voltage transition regardless of the resistance. Choose the capacitance to cause the 2-watt resistor to dissipate half of its power rating, one watt. For two times f_s transitions per second, the resistor will dissipate one watt when:

$$1 = (\frac{1}{2}C_s V_o^2)(2f_s) \quad f_s = \text{switching frequency}$$

$$C_s = \frac{1}{V_o^2 f_s}$$

As an illustration, suppose that you have designed a switchmode converter and you want to snub one of the transistor switches. The switching frequency is 50 kHz and the open-switch voltage is 160 Vdc with a maximum switch current of 5A. The resistor value must be:

$$R \leq 160/5 = 32 \Omega$$

and the capacitance value is:

$$C_s = \frac{1}{(160)^2(50 \times 10^3)} = 780 \text{ pF}$$

Optimum Snubber Design: For optimum snubber design using the AC characteristics of your circuit, first determine the circuit's intrinsic capacitance and inductance. Suppose you were designing a snubber for the same transistor switch as in the "Quick" example. Then on a scope note the ringing frequency of the voltage transient when the transistor turns off. Next, starting with a 100 pF mica capacitor, increase the capacitance across the transistor in steps until the ringing frequency is half of the starting frequency. The capacitance you have added in parallel with the transistor's intrinsic capacitance has now increased the total capacitance by a factor of four as the ringing frequency is inversely proportional to the square root of the circuit's inductance capacitance product:

$$f_o = \frac{1}{2\pi \sqrt{LC}}$$

So, the transistor's intrinsic capacitance, C_i , is $\frac{1}{3}$ of the added capacitance, and the circuit inductance, from the above equation, is:

$$L_i = \frac{1}{C_i(2\pi f_i)^2} \quad \begin{array}{l} f_i = \text{initial ringing frequency} \\ C_i = \text{intrinsic capacitance} \\ \quad \quad \quad \text{(added capacitance) } / 3 \\ L_i = \text{intrinsic inductance} \end{array}$$

When the transistor switch opens, the snubber capacitor looks like a short to the voltage change, and only the snubber resistor is in the circuit. Choose a resistor value no larger than the characteristic impedance of the circuit so that the inductive current to be snubbed can continue unchanged without a voltage transient when the switch opens:

$$R = \sqrt{L_i/C_i}$$

You may need to choose an even smaller resistance to reduce voltage overshoot. The right resistance can be as little as half the characteristic impedance for better sampling of the Intrinsic LC circuit.

The power dissipated in the resistor is the energy in the capacitance, $\frac{1}{2}C_s V_o^2$, times the switching

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frequency, f_s , times the number of voltage transitions per cycle. For example, if your circuit is a half-bridge converter, there are two voltage transitions per cycle and the power in the resistor is:

$$P_r = C_s V_o^2 f_s \quad \begin{array}{l} C_s = \text{snubber capacitance} \\ V_o = \text{off voltage} \\ f_s = \text{switching frequency} \end{array}$$

Choose a snubber capacitance value which meets two requirements:

1) It can provide a final energy storage greater than the energy in the circuit inductance

$$\frac{1}{2}C_s V_o^2 > \frac{1}{2}L_i I^2 \quad I = \text{closed circuit}$$

$$C_s > \frac{L_i I^2}{V_o^2}$$

and,

2) it produces a time constant with the snubber resistor that is small compared to the shortest expected on-time for the transistor switch.

$$RC_s < t_{on}/10$$

$$C_s < t_{on}/10R$$

Choosing a capacitance near the low end of the range reduces power dissipated in the resistor, and choosing a capacitance 8 to 10 times the intrinsic capacitance, C_i , almost suppresses the voltage overshoot at switch turn off. Try a capacitance at the low end of the range as the initial value and increase it later if needed.

Now revisit the “Quick” example with the added data permitting “Optimum” design. You’ve taken some more measurements on your switchmode converter: the ringing frequency of the voltage transient when the transistor switch opens is 44 MHz and an added parallel capacitance of 200 pF reduces the ringing frequency to 22 MHz. The switching frequency is 50 kHz with a 10% minimum duty cycle, and the open-switch voltage is 160 Vdc with a maximum switch current of 5A. So you know the following:

$$\begin{array}{l} f_i = 44 \text{ MHz} \\ C_i = 200/3 = 67 \text{ pF} \\ f_s = 50 \text{ kHz} \\ t_{on} = 0.1/(50 \times 10^3) = 2 \text{ } \mu\text{s} \\ V_o = 160 \text{ Vdc} \\ I = 5 \text{ A} \end{array}$$

And calculate the circuit inductance:

$$L_i = \frac{1}{(67 \times 10^{-12})(2\pi 44 \times 10^6)^2} = 0.196 \text{ } \mu\text{H}$$

And the snubber resistor value:

$$R = \sqrt{0.196/67} (10^{-3}) = 54 \text{ } \Omega$$

Before you can calculate the resistor power dissipation, you must first choose the snubber capacitance:

$$\frac{L_i I^2}{V_o^2} < C_s < \frac{t_{on}}{10R}$$

$$\frac{(0.196 \times 10^{-6})(5)^2}{(160)^2} < C_s < \frac{2 \times 10^{-6}}{(10)(54)}$$

$$192 < C_s < 3700 \text{ pF}$$

Since power dissipation in the resistor is proportional to the capacitance, choose a standard capacitance value near the low end of the above range. For a 220 pF capacitor and two transitions per cycle, the power dissipation in the resistor is:

$$P_r = (220 \times 10^{-12})(160)^2(50 \times 10^3) = 0.2 \text{ W}$$

Comparing the “Quick” design to the “Optimum” design, you see that for the same converter switch the required snubber resistor’s power capability was reduced by a factor of 5, from 1 W to 0.2 W, and the snubber capacitance was reduced by a factor of 3.5, from 780 pF to 220 pF. This was possible because the additional circuit measurements revealed that the source impedance was actually 54 Ω rather than 32 Ω , and that the circuit inductance permitted a smaller capacitance to swallow the circuit’s energy.

Usually the “Quick” method is completely adequate for final design. Start with the “Quick” approach to prove your circuit breadboard, and go on to the “Optimum” approach only if power efficiency and size constraints dictate the need for optimum design.

NOTE: For more on RC snubber design, for RCD snubber design, and for snubber design using IGBT snubber modules, get the application note, “Design of Snubbers for Power Circuits,” at www.cde.com