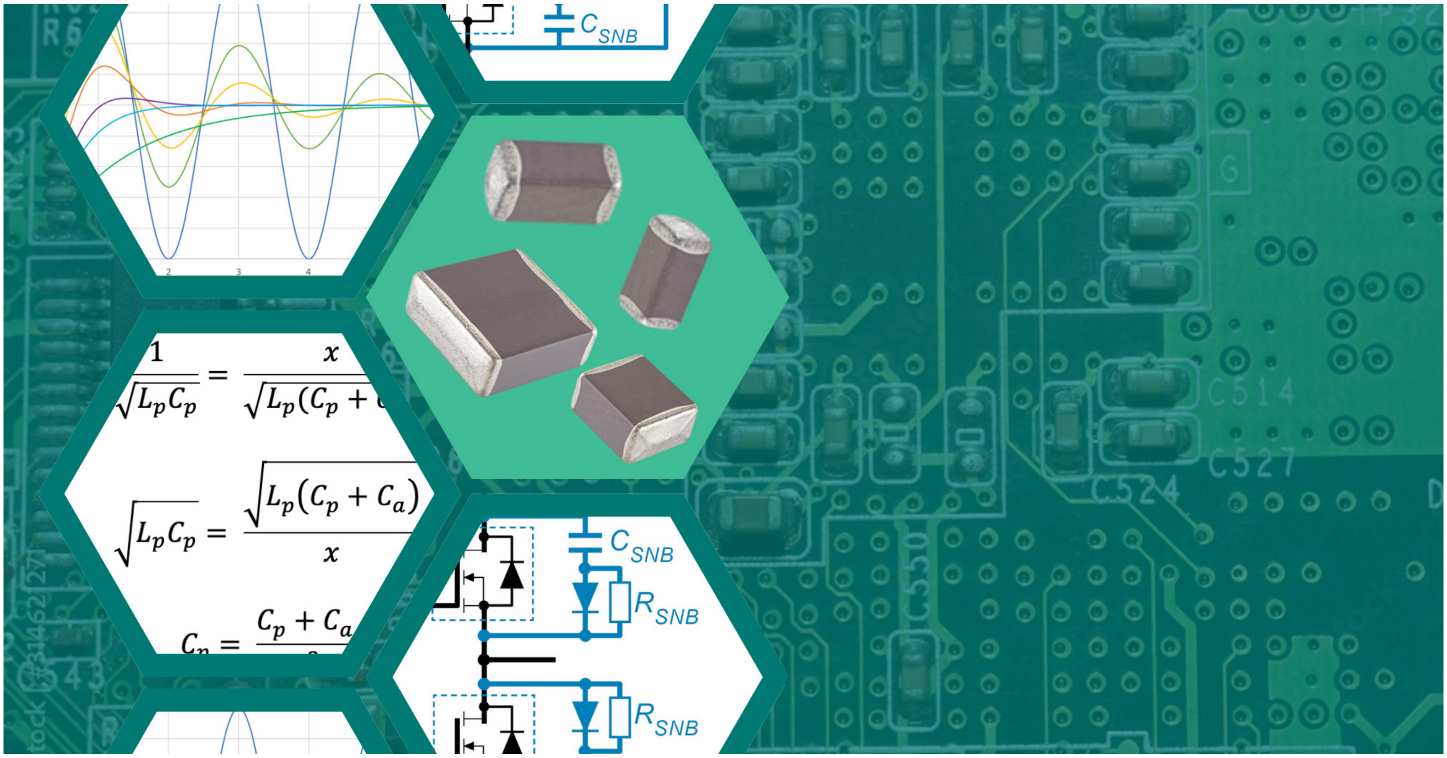
WHITE PAPER

HOW TO SIZE A SNUBBER CAPACITOR FOR YOUR POWER SUPPLY

Jordan Yates, Marketing Engineer, Knowles Precision Devices
Matt Johnson, Applications and R&D Engineer, Knowles Precision Devices



It's becoming more common to see power supply circuits with wide-bandgap semiconductors rather than traditional silicon insulated-gate bipolar transistors (IGBTs). The performance benefits of this switch are known and observed, but with costs coming down, silicon carbide (SiC) and gallium nitride (GaN) semiconductors are more accessible than ever before.

Transitioning components impacts design, performance and reliability in power electronics across the automotive and defense sectors. There's a growing need for engineers to adapt to these new challenges, especially as they relate to circuit design and component selection.

Circuit Design Challenges Associated with Wide-Bandgap Semiconductors in Power Electronics

While the fundamental circuit design process doesn't change, substituting a component as vital as a semiconductor causes a domino effect in the component selection process. With the shift toward wide-bandgap semiconductors, engineers need to step back and take a fresh look at factors like voltage rating, capacitance value, equivalent series resistance (ESR) and equivalent series inductance (ESL) in the design process.

Efficiency and reliability remain central concerns in power electronics, and component selection and implementation are critical to achieving performance specifications with different switches in place. SiC and GaN are associated with higher switching frequencies, so it becomes more important to manage parasitic inductances and capacitances in circuit design. Snubber capacitors are essential components in power supply circuits because of their role in damping (or "snubbing") excessive ringing in converters, like flybacks.

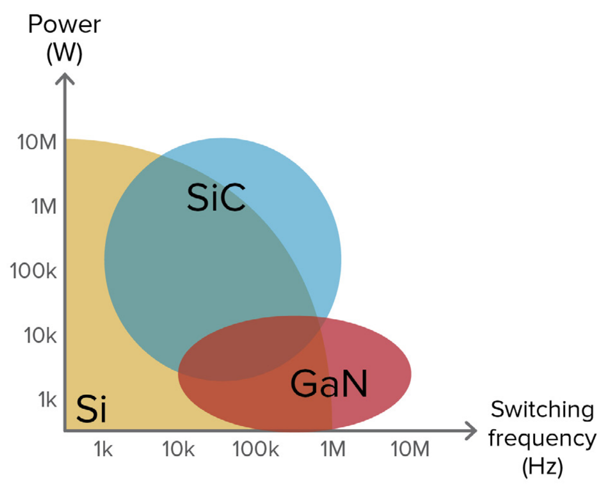


Figure 1: The combination of higher power and higher frequency increases the overall switching frequency for wide-bandgap semiconductors

The structure and material of these capacitors require careful consideration. Depending on your application-specific requirements, there are several capacitor varieties that can serve as snubbers, including ceramic, film and electrolytic capacitors. System specifications such as type of semiconductor, voltage rating and frequency of switching will guide selection.

Ceramics offer high reliability, excellent performance over a wide temperature range and self-healing properties to cope with voltage spikes. In particular, Class I MLCCs are minimally impacted by changes in voltage and are not as susceptible to aging.

Wide-bandgap semiconductors don't make snubber capacitors any more complicated to size, but the shift in rating causes expected values to shift in the rest of the downstream sizing equations. In this white paper, we'll cover basic snubber derivation for a simple switching circuit. While snubber circuits are much more complex in practice, this exercise is useful for understanding how these switches impact snubber capacitor sizing

Basic Snubber Capacitor Sizing Calculation

Sizing a snubber capacitor requires calculating a circuit's parasitic capacitance and inductance. Those values are used to identify the snubber capacitor and resistor values. For a basic example, we'll look at an RC snubber circuit when power dissipation is not critical.

Identifying Critical Parameters

To start, we select a snubber capacitor that's twice the sum of the switch's output capacitance and the estimated mounting capacitance. These values are typically available on component datasheets.

The snubber resistor (R_s) is selected using the equation:

$$R_s = \frac{V_{pk-pk}}{I_{rms}}$$

The resulting power dissipation associated with (R_s) can be estimated as:

$$Pd = C_S \left(V_{pk-pk}\right)^2 F_S$$

Where is power Pd dissipation and (F_s) is switching frequency.

Analyzing Switching Characteristics

Switching stresses in a circuit can be very high due to parasitic inductance (L_p) and capacitance (C_p). C_p encompasses the output capacitance of the switch and stray capacitance associated with PCB layout and mounting, while L_p accounts for the parasitic inductance associated with PCB routing and MOSFET lead inductance.

In combination, C_p and L_p form a filter that resonates after hard switching. This parasitic resonance causes excessive voltage ringing. A basic RC snubber circuit suppresses voltage ringing so long as it meets two main criteria:

- **Resistor:** The resistor value must be close to the impedance of the parasitic resonance it needs to damp.
- **Capacitor:** The capacitor value must be larger than the parasitic capacitance, yet small enough to keep the power dissipation of the resistor low.

Calculating and Optimizing Snubber Capacitor Values

To optimize the effect of an RC snubber, we need to use known equations to determine the exact resistor and capacitor values.

The relationship between ringing frequency, parasitic capacitance and parasitic inductance is based on the standard equation for a resonant circuit:

$$F_{ring} = \frac{1}{2\pi\sqrt{L_p C_p}}$$

First, measure ringing without any snubbing effects in place. Record this frequency as F_{ring0}. Next, place an additional capacitor, C_a, across the switch node, resulting in a new ringing frequency, F_{ring1}. The value of C_a should start in the region of 100pF, and F_{ring1} must be less than F_{ring0}. The difference between these two separate states of capacitance, with different ringing frequencies, allows us to draw an algebraic comparison and establish exact values for parasitic capacitance and inductance.

$$F_{ring0} = \frac{1}{2\pi\sqrt{L_p C_p}}$$

If we describe the relationship between F_{ring0} and F_{ring1} as a proportion, x, by which F_{ring0} is reduced, we have:

$$x = \frac{F_{ring0}}{F_{ring1}}$$

So, we can express F_{ring1} in terms of C_a:

$$\frac{F_{ring0}}{x} = \frac{1}{2\pi\sqrt{L_p(C_p + C_a)}}$$

Therefore:

$$\frac{1}{2\pi\sqrt{L_pC_p}} = \frac{x}{2\pi\sqrt{L_p(C_p + C_a)}}$$

Working through this equation, we can derive a value for parasitic capacitance based on X and C_a.

$$\frac{1}{\sqrt{L_pC_p}} = \frac{x}{\sqrt{L_p(C_p + C_a)}}$$

$$\sqrt{L_pC_p} = \frac{\sqrt{L_p(C_p + C_a)}}{x}$$

$$C_p = \frac{C_p + C_a}{x^2}$$

$$C_px^2 - C_p = C_a$$

$$C_p(x^2 - 1) = C_a$$

$$C_p = \frac{C_a}{x^2 - 1}$$

With this relationship determined, we can find C_p and L_p by measuring F_{ring0} without C_a and adding our known values of C_a and F_{ring1} (measured).

After finding C_p, we can determine L_p using the original equation for F_{ring0} where:

$$L_p = \frac{1}{C_p(2\pi F_{ring0})^2}$$

With values for C_p and L_p, we can identify values for R_s and C_s for an optimal snubber configuration by implementing equations for the cutoff frequency and intended damping factor:

$$\zeta = \left(\frac{1}{2R_s}\right)\sqrt{\frac{L_p}{C_p}}$$

$$R_s = \left(\frac{1}{2\zeta}\right)\sqrt{\frac{L_p}{C_p}}$$

Here, the numerator is initially set to 1 to indicate critical dampness. $\zeta = 0$ represents indefinite oscillation, or under-damping, and values higher than 1, indicative of over-damping, cause the waveform to take longer to reach its final value.

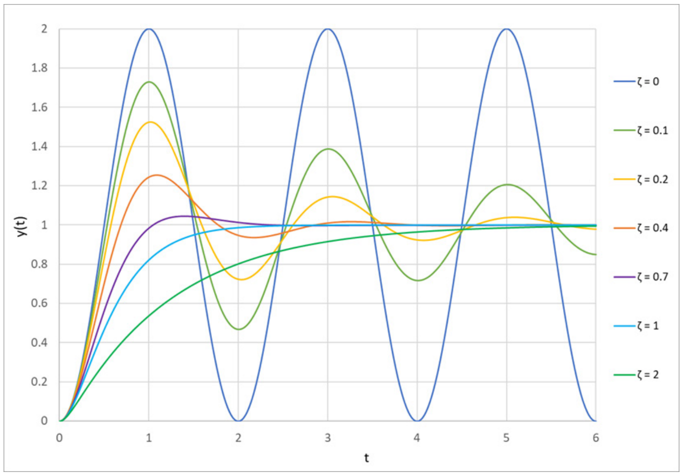


Figure 2: Time response of a second-order system with various damping ratios

Solving the equation with our known values of L_p and C_p gives us R_s. In some cases, R_s can be used alone; however, snubber placement can affect functionality by shorting the circuit with just a resistor. The value of C_s must be chosen to allow normal operation. Here, F_c represents cutoff frequency.

$$F_c = \frac{1}{2\pi R_s C_s}$$

$$F_c = F_{ring0}$$

$$C_s = \frac{1}{2\pi R_s F_{ring0}}$$

For cutoff frequency, we need to select a value low enough to short-circuit the undamped ringing frequency, F_{ring0}, but not low enough to provide a significant conduction path at the main operating frequency of the circuit. With values for C_s and R_s, we can implement the snubber circuit and re-measure the waveform. Fine-tuning the circuit and minimizing ringing is a process that requires incrementally changing the values of F_c and ζ in the equations for damping factor and cutoff frequency.

Increasing Complexity in RCD Snubber Circuits

The design procedure for a discharge RCD snubber is similar to that of an RC snubber; resonant frequency isn't considered because surges are absorbed by a fast-recovery diode.

On the other hand, non-discharge RCD snubber circuits only consume energy from the surge voltage, so the amount of power R_s can dissipate decreases. By extension, C_s and clamping effectiveness can increase, enabling higher switching frequencies. Further complexity can be achieved using soft-switching active snubber circuits.

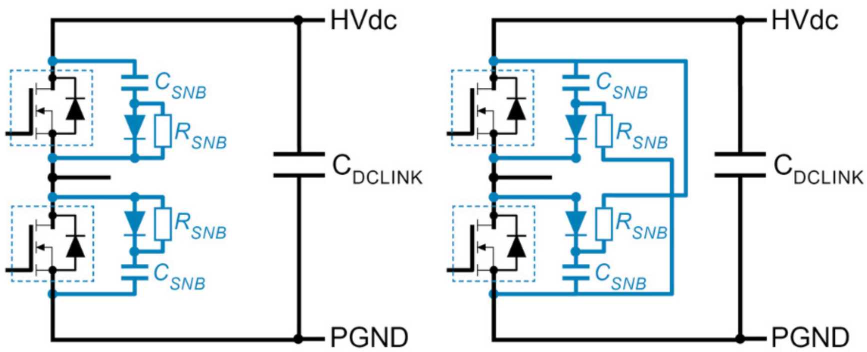


Figure 3: Discharge RCD snubber (left) and non-discharge RCD snubber (right)

Leveraging Knowles Precision Devices' Snubber Circuit Expertise

The team at Knowles Precision Devices has extensive knowledge and expertise in high-reliability ceramic capacitors. We're here to provide comprehensive technical support for engineers who are choosing and implementing components in the face of evolving circuit design guidance and new values in snubber circuit calculations.

For more information, review our AEC-Q200 capacitor offerings or contact our sales team, and they'll make sure you get the engineering support you need.