Power Tip 20: Watch Those Unintended Resonant Responses

Understand how filter ringing can lead to power-supply failures

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(Editor's note: there is a linked list of all entries in this series at: http://i.cmpnet.com/powermanagementdesignline/2010/02/PowerTipSerieslist.pdf)

Have you ever snapped on the input voltage to your power supply and found that your power supply has failed? A rapid input-voltage rise time and high Q resonant circuit that can produce twice the voltage of the input supply may be the problem. Similar problems can occur if you rapidly interrupt current flow in inductive elements. Examples of places where these kinds of problems arise are in hot-swap or hot-plug circuits, or when trying to open the input to an electromagnetic interference (EMI) filter.

Figure 1 shows a simplified filter schematic along with a switched input. The inductance in the circuit can be intentional, or it can be accidental such as the result of long hook-up wires in a power over Ethernet (PoE) system. The figure also shows the input voltage waveform being stepped and the resulting output voltages when the damping factor is less than one. (Damping factors higher than one provide no overshoot.)

The lower damping factor’s response takes the form of:

\[ V_{out}(t) = V_{step} \left(1 + e^{-\zeta\omega_n t} \sin(\omega_n \sqrt{1 - \zeta^2} \cdot t + \phi) / \sin \phi \right) \]  

(Equation 1)

Where: \( \zeta \) is the ramping ratio, which is also equal to \( 1/(2*Q) \).
\( \omega_n \) is the natural frequency set by the inductance and capacitance
\( \phi \) is the arc-cosine of \( \zeta \)

Shown is a series resonant circuit and you can find the Q easily. It is simply the characteristic impedance divided by the series resistance or:

\[ Q = \frac{Z_n}{R_s} = \sqrt{\frac{L}{C}} \]  

(Equation 2)
A high Q (low damping) system is undamped and the filter output voltage can ring to twice the input source (Vin). A lower Q system constrains the peak ring voltage. **Figure 2** shows the percentage overshoot as a function of damping ratio. With a damping ratio of 0.4 (Q of 1.25), the ring voltage can be limited to 130 percent of the source voltage.

This may not be practical, as additional losses in the damping resistor, or the loss of filtering from putting a resistor in series with the capacitor, may be unacceptable. If your design cannot tolerate the losses, you may need to add additional components. For instance, the circuit can be further damped with a series resistor and capacitor connected in parallel with the filter capacitor (C1). You can also use a hot swap circuit to limit peak currents in the filter; or you can connect a diode in parallel with the inductor to provide a low-impedance charging of the capacitor.
Things may not be as bad as they seem, as the current in the inductor may cause it to saturate, and the capacitor charging may be accomplished with a much lower than expected series inductance. If the inductor saturates, the filter characteristic impedance drops as does the Q, giving rise to reduced overshoot. To check whether this may be the case in a high Q system, calculate the peak current as the voltage step divided by the characteristic impedance of the system. Then consult the inductor data sheet to see if it will saturate.

To summarize, filter ringing due to stepped input voltage can lead to destructive voltages for downstream electronics. This is a problem particularly for systems such as PoE that tend to be high Q when using low-loss ceramic capacitors and inductances that do not saturate. If the voltage reaches an unacceptable level, these systems will need additional damping, current limiting or an alternate charging method. Here is a simple process to determine if you have a problem:

1) Decide if your system is subjected to a voltage step from a low impedance and determine its rise time. This voltage step can be a switched or hot swapped connection.
2) Estimate the charging inductance and filter capacitance. Cable inductance can be estimated as 15 nH/inch.
3) Determine total resistance in the charging path including the inductor, cable and connector resistances, and capacitor ESR.
4) Calculate resonant frequency \( \omega_n = \frac{1}{\sqrt{L \cdot C}} \) and determine if the input rise time is much faster than the natural filter response.
5) Calculate the damping factor \( \zeta = \frac{R_s}{2 \sqrt{L \cdot C}} \) and refer to Figure 2 to determine the overshoot.

Our next entry in the Power Tips! Series will discuss error amplifier configurations.

About the author

Robert Kollman is a Senior Applications Manager and Distinguished Member of Technical Staff at Texas Instruments. He has more than 30 years of experience in the power electronics business and has designed magnetics for power electronics ranging from sub-watt to sub-megawatt with operating frequencies into the megahertz range. Robert earned a BSEE from Texas A&M University, and a MSEE from Southern Methodist University.