Technical Article

Hot plugging DC/DC converters safely

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In power converters, the input capacitors are fed through inductive cabling to the power source. Parasitic inductance will cause ringing of the input voltage to almost twice its DC value when first plugged into the system, also called hot plugging. An insufficiently damped power converter input and a lack of inrush control can damage the converter.

Using input bulk electrolytic capacitors to dampen the input voltage of the off-battery converters can prevent excessive voltage ringing when first applying battery power, while also preventing resonances that can destabilize the converter. With the move to 24V_{IN} and 48 V_{IN} systems from the traditional 12V automotive battery, the need to properly dampen the input becomes even more important. 12V battery systems typically use components rated for 40V or higher to survive short-duration voltage spikes under load-dump conditions. The maximum DC voltage for these 12V systems can reach 18V_{DC}. Hot plugging can cause input ringing with the voltage nearing twice the input, such as 36V. This is well below 40V or higher rated components. However, in a 48V system where steady-state input voltages can reach 54V, ringing on the input can potentially exceed 100V, damaging components rated for 80V.

With traditional 12V systems, one often assumes the damping capacitors have enough effective series resistance (ESR) to tame the resonance. But, with low-cost aluminum electrolytic capacitors, the actual effective ESR is generally much lower than the published maximum, resulting in much less damping and much more ringing when applying battery power. With 12V systems, the reduced damping may still be enough to prevent destabilization of the downstream DC/DC, and the ringing will not cause damage. However, in 48V systems that are more vulnerable to ringing, you can add discrete resistors in series with the input damping capacitors. Based on steady-state ripple currents, a size 0603 (1608 metric) should suffice.

In Figure 1, L1 and C1 values from an existing DC/DC converter's input filter create a resonance that is expressed by Equation 1:

$$\frac{1}{2\pi\sqrt{L_1 C_1}} = 8\text{kHz} \tag{1}$$

We chose the target damping capacitor (C_d) and damping resistance (R_d), based on the TI E2E™ design support forums technical article, "Damping input bead resonance to prevent oscillations". C_d should be ideally at least three times C_1. We chose a 150 µF standard value for C_d.

Equation 2 expresses the target damping resistance:

$$Z_o = \sqrt{\frac{L_1}{C_1}} = 0.5\Omega \tag{2}$$

For damping resistor (R_d), add two paralleled 1Ω resistors in series with C_d.

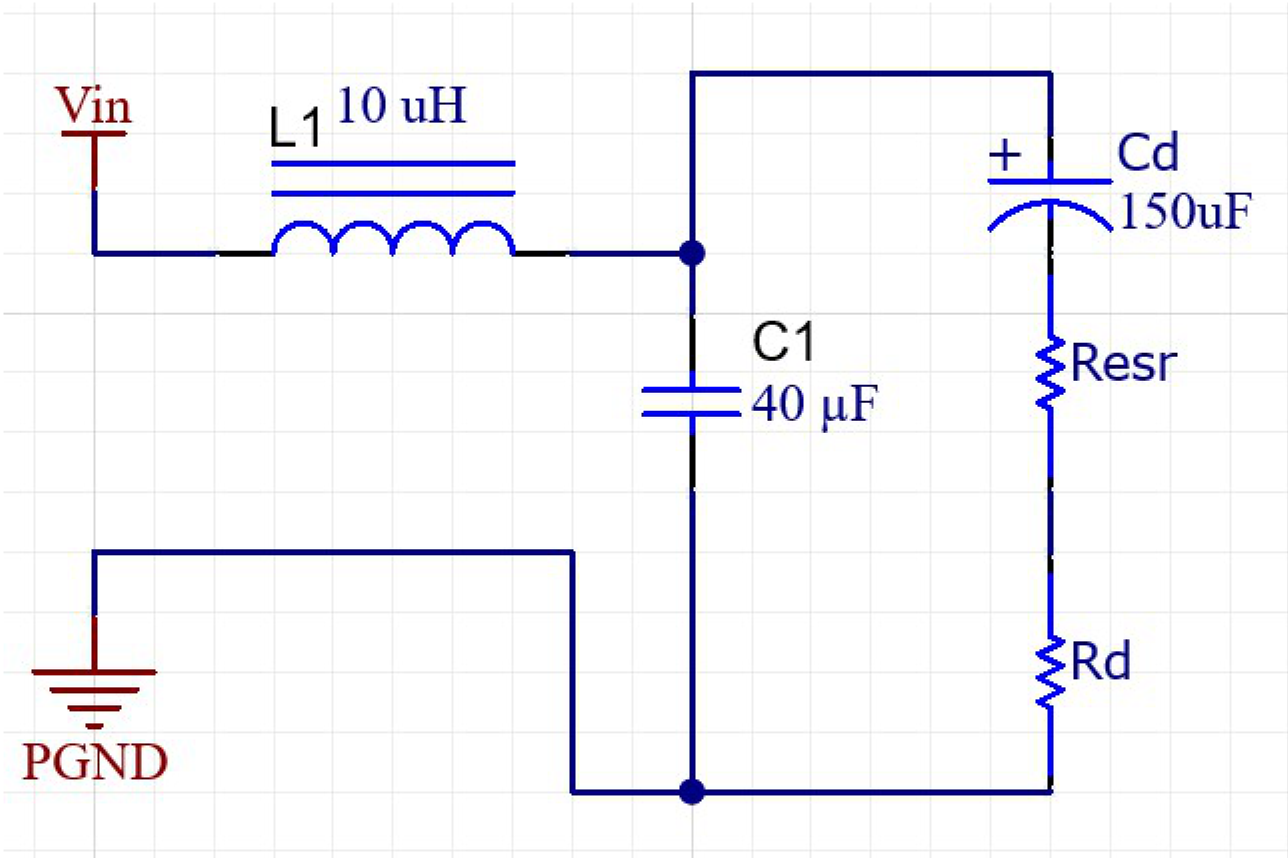

Figure 1. A simplified input filter with damping to prevent excessive voltage ringing when first applying battery power, while also preventing resonances that can destabilize the converter.

Figure 2 shows the simulated hot-plug response both without and with the added 0.5Ω damping resistor in series with C_d.

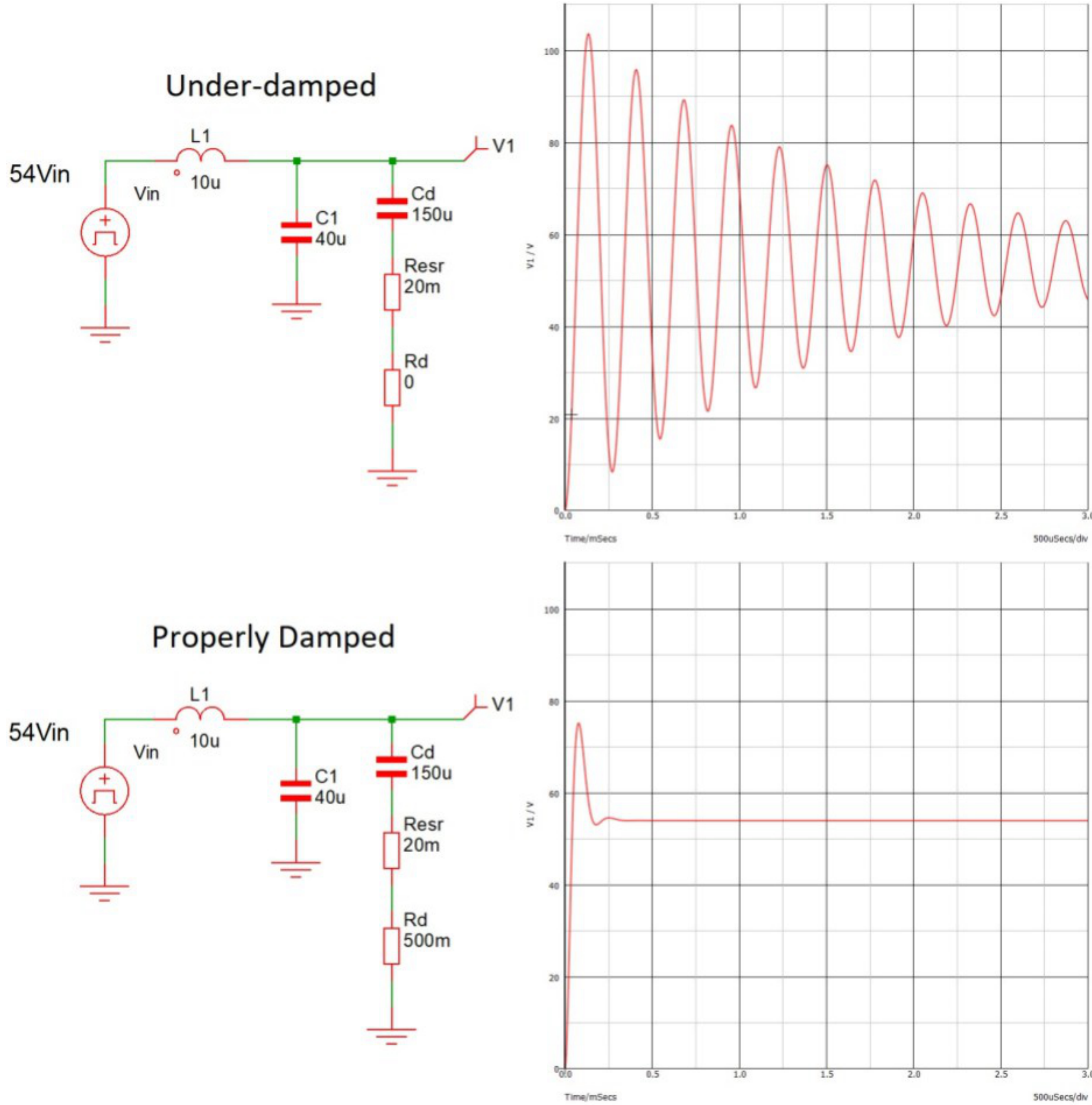

Figure 2. Simulation of hot plugging without and with damping 0.5Ω damping resistor in series with C_d.

We achieved damping of the input filter by using the correct damping resistor and capacitor combination. There is one aspect, however, that is easy to overlook. In the lab, we experienced the destruction of the damping resistor (R_d) when hot plugging to the supply. What we realized is that the damping resistor has a peak power expressed by Equation 3:

$$P_{pk} = \frac{V_{IN\_Max}^2}{R} \tag{3}$$

For our 1 Ω resistors across 54V, that would be about 2,900W peak in each resistor. Furthermore, the resistor dissipates nearly the same energy as that stored in the damping capacitor (C_d) in a very short period of time. This energy stored in the damping capacitor is expressed by Equation 4

$$E_{C_d} = \frac{(C_d)\left(V_{in}^2\right)}{2} \quad (4)$$

In our case, that energy is shared equally between the two 1Ω resistors. A capacitance of 150μF at $54V_{IN}$ is approximately 220mJ total, or 110mJ in each 1Ω resistor. This is a slightly stringent assumption, as the internal ESR of C_d reduces the actual peak voltage across these resistors by about 4%.

Mapping the actual inrush surge to the curve in the surge rating graphs is not straightforward. The actual surge profile will be roughly a decaying exponential waveform, while the resistor ratings assume a fixed-duration constant power, as shown in Figure 3.

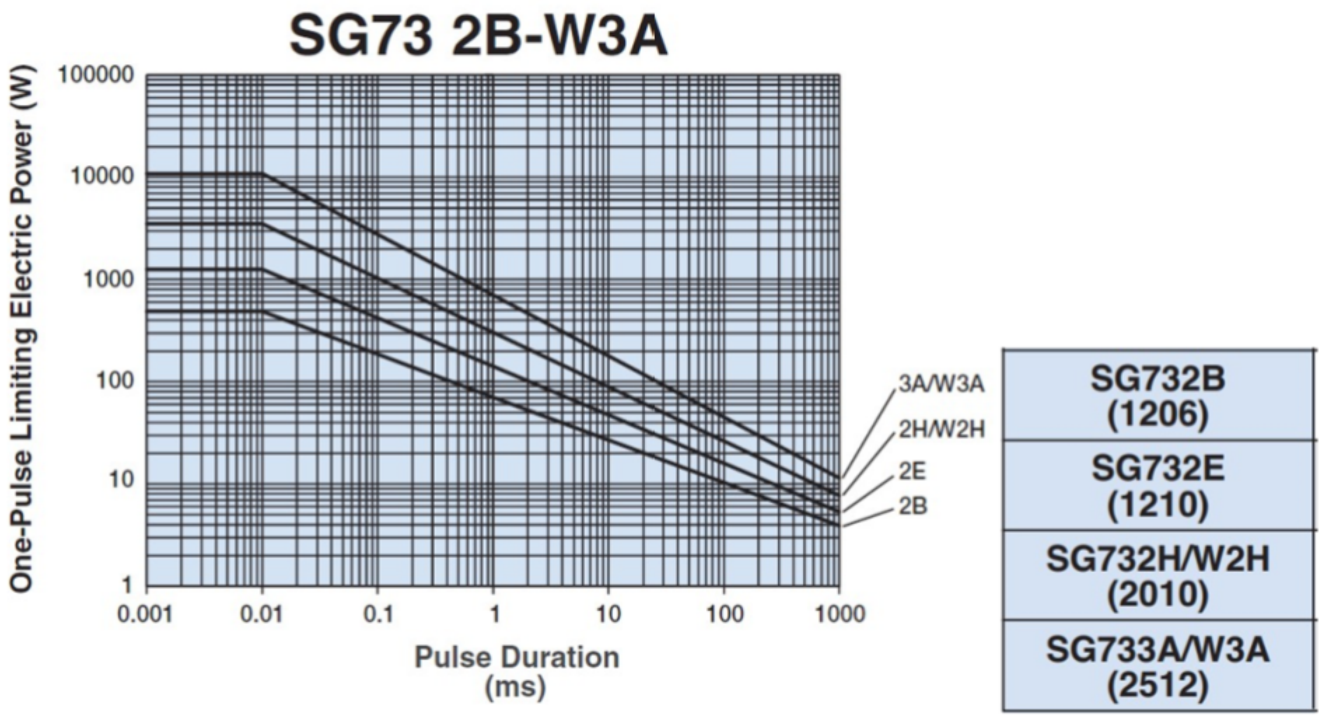

Figure 3. Example of surge-rated resistor ratings showing a roughly decaying exponential waveform.

A conservative approach would be to divide the total energy dissipated in the resistor by the peak power. You can then check this resulting pulse duration against the surge rating graph of the resistor. The calculated pulse will be more severe than the actual pulse, which is the same heating energy spread out over a greater time frame. For our case, in each resistor, 110mJ divided by 2,900W is 38μs. A surge-rated resistor size of 2512 SG733A/W3A can handle 4.5kW for approximately 40μs, which means that this package resistor is suitable for this application. General-purpose resistors in the same 2512 package have power ratings more than an order of magnitude lower than surge-rated resistors.

This calculation does ignore the series inductance effect. An inductor will slow the rise of current into the resistor and reduce maximum power, but will also add total losses from overshoot, as shown in Figure 2. The simulation results including the 10μH inductor show peak power in the resistor dropping by 30% from the 2.9kW calculated power, but the total energy in the resistor is 17% higher than the 110mJ calculated earlier. The rating curves show that the allowed energy follows the peak power ratio to the negative two-thirds power. Thus, a 30% reduction in peak power enables 27% more losses, and our calculations remain conservative for both without and with series input inductance.

Avoiding failures from hot plugging

While the best automotive installation and maintenance practices will avoid hot plugging, there is a realization that errors will occur. Following procedures stated in this article will avoid costly damage to the system. As your partner in power management, TI is in constant pursuit of pushing the limits of power.

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