Designing USB for short-to-battery tolerance in automotive environments

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Explore solutions for protecting a V_{BUS} line against vehicle battery shorts.

As vehicle manufacturers continue to make automotive infotainment systems an extension of the mobile media consumption experience, universal serial bus (USB) becomes more ubiquitous in the infotainment architecture. While USB was originally a purely consumer interface, it has since been co-opted into environments with much more stringent protection requirements. Among these is the need to protect against shorts to a car battery. This paper explores the challenges with protecting the V_{BUS} line for USB and presents three different solutions to the problem.

V_{BUS} to car battery – a hot plug-like event

First and foremost, a protection device must be used in series with the V_{BUS} connection to provide protection against overvoltage. Since the standard V_{BUS} on USB outputs 5V DC, a DC voltage of 12-18V poses a problem to an unprotected circuit. Using a protection solution such as the TPD3S714-Q1 will provide the overvoltage and DC-blocking protection that will solve an overvoltage problem. The sudden shorts to car battery, however, introduce transients to the V_{BUS} line. Since the protection device essentially acts as an open path once it responds and turns off, the short-to-car battery should emulate an ideal resistor, inductor and capacitor (RLC) circuit response (**Figure 1**).

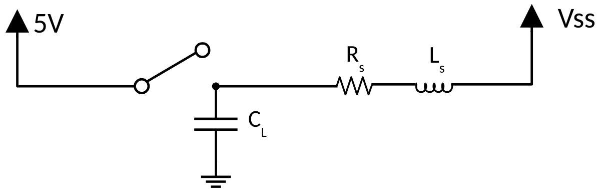


Figure 1: Ideal model of short-to-battery transient

The cabling used to do shorts is represented by R_S and Ls; V_{SS} represents the car battery, and the output capacitance of the 5V V_{BUS} is represented by C_L. Since both the cabling resistance and the capacitor resistance in ceramic capacitors are very small, one would expect nearly an ideal underdamped response of double the applied step voltage (**Figure 2**).

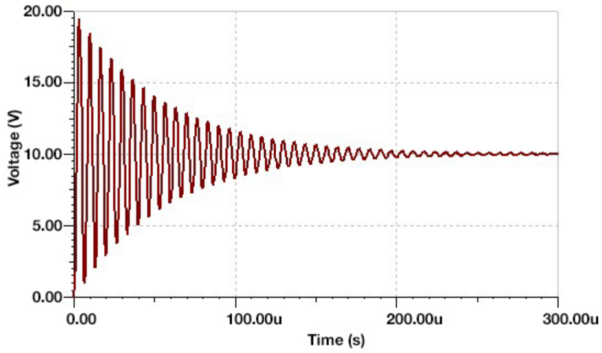
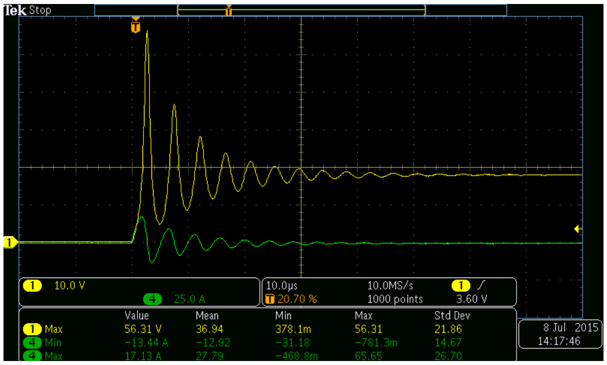


Figure 2: Example RLC series step response to 10V

In our initial testing, we noticed that voltage was not actually double the expected ringing – in some cases this was causing early failures of our protection device. When testing the capacitor by itself, we found the ringing was actually three times greater than the applied DC voltage. **Figure 3** shows a 1 µF X7R 50 V-rated ceramic that rings above the maximum rated voltage when an 18 V short is applied. After some thought and experimentation we found the root cause: ceramic capacitor derating versus applied voltage.

Our 50-V capacitor would derate to nearly 10 percent of the original capacitance during ringing.

Since our short-to-battery testing simulates a short through a cable, the cable inductance (which stays constant) forces a sinusoidal current even as the capacitance of the ceramic drops rapidly. This causes the strange peaking shown in **Figure 3** and was the reason for our early failures. By more careful design on the output of V_{BUS}, these problems can be prevented. Three options are presented as solutions, each with their own advantages and disadvantages.



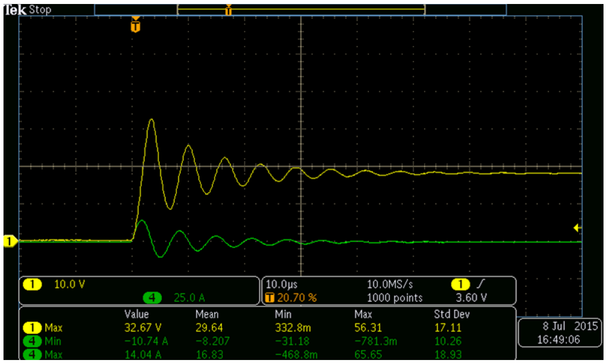
	Value	Mean	Min	Max	Std Dev
1 Max	56.31 V	36.94	378.1m	56.31	21.86
4 Min	−13.44 A	−12.92	−31.18	−781.3m	14.67
4 Max	17.13 A	27.79	−468.8m	65.65	26.70

Figure 3: 1µF 50V X7R ceramic shorted to 18V through a 1-m cable

Short-to-battery hot plug solutions

Choosing capacitors by derating curves

Although examining capacitor derating curves may make sense, this is something that designers often overlook during component selection. Although a ceramic capacitor is rated for a DC voltage of 50 V, it does not mean it will be anywhere near the rated capacitance on the label at 50 V. The capacitors we ended up settling on for our short-to-battery testing were 100 V, 1 µF, X7R ceramics. The derating curve put these at approximately 80 percent of the original capacitance at our peak overshoot voltage of 36 V. By keeping the capacitance closer to constant over the working voltage we reduced ringing and overshoot significantly.



	Value	Mean	Min	Max	Std Dev
1 Max	32.67 V	29.64	332.8m	56.31	17.11
4 Min	−10.74 A	−8.207	−31.18	−781.3m	10.26
4 Max	14.04 A	16.83	−468.8m	65.65	18.93

Figure 4: 1 µF 100V X7R ceramic shorted to 18V through a 1-m cable

Figure 4 demonstrates the difference capacitor selection can have for the exact same short as applied in **Figure 3**.

Advantages:

- fewer system components
- smaller footprint

Disadvantages:

- capacitor cost increase
- smaller output capacitance

Employing an R-C snubber circuit

Although perhaps the trickiest to design, the R-C snubber circuit can prevent overshoot ringing altogether by choosing the right component values. In addition to the output capacitance, another capacitor with a resistor in series can be added to push the response of the hot plug closer to critically damped. First, the maximum cable length and cable gauge should be analyzed to give an approximate cable inductance of the system. Our testing uses a 1-m, 18 American wire gauge (AWG) cable which results in approximately 1.5 µH of effective inductance. Coupled with the existing output capacitance of 1 µF, we first need to choose a snubber capacitance that will dominate during transient events. A good rule of thumb is to use 10 times the load capacitance. Since capacitance of the V_{BUS} FET while off is negligible compared to the 1 µF, a 10 µF capacitor should be used.

Since the goal is to try to dampen the overshoot without causing too many issues, we want to design for a critically damped per the series RLC equation

(1) $\zeta = \frac{R}{2}\sqrt{\frac{C}{L}} = 1$

Plugging in our snubber capacitance of 10 μF and cable inductance of 1.5 μH gives us a required R ≈ 775 mΩ. With these, it is always wise to run a quick simulation to make sure our assumptions are correct. See **Figures 5 and 6** for simulation results showing the difference that adding a snubber can have on a system.

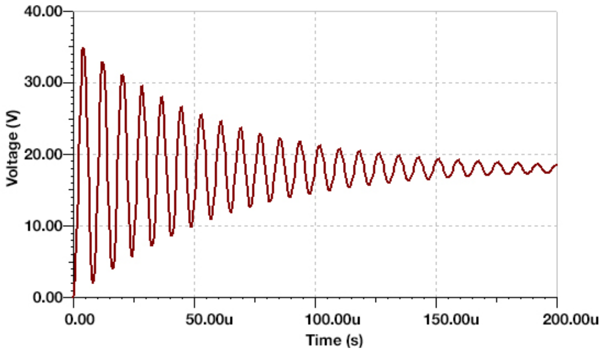


Figure 5: Undamped RLC simulation

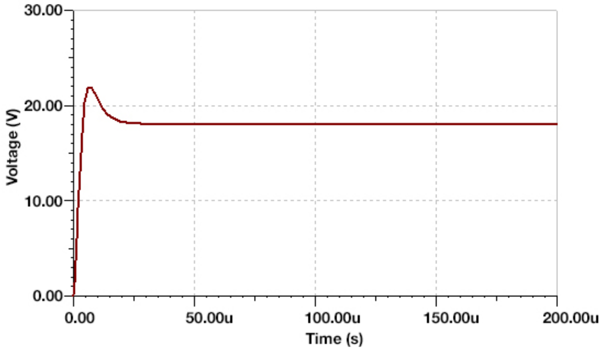


Figure 6: Damped RLC simulation

Advantages:

- can provide best protection against overshoot

Disadvantages:

- more complicated to design
- most components required

Adding an external TVS diode

The third and final method for solving the ringing issue is perhaps the simplest: adding a small transient voltage suppressors (TVS) to aid in clamping the ringing. By choosing a TVS rated slightly above the working voltage (for example, a 20-V TVS for an 18 V maximum short-to-battery system), the clamp will react during the initial ringing but should not conduct under DC steady-state conditions. In our experience, a small 0603-sized TVS should provide enough clamping to dampen the ringing and prevent any capacitance related overshoot.

Advantages:

- simplest to design

Disadvantages:

- additional components and board space
- TVS may be more expensive than capacitor or snubber solutions

Summary

Designing for short-to-battery faults in a USB system can be challenging, but using some of the techniques presented can help prevent any missteps while designing for the V_{BUS} transients. Any of the three options presented will do the job adequately, but each has their own advantages and disadvantages. Proper capacitor selection to handle derating may be more costly per capacitor, but it is the smallest solution size. Using an R-C snubber will provide the best defense against overshoot, but requires the most calculation and design. A TVS may be the easiest to design, but could be the most expensive solution.

References

1. More information on TI's ESD protection solutions.
2. Download the TPD3S714-Q1 data sheet.

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