TT Electronics

Authored By Dylan Howes
Engineering Manager
@ Dylan.Howes@ttelectronics.com
978-567-9600 x 230

Specification Demystification II:
Understanding Power Supply Inrush Current

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Introduction

Knowledge of a power converter's input current characteristics can prove useful for determining how many devices can be powered by a given electrical service/outlet without tripping breakers in the power system. Input current ratings given on switch-mode power supply (SMPS) nameplates are worst-case steady state figures and therefor can only provide useful insight into the devices input current characteristics during worst-case steady state operation. SMPS input currents can momentarily exceed these steady-state figures during transient events such as load steps or, more notably, during start up. The transient input current spike that occurs when an SMPS is first energized is known as inrush current. Understanding a devices inrush current is another critical element of determining how the device will interact with protective features in the power system such as breakers and fuses. Excessive inrush currents can also cause premature power supply failures. This month's technical bulletin will provide an overview of what causes SMPS inrush currents, how they are typically minimized, and what implications they may have on the greater power system.

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QUANTIFYING INRUSH CURRENT

During roughly the first half-second following the application of AC voltage to an SMPS, the devices equivalent network is essentially reduced to bridge rectifier and a bulk capacitor. During this brief period of time before the control network "wakes-up" the isolation transformer is open circuited by the main switching element(s), and the entire secondary network is out of circuit. Indeed, there are typically several other elements preceding the bridge rectifier for circuit protection and emissions mitigation, as well as shunts off the high voltage rail (in parallel with the bulk capacitor) for starting up control chips etc. However, these elements can all be ignored for the sake of this discussion as they are negligible in the determination of inrush current. The simplified network shown in Figure 1 is a suitable model for the front end of an SMPS in roughly its first half-second of operation.

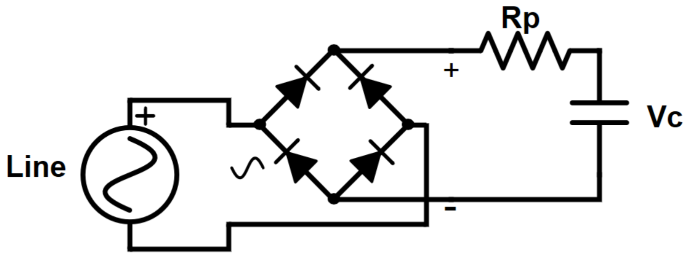

Figure 1

In the equivalent circuit model of Figure 1, the bridge diodes are assumed to be ideal, and Rp represents parasitic series resistances in the AC front end including the equivalent resistances of the bridge elements, boost chokes/rectifiers, and the ESR of the bulk capacitor.

In examining the equivalent circuit of Figure 1, it becomes clear that start-up inrush current is a function of line voltage, parasitic resistance, bulk capacitance, and the [residual] voltage across the bulk capacitance. Power Supply inrush current is assessed during what is called a cold start, which implies that there is no residual energy stored within the SMPS (the voltage across the bulk capacitor is 0V) when AC is first applied.

Upon initial application of AC, the bulk capacitor acts momentarily as a short circuit, and current flows into the capacitor impeded only by Rp. The current drawn by the capacitor is proportional to the rate of change of the voltage across it, so the smallest possible inrush would occur if the AC voltage is applied at an initial phase angle of 0°(zero potential between Line and Neutral). This may sound a bit counter-intuitive at first, because the greatest rate of change of the AC waveform occurs at this point, but the rate of change of a 60Hz sine wave at 0° is still infinitely slower than than the rate of change of an instantaneous electrical contact made at any potential other than 0V.

When AC is applied at 0° phase angle, the voltage across the capacitor would (relatively) slowly ramp up to the peak line voltage over the first quarter cycle. For all practical SMPS designs that are small enough to be powered off a typical 15A or 20A outlet, the bulk capacitance would be small enough to fully charge to the AC peak voltage in the first quarter cycle (about 4.2ms at 60Hz), assuming nothing were done to slow the inrush. Accordingly, the inrush current would approximate the peak steady state current seen in the equivalent *unrectified* RC network:

$$I_{inrush}^{0°} = \frac{\sqrt{2} \cdot line}{\left| Rp - \frac{j}{2\pi f C} \right|}$$

Where the line voltage is an RMS quantity.

Probabilistically, a user is only likely to plug their power converter into the mains at a phase angle near zero degrees (±1°) about once every 90 times, which makes the best-case scenario an unlikely one. The other 89 times, inrush currents will be much greater. At phase angles greater than 0° the bulk capacitor is subjected to a voltage discontinuity, giving it a instantaneous impedance of 0Ω. The peak current drawn is then simply the instantaneous line voltage divided by the parasitic resistance:

$$I_{inrush}^{\neq 0°} = \frac{\sqrt{2} \cdot line \cdot \sin(\varphi)}{Rp}$$

Where φ is the phase angle of AC application and the line votlage is once again an RMS quantity.

Regardless of what phase the AC waveform is in when applied to the converter, there is a direct linear relationship between the RMS line voltage and the inrush magnitude. For this reason, inrush currents for universal converters should always be specified for both high (c. 240VAC) and low (c. 120VAC) line conditions.

THE PROBLEM WITH INRUSH

Depending on the installation, large inrush currents can trip circuit protection devices within the larger power system such as breakers. In most residential/ commercial systems, unhindered inrush to a single SMPS (even a rather large one) won't typically trip breakers as they are designed to allow for inrush events that last for about 1 quarter cycle. Nuisance trips are more likely to occur if a number of SMPS devices are switched on simultaneously.

Perhaps more importantly, excessive currents flowing through the bridge rectifier and any front-end filter elements and fuses can damage these components either immediately, or over time depending on the exact stresses to which they are subjected. The SMPS must be designed so as to limit the inrush current in a manner that will prevent damage to other front-end components.

LIMITING INRUSH

To avoid nuisance trips, and to mitigate reliability concerns associated with high inrush currents, switch mode power supplies are designed to limit the current that can flow into the bulk capacitor at start up. There are a number of ways to accomplish this goal, but really just one that checks all the boxes for cost, size, and dissipation viability for most converters. Often, the most practical inrush limiting approach for low to medium power converters is to employ an NTC thermistor in series with the bulk capacitor. When stored within the PSUs rated storage temperature range, the NTC exhibits an impedance that when summed with Rp, is high enough to limit the 90° (worst-case) inrush to a level that is safe for the other internal series components to regularly withstand. As current flows through the NTC, I2R losses are dissipated as heat. As the temperature of the NTC rises, its impedance falls and ultimately arrives at a value that supports the allowable steady state dissipation in line with efficiency mandates. This solution is not lossless.

There are some clever solutions that employ a MOSFET or other low RDSon transistor in series with the bulk capacitor which is held as an open circuit until a zero crossing in the AC voltage waveform is sensed ensuring that the AC is always applied at 0°. Such a solution would reduce losses but is more costly and complicates the design, and is therefore not widely used at this time. As efficiency mandates around the globe continue to grow stricter, this approach may someday be essential.

YOUR NEXT DESIGN

Properly limiting SMPS inrush current is essential for maintaining device reliability and for ensureing proper integration of the converter into the larger power system. If your next designs is up against a tricky set of inrush constraints, reach out to a member of our team to learn more about how SMPS inrush current can be controlled.