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SPECIAL FEATURE

Inrush Current Control Technology Boosts Power Converter Reliability

Large peak inrush currents can cause a host of problems in military electronic systems. Choosing the right power protection solutions can avoid damage to mission-critical equipment.

STEVE BUTLER, VICE PRESIDENT OF ENGINEERING VPT

November 2011

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Designing power subsystems for platforms like military vehicles, aircraft and shipborne gear requires special care. It's critical to protect those multimillion-dollar machines from failing while ensuring reliable performance in mission-critical situations. Among the challenges is dealing with the problem of inrush current. Inrush current is the current drawn by a power system when power is applied or it is turned on.

The input EMI filter will include some capacitance connected across the input line. The DC/DC converter will have capacitance internally across its input and output. A typical power system is shown in Figure 1. There may be additional capacitance at the input to the DC/DC converter, and the load will usually include additional, possibly distributed, capacitance. Each of these capacitors requires current to charge them from their initial or zero state to their final steady state voltage. This current can have a high peak magnitude depending on the input voltage rise time and source impedance, and is referred to as the inrush current. Large peak inrush currents are usually governed by a system-level specification. There is a concern that high spike currents can trip an upstream protection circuit or create electromagnetic interference, upsetting sensitive adjacent circuitry or interfering with RF signals.

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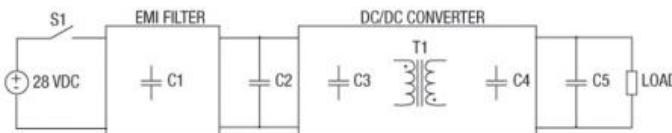


Figure 1
Typical power system showing relevant capacitances.

Inrush Current Waveform

A typical power system inrush current waveform is shown in Figure 2. It has two current peaks. The first "inrush spike" peak current occurs when the input voltage source is turned on. This peak current flows into the EMI filter capacitors and any capacitors on the input side of the DC/DC converter, charging them to their steady state value. The second current peak occurs when the DC/DC converter turns on. This peak current flows through the power transformer in the DC/DC converter to the output capacitor and into any load capacitance, charging them to their steady state value. There can be multiple occurrences if there is more than one DC/DC converter.

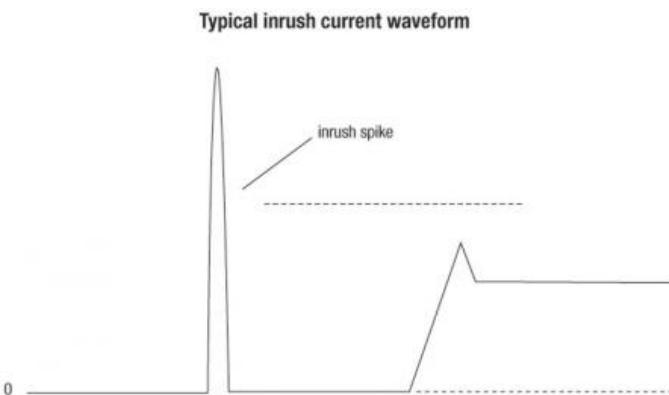


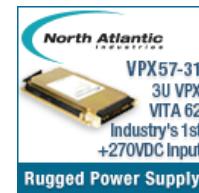
Figure 2
Shown here is the waveform of a typical power system's inrush current. It has two current peaks. The first "inrush spike" peak current occurs when the input voltage source is turned on.

The first current peak is often referred to as the inrush spike. Its peak value and shape are highly dependent on the characteristics of the input source, specifically the voltage rise time or dv/dt and source impedance. A fast rising input voltage waveform, such as from a mechanical switch or relay closure, will produce a very high and narrow current peak, limited only by series resistance and inductance. EMI magnetics are usually too small in value or quickly saturate under high peak currents. And the resulting peak is limited only by the source, line and parasitic resistances.

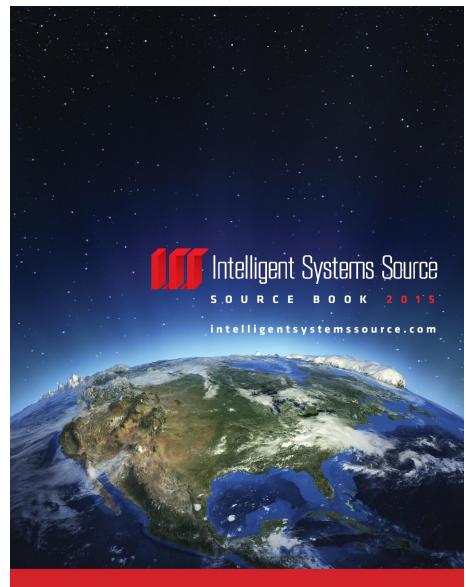
Switching power converters typically have output voltage rise times on the order of a few milliseconds, solid state power controllers (SSPC) usually from 50μs to 500μs, and large capacitor banks cannot be charged in less than several milliseconds. These slow rise times will not produce excessively high current peaks and may meet system specifications without additional protection. While the peak inrush current must be tested for spec compliance, the $i2t$ of the current waveform should also be evaluated, as it could trip an upstream fuse, circuit breaker or SSPC.

Turn-On Current

The second current peak is also considered part of the inrush current. This peak occurs when the DC/DC converter turns on and draws current from the source to charge its output capacitance and any load capacitance. Typical turn-on current waveforms are shown in Figure 3. The turn-on current is the same whether the converter is turned on by applying an input voltage or via an enable/inhibit signal. The turn-on current waveshape and peak value will be well-controlled as long as the converter has an output soft start feature. But it could require a higher peak current when starting into a large capacitive load.



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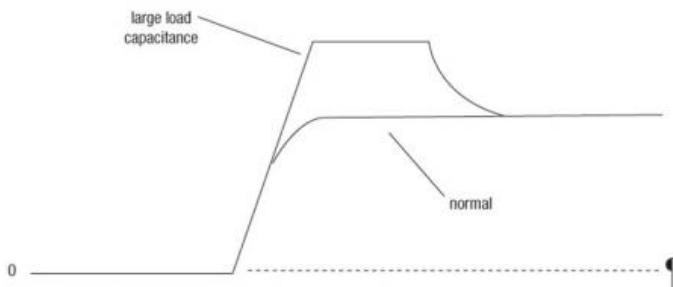
Typical turn-on current waveform

Figure 3

In this waveform of a typical turn-on current, turn-on current is the same whether the converter is turned on by applying an input voltage or via an enable/inhibit signal.

Soft start

VPT's DC/DC converters, for example, use a proprietary magnetic feedback scheme with a well-controlled internal start-up sequence and a precise output voltage soft start feature. The voltage soft start feature ensures the output ramps up in a controlled manner, with controlled dv/dt. Due to the soft start, the input current usually does not exceed the steady state input current of the converter during turn-on. These DC/DC converters also feature continuous constant output current limit. They will supply full rated current into any load; they do not hiccup or shut down and restart. This allows them to start any load capacitor, regardless of size. For cases with very large load capacitance, the DC/DC converter might enter this constant current limit mode during turn-on. In this case the input current would not exceed approximately 1.5 times the steady state input current. This is not high enough to cause any interference or trip upstream protection devices. For VPT's DC/DC converters, this second inrush peak will not cause adverse effects in the system design.

Active Inrush Limiting**Resistor Method explained here**

In some applications there is a requirement to limit the inrush spike current into the input capacitors. The only way to accomplish this is to insert a series element into the circuit in front of those capacitors. There are several approaches: a resistor with a bypass switch, an inductor, a controlled MOSFET, or a dedicated inrush current protection module. In a basic inrush limiting circuit using a series resistor and a bypass switch, the resistor will limit the input current until the input capacitors are charged. The switch will then close to allow the full current to flow to the downstream DC/DC converter. The switch can be a relay or semiconductor switch, and can be driven from the 28V input such that it is somewhat automatically controlled. The resistor also can be replaced with a positive (PTC) or negative temperature coefficient (NTC) thermistor. The NTC thermistor does not require a bypassing switch S1, but does require time to cool after power is removed, before it is functional again.

An inductor could also be used to limit inrush current. It would not need to be bypassed since it can carry DC current with low loss. However, a large inductance value and size would usually be required, and care must be taken to damp its resonance with the system capacitances to avoid transient ringing, control loop interactions and instabilities with the DC/DC converter.

Another Configuration

Another practical circuit uses a series MOSFET placed in the negative power lead. The MOSFET is normally off, with its gate pulled low through a resistor. When input voltage is applied, the gate will charge through the first resistor. The charge time and turn-on of MOSFET can be chosen to allow the input capacitors to charge slowly, limiting the inrush current. After the input capacitors are charged, the gate of the MOSFET will charge to the zener voltage and it will remain fully on. During the inrush period, the voltage across the MOSFET results in a large voltage difference between the return lead of the source and the input return of the DC/DC converter. This voltage will interfere with primary referenced control interfaces, requiring additional isolation for the control signals.

A better solution is to move the series MOSFET to the positive lead. While this can be accomplished by using a P-channel MOSFET, a better approach is shown in Figure 4. The MOSFET is located in the high side, allowing primary circuits to share a common return, but an N-channel MOSFET is used. The N-channel MOSFET will have a lower on-resistance, reducing power loss. A charge pump is required to drive the gate of the MOSFET above the input voltage. The MOSFET can also be operated in the linear region as a source follower to provide input transient protection.

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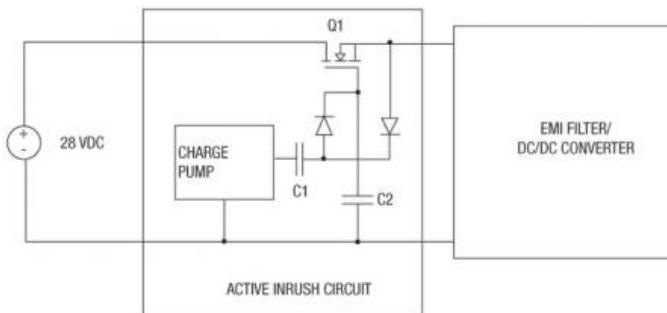


Figure 4

The MOSFET is located in the high side, allowing primary circuits to share a common return, but an N-channel MOSFET is used. This MOSFET will have a lower on-resistance, reducing power loss.

Input Modules with Inrush Limiting

VPT now offers a new approach to solving the inrush current problem. The DVCL28 is a dedicated Inrush Current Limiter Module, packaged in a tiny 1-inch square hermetic case. It can power multiple EMI filters and DC/DC converters up to 11A or 200W over the full military temperature range of -55° to +125°C. The DVCL28 uses the circuit diagrammed in Figure 6 to control the output voltage ramp rate or dv/dt. The voltage waveforms shown with and without the inrush limiter are shown in Figure 5 and Figure 6. A 28V step function waveform is applied to the input. The rising slope of the output voltage is controlled to 6 V/ms, limiting the inrush current into a 500 uF capacitor to less than 3.5A peak.

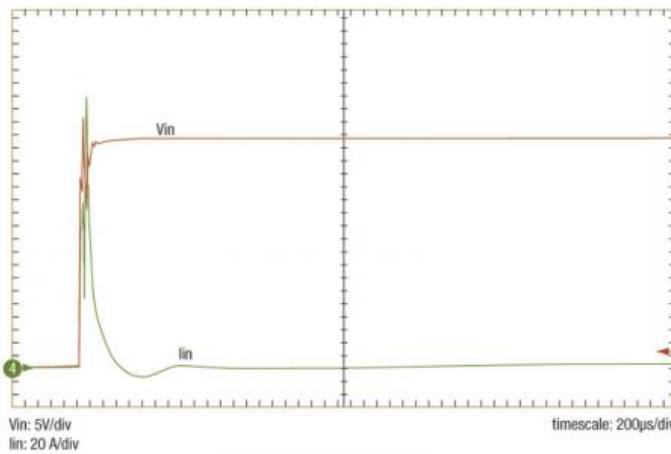


Figure 5

Shown here is the operation of a typical power system without a DVCL Inrush Current Limiter.

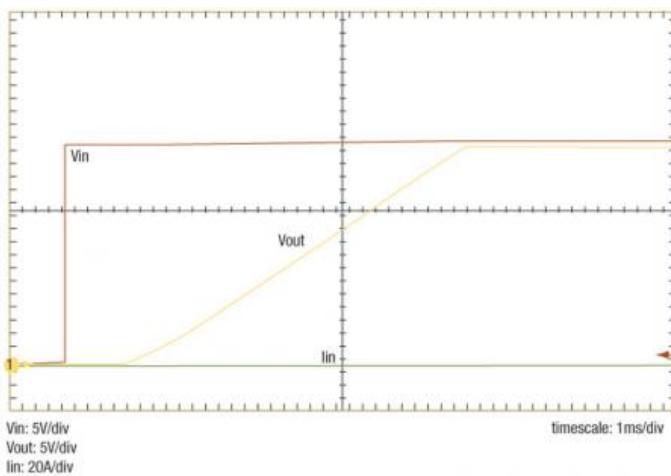


Figure 6

Shown here is the operation of a typical power system with a DVCL Inrush Current Limiter. A controlled voltage waveform is applied to the EMI filter and input capacitors. Inrush is negligible.

An off-the-shelf solution such as the DVCL Inrush Current Limiter Module saves engineers the design time

required to create some of the other solutions discussed in this article. A single DVCL can limit the inrush current of multiple devices, up to a maximum of 200W combined. The DVCL is designed to comply with MIL-STD-461 EMI requirements and will not inject additional noise onto the input line. It also provides an output signal to delay the turn-on of downstream electronics until the inrush cycle is completed. For engineers designing avionics, military, or other high-reliability systems, the DVCL module is plug-and-play, meeting all hi-rel system specifications including the wide military temperature range of -55° to +125°C.

VPT offers several additional input modules that include built-in inrush current limiting. These modules each use a series N-channel MOSFET in the positive lead. The N-channel MOSFET achieves the lowest ON-state resistance to minimize power losses. Locating it in the positive lead leaves the return path unbroken, simplifying system design. Using modules with built-in inrush current protection saves the engineer design time, board space and cost.

Filtering and Transient Voltages

Several modules also provide EMI filtering and input voltage transient protection. EMI is specified to MIL-STD-461. The EMI filter and inrush circuits are optimized to work together. The inrush circuit limits any current flowing into the EMI capacitors, but does not introduce any additional EMI into the input lines, as is possible with a discrete circuitry. Transient protection is specified to MIL-STD-461, MIL-STD-704, MIL-STD-1275, DEF-STAN 59-411 and ISO 7637-2 depending on the module. For transient protection, the high-side series MOSFET is used for dual purposes to provide both inrush limiting and transient protection. The VPTPCM-12 is a special case in that it also contains switching elements, so it may require additional EMI filtering at its input.

Inrush current is the peak current that flows into the power converter when the input voltage is applied or at turn-on. Many system specifications will be met with VPT's DC/DC converters and EMI filters alone. Some applications that place limits on this inrush current may require additional inrush protection. This inrush protection can take several forms, from a passive thermistor, to discrete active circuitry, to a dedicated active inrush current limiter module. It is worth the effort to examine your design to see which solution meets your system specifications for the most efficient use of time and cost.

VPT

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