

# Controlling Inrush Current in DC-DC Power Converters

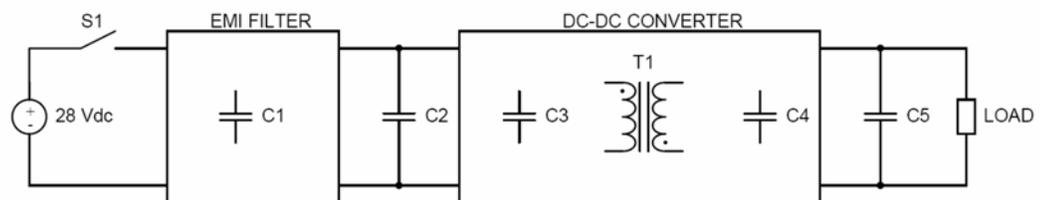
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### Introduction

Inrush current is the current drawn by a power system when power is applied or it is turned on. A typical power system is shown in Figure 1. 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. 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.



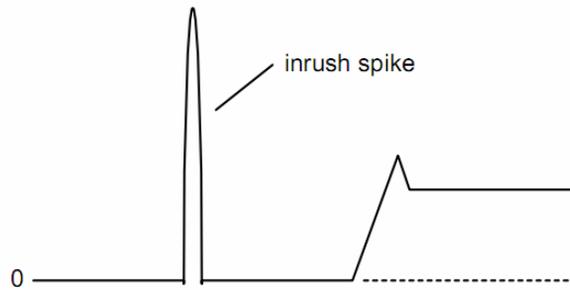
**Figure 1:** Typical power system showing relevant capacitances

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.

### 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.** Typical inrush current waveform.

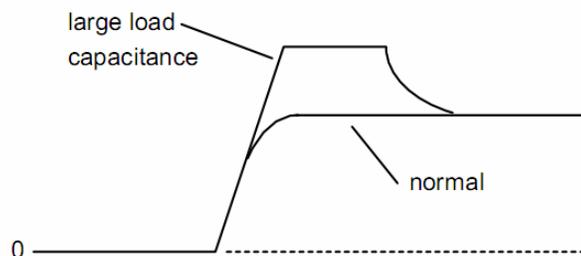
### Inrush Spike Current

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.

For a slower rising input waveform, the peak value of the inrush current is determined by the equation,  $i=C \cdot dv/dt$ . The capacitance is the total capacitance in the EMI filter and on the input side of the DC-DC converter. The  $dv/dt$  is the slope of the applied voltage waveform. Switching power converters typically have output voltage rise times on the order of a few milliseconds, solid state power controllers (SSPC) usually from 50 $\mu$ s to 500 $\mu$ s, 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  $i^2t$  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 of Figure 2 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.



**Figure 3.** Typical turn-on current waveform.

VPT's DC-DC converters utilize 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, see the normal curve shown in Figure 3.

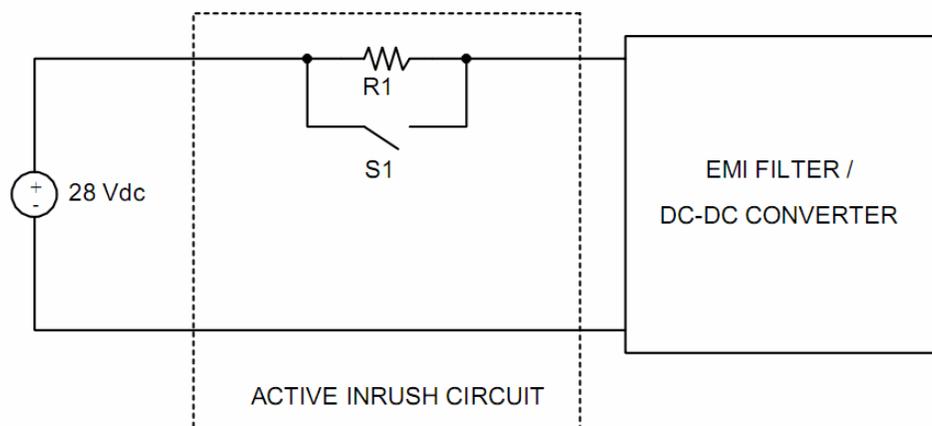
VPT's DC-DC converters also feature continuous constant output current limit. They will supply full rated current into any load; they do not hiccup or shut down and restart. This allows them to start any load capacitor, regardless of size. For cases with very large load capacitance, the DC-DC converter 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, see the large load capacitance curve in Figure 3. 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

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:

1. A resistor with a bypass switch
2. An inductor
3. A controlled MOSFET
4. A dedicated inrush current protection module

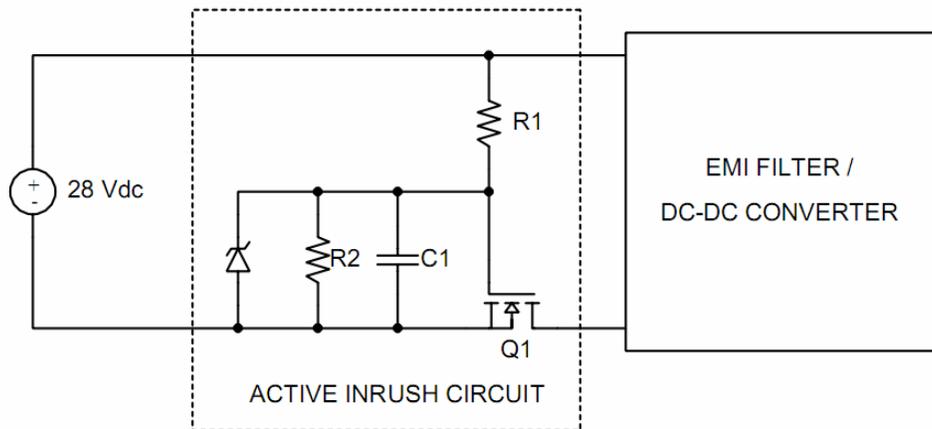
Figure 4 shows a basic inrush limiting circuit using a series resistor and a bypass switch. The resistor R1 will limit the input current until the input capacitors are charged. The switch S1 will then close to allow the full current to flow to the downstream DC-DC converter. The switch can be a relay 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.



**Figure 4.** Discrete active inrush current limiting circuit using a series resistor.

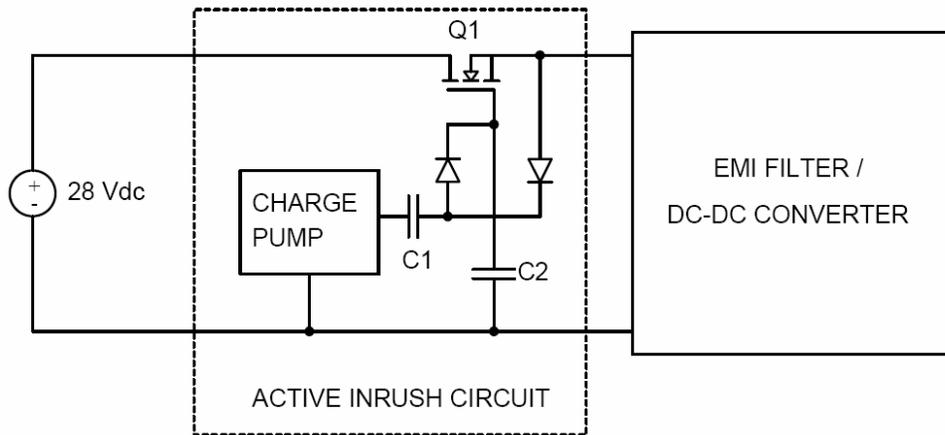
An inductor could also be used to limit inrush current. It would not need to be bypassed since it can carry DC current with low loss. However a large inductance value and size would usually be required, and care must be taken to damp its resonance with the system capacitances to avoid transient ringing,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

Another practical circuit is shown in Figure 5. This circuit uses a series MOSFET Q1 placed in the negative power lead. Q1 is normally off, with its gate pulled low through R2. When input voltage is applied, the gate will charge through R1. The charge time and turn-on of Q1 will be slowed by C1. R1 and C1 can be chosen to allow the input capacitors to charge slowly, limiting the inrush current. After the input capacitors are charged, the gate of Q1 will charge to the zener voltage and Q1 will remain fully on. During the inrush period, the voltage across Q1 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.



**Figure 5.** Discrete active inrush current limiting circuit using a series MOSFET.

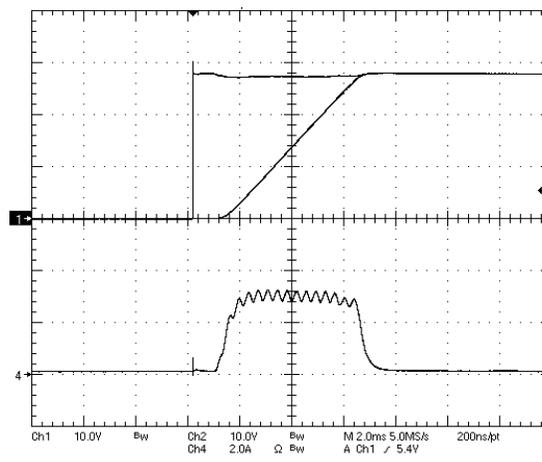
A better solution is to move the series MOSFET to the positive lead. While this can be accomplished similarly to the circuit of Figure 5 by using a P-channel MOSFET, a better approach is shown in Figure 6. Q1 is located in the high side, allowing primary circuits to share a common return, but an N-channel 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.



**Figure 6.** Active inrush current limiting circuit using a series high side MOSFET.

### 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°C to +125°C. The DVCL28 uses the circuit diagrammed in Figure 6 to control the output voltage ramp rate or  $dv/dt$ . The input and output voltage waveforms are shown in Figure 7. A 28V step function waveform is applied to the input. The rising slope of the output voltage is controlled to 6V/ms, limiting the inrush current into a 500uF capacitor to less than 3.5A peak.



**Figure 7.** Input and output waveforms of DVCL28 module.

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°C to +125°C.

Finally, VPT offers several additional input modules which include built-in inrush current limiting. They are listed in Table 1. These modules each use a series N-channel MOSFET in the positive lead similar to the circuit of Figure 6. 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.

Table 1. Modules with inrush current limiting.

Model	Series	Function	Rating	EMI	Inrush	Transient
DVCL28	Military and Avionics Hermetic Hybrid	Inrush Current Limiter	11A, 200W		✓	
DV-704A	Military and Avionics Hermetic Hybrid	EMI Filter and Voltage Spike Protection	2A	✓	✓	✓
VPTi10-28	VPT Series Metal Modules	EMI Filter / Transient Protection Module	10A, 200W	✓	✓	✓
VPTc10-28	VPT Series Metal Modules	EMI Filter / Transient Protection Module	10A, 150W	✓	✓	✓
VPTPCM-12	VPT Series Metal Modules	Preconditioning Module	120W		✓	✓
DVMN28	COTS Potted Modules	EMI Filter and Input Attenuator	14A / 250W	✓	✓	✓

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 purpose 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.

## Conclusion

Inrush current is the peak current which 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 which 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.

## Additional Information

For additional information on designing power systems to comply with peak inrush current requirements or VPT products contact VPT at 425.353.3010 or [vptsales@vpt-inc.com](mailto:vptsales@vpt-inc.com). Or visit VPT at [www.vpt-inc.com](http://www.vpt-inc.com).