WHITE PAPER

Reduce Load Capacitance in Noise-Sensitive, High-Transient Applications, through Implementation of Active Filtering

Chester Firek, Product Marketing Manager
and Bob Kent, Applications Engineer

Abstract

Power architects engaged in designing systems requiring low-output noise and fast transient response, such as RF transmitters, power amplifiers, test systems, displays, designs supporting low voltage ASICs and laser-diode transmitters, understand that when attempting to tailor power systems to meet both requirements using passive components, the two objectives become diametrically opposed. Minimizing periodic and random deviations (PARD) requires filtering, whereas fast transient response is impeded by filtering.

The characteristics of the DC-DC converter, the load, the electrical characteristics of the passive components and the available PCB area all present additional design constraints that further limit the designer's options. This task becomes more difficult if the designer is unable to begin the design with an optimized DC-DC converter, to match the transient and noise requirements. This may be due to either a lack of in-house design resource, a short design window or the desire to use products already on their approved vendor list. In this instance a high efficiency off-the-shelf DC-DC converter may be used.

The following white paper uses a typical off-the-shelf isolated DC-DC converter to demonstrate how an active filter will not only provide superior filtering, as compared to the passive approach, but will also provide a simple turnkey solution to meet challenging transient-response requirements. This approach can either eliminate the need for load capacitance all together for noise reduction or reduce the amount required by as much as a factor of ten, for equivalent transient capability. The performance improvements demonstrated in this paper would also apply to applications using optimized custom DC-DC converters.

DC-DC converter considerations

In order to properly understand the issues involved in optimizing a "power system" for low noise and fast transient response, it is important to first establish the baseline performance of the DC-DC converter. Many of today's off-the-shelf high-density switch-mode power converters are designed to optimize for power density and efficiency, two of the most commonly used criteria for converter selection. DC-DC converters are only part of the total power system, a component, not a total solution. Although the output ripple and noise levels from some converters are adequate for the needs of today's end systems, they may not be adequate for some of the more sensitive analog or digital systems. And as a power component, the DC-DC converter will generally provide a good current-source "engine" to support load transients, but will generally not have much internal energy storage capability. Parameters such as low ripple and fast transient response are design trade-offs for density and efficiency and because specific needs may vary from application to application, the DC-DC manufacturer will provide methods to further optimize these parameters with the use of external components, rather than add them internally to the converter. The ability of the converter to be optimized (with external components) for low noise and fast transient response will depend on the converter topology, switching frequency and any limitations the converter manufacturer may impose on use of external components; i.e., maximum load capacitance.

Options for reducing ripple

The two major sources of ripple and noise on the output of a DC-DC converter are the switching noise generated by the converter and the line ripple from the converter source (usually 120Hz if powered by an off-line source). For the line ripple, a DC-DC converter will provide some level of ripple rejection; any remaining ripple will appear at the load. In general terms, the output ripple specification for a regulated DC-DC converter can range anywhere from $100mV_{P-P}$ (5V output) to $240mV_{P-P}$ (24V output) or more, depending on the converter. As a percentage of output voltage, the range could be 2% for a $5V_{OUT}$ converter and 1% for a $24V_{OUT}$ converter (see Table 1). The addition of low ESR (Equivalent Series Resistance) capacitors can reduce the ripple by up to 50%; using the previous examples would yield a range of 50 – $120mV_{P-P}$. Further reduction in ripple can be achieved by adding an inductor, with low DC resistance, in series. Adding an inductor can provide up to an additional 50 – 60% improvement; reducing the ripple to roughly $20mV_{P-P}$ for a $5V_{OUT}$ converter and $50mV_{P-P}$, or more for a $24V_{OUT}$ converter. Although the improvement is significant, an application using a 28V RF power amplifier (P.A.) may require the ripple levels to be as low as $10mV_{P-P}$ or less, to prevent sideband frequency peaks. Further improvements to reduce input line-reflected ripple would require better attenuation at low frequencies which requires the use of larger inductors and more capacitance. For space savings, the more practical approach to attenuate the remaining lower frequency noise is to use active filtering.

Table 1

Output ripple specifications for isolated DC-DC converters with various filter solutions

Filter Solution	**Output Voltage**		
	5V	**12V**	**24V**
No Additional Filter	100mV	150mV	240mV
Low-ESR Cap	50mV	75mV	120mV
LC Output Filter	20mV	35mV	50mV
QPO and µRAM Series Active Filters	<10mV	<10mV	<10mV

Transient response

Noise-sensitive applications such as RF power amplifiers and laser diode transmitters also require very fast transient-load response. In the case of an RF power amplifier, the system may operate steady state at 10% load and then have the load increase to nearly 100% almost instantaneously. For the average DC-DC converter the response to a large load step can take a few hundred microseconds, where the P.A. may require the load to recover in less than one hundred microseconds. For an off-the-shelf isolated DC-DC converter, the response time for the control feedback loop (approximately equal to 1/5 the converter switching frequency) is far too slow to be able to recognize a transient event and respond to it in enough time to avoid a significant droop in output voltage. Adding passive components further slows down the converter loop response. Active filters provide a buffer between the DC-DC converter and the load as opposed to passive solutions that do not offer this capability. The load response is provided primarily by the active filter which can provide a loop response several orders of magnitude faster than the DC-DC converter. The waveforms in Figure 1 depict a typical converter's response to a 7.7A transient load current with no external filtering or capacitance.

For the converter in Figure 1, the steady-state output ripple is approximately $100mV_{P-P}$, far too high for most noise-sensitive applications. However, the larger concern for system designers may be the droop in output voltage. In the example shown, the output droops when the load-transient event begins and then overshoots at the end of the transient event when the load current falls creating an overall output voltage deviation of approximately ±250mV; which once again will be an issue in a sensitive application.

In order to provide a quicker response to load transients, additional output hold-up capacitance usually needs to be added as a source of current to satisfy the additional load. Depending on the transient requirements, this could mean that a very large amount of extra capacitance would need to be added. The drawbacks to adding extra capacitors are the cost of the components, the board space they occupy, and the impact of additional capacitors on system reliability. Furthermore, capacitors do not provide an ideal solution as there will still be an inherent transient voltage drop due to a capacitor's internal ESR. The ability of this configuration to maintain a clean stable output voltage during a transient is dubious. The topic of added capacitance is discussed further in the Adding "Hold-Up" Capacitance and Comparing Solution Size and Weight sections.

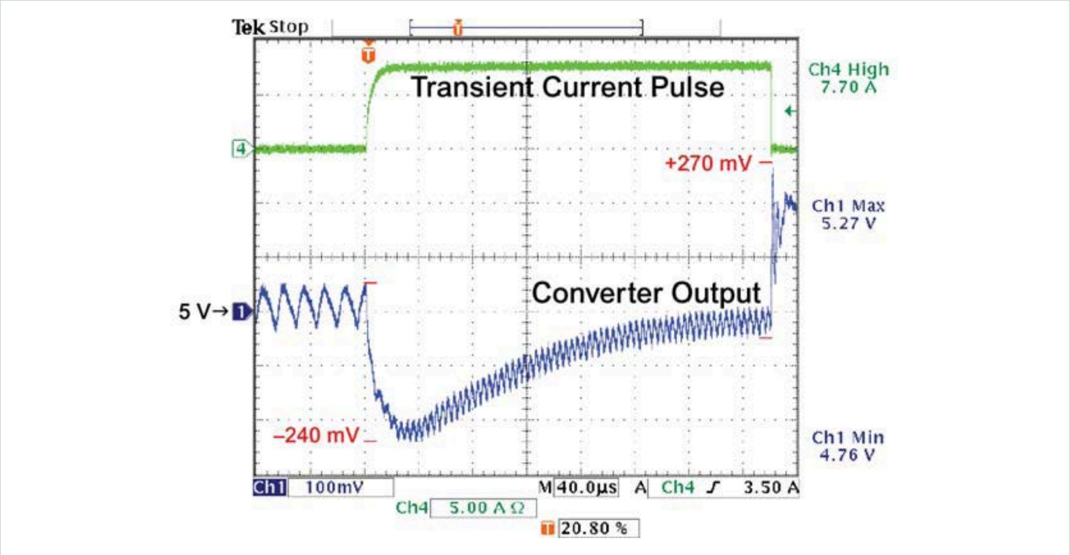

Figure 1
Transient load current with a 5V output converter [a]

LC filter networks

The most common method of filtering output ripple is to add inductance in series and capacitance in parallel at the output of the converter, commonly referred to as an "LC network," (as shown in Figure 2). As illustrated in Table 1, the inductor in the LC network helps provide better ripple attenuation than the capacitor alone.

The inherent problem with adding inductance is that when a transient load occurs, the current through the inductor cannot change fast enough to provide current to the load, so all the energy must be supplied by the load capacitor(s). The amount of capacitance that is required will depend on the system requirement and change in load current versus time [dI/dt]. But as the capacitors provide the necessary current, there may still be an unwanted drop in output voltage due to the non-ideal parasitic factors; equal to the value of the transient current multiplied by the equivalent series resistance (ESR) of the capacitor(s) and the frequency dependent drop across the electrical series inductance (ESL).

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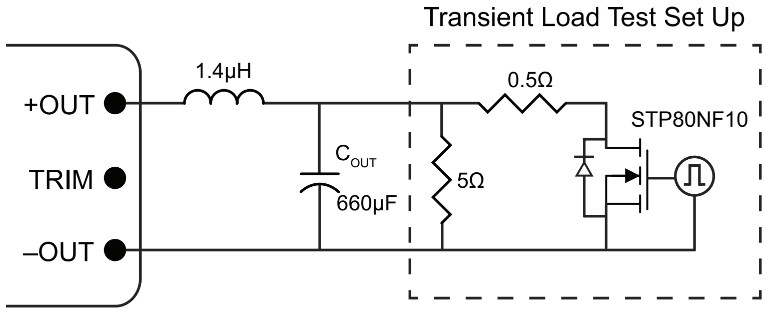
[a] The DC-DC converter used was Vicor part number V48C5C100BN.

Figure 2

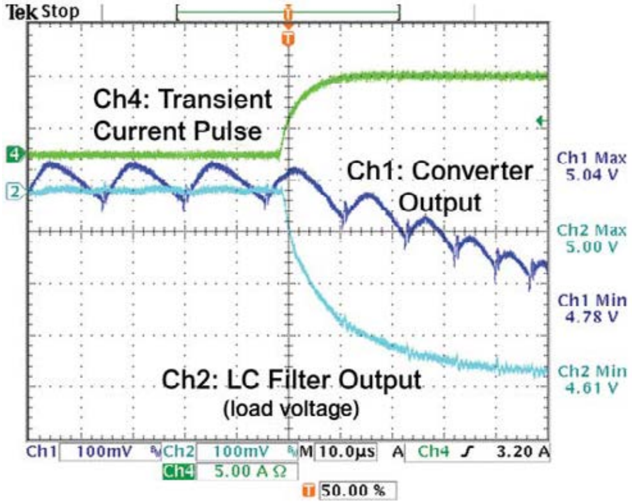
Test set up, DC-DC converter with LC Filter



The waveforms in Figures 3 and 4 show the results of the LC network filtering on the converter output ripple (Ch2). Although the ripple is significantly reduced the transient drop in load voltage has increased. At the start of the transient there is a sharp drop in the output voltage from the filter. Since the current through the inductor cannot change instantaneously, the current for the transient load must come from the output capacitors. This initial voltage drop is the result of the transient current multiplied by the capacitor ESR. To reduce the voltage drop, the overall ESR of the output capacitance would have to be reduced; by either careful selection of lower ESR caps or by using more capacitors to parallel the ESR component. In this instance, the voltage at the load droops by more than 300mV before the converter starts to recover and bring the output up to the regulation voltage.

Figure 3

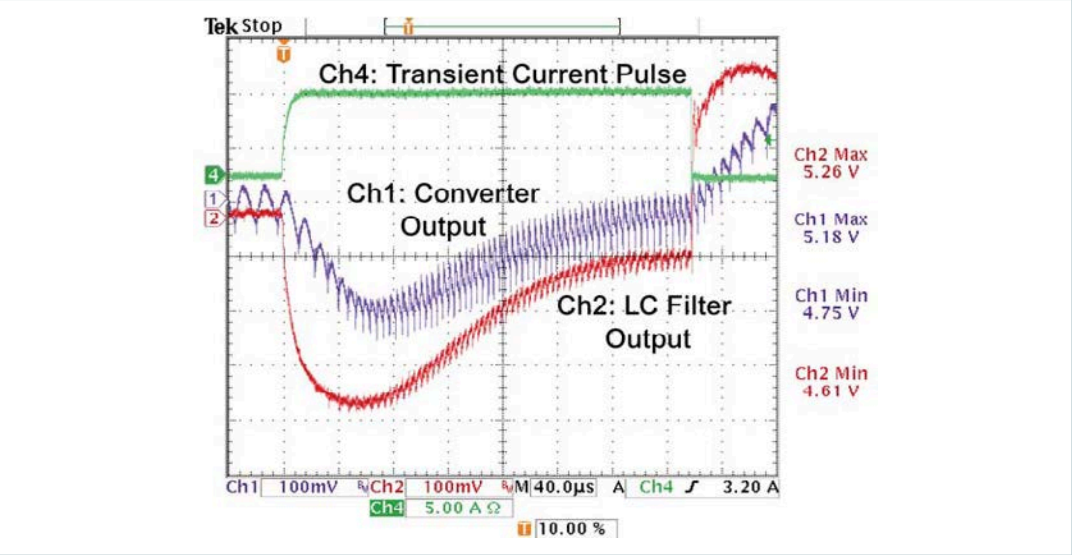
Ripple and load response of a $5V_{OUT}$ converter using a LC filter on the output



The waveforms in Figure 4 show the complete transient event and the resulting undershoot and overshoot of the LC filter, due to the LC filter ringing at its resonate frequency. By the end of the transient, the current through the inductor is providing the transient load current. When the load transient ends, the current through the inductor remains the same since it cannot change instantaneously and gets dumped into the load capacitors. Forcing this stored energy into the capacitors raises the output voltage by about 300mV; resulting in a peak-to-peak variation of 600mV due to the transient load change.

Figure 4

Complete transient load event with a 5V_{OUT} converter and LC network

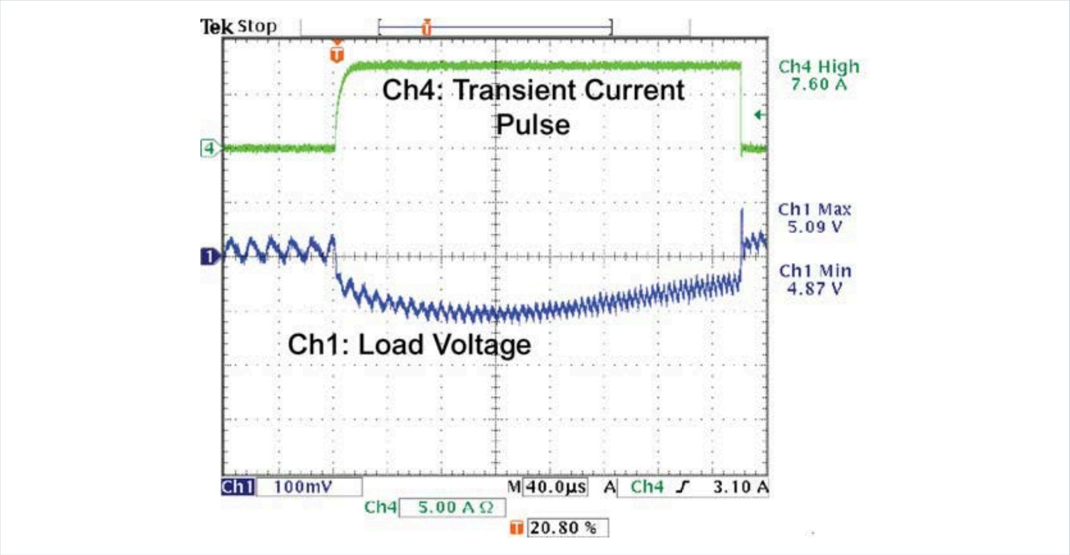


Adding "hold-up" capacitance

To compensate for such a dramatic variation in output voltage, additional capacitance needs to be added at the load to "hold up" the voltage at the load. To consider the affects of load capacitance, the same circuit will first be demonstrated without the inductor. The waveforms in Figure 5 show the same converter output voltage during the transient load with an additional 8mF of capacitance on the converter output.

Figure 5

Transient load current with a 5V_{OUT} converter and eight parallel 1mF caps (8mF total)



In this instance the added capacitance reduced the voltage droop to roughly 100mV, rather than 300mV with the LC filter. As expected the amplitude of the ripple has reduced (to approximately 40mV$_{P-P}$) as compared to the standalone DC-DC converter; although the ripple is higher than the with the LC filter.

Although the results using this approach show improved overall performance, achieving these results should be weighed against the total size of the solution as well as any potential reliability issues relating to compatibility with the converter.

Note: Most DC-DC manufacturers place limits on the amount of capacitance that can be added to the output of the converter in order to avoid loop stability issues. In the example shown above the maximum capacitance value set by the converter manufacturer was exceeded in order to demonstrate an extreme case. Always refer to the manufacturer's DC-DC converter specifications to determine acceptable capacitance levels.

Combining hold-up capacitance with inductance

Figure 6 shows a test circuit combining the 1.4µH inductor from the LC filter with the 8mF of hold-up capacitance from the previous example. The resultant waveforms in Figure 7 show that the output ripple has improved but the transient response has degraded slightly. Since the resonant frequency of the LC filter is much lower with the 8mF of capacitance, it is clear that the first step in voltage is due to the capacitor's ESR and the reactance of the inductor.

In this example, the load capacitance was increased by more than ten times the amount used in the first LC filter example shown in Figure 2. In this example the benefit of hold-up capacitance appears to have been maximized. Adding the inductor has once again reduced the ripple levels. Further reduction in ripple may be possible with larger inductors. These nearly optimized results of a passive design can now be compared to the performance of an active filter.

Figure 6

Test set up, 5V_{OUT} Converter with 1.4µH inductor and 8mF of load capacitance

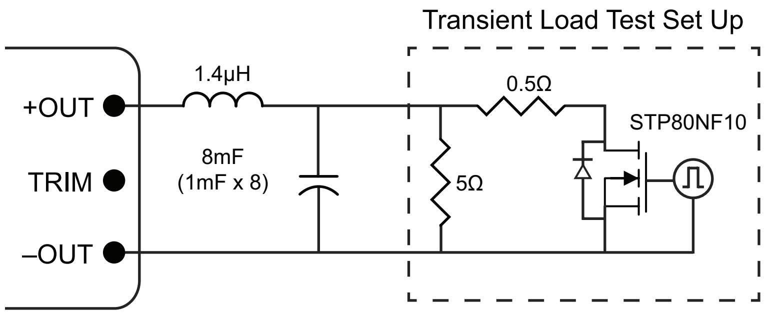
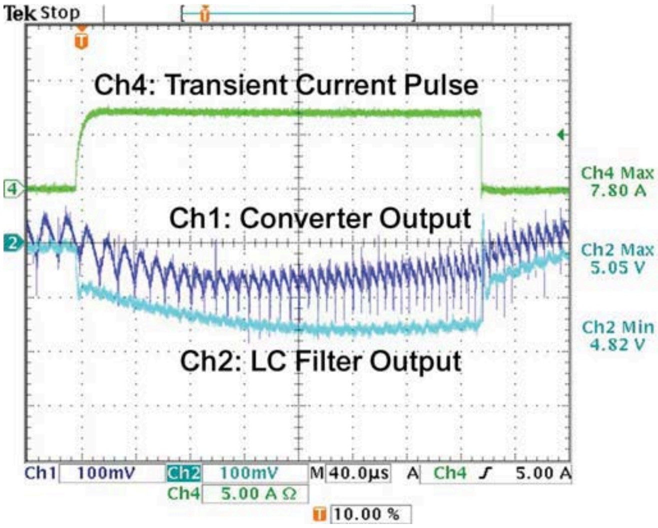


Figure 7

Transient load current with 1.4µH inductor and 8mF of load capacitance



VICOR PowerBench

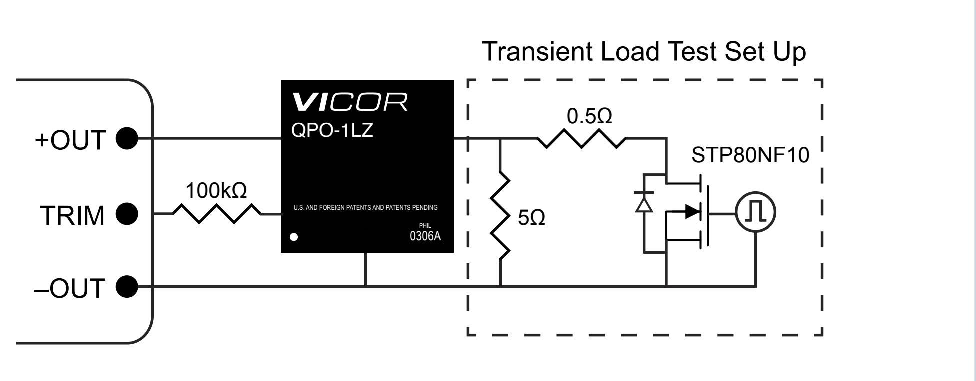
Active filtering and transient response

As illustrated in the previous examples, the primary drawbacks in the passive approach are the effect of the inductance on transient response and the voltage drop across the hold-up capacitance. Active filters provide improved transient response by replacing the passive inductance, which has inherently slow di/dt, with much faster and smaller active components as shown in Figure 8. In the active approach the inductor reactance is replaced by a power FET and a high-speed controller device that modulates the FET to create linear resistance. [b] During a transient condition, the loop gain of the filter increases the effect of capacitance at the input to the filter by a ratio of the change in the input voltage of the filter divided by the change in the output voltage of the filter ($\Delta V_{IN} / \Delta V_{OUT}$), drastically reducing the amount of capacitance required while decreasing transient di/dt response time.

Active filters such as the Vicor QPO™ and µRAM™ models are able to respond to transients much faster than converters by decreasing the internal resistance path between its positive input and output pins. Since the voltage is greater on the QPO input than its output, this voltage difference can be used to compensate for the additional load requirements of the transient. This voltage difference (ΔV_{HR}), referred to as the headroom voltage, is selected by the user providing an output voltage on the converter that is greater than the desired load voltage. During the transient, the output of the converter will droop and the active filter will compensate by reducing the headroom voltage to maintain a constant output voltage provided that the voltage droop is not greater than the selected ΔV_{HR}. The minimum voltage drop by the active loop of the QPO is based on the QPO minimum resistance.

Figure 8

Test set up, $5V_{OUT}$ converter with QPO-1 active-output filter



The waveforms in Figure 9 demonstrate the ability of the QPO to filter both the ripple voltage from the converter as well as the voltage droop of the converter during a transient load event. In this example the QPO test board was designed to have 350mV of headroom voltage under low load conditions; which for this test was a 1A constant load. Ch1 is the voltage seen on the QPO input; Ch2 is the QPO output voltage. Both channels are DC measurements with a 5V offset and referenced two divisions down from center.

In Figure 9 the load step (Ch4) monitors the transient current only and does not include the static 1A load. Examining the plot starting with the left edge of the waveforms, the average dc voltage difference between Ch1 and Ch2 is 350mV. After about 80µs, the transient current event occurs (~1A/µs) and the voltage from the converter (Ch1) droops. The QPO output voltage (Ch2) remains constant at 5V for the entire duration of the transient. As a result the QPO filter virtually eliminates the ripple and the load voltage drop associated with the 7.7A transient, with no additional capacitance, significantly outperforming all of the passive scenarios.

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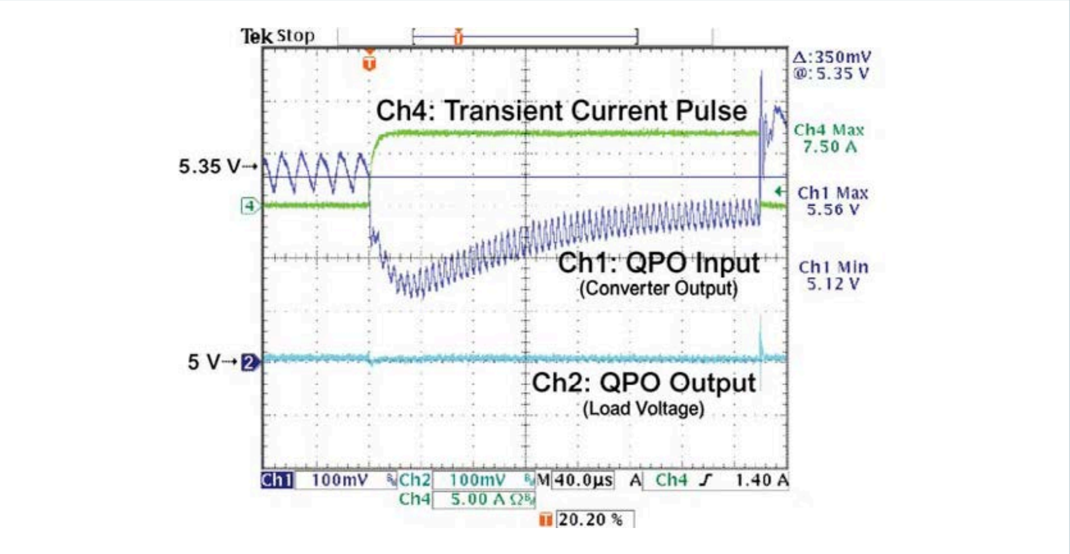
[b] "Active Analog Power Filters Provide Solutions for EMC & EMI" 2004, by Jeff Dumas, Bob Lanoue and Bishara Tahhan

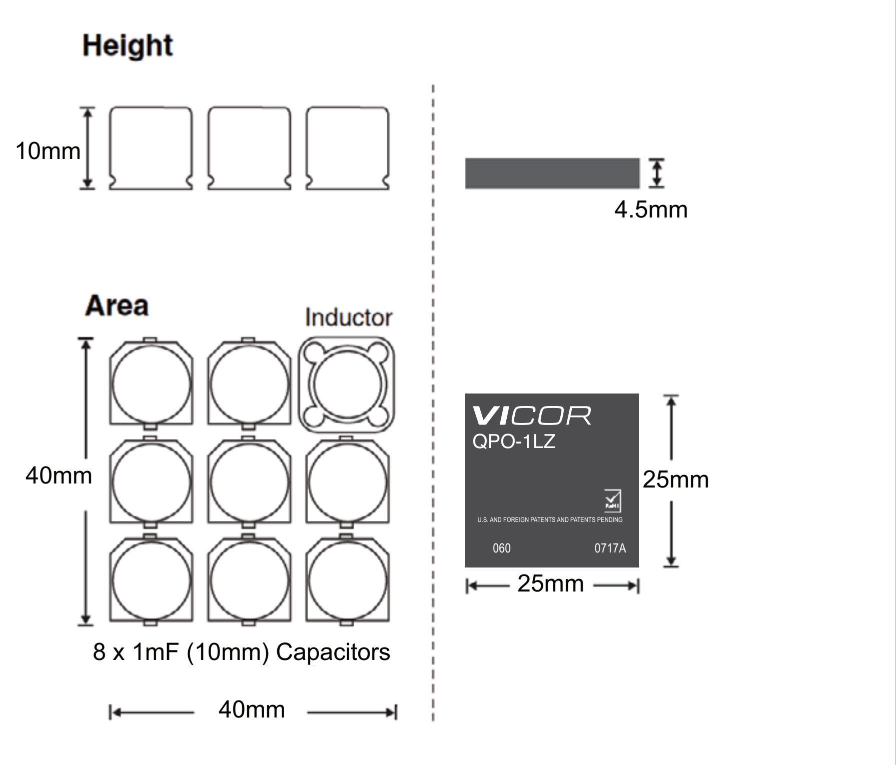
Figure 9
Transient load with the same 5V_{OUT} converter and a QPO active-output filter



Comparing solution size and weight

In addition to improved transient and output ripple erformance, active filters provide additional benefits in size and weight. Using the components from the circuit in Figure 6, a scale drawing of component size is illustrated in Figure 10. The amount of board area required for the inductor and capacitors, including appropriate clearance for each component, would be approximately 1,600mm^2, with a height of 10mm. In comparison, a single QPO™ filter occupies an area of 625mm^2, with a height of only 4.5mm; roughly a 60% reduction in area compared to the passive circuit and approximately 80% reduction in volume. In addition to the space savings, active filters are inherently light weight. The QPO filter in the example weighs only 3.1 grams, approximately the weight of just one capacitor, an additional benefit for portable or mobile equipment applications.

Figure 10
Size comparison of the QPO Filter and the passive components used in Figure 6



Summary

When designing power systems that require low noise and fast transient response it is important to understand the tradeoffs and limitations of all the components that will make up the "power system;" i.e., the DC-DC converter, filter and hold-up capacitors. The DC-DC converter will produce the baseline from which to improve upon. Adding passive filter components to the output of the DC-DC will reduce ripple but this will result in a negative affect on transient response, and may potentially create stability issues. More capacitance will be needed to improve transient response. Depending on the amount of ripple and transient response improvement needed, the passive solution may also become very large, potentially making the solution space prohibitive.

As demonstrated in the previous examples, active filtering provides better overall filtering and load transient performance than a passive approach due to faster loop response and lower resistance. In the example provided in Figures 8 & 9, the QPO-1 demonstrated a significant improvement in transient response with no additional load capacitance present. By reducing the amount of load capacitance required in low noise, high transient-load systems, the power design can become optimized for both performance and size.

Vicor active filters are available with input ranges from 0.5 to 30V, and can support current levels up to 30 Amps. QPO™ filters are available in 25 x 25mm surface mount LGA packages, µRAMs™ are 57.9 x 36.8mm, DC-DC 1/4 brick style, through-hole packages. Both are compatible with most DC-DC Converters.

Table 2
Vicor active-output filter models

Model #	Operating Voltage Range	Current Rating
QPO-1	3.0 – $30V_{DC}$	10A
QPO-2	0.3 – $5.5V_{DC}$	20A
µRAM-2	3.0 – $30V_{DC}$	20A
µRAM-3	3.0 – $30V_{DC}$	30A

Contact Us: http://www.vicorpower.com/contact-us

Vicor Corporation
25 Frontage Road
Andover, MA, USA 01810
Tel: 800-735-6200
Fax: 978-475-6715
www.vicorpower.com

email
Customer Service: custserv@vicorpower.com
Technical Support: apps@vicorpower.com