APPLICATION NOTE | AN:202

Filter Considerations for the IBC™

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Application Engineering

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Introduction

The Intermediate Bus Converter (IBC) Module is a very efficient, low profile, isolated, fixed-ratio DC-DC converter based on the Vicor patented Sine Amplitude Converter^{TM} (SAC^{TM}) technology. The IBC exhibits low levels of noise, has a very wide bandwidth and has a high efficiency.

This application note covers the necessary design considerations for applying a filter to the IBC to achieve optimal performance from the module. The material presented in this application note can be applied to other Vicor DC-DC converters, but the user must be aware of the characteristics of the converter that is being implemented.

IBC Attributes

The IBC has a very low insertion impedance and it is important to minimize the source impedance to keep the voltage drop low at the input. It has a wide bandwidth and allows power to be transferred very quickly to downstream non-isolated point of load regulators (niPOLs). Any voltage deviations at the input will be attenuated by the K factor at the output as most IBC's have a K factor of less than one.

The input inductance must be minimized to ensure a critically-damped response. Oscillations can occur if the distribution inductance exceeds the specified input inductance limit in the data sheet as the input capacitance of the converter can resonate with the high inductance.

It is important to place the filter at the input of the IBC to maintain a low impedance at the output. Output impedance is reduced by the square of the K factor between DC and roughly ½ of the switching frequency.

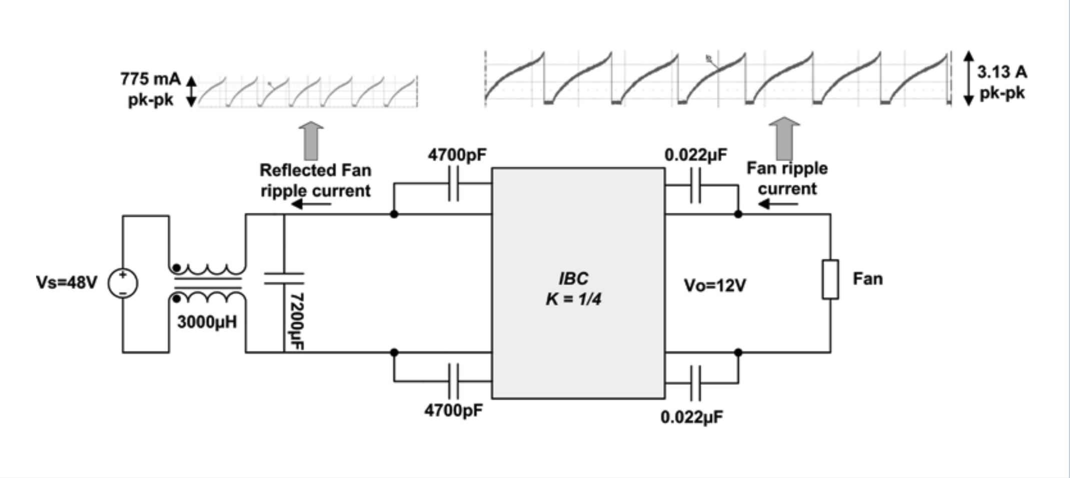


Figure 1
Response of IB048E120T32N1-00 Module with a Fan as Load

Figure 1 shows ripple current produced by a 12V fan connected to the output of an IBC and test setup of system. The IBC accurately reproduces the low-frequency noise (~680Hz) introduced by the fan and is reduced by the K factor at the input side of the converter.

Figure 2
Response of IB048E120T32N1-00 Module with a niPOL as Load

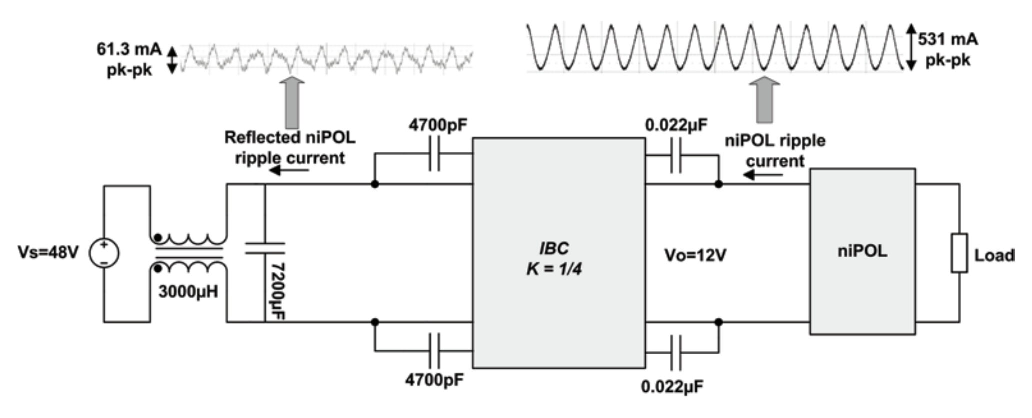


Figure 2 shows ripple current produced by a 12V niPOL connected to the output of an IBC™ and test setup of the system. Here, the IBC reproduces the high-frequency noise (~250kHz) introduced by the niPOL. The reflected-current ripple is reduced by the K factor at the input side of the IBC and further reduced by the circuit impedances. Figures 1 and 2 both demonstrate the IBC's ability to accurately transfer output load current ripple to the input due to its wide bandwidth.

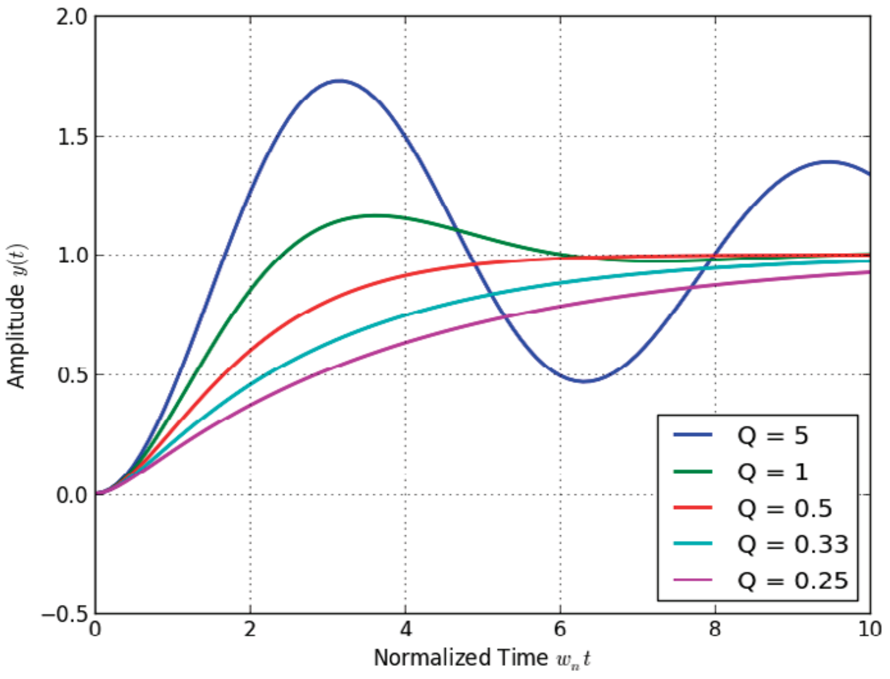
Input Filtering Considerations

Damping and Converter Bandwidth

The quality factor (or Q factor) describes the loss of a system's response. A system with a low Q factor, Q < ½, is overdamped; a system with a high Q factor, Q > ½, is underdamped; a system with an intermediate Q factor, Q = ½, is critically damped.

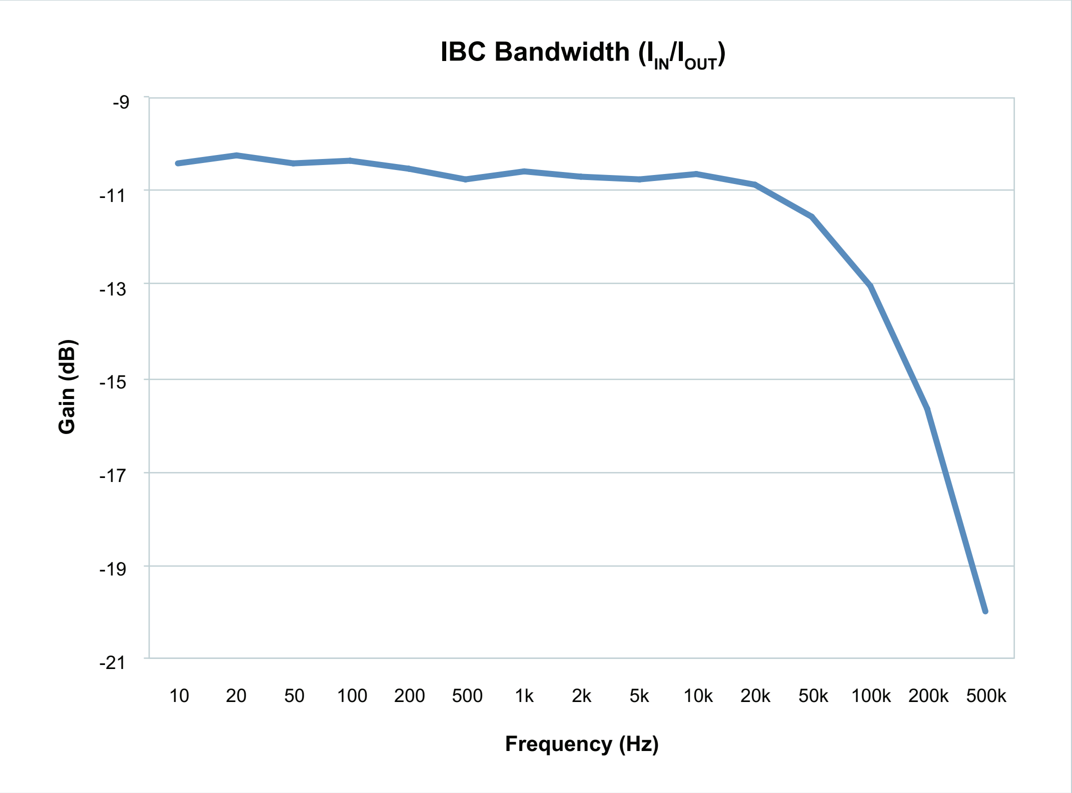
Figure 3 shows an example of a stepped response for a second-order system and shows the under-damped case (Q > ½), the overdamped case (Q < ½), and the critically-damped case (Q = ½).

Figure 3
Example of Various Q Factors



Due to the low input impedance of the IBC™, it is very important to keep the input inductance minimized to have a critically damped response. Resonances can be amplified by the negative impedance presented by downstream non-isolated point of load (niPOLs) converters and an under-damped input bus is susceptible to oscillations by the input reflected ripple currents.

Figure 4
Bandwidth of an IB048E120T32N1-00 Module

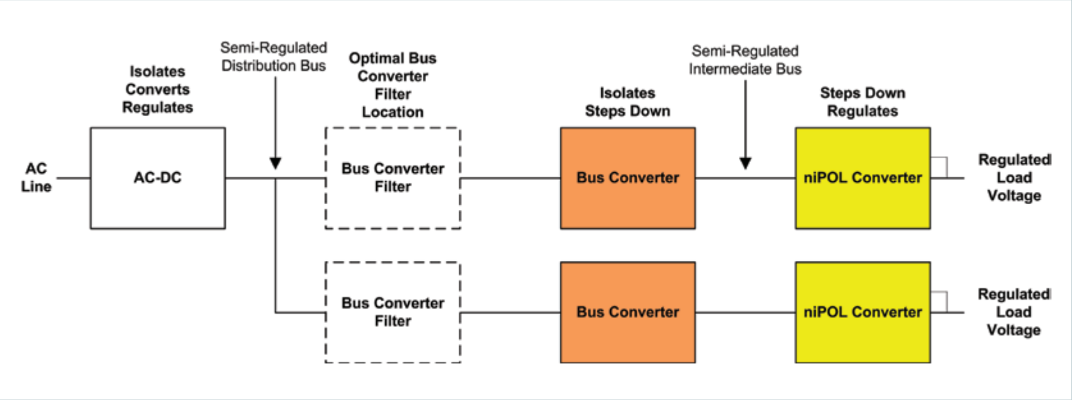


The bandwidth of an IBC is shown in Figure 4. The IBC has a wide-bandwidth response and can process signaling up to 500kHz. Any unwanted noise generated by downstream converters can be externally filtered. When designing a filter, inherent attributes like the Q factor need to be taken into consideration for optimal performance.

Filtering

Intermediate Bus Architecture (IBA) systems typically convert a high-voltage input bus (48V_{DC}) to an intermediate voltage (usually 5 – 15V_{DC}) through an isolated DC-DC converter referred to as the intermediate bus converter. The intermediate bus converter provides DC isolation and fixed-ratio voltage conversion. Point-of load (PoL) regulators, usually non-isolated buck regulators, converts the intermediate bus voltage and steps the voltage down to provide a regulated output. Figure 5 shows a block diagram of a typical IBA topology incorporating two IBC arrays. A filter can be designed and placed before the IBC module to attenuate noise generated by downstream loads and/or upstream converters.

Figure 5
IBA Block Diagram



In a system where multiple IBC's™ are used to convert intermediate voltages, the designer may want to place the filter before the entire paralleled array or place a filter before each array. Placing a filter before each array is better in practice from a signal integrity stand point as it will add isolation and damping.

If a single filter is put before multiple IBCs and their loads, common-mode and differential-mode currents could possibly travel from one array to another. Common-mode noise contains high-frequency harmonics and the magnitude of the common-mode voltages increase as ground-plane losses increase. Having a filter before each array will ensure that the common-mode emissions are minimized reducing the common-mode currents and suppressing both radiated and conducted emissions.

The IBCs are relatively easy to filter to meet international standards for conducted emissions due to their inherent low noise and high operating frequency. However, a large filter may be needed to filter unwanted noise generated by conventional point-of-load converters that operate at lower frequencies.

Filter Approach

A properly damped L/C filter can be used to minimize reflected input current. Figure 7 shows a general setup of an IBC with an external filter and Figure 8 shows an IBC with a damped L/C filter (the filter components are highlighted in red). To determine the filter values, the input impedance of the converter must be known and a cutoff point must be chosen. The input resistance (R_{IN}) of the converter is not constant and varies widely with the operating voltages and power rating. The apparent R_{IN} is at a minimum at low-line full power operation of the converter. For example, an IB048E120T32N1-00 module operating at low-line full load (an input voltage of 38V with an output current of 32A) will have an apparent R_{IN} of 40Ω as shown in Figure 6.

Figure 6
Apparent Input Resistance of an IB048E120T32N1-00 Module

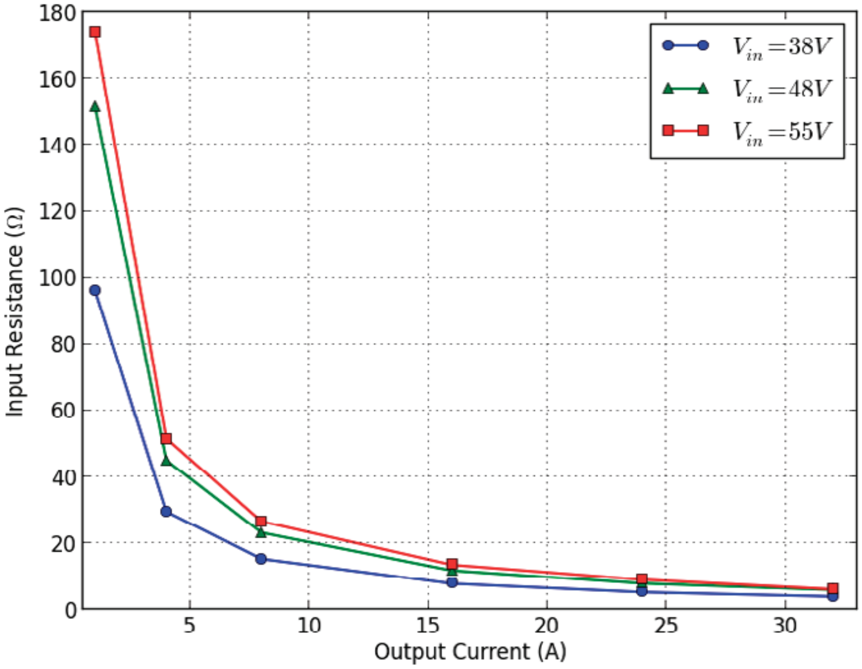


Figure 7
IBC™ with an External Filter

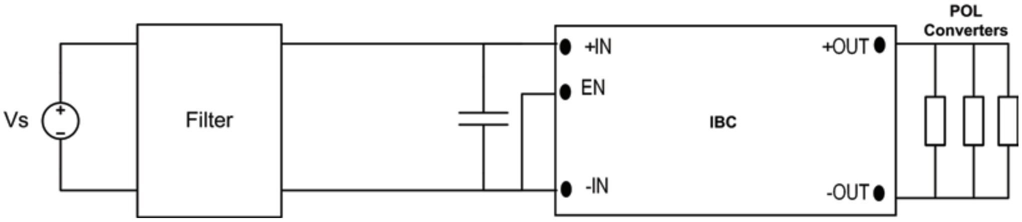
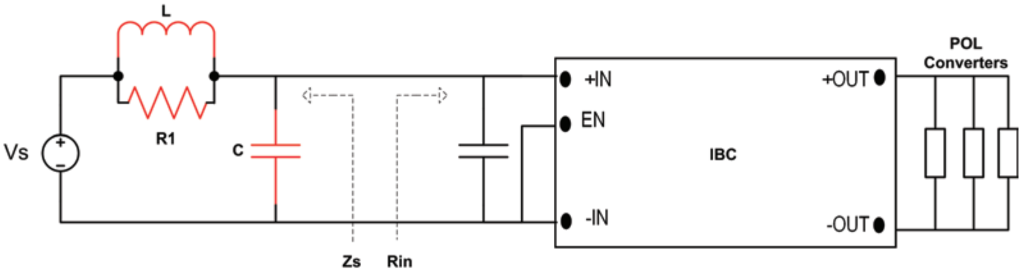


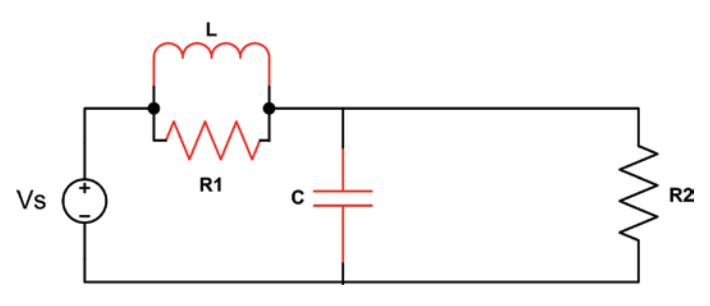
Figure 8
Shunt L/C Filter Circuit



The combined parallel impedance of R1 and L should be significantly less than 10% of Rin at any operating point within the converter's bandwidth as the filter's natural frequency has to be comparable to the bandwidth of the converter. If the minimum apparent Rin of the IBC™ is 40Ω, the parallel impedance of R1 and L should be less than 4Ω. NOTE: Source impedance should be minimized for dynamic load conditions as a 10% change in impedance results in a 9% change in load regulation.

R_{IN} of the IBC at dc will be referred as R2 to simplify the analysis as shown in Figure 9.

Figure 9
Natural Response Equivalent Circuit Model



The filter circuit acts as a low-pass filter to attenuate unwanted frequency content. The Q factor is dominated by R1 if R1 is much smaller than R2. It is important to minimize the Q factor of the filter to avoid risk of oscillation in the application.

When choosing an inductor for the filter, the Self-Resonant Frequency (SRF) must be taken into consideration. The SRF is the result of the resonant circuit that is formed by the inductor and its parasitic capacitance. The inductor should have a SRF greater than the desired cutoff frequency as inductors have capacitive properties for frequencies above the SRF where the filter will not provide the expected attenuation.

Q Factor of the L/C Filter

The Q factor of the L/C filter shown in Figure 9 can be calculated using the following equation:

$$Q = R1\sqrt{\frac{C}{L}}$$

The derivation of the equation above can be found in the appendix on page 15.

Common-Mode Inductors

A common-mode (CM) inductor can be used as a component in the damped L/C filter as it has characteristics that are very desirable for filtering noise.

A common-mode inductor attenuates common-mode noise and due to the leakage inductance in the windings, will also attenuate differential-mode currents. The combined inductance of the windings presents a high common-mode impedance to resist common-mode currents. It is also provides differential filtering as the magnetic fields generated by differential currents in the windings only partially cancel.

Figure 10

Common-Mode Inductor Model

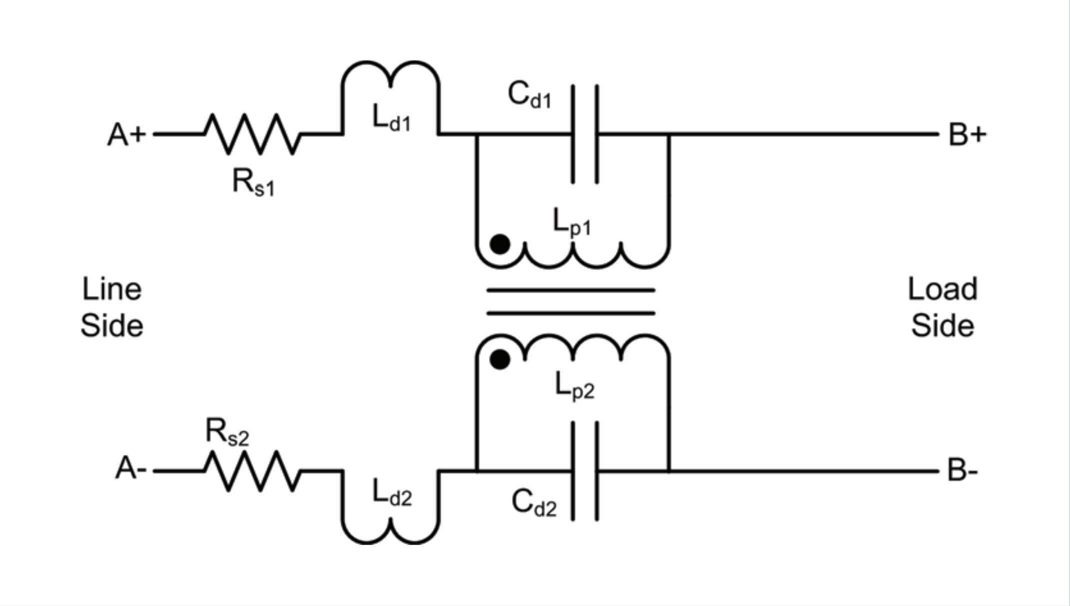


Figure 10 shows a circuit model representation of a CM inductor and its parasitics. The leakage inductance, shown as Ld1 and Ld2 in Figure 10 are the resultant of magnetic fields not having 100% magnetic coupling of Lp1 and Lp2. Distributed capacitance, labeled as Cd1 and Cd2, is another parasitic present in CM inductors due to inter-winding parasitic capacitance. The series resistance, labeled as Rs1 and Rs2, is the resistance introduced by the wire in the inductor.

Table 1 shows measured common-mode inductance, leakage inductance and percentage of leakage inductance of several CM inductors where the values were measured using a LCR meter operating at 1kHz. The leakage inductance of a CM inductor is not always specified by the manufacturer, but it is usually between 1% and 3% of the common-mode value. Leakage inductance can be measured by shorting one winding and measuring the inductance of the opposite winding.

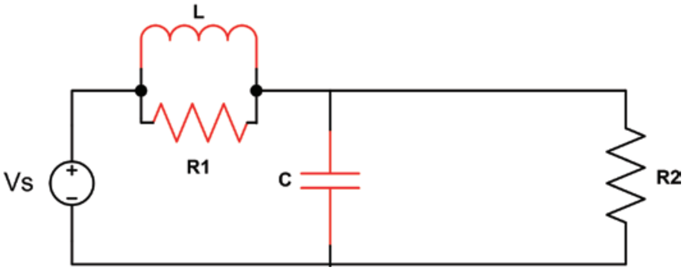
Table 1

Common-mode Inductor Measurements

Part Number	**Catalog Common-Mode Inductance**	**Measured Common-Mode Inductance**	**Measured Leakage Inductance**	**% Leakage (of measured values)**
Vicor 31742	3000µH	2800µH	11.5µH	0.4%
Vicor 31499-01	332µH	330µH	4.7µH	1.3%
Vicor 31742	1000µH	900µH	11.6µH	1.3%
Siemens B82723-A-N1	5600µH	5985µH	72µH	1.2%

Figure 11

Natural Response Equivalent Circuit Model



L/C Filter Applied to IBC™

Using an Inductor in the Filter

A damped L/C filter, using the configuration shown in Figure 9, was designed to filter the reflected current ripple generated by the fan used in Figure 1 and was placed between the IBC and load. Using Equations 2 and 7 (under the equation section in the appendix) can provide some guidance on choosing the values for R1 and C. When applying a filter to IBCs, make sure the maximum capacitance specified in the data sheet is not exceeded.

A 332µH inductor (Vicor part #31499-01) was chosen as the inductor in the filter. A 2200µF electrolytic capacitor and a 0.5Ω resistor were chosen to yield a Q factor of roughly 1.3 (using Equation 7) and a cutoff frequency of 320Hz to provide enough attenuation to filter the current ripple generated by the 12V fan and niPOL (the fan generates a 680Hz ripple and the niPOL has a switching frequency of 250kHz). From Equation 2 (in the appendix), the resonant frequency of the filter is 187Hz. The figures below show the simulated step response and measured step response of the filter.

Figure 12a
Step Response Filter Schematic

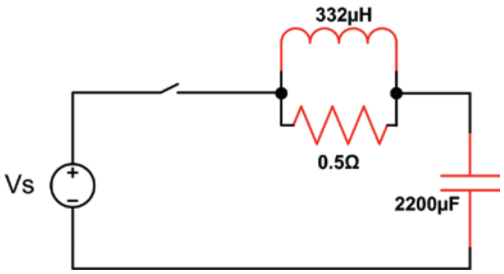


Figure 12b
Simulated Step Response of Filter Using Ideal Components (R = 0.5Ω, C = 2200µF, L = 332µH, Q = 2.3)

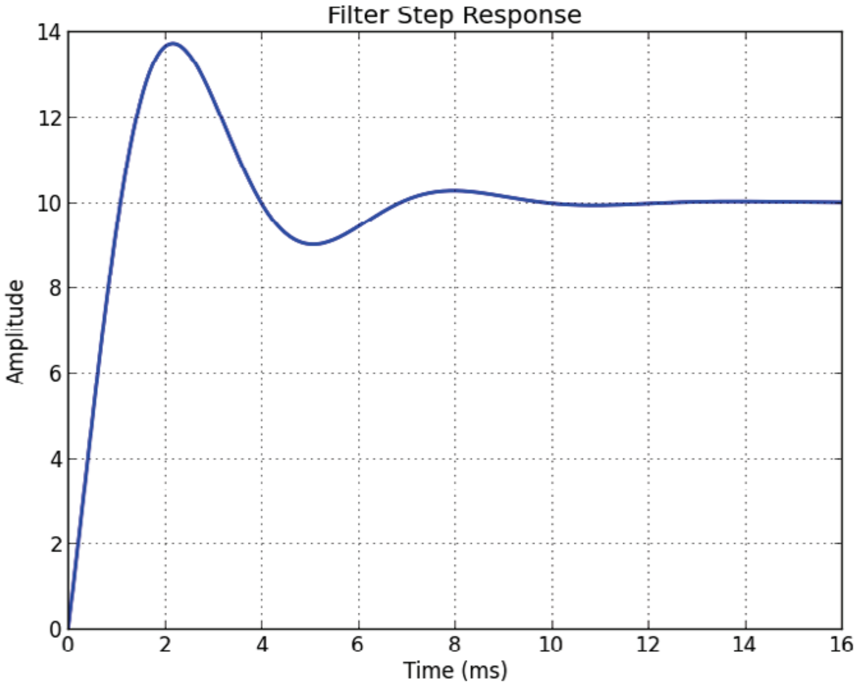


Figure 13

Measured Step Response of Filter (R = 0.5Ω, C = 2200µF, L = 332µH)

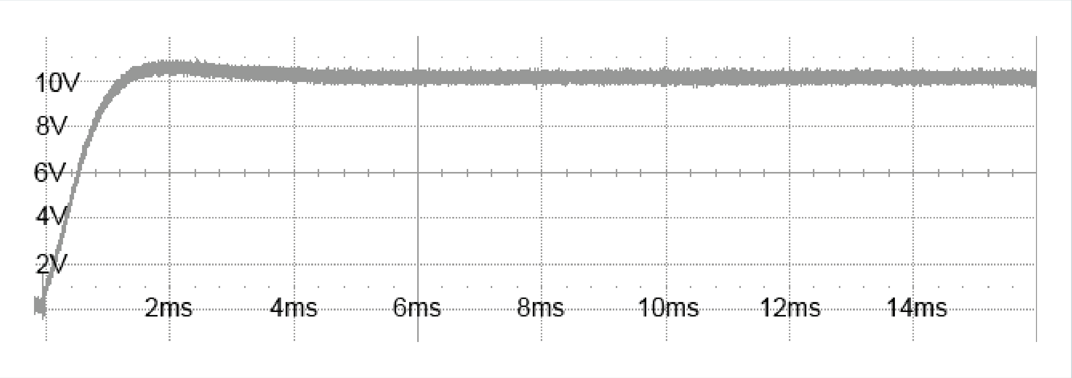
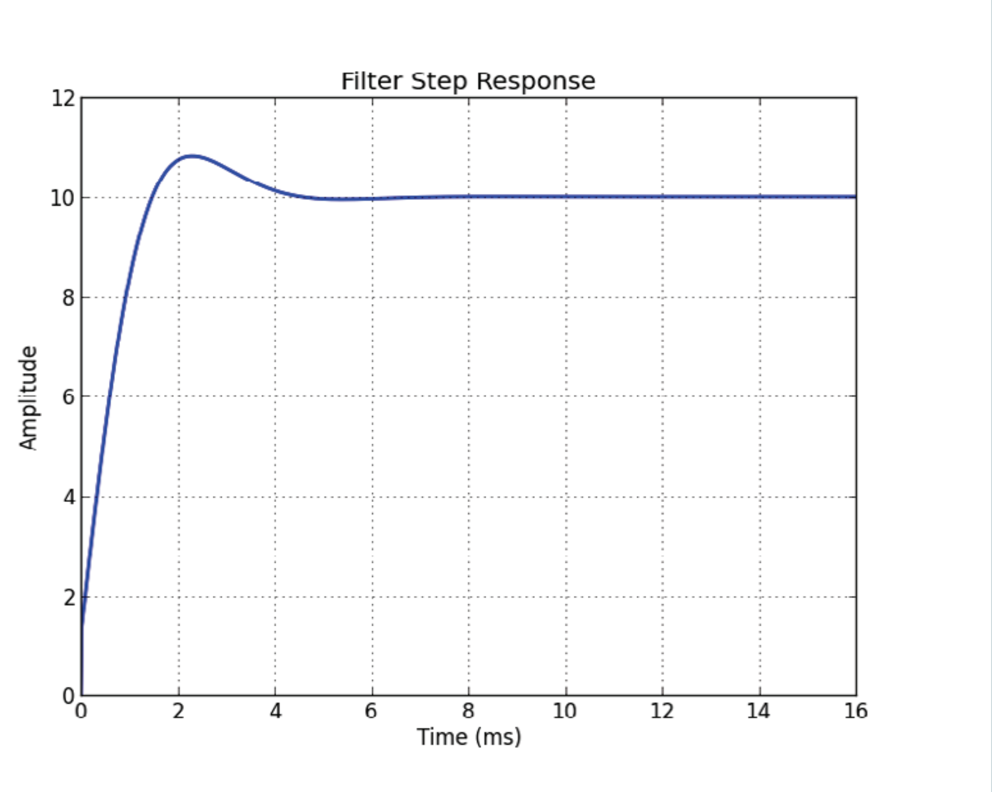


Figure 14

Simulated Step Response of Filter Including Component Parasitics (R = 0.5Ω, C = 2200µF, L = 332µH)



The inductor has an ESR of 0.27Ω and a distributed capacitance of 14pF. The ESR of the capacitor was measured as 0.07Ω. The parasitics of the inductor and capacitor added more damping to the filter when comparing the simulated step response to the measured step response shown in Figures 12b and 13. Figure 14 shows the simulated step response of the filter when the parasitics of the inductor and capacitor are included in the model.

Figure 15
Simulated Frequency Response of Filter (R = 0.5Ω, C = 2200µF, L = 332µH)

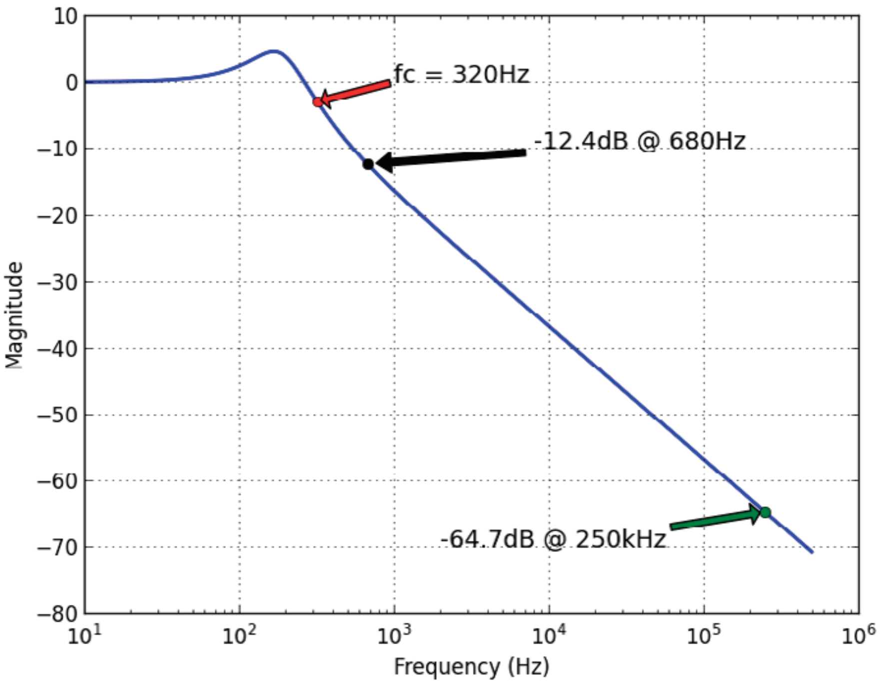


Figure 16
Simulated Frequency Response of Filter Including Parasitics (R = 0.5Ω, C = 2200µF, L = 332µH)

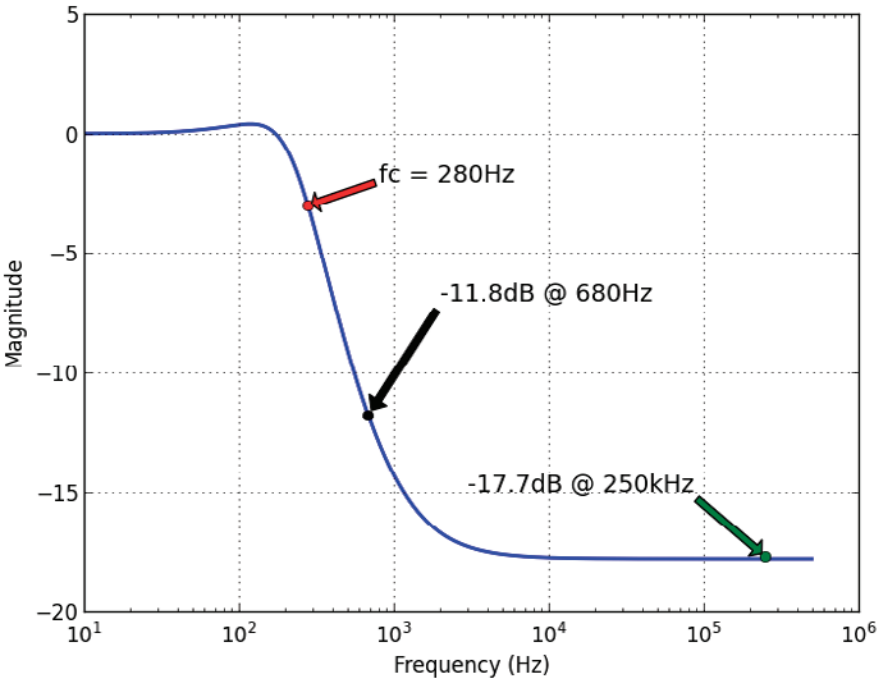


Figure 15 shows the simulated frequency response of the filter and Figure 16 shows the simulated frequency response when including the parasitics of the filter components. The parasitics of the components decreased the cutoff frequency from 320Hz to 280Hz, decreased the attenuation at 680Hz from –12.4 to –11.8dB and decreased the attenuation at 250kHz from –64.7 to –17.7dB.

Using a Common-Mode Inductor in the Filter

A CM inductor with an inductance of 3000µH (Vicor part # 31742) was chosen to replace both the 332µH inductor and 0.5Ω resistor in the filter due to its attractive damping characteristics and ability to filter CM and DM noise. The 3000µH CM inductor only has 11.4µH of differential inductance, therefore the filter with this inductor will be able to sufficiently attenuate the 250kHz noise generated by the 12V niPOL, but not the low-frequency noise generated by the fan. The measured step response is shown below in Figure 17b.

Figure 17a
Step Response Filter Schematic

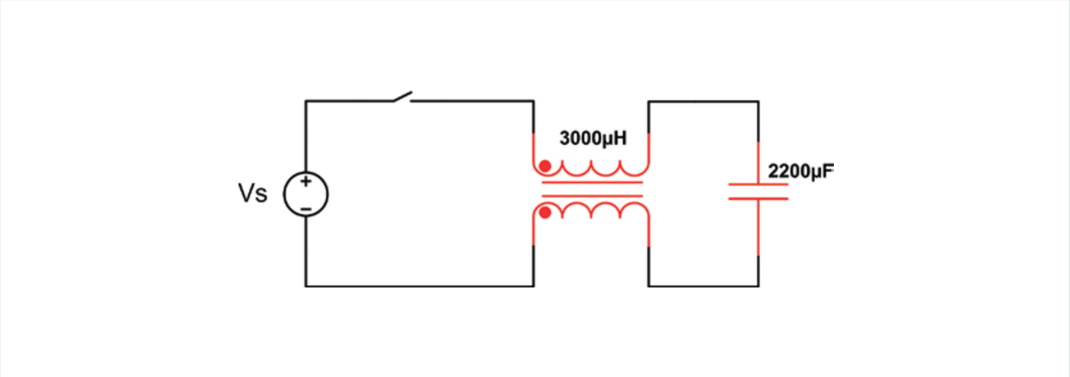
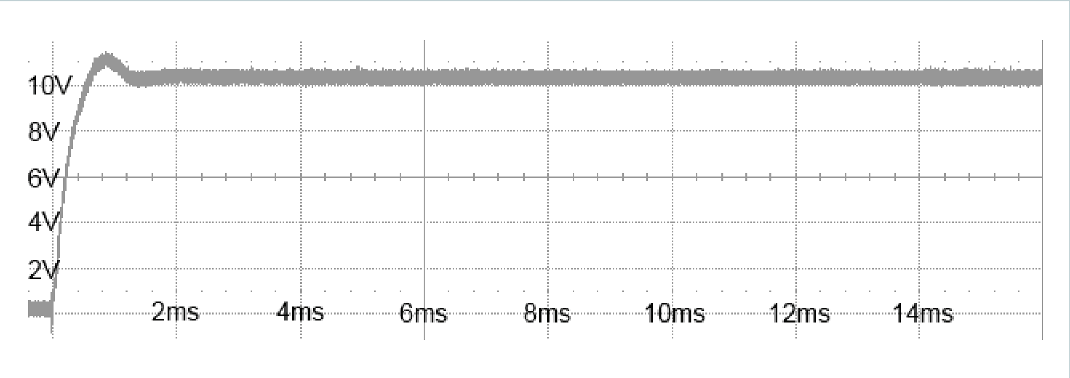


Figure 17b
Measured Step Response of Filter (C = 2200µF, L = 3000µH)



Due to the parasitics in the components, the filter provides sufficient damping even without a discrete resistor in the circuit. The CM inductor had a measured equivalent series resistance (ESR) of 0.04Ω and a parasitic capacitance of 46pF which yields a self-resonant frequency (SRF) of 450kHz.

Filtering Results

Figure 18
Filtered Response of IB048E120T32N1-00 Module with 12V Fan as Load and Inductor in Filter

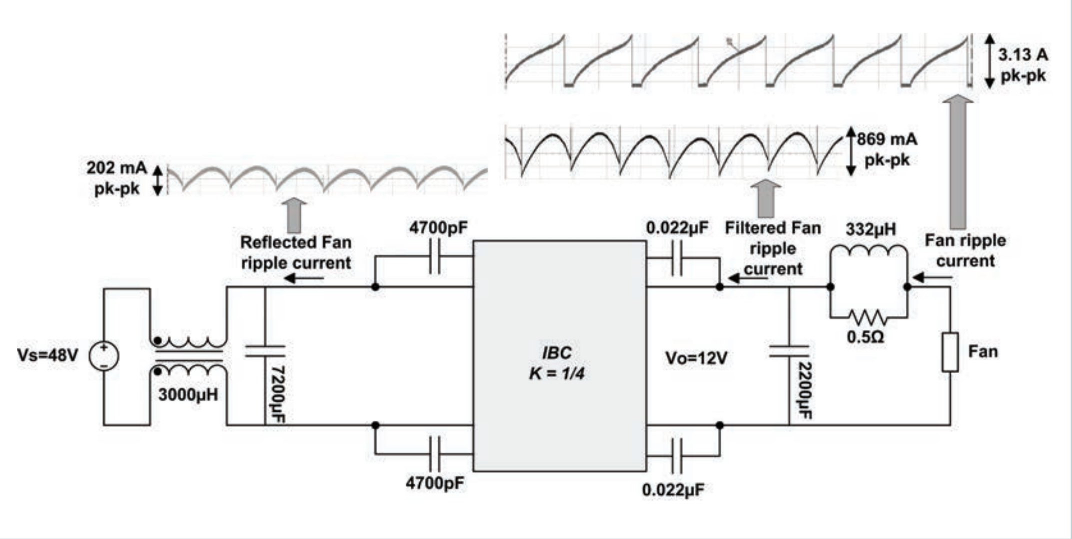
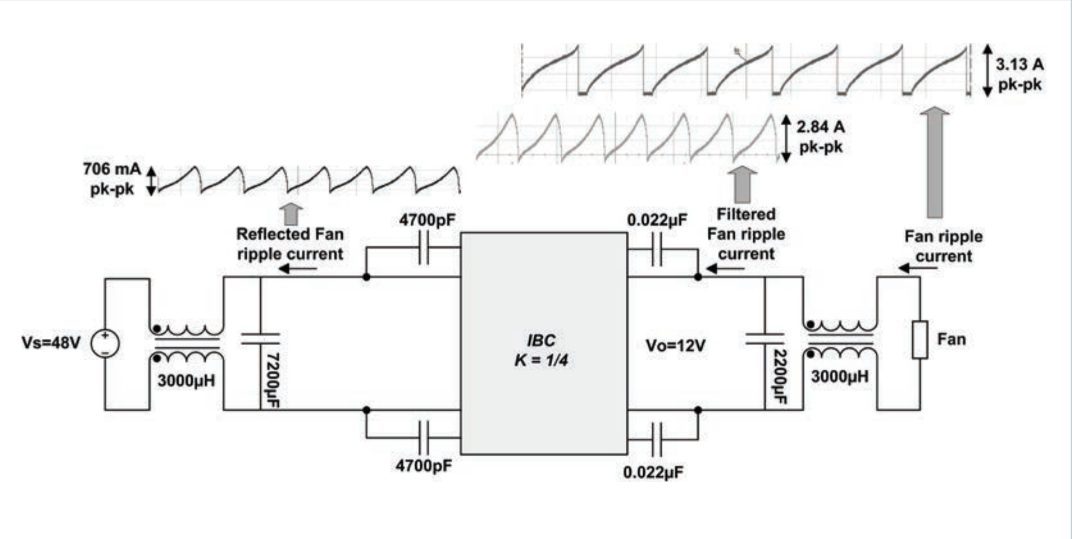


Figure 19
Filtered Response of IB048E120T32N1-00 Module with 12V Fan as Load and Common-Mode Inductor in Filter



When the damped L/C filter is placed between the IBC™ module and load, the ripple at the input (mirrored from noise generated by the load) is attenuated. Figure 18 shows the output ripple current and reflected input ripple current of an IBC with a 12V fan as the load and a 332µH inductor in the filter. The 332µH (Vicor part number 31499-01) inductor was replaced with a 3000µH CM inductor (Vicor part number 31742) for the reflected ripples shown in Figure 19. The current ripple generated by the fan was reduced by a factor of 3.6 (11.1dB) when using the 332µH inductor in the filter and was reduced by a factor of 1.1 (0.84dB) when using 3000µH CM inductor.

In this case, the filter using the 332µH differential inductor performed better than the filter with the 3000µH CM inductor since the leakage inductance of the CM inductor is only 11.5µH which is less than 3.5% inductance than the differential inductor. Doubling or tripling the amount of the capacitance would improve the performance of the filter, but this would exceed the maximum output capacitance of the IBC.

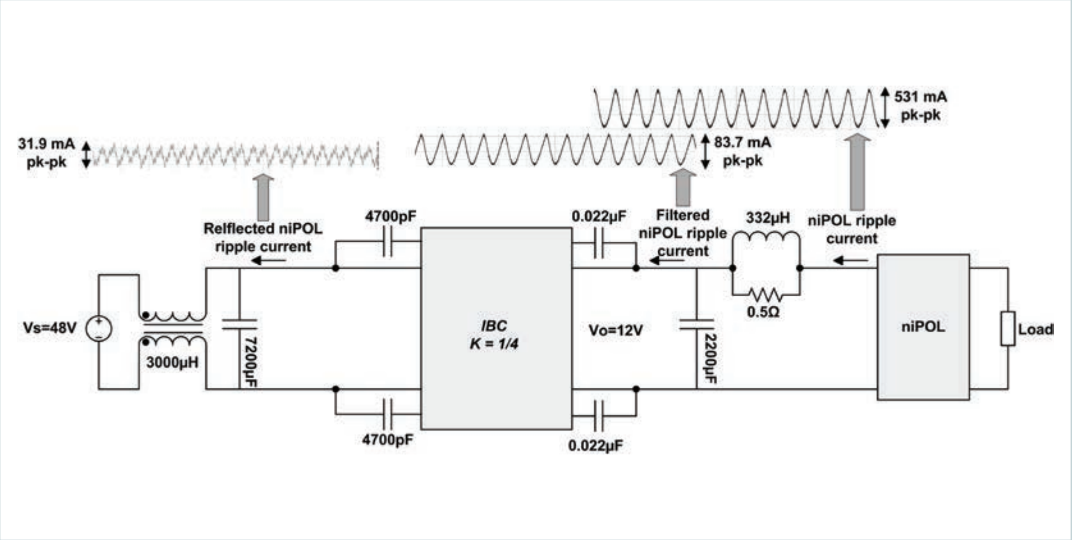


Figure 20
Filtered Response of IB048E120T32N1-00 Module with niPOL as Load and Inductor in Filter

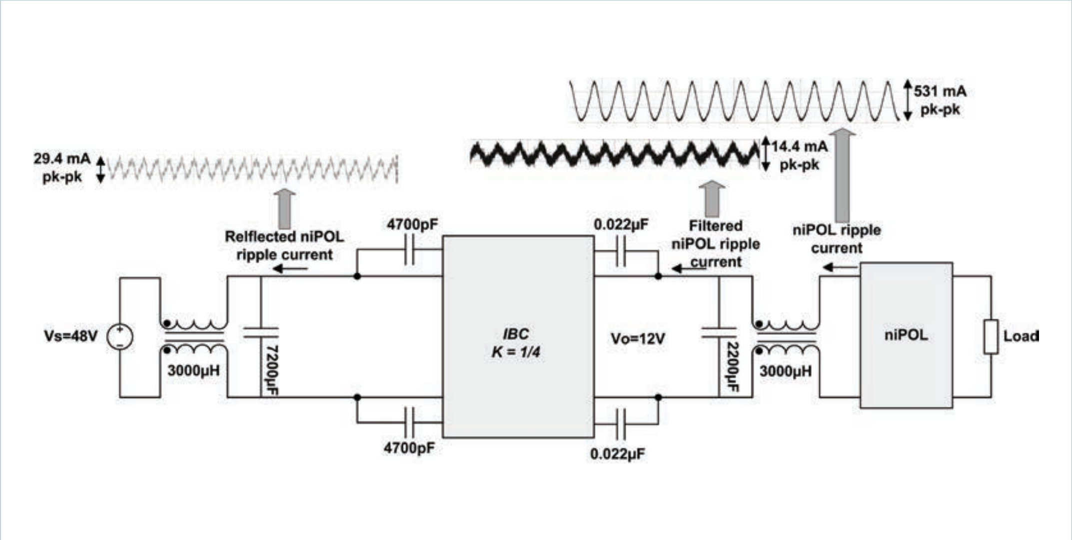


Figure 21
Filtered Response of IB048E120T32N1-00 Module with niPOL as Load and Common-Mode Inductor in Filter

Figures 20 and 21 show the output ripple current and reflected input ripple current of an IBC™ with a niPOL as the load. The ripple current generated by the niPOL was reduced by a factor of 6.3 (16dB) when using the 332µH inductor in the filter and was reduced by a factor of 36.9 (31.3dB) when using 3000µH CM inductor. In this case, the filter with the 3000µH CM inductor performed better than the filter with the 332µH inductor as the parasitics in the components limited the attenuation of the filter as shown in Figure 16 on page 10.

The filters attenuated the reflected noise generated by the 12V fan and niPOL however, the attenuation was limited as the fan is a low-frequency switching load. Using common-mode inductors can effectively filter IBC switching noise and reflected ripple currents from downstream niPOLs.

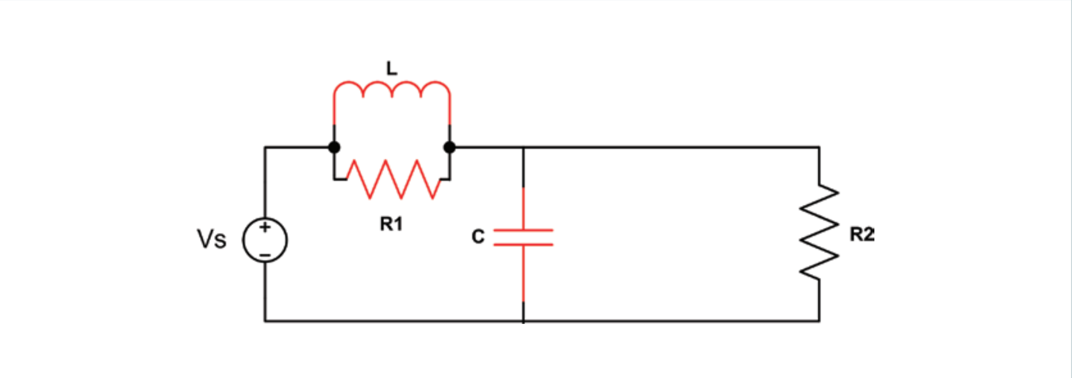
For help designing a damped L/C filter or other filter topologies, please try using our online filter tool: http://app2.vicorpower.com/filterDesign/intiFilter.do.

Conclusion

This application note covered how a simple L/C filter can be implemented for an IBC™ to filter emissions from different loads. Due to the inherent low noise of the IBC, it is easy to meet levels outlined in international standards for emissions. Multiple IBC systems can be filtered with a filter for each array as the emissions are spread over the spectrum.

Appendix

Equations



The transfer function of the filter shown in the figure above can be calculated as:

$$TF = \frac{S \bullet \dfrac{1}{R1 \bullet C} + \dfrac{1}{L \bullet C}}{S^2 \bullet \dfrac{1}{R1 \bullet C} + \dfrac{1}{L \bullet C}} \qquad (1)$$

The natural resonant frequency of a RLC circuit is defined as:

$$\omega_n = \sqrt{\frac{1}{L \bullet C}} \qquad (2)$$

The filter is a second order system where and the damping ratio can be extracted from the characteristic equation of the system. The general second order characteristic equation has the following form:

$$S^2 + 2 \bullet \zeta \bullet \omega_n \bullet s + \omega_n^2 = 0 \qquad (3)$$

Using equations 1 and 3, the damping ratio can be calculated:

$$2 \bullet \zeta \bullet \omega_n = \frac{1}{R1 \bullet C} \qquad (4)$$

$$\zeta = \frac{1}{2 \bullet R1} \bullet \sqrt{\frac{L}{C}} \qquad (5)$$

The Q factor is directly related to the damping ratio:

$$Q = \frac{1}{2 \bullet \zeta} \tag{6}$$

Using equations 5 and 6, the Q factor of the filter can be found:

$$Q = R1\sqrt{\frac{C}{L}} \tag{7}$$

Glossary

Bandwidth – A range of frequency over which a certain phenomenon is to be considered.

Capacitive coupling – Coupling of a signal between two circuits, due to discrete or parasitic capacitance between the circuits.

Common-mode noise – Noise present equally on two conductors with respect to some reference point; often used specifically to refer to noise present on both the hot and neutral AC lines with respect to ground.

Damping ratio – The parameter that describes the decay of oscillations in a system.

Differential-mode noise – Noise that is measured between two lines with respect to a common reference point excluding common-mode noise. The resultant measurement is the difference of the noise components of the two lines. The noise between the DC output and DC return is usually measured in power supplies.

ESR – Equivalent series resistance. The value of resistance in series with an ideal capacitor that duplicates the performance characteristics of a real capacitor.

Impedance – The ratio of voltage to current at a specified frequency.

Output impedance – The ratio of change in output voltage to change in load current.

Parallel operation – Connecting the outputs of two or more power supplies together for the purpose of obtaining a higher-output current. This requires power supplies specially designed for load sharing.

Q factor – Quality factor. This parameter is based on the inverse of the damping ratio and describes the losses present in a system.

Reflected ripple current – The rms or peak-to-peak AC current present at the input of the power supply that is a result of the switching frequency of the converter.

Ripple and noise – The amplitude of the AC component on the DC output of a power supply usually expressed in millivolts peak-to-peak or rms. For a linear power supply it is usually at the frequency of the AC mains. For a switching power supply, it is usually at the switching frequency of the converter stage.

Switching frequency – The rate at which the switches turn on and off in a switched-mode power supply.

Y-capacitor – Power conversion modules generally require bypass capacitors from line to chassis (earth ground) to shunt common-mode noise currents and keep them local to the converter. In cases where the converters are operating from rectified AC line voltage, the failure of a bypass capacitor could result in excessive leakage current to the equipment chassis thus creating a ground fault and shock hazard. For this reason, a special classification of capacitor, referred to as a Y-capacitor, is recommended. These capacitors contain a dielectric with unique “self-healing” properties to help prevent against excessive leakage.

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