Filter Network Design for VI Chip® DC-DC Converter Modules

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Contents   **Page**

Introduction

The design of a filter network is generally needed for DC-DC converters to have low electromagnetic interference (EMI) and high input noise rejection.

Depending on the application of the power supply, different EMI standards may apply. EMI standards are system requirements and typically the complete system will need to meet specific EMI standards. It is usually not efficient to design each individual part of a system to meet an EMI standard. However, because a power supply has switches, it may contribute a more significant component of the overall system EMI, and therefore basic EMI suppression specific to the power supply is practiced so that interference with other parts of the system is minimized. Typically, additional EMI filtering is designed for the front end of the complete system as well as enclosing all the noise sources in a shielded case to provide sufficient EMI attenuation.

In some cases EMI standards become requirements for a power supply. This condition is more likely to occur with AC-DC power supplies. For example, when a power supply module is used to connect wall power to a load, the power supply serves as the front end of the equipment, and thus it needs to provide EMI filtering for both itself and the downstream load.

Input noise rejection is also a basic function of the filter network. A power supply could suffer from a noisy input source, if there is no protection up front. The goal of the input filter could be set to filtering out both input noise (V_{IN}) and reflected input current ripple (I_{IN}). They both can be typically achieved by one common low pass input filter.

Input Filter Design

For your reference, an input filter design tool is available at: http://app2.vicorpower.com/filterDesign/intiFilter.do

You can choose your own attenuation target, pick a topology, and then design your input filter within 3 steps.

A typical single stage input filter has the following structure as shown in Figure 1. It is a combination of a basic LC filter, and a damping resistor with a serial capacitor.

The basic LC filter has an ideal transfer function of $H_1(\omega) = V_2/V_1 = 1 / (1-\omega^2 L_1 C_1)$. For frequencies close to its cutoff frequency, there is a large spike in the transfer function curve, which is not desired and could cause oscillation. Resistor R_2 provides the damping to control this. A pure R_2 branch would work, but the power dissipation would be unacceptable. C_2 is used to block the DC route, so that the power dissipation in R_2 is minimized.

Figure 1
A Typical Input Filter
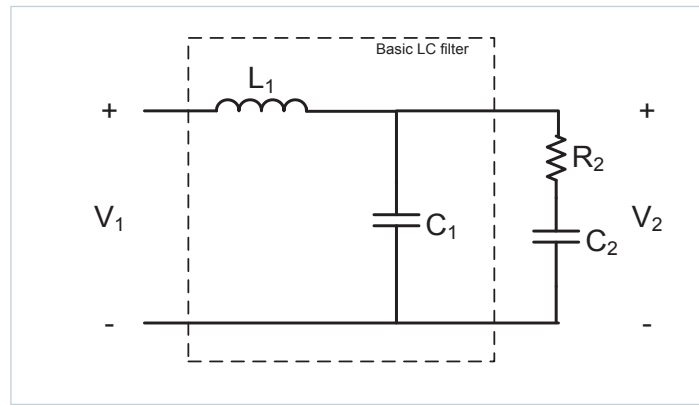
The transfer function of the input filter in Figure 2 is:

$$H_2(s) = \frac{1 + s \cdot C_2 \cdot R_2}{1 + s \cdot (C_2 \cdot R_2) + S^2 \cdot [L_1 \cdot (C_1 + C_2)] + s^3 \cdot L_1 \cdot C_1 \cdot C_2 \cdot R_2} \qquad (1)$$

To help understand how this filter works, we can simplify $H_2(s)$ in an intuitive way. When the frequency is much higher than $\frac{1}{2\pi \cdot R_2 \cdot C_2}$, the RC branch acts similarly to a single resistor R_2. The transfer function becomes:

$$H_3(s) = \frac{1}{L_1 C_1 s^2 + \dfrac{L_1}{R_2} s + 1} = \frac{1}{\dfrac{s^2}{\left(\dfrac{1}{\sqrt{L_1 C_1}}\right)^2} + 2 \cdot \left(\dfrac{1}{2R_2}\sqrt{\dfrac{L_1}{C_1}}\right) \cdot \dfrac{s}{\dfrac{1}{\sqrt{L_1 C_1}}} + 1} \qquad (2)$$

From $H_3(s)$, which is an approximation of $H_2(s)$, we can see that:

- The cutoff frequency is $\frac{1}{2\pi\sqrt{L_1 \cdot C_1}}$
- The damping factor (ζ) is $\frac{1}{2R_2}\sqrt{\frac{L_1}{C_1}}$
- This filter provides 40db/decade of attenuation after cutoff frequency.

Choosing $\frac{1}{3}\sqrt{\frac{L_1}{C_1}} \le R2 \le \sqrt{\frac{L_1}{C_1}}$ will give a damping factor between 0.5 and 1.5.

The assumption of this simplification is that the frequency is much higher than $\frac{1}{2\pi \cdot R_2 \cdot C_1}$ and this needs to happen well before the cutoff frequency $\frac{1}{2\pi\sqrt{L_1 \cdot C_1}}$. To ensure this, the value of C_2 needs to be several times greater than the value of $\frac{\sqrt{L_1 \cdot C_1}}{R_2}$.

A general recommendation for choosing C_2 and R_2 could then be:

$$R_2 = k\sqrt{\frac{L_1}{C_1}} \; , \; \frac{1}{3} \le k \le 1 \qquad (3)$$

$$C_2 \ge 4 \cdot \frac{C_1}{k} \qquad (4)$$

It is interesting to notice that the cutoff frequency $\frac{1}{2\pi\sqrt{L_1 \cdot C_1}}$ is not related to C_2 by using this approximation, as long as the criteria Equation 3 and Equation 4 are met.

Using an electrolytic capacitor with its substantial internal ESR may provide C_2 and R_2 in a single component, however, the internal ESR may vary with temperature and frequency, so please keep in mind your temperature and frequency range when choosing the electrolytic capacitor.

Figure 2

A Two-Stage Input Filter
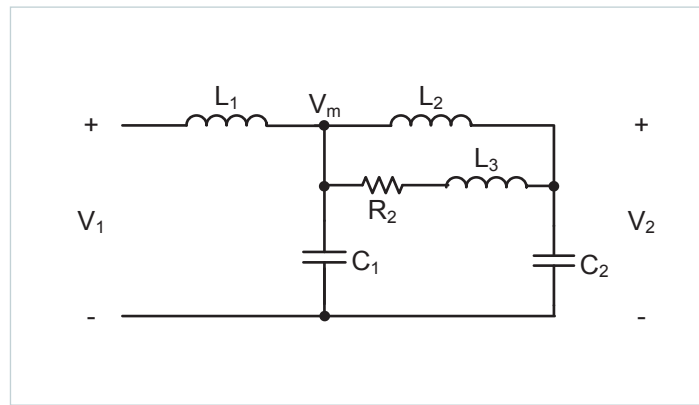
A two-stage filter could achieve the filter goal with a much lower capacitor value. This is especially valuable when the space is limited and the voltage rating is high, since high voltage capacitor intends to be massive and costly.

Figure 2 is a typical two stage input filter. The main idea here is to get 40db/decade attenuation after cutoff frequency per stage, that is to say, from V_1 to V_m get 40db/decade attenuation, and from V_m to V_2 get another 40db/decade attenuation, to get an 80db/decade attenuation overall.

Using a two-stage input filter could also get less output impedance with the same attenuation effect, which is stability related, as mentioned in the following section.

Inductors in the input filter can vary the input voltage of converter. Take the filter in Figure 1 as an example, the real input voltage $V_{IN} = V_{IN} - L_1 di/dt$ has a difference of $L_1 di/dt$ with V_{IN}, which could interact with the input voltage undervoltage / overvoltage lockout and cause issues. Smaller inductor value will reduce this effect.

Stability Issue with an Input Filter

The interaction between the input filter and the negative input impedance of the converter may cause stability issues. Routh-Hurwitz absolute stability criterion can be used to check the stability of the complete system (converter and input filter). Let assume that the input impedance of the converter ($-r$) can be approximated by $-r = -V_{IN}^2/P_{OUT}$.

For this filter in Figure 1 the sufficient and necessary conditions for a stable system can be simplified as:

$$R_2 < r + r \bullet \frac{C_1}{C_2} \tag{5}$$

$$R_2 > \frac{L_1}{r \bullet C_2} \tag{6}$$

$$C_2 \bullet L_1 + C_2^2 \bullet r^2) \bullet R_2 > r \bullet L_1 \bullet (C_1 + C_2) + C_2^2 \bullet r \bullet R_2^2 \tag{7}$$

The higher the ratio of the input impedance of the converter ($-V_{IN}^2/P_{OUT}$) to output impedance of the input filter, the lower the chances of instability. The full load, low input voltage will therefore be the worst case to check for this purpose. In the considered converter, full load is 470W, low input voltage is 36V, which brings the input resistance as low as $-r = -2.76\Omega$.

Output Filter Design

Output filter design is actually part of job of the converter. Once the converter is finished, the output filter design has been finished. Putting external capacitor as required, as shown in Figure 3 (a), should be enough. More than that may cause issues. For example, in Figure 3 (b), an external LC filter is added in the output side. Now the controller of the converter is to compare Vout with the internal Vref to keep Vout as the set value. The real output voltage $V_{OUT} = V_{OUT} - Ldi/dt$ has a difference of Ldi/dt with V_{OUT}, and could bring issues when output current is changing rapidly.

Output filter could possibly be used if the load current is relatively steady, and the voltage ripple of the power supply output needs to be reduced further.

(a) With external C only   (b) With external LC
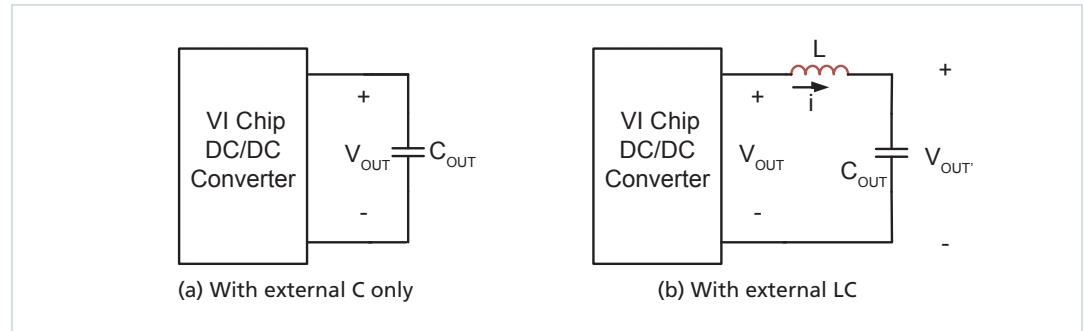
Common Mode Noise Rejection

The switching in a power supply can cause common mode noise. One example is: The primary side of the transformer is coupled with secondary side, and the windings on top of each other make some parasitic capacitance. When the switches turn on and off, as shown in Figure 4(a), the dV/dt cause current flowing through the capacitors.

Because of the ZVS/ZCS technology VI Chip® is using, this common mode noise from VI Chip converter is much less than conventional products.

A simple way to attenuate this noise is to connect capacitors to each of the external power pins, as shown in Figure 4(b). If there are no common mode external capacitors, the common mode current is going to flow through the stray capacitors in the converter. Stray capacitors are typically very small, causing more voltage drop for the same di/dt. With external capacitors, the common mode noise voltage could be much reduced.

Figure 4
Common Mode Noise's Cause
and Solution

(a) Cause of common mode   (b) Solution
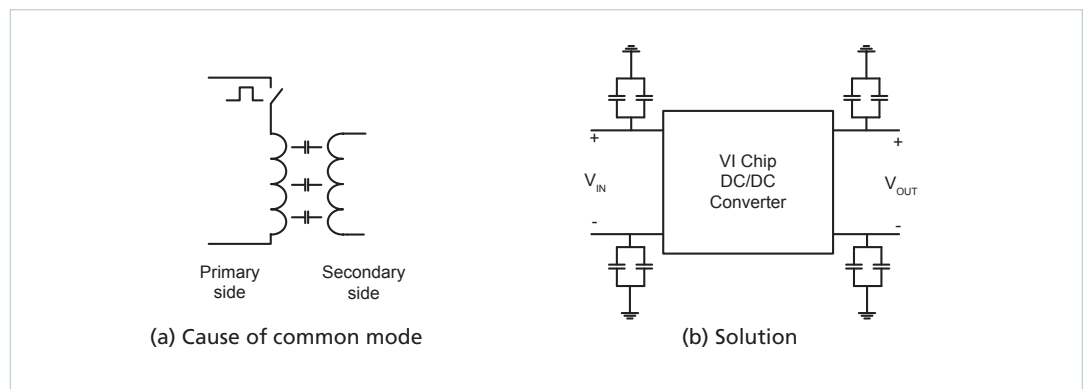
Radiated EMI Noise Rejection

Radiated EMI noise rejection is not a significant issue in the filter network design of VI Chip® DC-DC converter. The reason is because radiated EMI happens more in high frequency (30MHz) or more, which is far more than the switching frequency of the power supply. In addition, VI Chip DC-DC converters use ZVS/ZCS switching technology and have a narrow spectrum of switching noise, which enable even lower radiated EMI noise.

For radiated EMI noise considerations, three things needs to be taken into account:

1. Reduce large di/dt or dV/dt that could excite radiating conductors in the system (antenna).
   This is already addressed within the design of the VI Chip converters.

2. Eliminate the transmitting antennas.
   Current loops in the circuit, act as transmitting antennas, should been minimized.

3. Block the radiated fields.
   This could be done at a system level, by enclosing all the noise sources in a shielded enclosure.

Figure 5
Current Loops Minimization

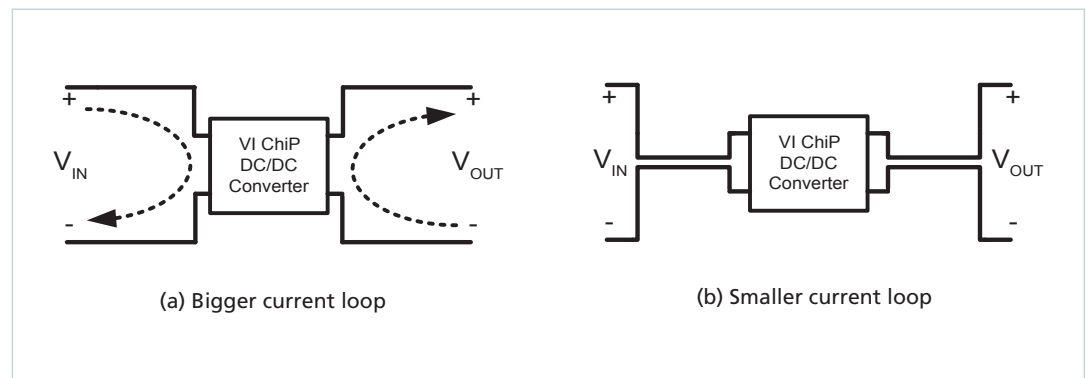(a) Bigger current loop   (b) Smaller current loop

Figure 5 shows two ways of routing current in/out the converter. Figure 5(b) has a much smaller current loop than (a), thus to minimize the antenna effect. In some case, there are signal circuits also standing in the circuit, and it will become harder to make the power traces closer, since signal circuits need to be separated from power traces. Keep the power traces short to minimize the current loop.

Conclusion

While noise is an unwanted by product of any switch mode power supply, following some simple design rules can enable a system designer to insure that the effects of the noise is minimal and the system as a whole functions as desired.

Appropriate filtering techniques for VI Chip DC-DC converters have been discussed with several recommended approaches. Important considerations have also been explored such as: single vs. dual stage filtering, the importance of damping, and the correct sizing of components for optimal performance. Finally, sources of common mode and radiated noise have been noted along with recommendations on how to minimize these additional sources of noise.

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