Input Filter for DCDC Converter

Design and Application Considerations of Input Filter to reduce Conducted Emissions caused by DC/DC converter

Introduction

DC/DC converters emit conducted emission noise over power supply lines. Therefore, many DC/DC converter ICs have implemented a spread spectrum feature that lowers noise, with reduced filter component size and BOM cost. However, to really reduce the level of conducted emissions to an acceptable level, an input filter is required. This application note considers both design and application of input filters for DC/DC converters.

How conducted emissions occur

The input current flow of the DC/DC converter alternates with the switching frequency of the DC/DC converter. The input capacitor connected to a converter IC input has an equivalent series resistance (ESR) causing voltage ripples due to the alternating input current flow. The amplitude of this voltage ripple occurring is essentially dependent on the ESR of the used capacitor.

Electrolytic and polymer capacitors have a relatively high ESR. With this kind of capacitors in use, the value of the voltage ripple, which can range from just a few milliohms up to several ohms. Multilayer ceramic capacitors (MLCCs), on the other hand, have a very small ESR of just a few milliohms and thus result in a noise voltage of a few millivolts.

When running an analysis within the time domain, the AC components at the DC/DC converter's input can be analyzed by using an oscilloscope. This facilitates the measurement of any interference spectrum during the design phase of a DC/DC converter and provides a simple way to estimate any conducted emissions / EMC issues.

For example, Figure 1 shows the input ripple voltage of an automotive DC/DC converter from the PD9Pxx5EFV-C series.

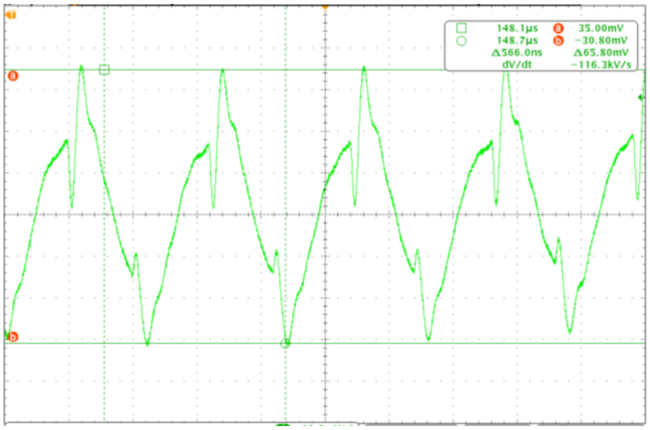

FIGURE 1: VOLTAGE RIPPLE AT DC/DC CONVERTER INPUT CAPACITOR

In this case, the application conditions were 12V DC input voltage, 5V DC output voltage and 1A at resistive load.

MLCCs are state of the art and used in this application example as input capacitors for the DC/DC converter. In this case, despite their low ESR, the input ripple voltage is 68 mV. This ripple voltage leads to differential mode noise and causes conducted emission noise at the DC/DC converter input, as shown in Figure 2.

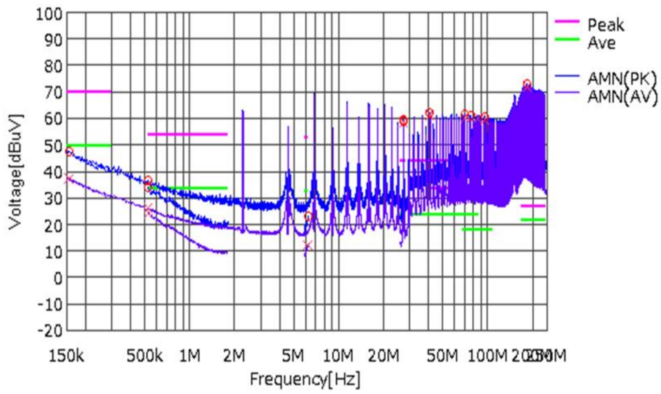

FIGURE 2: CONDUCTED EMISSION NOISE BY DC/DC CONVERTER WITHOUT INPUT FILTER

Figure 2 shows conducted emission test results according to the automotive CISPR 25 standard in a frequency range from 150 kHz to 300 Mhz. In this case, the spread spectrum has been disabled and the DC/DC converter is in constant PWM mode. The fundamental noise of 2.2 Hz with a highest noise peak of 65 dBµV is equal to the DC/DC converter switching frequency range. Every peak value of further harmonic noise is more than 20 dBµV above the accepted noise limit.

Reducing conducted emissions

To reduce conducted emissions caused by a DC/DC converter, an input filter is required in order to pass the electromagnetic compatibility (EMC) test. Figure 3 shows the limited conducted emission results from aforementioned DC/DC converter from the BD9Pxx5EFV-C series.

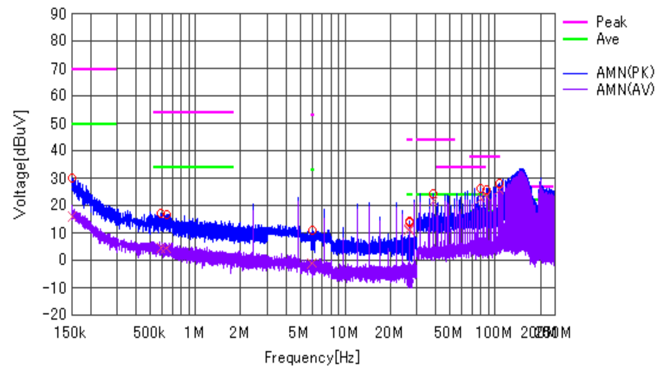

FIGURE 3: CONDUCTED EMISSION NOISE BY DC/DC CONVERTER WITH INPUT FILTER

The application conditions were the same as before. Fundamental noise is recognized at the DC/DC converter's switching frequency in the conducted emission test, as well as further harmonic noise, but the average (AV) and peak (PK) noise levels are reduced over the tested frequency range down to a low, acceptable level.

The main purposes of an input filter are to suppress the noise and surge from the front-stage power supply and to decrease the interference signal at the switching frequency and its harmonic frequencies, to keep them from emitting noise over the power supply and interfering with other devices that use the power supply.

Usually a π-type input filter, as shown in Figure 4, is used for filtering the input current, thereby decreasing the AC amplitude of the voltage ripple, which can reduce the conducted emissions to an acceptable value.

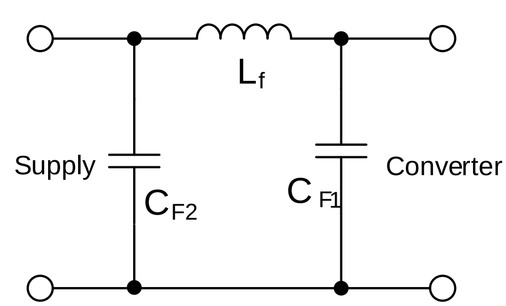

FIGURE 4: Π-TYPE INPUT FILTER

Design of input filter

The first step to designing an input filter that will reduce AC amplitude is to place a capacitor at the DC/DC converter IC input. This is also known as a HF bypass capacitor (C_{F1}) as shown in Figure 4.

Due to its negligibly low ESR, a ceramic type input capacitor (MLCC) can short-circuit high-frequency voltages to ground with low impedance. The AC ripple has the same frequency as the converter IC switching frequency. The capacitance of the first filter capacitor should be selected with a self-resonance frequency close to the switching frequency.

Figure 5 shows the impedance and ESR curves of a 4.7 µF EIA1206 chip size MLCC capacitor.

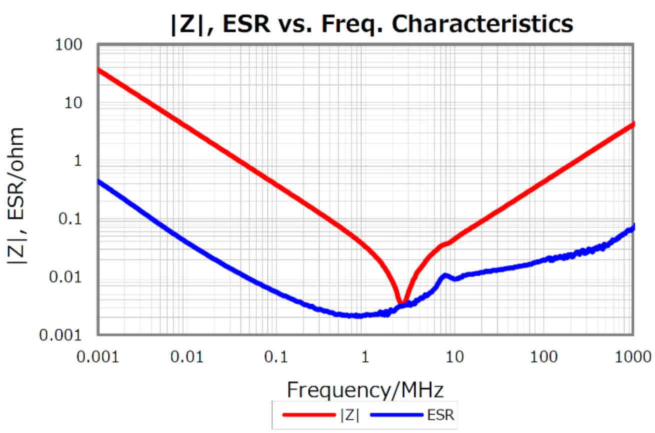

FIGURE 5: CHARACTERISTICS OF 4.7µF MLCC

The impedance is lowest at its self-resonant frequency (SRF), where ESR is also low. A low ESR is required so as the peak attenuation characteristic of Z at SRF is not damped. For example, a 4.7 µF EIA0805 chip size MLCC as shown in Figure 5 is the best choice when using a DC/DC converter IC like the BD9Pxx55EFV-C with a switching frequency of 2.2 MHz.

Next, a filter inductor, henceforth referred to as L_F, and an additional filter capacitor (C_{F2}) should be placed at the input of the DC/DC converter, to form an LC-filter. An LC filter reduces the noise from in- to output by 40 dB / decade.

To reduce noise from a DC/DC converter, the LC filter should be optimized with a corner frequency of 1/10 of the switching frequency. The corner frequency is described in equation (1):

$$f_C = \frac{1}{2\pi \cdot \sqrt{L_f \cdot C_{f2}}} \qquad (1)$$

The filter inductor is usually the most expensive part. To reduce BOM costs, an inductor with low inductance can be selected, e.g. 10 µH. To achieve high damping by the filter inductor, it is recommended to select an inductor with an inductance SRF value lower than the capacitance value of the filter capacitor.

The higher the inductance, the smaller the SRF. In practice, a filter inductance with a maximum value of 10 µH is selected since, depending on the design, such an inductance has a self-resonant frequency of approx. 30 MHz.

At low switching frequencies in the range of 60 to 400 KHz, a filter inductor with a metal powder core is suitable. At switching frequencies higher than 1 MHz, ferrite core inductors are preferred.

Exceeding the rated current of the filter inductor may result in damage to the wire winding. Therefore, it is recommended to select an inductor with low DCR so as not to reduce the efficiency of the SMPS.

It is possible to calculate the effective input current of the power module using equation (2):

(2) $$I_{in} = \frac{V_{out} \cdot I_{out}}{V_{in} \cdot \eta}$$

The rated current of the filter coil should be higher than the input current.

The filter capacitor C_{F2} can be calculated using equation (3).

(3) $$C_{f2} = \frac{1}{(2\pi \cdot 0{,}1 \cdot f_{sw})^2 \cdot L_f}$$

Depending upon both cost and application, for filter capacitor C_{F2} an MLCC or electrolytic capacitor can be selected. An electrolytic capacitor has the benefit of a high ESR, which is suitable for damping transient voltages on the power supply line. MLCCs are cheaper than electrolytic capacitors, but have a decreased capacitance as their DC bias voltage is increased.

As an example, figure 6 shows the voltage bias of a 150 nF, 50V, X7R-rated MLCC.

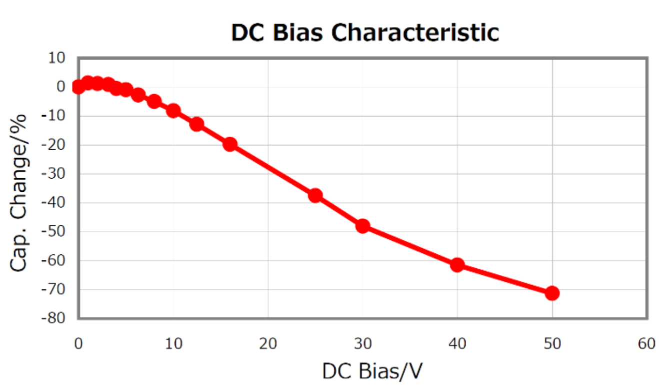

FIGURE 6: OF A 150 NF, 50V RATED X7R MLCC

With respect to the voltage bias of MLCCs, the rated voltage of the MLCC is selected to achieve the required capacitance at an applied voltage. A general guideline is to select a capacitor rating 2 x higher than the highest occurring voltage on the capacitor.

Filter damping

The input filter can change or influence the converter transfer function and thus change the loop gain, which is an important measure for the control-loop stability of the DC/DC converter. In other words, adding an input filter can lead to control loop instability if certain conditions are not met.

The input filter has a Q factor (Q) and an output impedance (Z_{OutF}), while the DC/DC converter has an input impedance (Z_{InCon}), as shown in Figure 7.

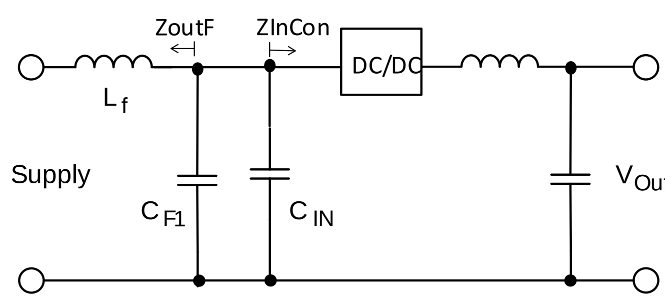

FIGURE 7: IMPEDANCE OF INPUT FILTER AND DCDC CONVERTER

An LC input filter has an effect on the control loop of the DC-DC converter, because the output impedance Z_{OutF} of the input filter influences the DC/DC converter input Z_{InCon} impedance. The input filter decreases the phase margin and thus degrades the transient response performance.

When the input filter's Q is too large, oscillations may occur whenever the input voltage changes at the DC/DC converter input, and its control loop can become unstable after applying.

The input filter Q is defined with equation (4):

(4) $$Q = R_{\mathrm{d}} \cdot \sqrt{\frac{C_{\mathrm{f1}}}{L_{\mathrm{f}}}}$$

The stability criterion that applies here is that the output impedance of the input filter Z_{outF} has to be lower than the input impedance of the DC/DC converter input Z_{in}.

This is described in equation (5):

(5) $$Z_{\mathrm{OutF}} \ll Z_{\mathrm{InCon}}$$

In addition, the corner frequency f_c of the input filter should be much lower than the crossover frequency f_{COCon} of the DC/DC converter.

(6) $$f_{\mathrm{C}} \ll f_{\mathrm{COCon}}$$

Adding an R-C network to the filter as shown in Figure 8 lowers the input filter's Q.

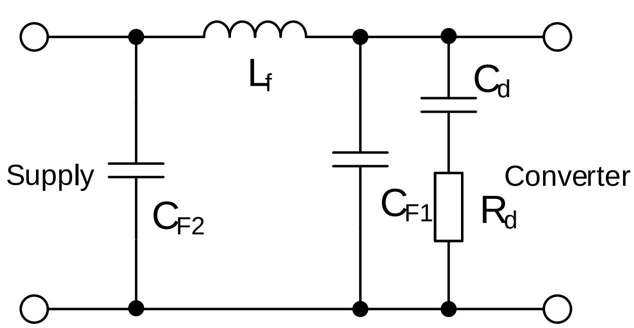

FIGURE 8: INPUT FILTER INCLUDING DAMPING NETWORK

The purpose of the resistor R is to damp the filter, and the purpose of the capacitor in series is to block the DC portion of the input voltage in order to reduce dissipation in the damping resistor.

Equation (7) is used for calculating the damping resistor Rd for a filter with a Q value of $Q_f = 1$:

(7) $$R_{\mathrm{d}} = \sqrt{\frac{L_F}{C_{\mathrm{F1}}}}$$

A ceramic capacitor C_d in series with the R-C network has a factor of 5 to 10 of the filter-capacitor capacitance.

(8) $$(5 \cdot C_{\mathrm{F1}}) < C_{\mathrm{d}} < (10 \cdot C_{\mathrm{F1}})$$

With respect to price and space, alternatively the filter could be damped by selecting an electrolytic capacitor that is connected in parallel to the filter output instead of the R-C network. However, it should be noted that the ESR value of the electrolytic capacitor is not sufficient to have adequate filter attenuation.

Position of input filter

Optimally, an input filter should be placed as close as possible to the input of the DC/DC converter.

In case the input filter is placed further away due to geometric circumstances, power traces may act as an antenna between the input filter and the DC/DC converter at higher frequencies. These power traces have a capacitive coupling to the housing, causing common mode noise, which leads to radiated emissions.

From another point of view, power trace inductance also acts as a coupling with the ceramic capacitor C_{F2}, which is shown in Figure 8 as an LC filter. This reduces the voltage ripple to a certain low value, but is not efficient enough to reduce the conducted emissions to a required limit.

Conclusion

- An input filter is widely used to optimize the EMC of DC/DC SMPS. And in a proper design, the input filter should not cause a stability problem in the DC/DC converter's control loop.
- Adding a π-type input filter limits conducted emission by reducing the DC/DC converter's input voltage ripple.
- The output impedance of the input filter can be matched to the DC/DC converter's input impedance in order to avoid instability.
- The Q factor of the input filter can be reduced with an RC-damping network.

By Stefan Klein, FAE; ATSC

Reference

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