Application Note

OPTIMIZING EMI INPUT FILTERS FOR SWITCHED MODE POWER SUPPLIES

Products:

► R&S®RTO64

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1 Overview

Almost every switched-mode power supply (SMPS) needs an EMI (Electro Magnetic Interference) input filter to suppress any disturbances of the SMPS on the power lines. This requirement having an input filter in the design ensures that no negative effect will occur in other parts of the systems connected to the power lines. Therefore, the design and the validation of the input filter is a major task during a typical power supply design. The conducted emission (CE) test according to a specific standard is a suitable and a common validation method to release the design at the end of the development cycle. Nowadays, this conducted emission test will be performed as pre-compliance test during the development phase in the lab as well. In this case, the designer will obtain an early feedback whether the design has to be optimized regarding any disturbances present on the power lines. In most cases, the designer has to adjust the input filter to obtain a more effective suppression of disturbances generated by the SMPS. However, the designer needs to know details about the noise spectrum to optimize the input filter as effective as possible. In addition to magnitude and frequency information of the noise source, it would be very helpful to know whether the noise is generated by a common mode source or by a differential mode source. During the standard conducted emission test, common and differential mode noise is a combination in the measurement results and thus not possible to gain deeper insights. This document will describe a method to separate common-mode and differential-mode separation using two oscilloscope channels. This separation approach works without any additional hardware component like a noise separator. The designer will be able to distinguish between common-mode (CM) and differential-mode (DM) noise. This additional information about the dominant mode provides the capability to optimize input filters very efficiently.

2 EMI Input Filter Consideration

2.1 Noise Source

The SMPS is a product with relative high amount of generated noise due to the switching principle. Typically, a power converter operates at a switching frequency in the range between 10 kHz and 1MHz. However, if there is the need of using a SMPS to be very efficient in power conversion, you should keep in mind that each topology could create different noise magnitudes. For example, a dual interleaved boost topology creates less noise compared to a simple boost converter. Therefore, your input filter design has to be adapted to your specific topology. Once the topology decision is made, there are several design parameters, which can support the designer to influence the noise level. The switching frequency parameter of the converter is one of the key values, which has tremendous impact on the generated noise level of the converter. Very often, a high switching frequency is chosen to obtain a compact design. However, high switching frequencies can be the root cause for a high noise emission and has to be taken into consideration at the beginning of the design. Beside the switching converter frequency, it is very important to understand the correlation between rise and fall time of the switching element and the generated noise. Typically, the designer is forced to obtain high efficiency of the converter and therefore using a fast switching element is the first choice. Nowadays, even wide band gap devices like SiC or GaN become very popular in power converter designs to increase efficiency. These fast switching elements act as the noise source within the converter when the design is not done very carefully. In addition to the design parameters, it is always very helpful to minimize the parasitic elements in the whole design including the printed circuit board (PCB). For example, the high-voltage switching element combined with a connection to the metal housing for cooling purpose will create a parasitic capacitance. This parasitic element creates a path where common mode noise may leave the system.

2.2 EMI Input Filter Structure

An input filter is required in most power supply designs even if you have considered all precautions described in the last paragraph. The motivation for the required input filter is mostly due to the EMI standards and regulations.

The input filter can be divided into two functional parts. One part is responsible to damp the unwanted common-mode noise and the other part is responsible to suppress the differential-mode noise. A filter typical structure is shown in the Fig. 2-1 below:

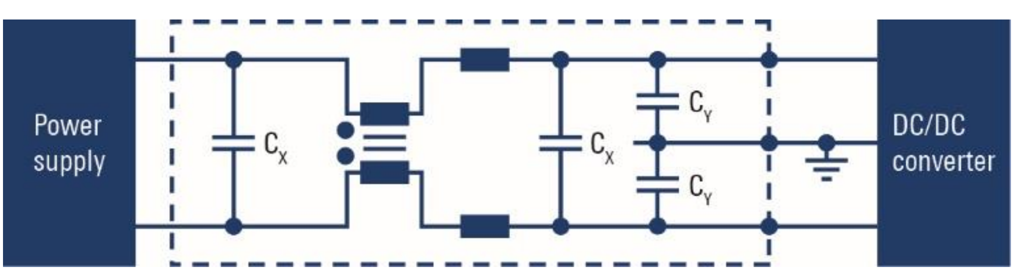

Fig. 2-1 EMI Input Filter

It consists of several different key components like the Common Mode (CM) Choke, Differential Mode (DM) Inductors, X-Capacitors and Y-Capacitors. While the X-Capacitors and the DM-Inductors are very effective in damping the DM noise, the CM-Choke and the Y-Capacitors are very effective in damping the CM noise. In some cases, the DM-Inductors are not used because the CM-Choke can be designed to act as common mode and differential mode.

Very often, the filter is simulated in an electronic circuit simulator tool in advance to obtain the transfer function after calculation of the key elements and to estimate if the structure is suitable to fulfil the design requirements. However, the problem with the simulation is always that it does not consider all the parasitic components, which mainly influence the noise coupling. Furthermore, a simulation is as good as their simulation models are. Therefore, the filter design in conjunction with the converter itself has to be proven with a suitable measurement method. This measurement method is the well-known Conducted Emission (CE) Test and is part of the defined standard like the CISPR standard.

In case, the filter is not effective enough, the conducted emission test will fail and the designer has to improve the design regarding conducted emissions. For this reason, the input filter has to be adjusted to be more effective. For adjusting the components of the input filter, the designer has to decide which kind of component (common-mode suppressor or differential-mode suppressor) change is the most promising one. If the designer would know the details whether the noise source is dominated either by common-mode noise or by differential-mode noise, it would be possible to optimize the EMI filter design to be effective in damping and in addition, cost and size will be as small as possible. Especially in converter designs for higher power levels, the filter component can become large and costly and therefore the filter design optimization is an important task during the design. This is exactly where the enhanced measurement method can support the designer tremendously.

3 Conducted Emission Measurement

This chapter describes the standard CE test and the enhanced method including some theory of the measurement principle.

3.1 Standard Conducted Emission Test

The typical conducted emission test consists of a line impedance stabilization network (LISN), the device under test (DUT) and a power supply to supply the DUT with power. Of course, a suitable measurement device like an EMI-receiver is needed to measure the magnitudes of the spectrum in a defined frequency range according to the defined standard. The emissions have to be measured on the positive and on the negative conductor over the whole frequency range and must be below the specified limit as specified in the standard. The measurement setup is shown in Fig. 3-1:

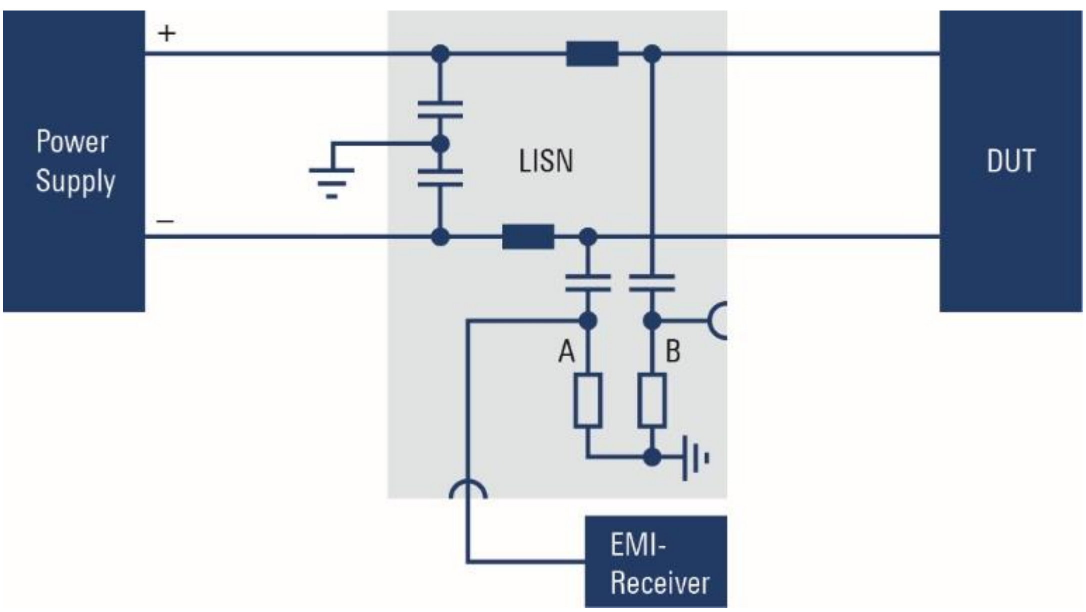

Fig. 3-1 Conducted Emission Measurement Setup

3.1.1 Line Impedance Stabilization Network(LISN)

The LISN also called artificial network is required for several reasons. First, it creates a defined impedance between the external power supply and the DUT to obtain measurement results, which are reproducible between different measurement locations. In addition, it also attenuates the unwanted RF signals coming from the suppling power source. These unwanted RF signals may also differ between different measurement locations. Furthermore, it provides a measurement port for the measurement equipment. The RF measurement port is a dedicated interface for coupling the measurement value to a device like an EMI Receiver, Spectrum Analyzer or a high-end Oscilloscope with enhanced FFT capabilities. In the general The LISN ensures that conducted emission measurements are highly reproducible.

The LISN can be designed as single output or as dual output device. The dual output LISN is more flexible to use and is required for the new common-mode /differential-mode separation measurement method as discussed in this document. In case a dual output LISN is used, the user has to ensure that the RF ports are equally balanced. The EMI-Receiver provides an internal 50-Ohm impedance to ground and therefore the unused RF port needs an additional 50 Ohm to ground to have a balanced system. The DC-LISN used in the case study was a homemade design by Würth Electronic and is a dual output LISN, which is capable to measure the EMI spectrum on both conductors simultaneously. This design was dedicated for debugging purpose only.

3.1.2 Measurement Equipment

As described in the previous chapter several measurement devices exist, which have the capability to measure very small magnitudes with highest signal fidelity. In general, all mentioned devices are more or less suitable for the generic conducted emission measurement setup. Several aspects are discussed in this chapter to find the right choice for the enhanced measurement method.

The first thing the user has to estimate is how close you want to be with your measurements results to the final compliance test values. Of course, the EMI receiver is the right choice when a measurement of an EMI spectrum with the highest fidelity is required for passing the certification. However, the focus is to optimize the EMI input filter and this is typically done during the development cycle. In this case, the highest accuracy is not required because the design is not yet finalized.

The second topic you have to consider is what kind of device you have already on the bench. Of course, this is for sure the oscilloscope when a power supply has to be designed. The oscilloscope is the workhorse of any power electronic design engineer to measure time domain related signals. Their ability to perform EMI debugging tasks in addition provides a more cost-effective solution that eliminates the need for additional equipment. State-of-the-art oscilloscopes are ideal tools for EMI debugging because they are able to transform signals from the time domain into the frequency domain by Fast Fourier Transform (FFT). The required dynamic range and the sensitivity in modern oscilloscope is sufficient to perform the CE test with focus on debugging.

Some additional key aspects for choosing an oscilloscope for EMI are:

a) Low-noise frontend in order to have enough dynamic range when measuring weak emissions

b) Direct input of frequency parameters such as start and stop frequency or resolution bandwidth.

c) Fast and efficient FFT analysis

3.1.3 Limitation of the Standard Conducted Emission Setup

According to the standard, it is required to measure the conducted emissions on both power lines and the measured voltages must be below the specified limit at every frequency in the limit frequency range. This measurement is typically performed sequentially on both power lines. Even this is sufficient to pass the conducted emission test standard, it does not provide the user deeper insights of the noise propagation mechanism because the measurement is a combination of common-mode and differential-mode noise on the conductors. Therefore, the standard conducted measurement setup is not sufficient to optimize the EMI filter very efficiently to obtain a design with focus on smallest size and lowest cost. The principle, how the noise current flows within the setup is shown in Fig. 3-2:

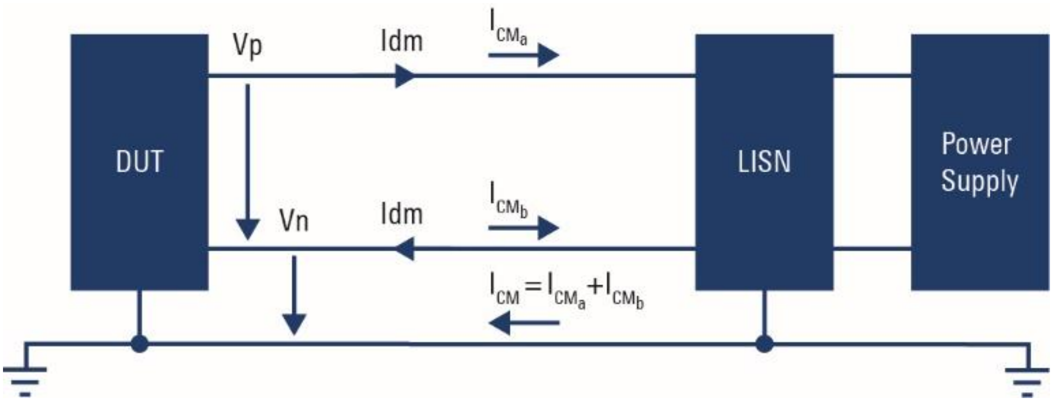

Fig. 3-2 Common Mode / Differential Mode Flow

The CM current portion Icm flows from the DUT on both lines into the LISN and flows back via the external ground path to the DUT. This results in the sum of the two current portions in the external ground path. The amplitude and phase are the same on both conductors, positive and negative. The DM current shows a different characteristic. The DM current on the positive conductor flows into the LISN and the return path of the DM noise is the negative conductor. The only difference is the phase between these two currents. They differ by 180° and ideally, they would cancel out.

3.2 Theory of Common / Differential Mode Noise

Knowing the relations of the CM / DM current flow in the previous chapter, there is an easy mathematical correlation of the current in the conductors, which is described in the following equations:

$$I_P = I_{CM_a} + I_{DM}$$

$$I_N = I_{CM_b} - I_{DM}$$

The fact that the current flows in the impedance of the LISN, this leads to the following equations:

$$V_P = \left(I_{CM_a} + I_{DM}\right) * Z_{LISN}$$

$$V_N = \left(I_{CM_b} - I_{DM}\right) * Z_{LISN}$$

If we would sum the two voltages of the conductor, the result would be twice of the common mode portion flowing in each conductor and the differential mode component will cancel out. This leads to the following equation for the common mode:

$$V_P + V_N = V_{CM_a} + V_{CM_b}$$

This results in:

$$V_{CM} = V_{\mathrm{P}} + V_{\mathrm{N}}$$

This common mode portion represents the total amount of common mode noise and flows in the external ground path.

For a separation of the DM voltage, an additional operation has to be applied. By adding a subtraction to one of the summing point (the DM current is 180° shifted in phase), we obtain the following equation:

$$V_{DM} = \frac{V_P + (-V_N)}{2}$$

It is noticeable that when you perform a simple subtraction you obtain twice of the DM noise level or 6dB extra. Translated into the dB world, this would be extra 6dB, which you have to consider during evaluation of the results.

Now, we know that we have to do a simple math calculation to distinguish between common mode noise and differential mode noise. We just have to consider that the magnitudes of the differential results have to be subtracted by 6dB. Of course, this is only true when you measure the noise on the two conductors at the same time. Furthermore, the simple math calculation works great, if the setup (cable, components of the LISN, etc.) is as symmetrical as possible. In the next chapter, this calculation is demonstrated on a high-end performance scope.

3.3 Debugging Conducted Emissions Test

Based on the theory discussed in the previous chapter, the setup to measure the common-mode / differential-mode separately is slightly different. The new enhanced setup to measure the common-mode and differential-mode is shown in Fig. 3-3:

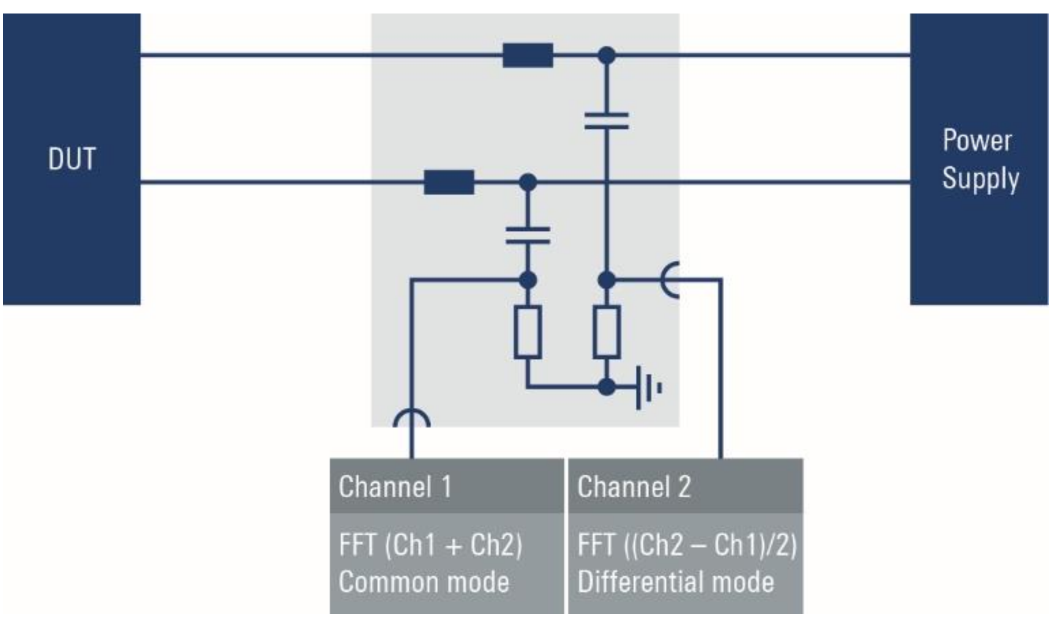

Fig. 3-3 Enhanced Measurement Setup

The main difference in this concept is that the measurement has to be performed simultaneously on both RF outputs of the dual LISN. Instead of a dual LISN, two identical single port LISN may be used to perform the measurement. However, using a dual LISN is recommended to avoid external wiring which may add asymmetrical parasitic components. This may have some impact on the accuracy of the results. The required math calculation will be performed in the math functionality of the FFT setup within the oscilloscope.

The RF connections between the channels should be identical of length, shielding quality and impedance characteristics to avoid any shift in time or loss in amplitude. Furthermore, the sensitivity setting of the channels in the time domain should be the identical and optimized. A wrong vertical scale setting may lead to clipping of the measured signal in the time domain and this effect will lead to wrong results in the frequency domain.

4 Case Study

This case study was performed to demonstrate the capability of the enhanced measurement method of measuring the disturbances and be able to distinguish between common mode and differential mode noise.

4.1 DUT Setup

The DUT is a simple step-down buck converter and the DUT input filter design is a simple PI-LC-filter, which is very effective in damping any differential mode noise in the lower frequency region. In the used setup, it is very easy either to include or to exclude this PI-Filter. No common mode filters are foreseen on the printed circuit board (PCB) and thus the common mode choke was attached external by means of wires to the PCB. The converter is not build within a housing instead, the printed circuit board was placed on an isolation block and the isolation block was placed on a metal ground plane.

Remark:

Typically, parasitic components are formed between the housing and the converter parts like a heatsink. Therefore, the measurement setup was not optimized to generate a big amount of common mode noise.

4.2 No Filter Applied to the System

The first measurement was performed to obtain the emissions without any filter components. This kind of measurement is a typical a good starting point to evaluate the required insertion loss for the filter components. In advance, a reference level measurement (Ref1 and Ref2) was performed to measure the noise level of the system while the DUT is switched off.

The conducted emissions of the converter where no filter components are applied is shown in Fig. 4-1. The top part of the measurement window illustrates the differential noise emissions (M1) whereas the bottom window shows the common mode noise (M2). The math which is required to distinguish between the two modes is set in the math channel menu and visible on the right. The time domain signals are not shown in detail in the main window because the frequency domain is the focus in this case study.

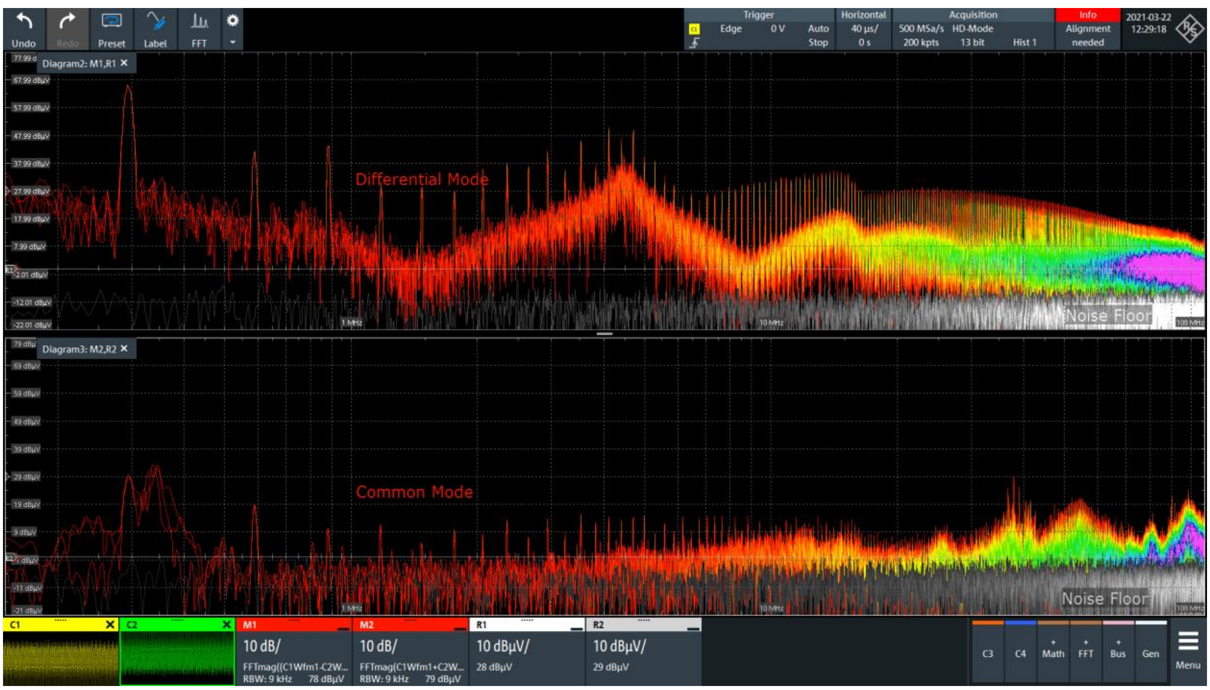

Fig. 4-1 No EMI Filter Applied

The peaks in the common mode window at around 300 kHz in the reference line are generated by the system itself and not by the DUT. Therefore, these emissions can be ignored at least for the magnitude up to 25dBµV. The high magnitude approx. 65dBµV in the differential mode noise during the measurement at 300 kHz is caused by the switching frequency of the converter. Of course, these harmonic and all higher odd multiples of this frequency is caused by the reflected input ripple current and this ripple current dominates the differential mode spectrum.

In the common mode spectrum, some portions are also visible and those magnitudes may not be filtered by a differential filter structure.

4.3 DM-Mode PI Filter Applied to the System

A LC filter was calculated to damp especially the fundamental magnitude at the frequency of 300 kHz. The calculated filter resonance frequency is at 19.3 kHz, which should result in a suppression of about 40dB at the switching frequency. The filter structure is a filter of second order and thus the damping is about 40 dB/Decade.

The measurement shown in the Fig. 4-2 below shows the effect of the filter to the result of the spectrum.

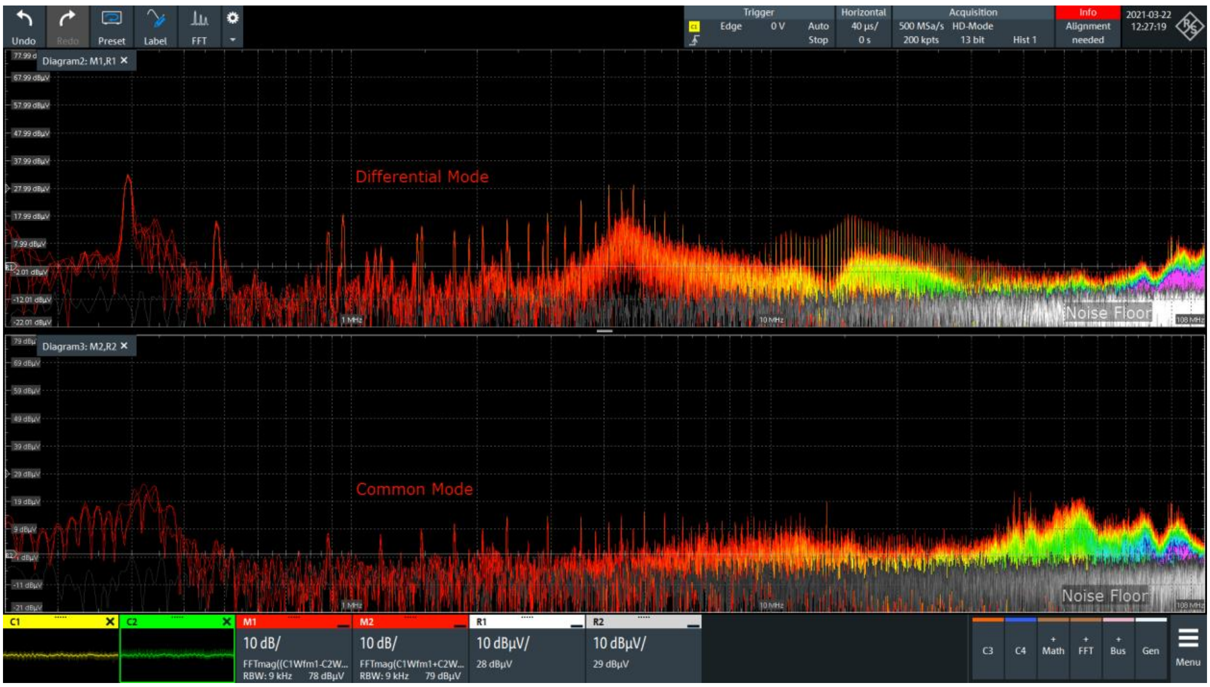

Fig. 4-2 Differential Mode Filter Applied

The differential mode spectrum is reduced in the frequency regions up to 10 MHz very efficient. The magnitudes are damped up to 30dB compare to the previous unfiltered value. Especially the fundamental at 300 kHz and multiple higher harmonics are much lower in the magnitude. In the higher frequency region, the filter is not as effective and thus the magnitudes are damped only up to 10dB.

Of course, the common mode noise visible in the spectrum is not reduced that much because the filter was designed to filter the DM-Noise. If we would like to damp also the CM-Noise, we have to add a filter, which is more effective to common mode noise. This effect is demonstrated in the next chapter.

4.4 CM-Choke Filter Applied to the System

In this case, a common mode choke from Würth Electronic was inserted to reduce the visible noise in the CM window because using a Y-Capacitor was not possible due to the missing housing. The measurement shown in the Fig. 4-3 below shows the effect of the CM choke to the result of the spectrum.

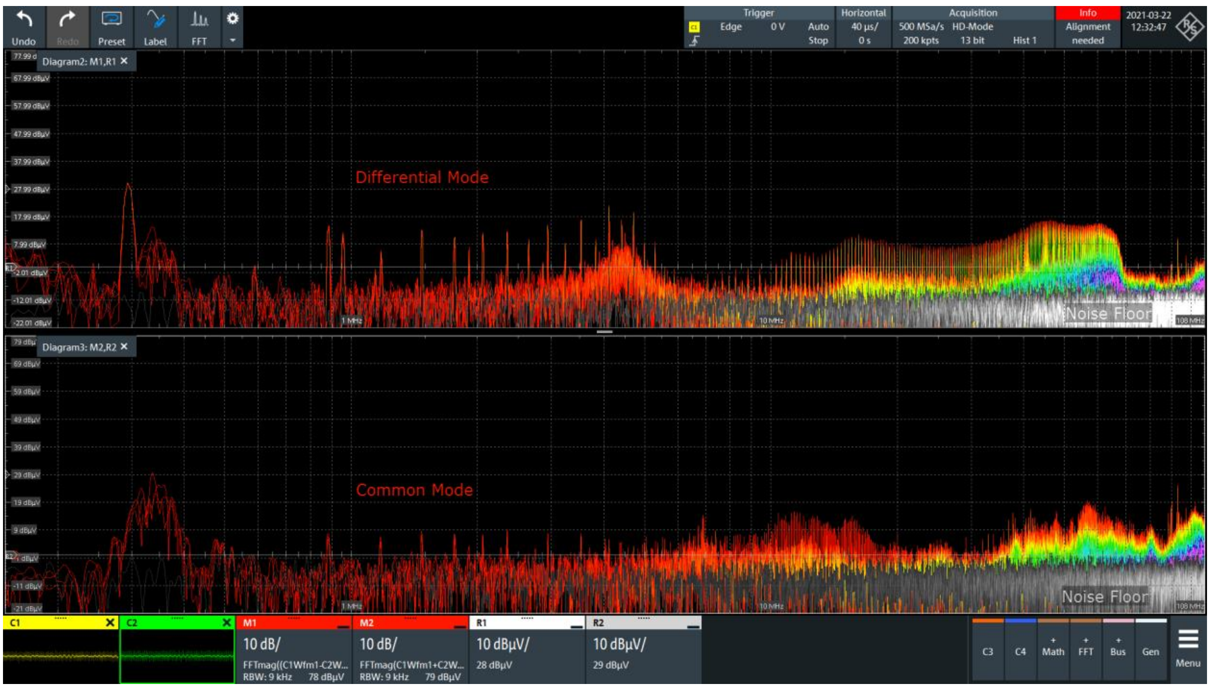

Fig. 4-3 Common Mode Filter Applied

The spectrum in the common mode is reduced tremendously especially in the frequency region from 2 MHz to 60 MHz. In addition, the differential mode is also damped because the common mode choke is not ideal and the resulting leakage inductance functions as a differential filter. Furthermore, the differential mode noise may also be affected because the setup was not optimized (No PCB for the CM choke) and therefore some asymmetrical components may lead to this additional damping effect. However, it is clearly visible that the common mode noise was damped very efficient due to the inserted CM-Choke.

5 Conclusion

A proper input filter design is an ambitious task to fulfil the standards regarding the conducted emission of a switching mode power supply. Knowledge about the conducted emission spectrum like the magnitude and frequency is helpful and a good starting point of your filter design but this information is not sufficient to optimize you filter in the most efficient way. The input filter designer has to deal very often with a filter structure where common mode and differential mode noise is filtered effectively. Therefore, the information whether the disturbances are dominated by common mode noise or are dominated by differential mode noise would lead to a very efficient way of designing an input filter. Thus, an efficient filter design would result in using the smallest components. Choosing the optimal components leads also to a more cost-effective design. Especially in high power converter applications or in high power motor applications, the size and cost of the filter design becomes a critical issue.

Using a dual LISN and the mathematical approach calculating the common and differential mode noise by using a high-end oscilloscope including a powerful FFT functionality offers the designer a very flexible way during the design of the input filter. The designer of the power supply has already great measurement support by using the oscilloscope in the time domain. Using the frequency domain function in addition to the time domain within the oscilloscope during the input filter design, it may reduce the development cycle regarding time and cost.

6 Literature

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7 Ordering Information

Designation	Type	Order No.
Oscilloscope, 6GHz bandwidth, 4 channels	R&S®RTO64	1802.0001.04

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