EMI Filter Design Method for Communication Power Sub-System

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Abstract- **This paper introduces an improved and simplified method to design EMI filters for switching power supplies (SPS), for both AC-to-DC and DC-to-DC. This method is based on using an engineer's way to measure the maximum and the minimum differential mode (DM) and common mode (CM) EMI noise impedance, and consider them in designing the EMI filters. Information of the topology and control method of the power supply is not needed. This method solves the limitations of the old EMI filter design methods, which are either too complicated to use, or based on ideal cases. The analyses and experimental results show that this method can guarantee that the required attenuation can be achieved, especially at low frequency.**

Keywords-EMI filter; Noise impedance

I. INTRODUCTION

In communication systems, distributing power systems are widely used. In these systems, off the shelf power modules are used to convert the input voltage to lower voltage to power the digital and/or optical circuits. These power modules normally cannot meet the EMI regulatory standard, such as FCC, CISPR. Additional EMI filters (normally both common mode and differential mode filters) are needed at the input of these power modules in order to filter out the switching noise and eliminate Electro-Magnetic interference to other equipment.

The design of these EMI filters is not easy because of two reasons. One is that the system engineers (or board engineers) do not know the details of the power module circuits and it is very difficult for them to design the EMI filters. The other is that EMI filter design is sometimes considered as a "black art" because we known little about the EMI source. Interaction between EMI source impedance and EMI filter's output impedance will cause poor noise attenuation. Therefore, simple and effective EMI filter design methods are required.

Unfortunately, only limited research has been done on the methodology of how to design the EMI filter to meet the requirement. Trial and error methods are usually used in EMI filter designing. Furthermore, the existing EMI filter design methods usually ignore the noise impedance of the switching power supply, which results in either over design, or system requirements not being met.

In this paper, the existing EMI filter design methods are reviewed in section 2. Their problems are also highlighted in that section. The effects of noise impedance on the EMI filter design and noise attenuation performance of the EMI filter are analyzed in section 3. A new method to design the EMI filter is proposed in section 4 and 5. The new method is easy to implement and it does not require phase information of the noise source impedance. Experimental results in section 5 and 6 show that the proposed method is an effective and easy way to design EMI filters. Section 7 is the conclusion.

II. REVIEW OF THE EXISTING EMI FILTER DESIGN METHODS

A procedure to design EMI filters was introduced in [1]. However, the impact of the noise impedance of the power supply was not considered. Because the procedure used to design the EMI filter is based on ideal case, it cannot guarantee to achieve the required attenuation and several design iterations may be needed.

In [2] a method was introduced to measure the DM (differential mode) and CM (common mode) noise impedance and three assumptions were made: (1) Common Mode noise impedance is much greater than the equivalent LISN resistor (25 ohm), (2) The large capacitor and inductor always behave ideally, and (3) Expensive equipment is available to measure the very small impedance. Unfortunately, these three assumptions are not necessarily valid in the actual case. When these assumptions are not satisfied, it is impossible for us to know the noise impedance accurately by using the method in [2], even when the assumptions are satisfied, it is very complex for engineers to use the method. Another disadvantage of it is that the method used to measure the noise impedance's phase angle is too complicated.

Because of the limitations of the above EMI filter design method, an improved EMI filter design method that can solve the limitations is needed. In this paper a method to solve the limitations is introduced.

III. NOISE IMPEDANCE'S EFFECT ON THE EMI FILTERS

In this section, the interaction between the noise impedance of the noise source and the output impedance of the EMI filter is analyzed. It shows that if the parameters of the EMI filter are not selected properly, the EMI filter will actually amplify the noise. In the measurement, a power combiner is used to separate CM and DM noise spectrum from the total line noise spectrum [3].

3.1 CM Noise Impedance's Impact

The attenuation of an EMI filter is defined by equation (1)

$$A_T = V_{load}without\_filter / V_{load}with\_filter \quad (1)$$

$V_{load}without\_filter$ is measured at the LISN shown in Fig.1 when no common mode inductor is added, which corresponds to the situation when no EMI filter is added. $V_{load}with\_filter$ is measured at the LISN when a common mode inductor is added. A_T is frequency related, it should be measured and calculated at different frequency points.

In order to simplify the analysis, it is assumed that 1) The common mode filter only has a common mode inductor. 2) The CM inductor only suppresses the CM noise. 3) CM noise current only goes from noise source to earth. Then we can get the CM equivalent when a CM inductor is added to the input of the SPS from Fig.1, the equivalent circuit is shown in Fig.2. ($Z_f = j\omega L_c$ is the impedance of CM inductor, R_{load} is the equivalent resistor of Line Impedance Stabilization Network). Noise voltage across R_{load} before and after the CM inductor is added can be expressed by equation (2) and (3).

$$V_{Noise} = \frac{R_{load} Z_s}{R_{load} + Z_s} \times I_s \quad (2)$$

$$V_{Wfilter} = \frac{R_{load} \times Z_s}{(R_{load} + Z_s + Z_f)} \times I_s \quad (3)$$

If (4) is satisfied, the noise voltage across R_{load} will be amplified after the CM inductor is added.

$$| R_{load} + Z_s + Z_f | < | R_{load} + Z_s | \quad (4)$$

Equation (4) can be illustrated by using Fig.3($Z_f = j\omega L$). From Fig.3 we can see that at some conditions the amplitude of vector $R_{load} + Z_f$ and Z_s can be almost the same, and the angle between vector $R_{load} + Z_f$ and Z_s is near 180 degrees. At this time the filter will amplify the noise. When the frequency becomes high enough ($j\omega L >> R_{load}, j\omega L >> Z_s$), the inductance becomes dominant. At this time the CM inductor can effectively suppresses the CM noise spectrum. Fig.4 shows the CM noise spectrum before and after a CM inductor is added to the input of the SPS. From the test result we can see the noise at 583KHz is amplified, but at higher frequency the noise is effectively suppressed. This verifies the above analysis is correct.

In the real case, more complex topologies for CM filters can be used, but if the CM filters are not designed to match the CM noise impedance, the deteriorated impact of the EMI filter also exists.

3.2 DM Noise Impedance's Impact

In order to simplify the analysis, it is assumed that 1) The differential mode filter only has an X capacitor. 2) The X capacitor only suppresses DM noise. 3) The DM current only goes from noise source to power ground. Then we can use the same method to analyze DM noise impedance's effect. Fig.5 is the DM noise equivalent circuit when an X capacitor is added to the input of SPS. Using equation (1) and the equivalent circuit in Fig.5, we can get equation (5). ($Zs << R_{load}$, Zs is the DM noise impedance of the SPS, Z_f is X capacitor's impedance $Z_f = 1 / j\omega C$).

$$| A_T | = | 1 + \frac{R_{load} Z_s}{Z_f (R_{load} + Z_s)} | \approx | 1 + \frac{Z_s}{Z_f} | \quad (5)$$

If -1< Z_s / Z_f <0, the amplitude of A_T will be less than one, the DM noise will be amplified. Fig. 6 shows the experiment result when an X capacitor is added to the input of the SPS. The DM noise spectrum at 4.15MHz is amplified.

In real the case, more complex topologies for DM filters can be used, but if the DM filters are not designed to match the DM noise impedance, the deteriorated impact of the EMI filters also exist.

From the above analysis, we can see that in order to effectively suppress the EMI noise, EMI filters should be designed to match the noise impedance. Inductor's impedance should be much bigger and capacitor's impedance should be much smaller than the noise impedance, especially when they face the input of the SPS, and we have no information of the phase angle of the noise impedance.

IV. DETERMINATION OF THE MAXIMUM AND THE MINIMUM CM AND DM NOISE IMPEDANCE

Noise impedance has a significant impact on the attenuation of the EMI filters. In order to effectively attenuate the EMI noise at the frequency range we are interested in, EMI filters should be designed to match the noise impedance. However, the noise impedance of a switching power supply has different phase angle and amplitude at different frequencies, and it is very difficult to measure the noise impedance's phase angle and amplitude accurately at a very wide frequency range (For FCC the frequency range is from 0.45MHz to 30MHz). Actually from the analysis in section 3 we can see that if we know the maximum and the minimum amplitude of noise impedance and select the EMI filter component properly we can design the EMI filter effectively. And measure the maximum and the minimum amplitude of the noise impedance is much easier. Their measurement methods are summarized below. In the measurement, a power combiner is used to separate CM and DM noise spectrum from the total line noise spectrum [3].

4.1 The Worst CM Noise Impedance Measurement

Assuming that 1) The CM inductor only suppresses the CM mode noise. 2) The CM noise impedance is bigger than the equivalent LISN resistor (CM noise impedance of SPS is usually bigger than 25ohm in real case). 3) The CM noise current only goes from noise source to earth.

To measure the maximum and the minimum CM noise impedance, a test CM inductor is added to the input of the SPS [2], the measurement setup is in Fig. 7. Fig. 7 can be further simplified to the CM equivalent of Fig. 2. Using the equivalent circuit in Fig. 2 and equation (1), we can get equation (6) (Z_f is the impedance of CM inductor, R_{load} =25 ohm is the LISN equivalent resistor).

$$A_T = \frac{\frac{R_{load}Z_s}{R_{load}+Z_s}\times I_s}{\frac{(R_{load}+Z_f)Z_s}{(R_{load}+Z_s+Z_f)}\times I_s \times \frac{R_{load}}{Z_f+R_{load}}} = 1+\frac{Z_f}{R_{load}+Z_s} \quad (6)$$

From (6), the following relation can be obtained:

$$|R_{load}+Z_s| = |Z_s|/|A_T-1| \quad (6.1)$$

It is noted that A_T is a complex number and only $|A_T|$ is available. The objective is to find the range of $|Z_s|_{Max}$ and $|Z_s|_{Min}$

$$|R_{load}+Z_s| = \left|\frac{Z_f}{A_T}\right| \quad (\text{if } A_T >>1) \quad (7)$$

Equation (7) is a circle (because R_{load} is fixed, and Z_s is complex number, Z_f and A_T are also know) and it is illustrated in Fig.8. From Fig.8 we can get the maximum and minimum magnitude of CM noise impedance.

1)When $A_T \geq 10$

$$Z_{s\max} = \left|R_{load}+\left|\frac{Z_f}{A_T}\right|\right| \quad (8)$$

$$Z_{sMin} = \left|R_{load}-\left|\frac{Z_f}{A_T}\right|\right| \quad (9)$$

3)When A_T <10

$$Z_{s\max} = \left|R_{load}+\left|\frac{Z_f}{|A_T|-1}\right|\right| \quad (10)$$

$$Z_{sMin} = \left|R_{load}-\left|\frac{Z_f}{|A_T|+1}\right|\right| \quad (11)$$

For example, at full load the CM noise spike of the SPS at 1MHz is 70dB, after a test CM inductor is added the CM noise is 50dB at 1MHz, then $A_T = 10^{\frac{70dB-50dB}{20}}$ =10. Using an impedance analyzer get the CM inductor's impedance at 1MHz is 5Kohm, using equation (8) and (9), $Z_{s\max}$ =525ohm $Z_{s\min}$ =475ohm, then the maximum and the minimum magnitude of CM noise impedance at 1MHz is 525ohm and 475ohm.Usually the CM noise impedance varies by frequency (for FCC the frequency range is from 0.45MHz to 30MHz), so we can select some frequency points in the frequency range we are concerned with and calculate the worst CM noise impedance at these frequency points.

4.2 The Worst DM Noise Impedance Measurement

In the DM noise impedance measurement, assuming that 1) The X capacitor only suppresses the DM noise impedance. 2) The DM noise impedance Zs is smaller than LISN equivalent resistor, (DM noise impedance of SPS usually much smaller than 100ohm in real case). 3) The DM noise current only goes from noise source to power ground.

When measuring the worst DM noise impedance a test X capacitor is added to the input of the SPS under test [2]. Fig. 9 is the test setup. Fig.9 can be further simplified to Fig.5.Using DM equivalent circuit of Fig.5 and equation (1), we can get equitation (12). (Zs<< R_{load} , R_{load} =100ohm, R_{load} is the LISN equivalent resistor).

$$|\ A_T\ | = \left|\ \frac{\frac{R_{load}Z_s}{R_{load}+Z_s}\times I_s}{\frac{R_{load}Z_sZ_f}{R_{load}Z_f+Z_sZ_f+RZ_s}\times I_s}\ \right| \approx \left|1+\frac{Z_s}{Z_f}\right| \quad (12)$$

$$|Z_{s\min}| = |Z_f|\times|\ |A_T|-1\ | \quad (13)$$

$$|Z_{s\max}| = |Z_f|\times|\ |A_T|+1\ | \quad (14)$$

It is noted that A_T is a complex number and only $|A_T|$ is available. Measuring the DM noise impedance is similar to the CM noise impedance measurement. And equations (13)-(14) are used to calculate the maximum and the minimum DM noise impedance at the frequency.

After measuring the worst CM and DM noise impedances, we can select EMI filter topologies and select EMI filter components based on the worst CM and DM noise impedance.

V. EMI FILTER DESIGN

In this section how to use the maximum and the minimum CM and DM noise impedance to design EMI filters is introduced. A DC/DC power supply is used as an example. The aim is to design an EMI filter for it, and make it pass the FCC Class B regulations for conducted EMI. When Designing the EMI filter, CM and DM filters are designed separately, and finally they are put together to make a whole EMI filter. The phase angle of the noise impedance is neglected, and the noise impedance is simplified to a resistor. The procedure to design the EMI filter is summarized below:

1) Test the CM and DM noise spectrum of the SPS.

2) Measure the maximum CM and DM noise impedance at the frequency range we concerned with. Design the EMI filter base on the worst noise impedance.

3) Test the EMI filter.

Fig.10 and Fig.11 show the CM mode and DM mode noise spectrum of the DC/DC SPS at full load according to FCC class B. From the test results we can see the CM mode noise is the dominant factor and its highest spike is from 0.45MHz to 2MHz .So the CM noise impedance measurement is focused on this range, Fig.12 Fig.14 show the worst CM noise impedance, Fig.13 shows the worst DM noise impedance.

5.1 EMI Filter CM Part Design

In order to design an EMI filter we need to know:

1) The attenuation required to make the CM noise spectrum pass the EMI standard at the frequency we are concern with.

2) The worst noise impedance at the frequency range we are concerned with.

For the EMI filter CM part, there are two topologies we can select. One is the CM inductor faces the input of the SPS, another is the Y capacitor faces the input of the SPS. (See Fig.15 and 16).

According to Fig.14. Fig.15 should be used, because it will provide higher attenuation at high frequency than the topology shown in Fig.16. Fig.17 shows the test results of the Fig.16 and Fig.15. From the result we can see the above predication is right. (In the test CM=100uH, CY=330nF). This result also confirms that noise impedance has a significant effect on the performance of EMI filters.

$$f_{cut} = F_0 / \sqrt{A_T} \qquad (15)$$

A_T is the attenuation needed at frequency F_0, f_{cut} is the cutoff frequency of the common mode filter. Using Fig.18 and equation (15), the smallest cutoff frequency is :

$F_o = 583KHz \quad A_T = 38 \quad f_c = 94KHz$

When selecting the value of common mode inductor, the maximum noise impedance is considered, from Fig.12 we can see that the maximum magnitude of the common mode noise impedance is 205ohm, the CM inductor's inductance at F_o should be bigger than 205ohm, this means $2\pi F_o L > 205$ L>55.9uH .In order to make the CM inductor's impedance bigger enough when compared with CM noise impedance, L=200uH is selected. Using equation (16)(Equation (16) is based on ideal case) get C=14.3nF. This value is calculated based on ideal case. We need verify the above calculation.

$$f_c = \frac{1}{2\pi\sqrt{LC}} \qquad (16)$$

The attenuation of the topology in Fig.15 when considering the CM noise impedance can be expressed by using equation (17). (Ignoring the phase angle of the noise impedance).

$$|A_t| = \left| \frac{R_{Load}(Z_1 + Z_L + Z_s)}{Z_1(R_{load} + Z_s)} \right| \qquad (17)$$

$Z_L = j\omega L \quad Z_c = \frac{1}{j\omega C} \quad Z_1 = R_{load} // Z_c \quad C = 15nF$

$R_{load} = 25ohm \quad L = 200uH \quad Z_s = 205ohm$

Put the components above into equation (17), we get At=5.5. That is too small. Make the capacitor bigger and try again when CY=150nF(two Y capacitor in parallel) we get the attenuation 45. Fig. 19 shows the experiment result. From the test result we can see that the desired attenuation is achieved. Fig.20 shows the test result when the filter is designed based on ideal case (L=200uH C=15nF), from the test result we can see that the desired attenuation is not achieved.

5.2 EMI Filter DM Part Design

Using a similar method, we can design the DM part of the EMI filter. To design the DM filter we need to know:

1) The attenuation required at the frequency we are concern with.

2) The worst DM noise impedance at the frequency range we are concerned with.

The π topology is selected to suppress the differential mode noise, because this topology can provide higher attenuation. The equivalent circuit of the topology is shown in Fig.21. Because X capacitor faces the input of the SPS, the minimum DM noise impedance is used in the EMI filter designing. The attenuation of this topology can be expressed by using equation (18)(Ignoring the phase angle of the noise impedance). Using Fig.11 we get the smallest cutoff frequency is at $F_o = 770KHz$,the attenuation we need is 4.5.In the DM filter designing the leakage inductor of CM inductor is used as DM inductor.

L_leakage=20uH Zs=0.2 $F_o = 770KHz \quad Z_L = j\omega L$

$$Z_{cl} = \frac{R_{load} Z_{cx}}{R_{load} + Z_{cx}} \quad Z_{cs} = \frac{Z_s Z_{cx}}{Z_s + Z_{cx}} \quad Z_{cx} = \frac{1}{j\omega C_x}$$

$$A_T = \frac{V_{Dwout}}{V_{Dwith}} = \left| \frac{Z_L(Z_{cx} + R_{load})(Z_s + Z_{cx})}{Z^2{}_{cx} R_{load}} \right| \qquad (18)$$

Using equation (18) we get when Cx=15nF and A_T =6(we need A_T =4.5). Fig.22 is the test result of DM noise spectrum before and after the DM filter is added. From test result we can see the filter works well.

Finally the CM and the DM filters are assembled together. The final EMI filter is showed in Fig.23. Its test result is shown in Fig.24.From the test we can see the filter can make the SPS pass FCC Class B. In Fig.23 a 200uF electrolytic capacitor is added to the output of the filter, this capacitor is used to make sure that the EMI filter will not destabilize the feedback loop of the SPS [4].

VI. EXTENDING THE METHOD TO DESIGN EMI FILTERS TO AC/DC SPS AND POWER SYSTEM

The same method is used to design another filter for an AC/DC power supply to pass FCC Class B. After measuring the DM and CM noise spectrum and noise impedance, the filter topology is selected. The Test result of the filter is shown in Fig. 25, from the test we can see the design aim is reached.

System engineers can also use this EMI filter design method to design EMI filters for paralleled switching power supply modules. At this time the paralleled power modules can be simplified to one equivalent power module, and use the method above to design an EMI filter for it.

VII. CONCLUSION

An improved method to design EMI filters is proposed in this paper. It is based on measuring the maximum and the minimum noise impedance, and considering them in EMI filter design. Design procedures are highlighted. And this EMI filter design method successfully solves the limitations of the existing EMI filter design methods. And it is very helpful in finding the right direction when designing EMI filters. The significant advantage of the new procedure is that it is easy to implement, only the maximum and the minimum amplitude of CM and DM noise source impedance are required, and the designed filter will guarantee that the desired attenuation can be achieved. In addition, the EMI filter designed by the proposed method will meet the requirement in one design cycle. Finally one EMI filter is designed for DC/DC switching power supply and another filter is designed for AC/DC switching power supply. Experiment results show that this method is an effective and easy way to design EMI filters. And it can guarantee to achieve the required attenuation (if the component can meet the requirements). In addition, this method can also be used to design EMI filters for power systems.

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[4]Input System Instability Application Note PQ-00-05-1 Rev. 01 http://www.synqor.com/support/3_1_app_notes.html

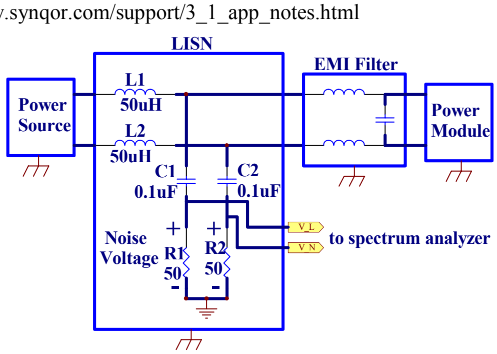

Fig.1 Setup of EMI Noise Measurement

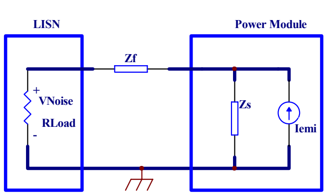

Fig.2 CM Noise Equivalent Circuit of SPS When A CM Inductor is Added

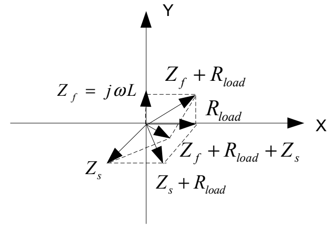

Fig.3 Vector Explanation of Equation 4

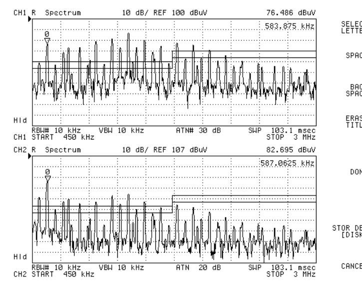

Fig. 4 CM Noise Amplified after a CM Inductor is Added

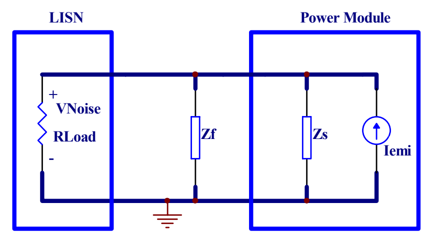

Fig. 5 DM Noise Equivalent Circuit After an X Capacitor is Added

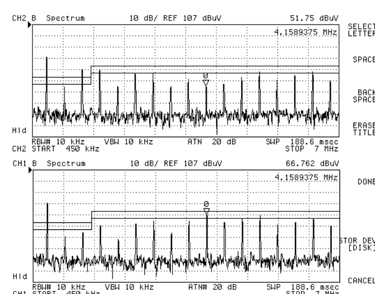

Fig. 6 DM Noise Amplified After an X Capacitor is Added

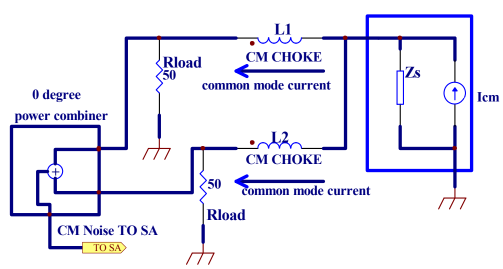

Fig.7 Setup of the CM Noise Impedance Measurement

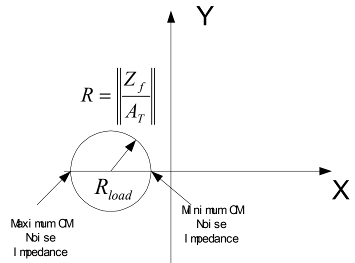

Fig. 8 Illustration of Equation 7

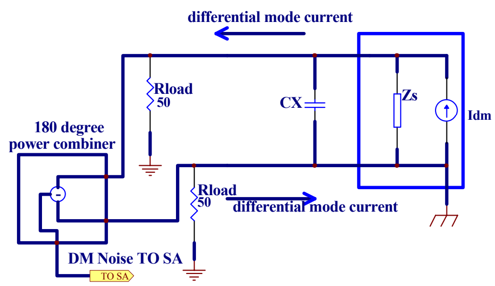

Fig. 9 Setup of the DM Noise Impedance Measurement

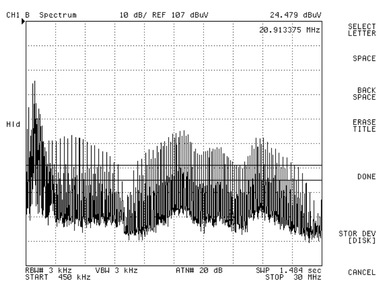

Fig. 10 CM Noise Spectrum of the DC/DC SPS at Full Load According to FCC Class B

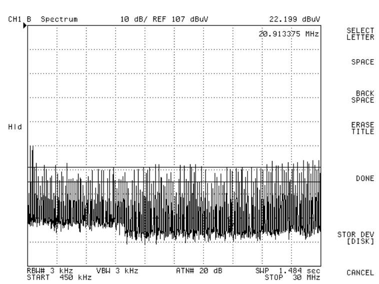

Fig. 11 DM Noise Spectrum of the DC/DC SPS at Full Load According to FCC Class B

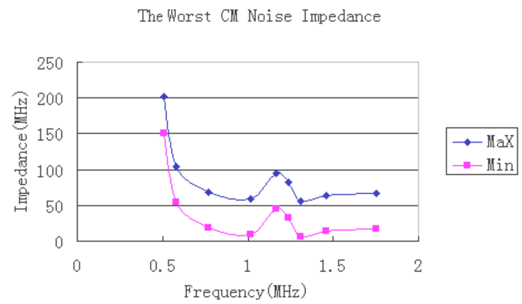

Fig. 12 The Worst CM Noise Impedance From 0.45MHz to 2MHz

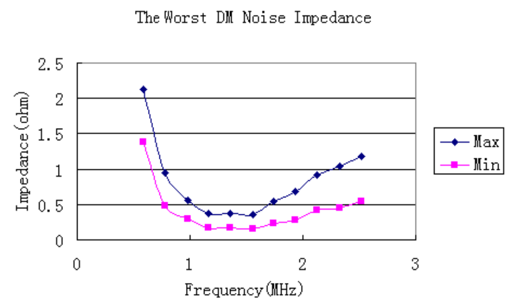

Fig. 13 The Worst DM Noise Impedance From 0.45MHz to 2.5MHz

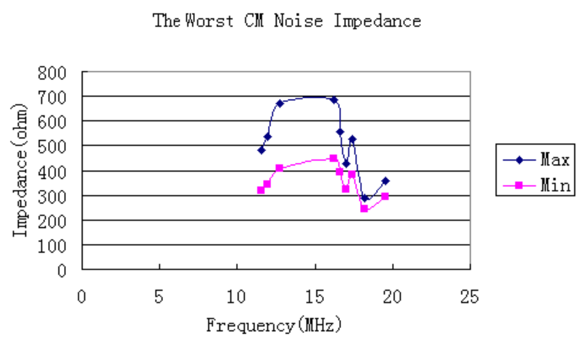

Fig. 14 The Worst CM Noise Impedance From 10MHz to 20MHz

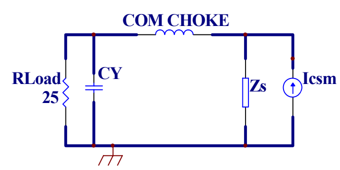

Fig. 15 The CM Inductor Face the Input of SPS

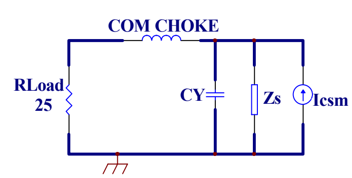

Fig. 16 The Y Capacitor Face the Input of SPS

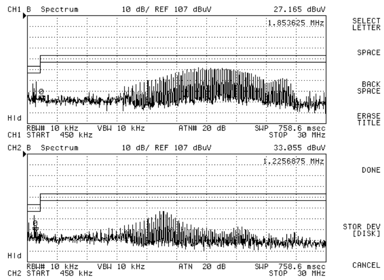

Fig. 17 CM Noise Spectrum Test Result of Fig.16 and Fig.15

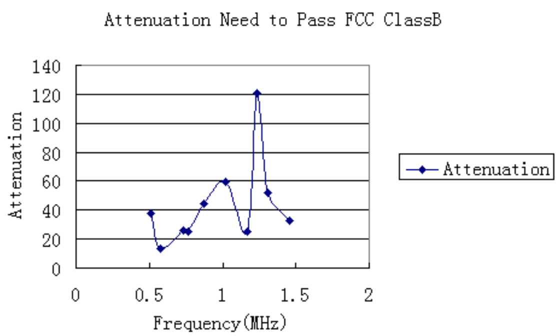

Fig. 18 Attenuation Needed for the CM Noise Spectrum to Pass FCC Class B with 3dB margin

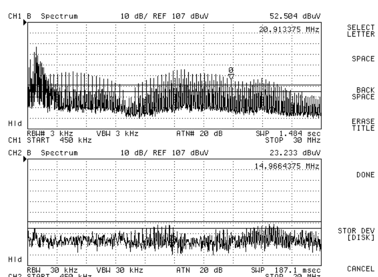

Fig. 19 Test Result of CM Noise Spectrum Before and After the CM Filter Added

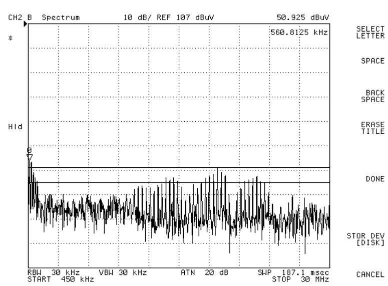

Fig. 20 Test Result of the CM Filter Designed Based on Ideal Case

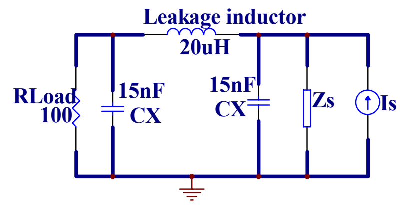

Fig. 21 Topology of DM Filter

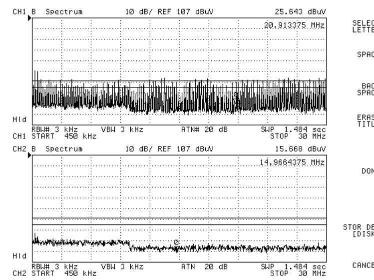

Fig. 22 DM Noise Spectrum According to FCC Class B before and after the PI Filter is Added

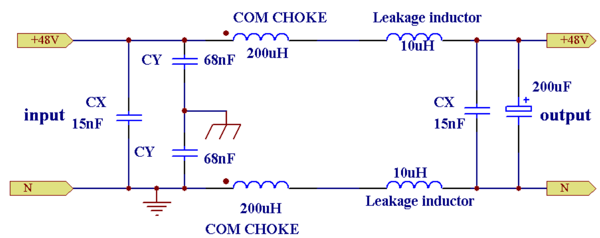

Fig. 23 The Whole EMI Filter When the DM and CM filters are put together

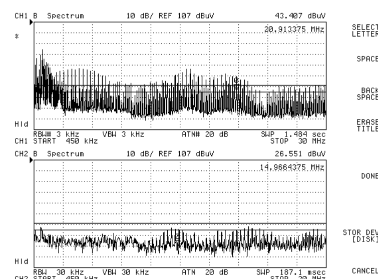

Fig. 24 Test Result of the Total Noise Spectrum according to FCC Class B Before and After the EMI Filter is Added to the Input of the SPS

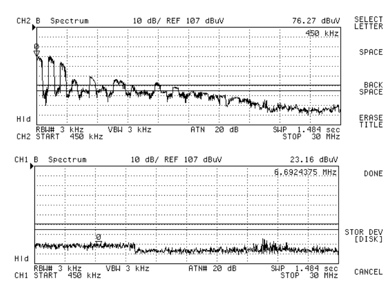

Fig. 25 Total Line Noise Spectrum According FCC Class B of The AC/DC SPS before and after the EMI Filter is Added