The Influence of EMI Power Filter’s Layout on the Measurement of Mains Terminal Disturbance Voltage

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Abstract. In the first place, this article analyzes the principles of electromagnetic interference (EMI) power filter from the aspects of the differential mode and the common mode disturbance. Afterwards, the design requirements of key components in the EMI power filter and the layout principles of filter is investigated. Next, the influence of layout of EMI power filter on the measurement of mains terminal disturbance voltage has been studied experimentally by the lap quality of the filter onto the equipment under test, the distance between the input and output power line of filter, as well as the input cable length of EMI power filter. Finally, we draw the conclusion that the layout quality of power filter has important impact on the measurement of mains terminal disturbance voltage. It means that the related rules should be strictly abided by when the EMI power filter is used to restrain the conducted disturbance.

1. Introduction

Even with a good design of shielding and grounding, it cannot prevent interference from the equipment through the cable. As in the field of electromagnetic compatibility (EMC), the cable usually acts as an effective receiving and transmitting antenna. Experience shows that it’s not sufficient to provide separation for the electromagnetic disturbance only by shielding and grounding. Filtering is another powerful measure to prevent the interference. Filtering can be effectively used to suppress the un-useful signal while allowing the useful signal to pass through, which is used to extract the signals while reducing the interference. According to different definitions, the filter can be classified as signal selection filter and electromagnetic interference (EMI) filter, or as analog filter and digital filter, or as passive filter and active filter. Whatever, the filter is used to remove useless signals and retain useful signals.

2. Principle of the EMI power filter

EMI filters can be classified as signal line filter, power line filter, printed circuit board filter, etc [1]. The power line is the main path for electromagnetic interference to import and export the equipment. Through the power line, the equipment can transfer electromagnetic disturbance to the power grid. Meanwhile, the disturbance from the power grid can also get into the equipment by the power line. As a low pass filter, the design purpose of the EMI power line filter is to suppress the electromagnetic interference passing through the power line. It means the disturbance circuit and the power supply are separated by a filtering network with the aid of reasonable selection of components and parameters. The working frequency signal (usually 50Hz or 60Hz) is allowed to pass through while the
disturbance is mostly suppressed. The circuit principle of one typical EMI power filter is shown in Figure 1.

Figure 1. Diagram of typical EMI power filter.

The EMI power filter is used to filter the electromagnetic interference from the power line. There are two forms of the disturbance signal in the power line: difference mode and common mode. Differential mode interference signal is transmitted between the fire line and the zero line, which always has the lower frequency and belongs to the symmetric interference. The common mode interference is transmitted between the line and the ground, which has the higher frequency and belongs to the asymmetric interference. The common mode disturbance might lead to the radiation around the wire, which is usually the main source of the EMC problem.

To reduce the differential mode interference can be realized by making the differential mode choke in series with the fire line and the zero line (Ld1 and Ld2 in Figure 1), as well as parallel the differential mode capacitance between fire line and zero line (Cx1, Cx2 and Cx3 in Figure 1). When the differential mode current flows through the line, the disturbance is filtered for the existence of differential mode choke and differential mode capacitance.

To reduce the common mode interference can be realized by connecting the common mode choke in the fire line and the zero line (Lc1 and Lc2 in Figure 1). Meanwhile, the common mode capacitance can be paralleled between the fire line, the zero line and the ground (Cy1 and Cy2 in Figure 1). When the differential mode current flows through the common mode choke, the magnetic fields produced in the two coils are equal in size, opposite to each other, and thus counteract each other. So the common mode choke has no influence on the power supply signal. In addition, when common mode current flows through the common mode choke, the magnetic field is strengthened in the same direction. Then the common mode disturbance is greatly attenuated for the large inductance from the common mode choke.

3. Requirements of key components for EMI power filter

3.1. Parameters selection

By adjusting the parameters of the key components, such as resistance, capacitance and inductance of the power filter, the suppression of differential mode interference and common mode interference can be realized respectively [2].

The differential mode choke is mainly used for large current applications, but the larger the current is, the easier the core of coil might be saturated. Therefore, in order to avoid saturation caused by working current, larger volume cores is needed.

The differential mode capacitor is connected between the fire line and the zero line, and it can only be used to attenuate the differential mode current.

The common mode choke has the large inductance and attenuation for the common mode current, while showing little impedance and attenuation for the differential mode current as the canceling effect of the magnetic field.

Considering the power input voltage and leakage current test of the electrical equipment, the capacity of common mode capacitance can not be too large. Table 1 shows the nominal value range of main components of the EMI power filter.
Table 1. Nominal range of main components of EMI power filter.

| Component name          | Nominal range       |
|-------------------------|---------------------|
| Differential mode choke | 10 μH - 1 mH        |
| Differential mode capacitor | 103-475 pF     |
| Common mode choke       | 1 mH - 200 mH       |
| Common mode capacitor   | 101-472 pF          |

3.2. Installation and layout principle

The installation of the power filter plays an important role on the filter performance. It should conform to the following basic principles [3-4].

- The filter should be installed at the outlet of the interference source as close as possible to the earth point of the equipment shell. If the internal space is limited, the filter should be installed on the outside of the outlet of the interference source cable.
- The filter should be completely shielded. In addition, the shielded shell should be well overlapped with the metal shell of the equipment. If the shell is nonmetallic, the shield shell should be connected to the ground point of filter and lapped well with the earth of equipment.
- The input and output cables of the filter must be separated and keep the proper distance in case of the interference.
- All the cables on the filter, including the input and output lines, the grounding wire, etc., should be as short as possible.

4. Influence of EMI power filter layout on measurement of terminal disturbance voltage

4.1. Situation of lapping between the filter and the equipment metal shell

In order to simulate the bad lapping between the EMI power filter and the metal shell of the device, an insulation pad is placed under the filter in the chassis, so that the ground of the filter is separated from the ground of the equipment. Table 2 shows the test data contrast.

Table 2. Data comparison of proper and improper lapping.

| Frequency (MHz) | Disturbance voltage under proper lapping $E_{1a}$ (dBμV) | Disturbance voltage under improper lapping $E_{2a}$ (dBμV) | $E_{2a}-E_{1a}$ (dB) |
|-----------------|----------------------------------------------------------|----------------------------------------------------------|----------------------|
| 0.15            | 40.56                                                    | 42.30                                                    | 1.74                 |
| 0.50            | 0.52                                                     | 0.53                                                     | 0.01                 |
| 1.00            | -0.55                                                    | -0.39                                                    | 0.16                 |
| 2.50            | -0.66                                                    | -0.59                                                    | 0.07                 |
| 5.00            | -0.86                                                    | -0.74                                                    | 0.12                 |
| 10.00           | -0.43                                                    | -0.26                                                    | 0.17                 |
| 20.00           | 6.35                                                     | 6.83                                                     | 0.48                 |
| 30.00           | 15.42                                                    | 15.65                                                    | 0.23                 |
The test results show that the disturbance voltage with proper lapping is basically lower than the disturbance voltage with the improper overlap situation. The maximum difference is 1.74dB at 0.15MHz. The minimum difference is 0.01dB at 0.50MHz. When the lapping is bad, the shell of the EMI filter is not connected to the chassis of the measured device, causing the ground of the filter capacitor in the filter to be floated. So the common mode capacitor will not filter the common mode disturbance when high disturbance voltage is produced. When the lapping is arranged well, the common mode capacitor in the filter operates in good condition. The lower disturbance voltage will be acquired. As can be seen from Table 2, the difference in the disturbance voltage is higher in the higher frequency part, which indicates that the lap joint has more significant influence on the common mode part in the disturbance voltage.

4.2. Situation of the filter input cable close to the output cable excessively.

![Diagram of the excessively close distance between the input and output cables.](image)

There are two situation under investigation. In one condition, the distance is set 0 cm between the input cable and the output cable of filter, which means the input cable and the output cable are bounded together. In the other condition, the distance is set 10 cm, which means the input cable and the output cable keeps the 10 cm distance or so. The results of the test are showed in TABLE.III.

| Frequency (MHz) | Disturbance voltage when distance is 10cm (dBμV) | Disturbance voltage when distance is 0cm (dBμV) | $E_{2b}-E_{1b}$ (dB) |
|----------------|-----------------------------------------------|-----------------------------------------------|----------------------|
| 0.15           | 40.38                                         | 40.73                                         | 0.35                 |
| 0.50           | 0.39                                          | 0.46                                          | 0.07                 |
| 1.00           | -0.47                                         | -0.25                                         | 0.22                 |
| 2.50           | -0.64                                         | -0.55                                         | 0.09                 |
| 5.00           | -0.86                                         | -0.81                                         | 0.05                 |
| 10.00          | -0.69                                         | -0.62                                         | 0.07                 |
| 20.00          | 8.14                                          | 10.94                                         | 2.8                  |
| 30.00          | 15.04                                         | 15.28                                         | 0.24                 |

As shown in the Table 3, the disturbance voltage of the filter with bigger spacing is lower compared with the smaller spacing situation. The maximum difference is 2.8dB at 20MHz, when the minimum difference is 0.05dB at 5MHz. When the spacing is excessively close, the parasitic capacitance will be produced among the cables. The higher frequency disturbance generated on the main board of the chassis, the more easily it is coupled to the input and output cables through the parasitic capacitance, which makes the performance of power filter deteriorate, and this may not realize the normal filtering function.
4.3. Situation of overlong input cable

![Diagram of the overlong input cable of filter.](image)

The best installation position of the power filter is at the outlet of the interference source, which is close to the connection location of the shell. In this test, the filter is installed at the outlet of the chassis of the interference source cable and the position near the power supply of chassis respectively, which corresponds to the shortest and the longest power line situations.

Table 4. Test result comparison of different length of the filter input cable.

| Frequency (MHz) | Disturbance voltage with shortest input power line $E_{1C}$ (dBμV) | Disturbance voltage with longest input power line $E_{2C}$ (dBμV) | $E_{2C}-E_{1C}$ (dB) |
|----------------|---------------------------------------------------------------|---------------------------------------------------------------|----------------------|
| 0.15           | 40.51                                                         | 40.76                                                         | 0.25                 |
| 0.50           | 0.32                                                          | 0.33                                                          | 0.01                 |
| 1.00           | -0.62                                                         | -0.47                                                         | 0.15                 |
| 2.50           | -0.67                                                         | -0.50                                                         | 0.17                 |
| 5.00           | -0.78                                                         | -0.69                                                         | 0.09                 |
| 10.00          | 0.95                                                          | 1.02                                                          | 0.07                 |
| 20.00          | 8.62                                                          | 10.45                                                         | 1.83                 |
| 30.00          | 14.69                                                         | 15.74                                                         | 1.05                 |

The test results show that the disturbance voltage under the overlong input cable condition is generally higher than the short input cable condition. The maximum difference is 1.83dB at 20MHz, when the minimum difference is 0.01dB at 0.50MHz. The high frequency disturbance couples to the input cable through the space radiation, at the same time, the radiation from the outside couples into the motherboard of equipment even without passing the filter. So the measured disturbance voltage becomes higher. When the filter is installed at the power line outlet of the shell, all the disturbance from the shell will pass through the filter. Therefore, the disturbance voltage is undoubtedly lower after the filtering.

![Figure 5. Diagram of three arrangement situations of filter.](image)
According to test data from Table 2 to 4, a contrast diagram can be drawn as shown in the Figure 5. The horizontal axis is the frequency where the longitudinal axis is the quasi peak value difference of the terminal disturbance voltage. The layout of the filter has little influence on the lower frequency section below 10MHz, and the difference is below 0.3dB basically. It has great influence on the higher frequency band above 10MHz, especially in the vicinity of 20MHz, and the maximum difference has reached 2.8dB. This difference is equivalent enough to affect the judgment of the test results. In the higher frequency section, the common mode part of the disturbance signal is more sensitive to the parasitic capacitance and inductance generated in the three test cases, which can be seen near the 20MHz frequency.

5. Conclusion
In addition to grounding and shielding, filtering is also a strong measure to suppress the electromagnetic interference. Not only can the filter reduce the disturbance from the power grid, but also can stop the noise signal from the inside of the device. The quality of parameter design and layout is crucial to the function of power filter to realize the filtering normally. The design of filter is mainly based on the principle that the network structure conforms to the maximum mismatch of impedance. By selecting the parameters of the components reasonably, the maximum attenuation of the disturbance shall be realized [5-7]. The layout of filters needs to strictly follow the principles, including to ensure the fine overlap between filters and devices, isolate the input and output cables sufficiently, and shorten the length of input cables as much as possible. Experiments show that, if not in strict accordance with the principles, EMI power filter is unlikely to filter normally due to the parasitic capacitance or other causes of spatial coupling. Hence the tested disturbance is probably higher than the result under the actual condition. Therefore, the layout of EMI power filter is sufficient to affect the judgment of the test results, which should be paid enough attention by the test engineer.

References
[1] Zhu Wenli. Electromagnetic compatibility design and countermeasures and case analysis, vol.8. Beijing: Publishing House of Electronics Industry, 2012, pp:148-152.
[2] Zheng Junqi. Analysis of EMC design and test case, 2nd. vol.4. Beijing: Publishing House of Electronics Industry, 2011, pp: 127-131.
[3] Pang Bing, Chen Ling, Zhang Peng, et al. “Selection Principles and Installation of Power Supply EMI Filter”. Safety & EMC, vol.5, pp:19-21, 2013.
[4] Chen Hengling, Qian Zhaoming. “Investigation of the Influences of Different Layouts on the Performance of EMI Filters”. Transactions of China Electrotechnical Society, vol.8, pp: 7-12, 2008
[5] Yan Peiqi, Lin Jinqian. “Selection and installation of EMI filter”. ELECTRIC AGE, vol.2, pp: 122-124, 2005
[6] Xie Bin, Yang Li. “Design and Application of EMI Mains Filter”, Fire Control Radar Technology, vol.35 (1), pp: 38-41, 2006
[7] Shen Xuemei, Jiang Ninghao, Fu Jingbo. “Influence Analysis of Grounding Mode to Conducted Disturbance at Mains Terminals”. Smart Grid, vol.8, pp: 781-784, 2016

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