

A Novel Measurement System for the Common-Mode- and Differential-Mode-Conducted Electromagnetic Interference

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Abstract—Electromagnetic Interference (EMI) test is an important part for the manufacture of power electronic equipment, which helps us not only analyze the noise characteristics of the Equipment Under Test (EUT) but also design EMI filters. The previous separation method for the Common Mode (CM) and Differential Mode (DM) noise was time consuming or costly. In this paper, a novel measurement system for CM and DM conducted EMI is described showing a good performance. The system consists of two parts, part 1: getting CM noise or DM noise through a current probe; part 2: obtaining another mode noise from a software-based method. A 150 w switch mode power supply is measured to verify the proposed measurement system. The noise spectra of CM and DM signal is shown, and the results obtained by software program are compared with those obtained from a current probe measurement showing a good concordance in terms of peak value.

1. INTRODUCTION

The power electronic equipment has been widely used, which brings some serious EMC problems [1–3]. In order to satisfy the standard limits, electronic engineers must propose reasonable noise rejection methods. Insertion of filters [4–7] is a common method which can reduce the conducted EMI for comfort and regulations. Separation of conducted differential-mode (DM) and common-mode (CM) noise is very useful for noise diagnosis [8, 9] and electromagnetic interference (EMI) filter design in power electronics applications.

Different techniques for separating measurement of the CM and DM signals have been reported. A noise separation network [10] was first introduced in 1988, in which a pair of center tapped radio transformers with the ratio of 1 to 1 working as a core to select different mode noises through a mechanic switch. But the high frequency identification capability of the separation network was affected by extra interference brought by the mechanical switch. Since then, [9] implemented vector addition and subtraction functions for the noise in the neutral line and the phase line by using two wideband radio frequency transformers to separate common mode and differential mode signal from the total interference, which covered the disadvantage caused by mechanical switch. A 0 degree or 180 degree power combiner had been used to design a high performance separation network [12], which was easy to operate. The obtained CM or DM interference had wider frequency. But due to the high cost of the power combiner, it is hard to promote the separation method widely. Two different separation networks [4, 8] based on decoupling the noise of the modulator and common-mode rejection coil were put forward. In 2000, another new noise separation network was proposed [13], in which the authors designed a DM rejection network to get the CM interference, then they calculated DM noise spectrum with the help of a computer-aided software tool, which was developed according to the relationship of common mode and differential mode. These separation methods for CM and DM interference have the characteristic of lower cost and are easy to operate. But the junctions between the resistances

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of differential-mode rejection network (DMRN) [14] and the ports connected to coaxial lines must be manufactured meticulously to conform wide-band response. This is time consuming.

A fast measurement for separating DM and CM noise is needed. At present the ordinary method is using current probes, which is a good choice for fast measuring. However, in some situation it is limited to measure the CM noise only due to the device's dimension. When we measure the DM EMI in single phase power supply, a line should be bent and put into the hole of the current probe as shown in Figure 1. But if the lines are so hard or short to bend or cannot be put into the hole of the current probe, this method does not work. The measurement system described below can overcome this disadvantage.

In this paper, a measurement system combining current probe and computer-aided software tools for CM and DM noise of conducted EMI is presented. The computer-aided software tool exports the text files of measurement results, which are used for drawing the amplitude spectra of DM and CM noise. We use a current probe to extract the amplitude spectra of both the CM and the total noise on each line. Then the amplitude spectrum of DM noise can be isolated from the total noise by the software program developed. In the following sections, the proposed measurement system description and algorithm will be discussed in detail. After that a 150 w ac/dc switch-mode power supply will be tested to verify the measurement system. The calculated results obtained from the software program are compared with the current probe measurement.

2. THE MEASUREMENT SYSTEM

2.1. Measurements Using the Current Probe

The current probe plays an important role in this measurement system for CM and DM noise. Its functions are represented as follows.

- Extracting the interference frequency spectrum of the phase line, the neutral line and CM, respectively. The experiment data can be used to calculate the DM interference frequency spectrum according to the algorithm that will be given in the following section.
- Obtaining the DM interference frequency spectrum. The measurement data will be used to compare with the result calculated by the software program. The process is to prove the validity of the given method.

The arrangement measuring the interference on the power line is shown in Figure 2. A line impedance stabilization network (LISN) is employed to decouple the EUT from the power grid. The conducted interferences are measured by the current probes. When using a magnetic probe with toroid shape, a proper wire arrangement can be utilized to measure the CM/DM noise. Figure 1 and Figure 2 show the wire arrangements for DM and CM interference measurements, respectively. In the same way, the conducted interference on each wire can be obtained as shown in Figure 2. The output port of the current probe is connected to the measurement receiver. Here the spectrum analyzer plays the role as the measurement receiver.

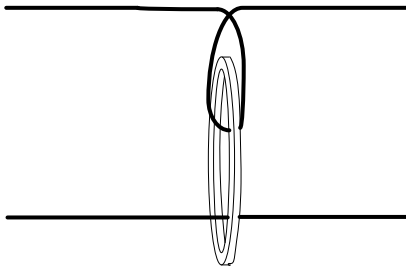


Figure 1. Arrangement for the DM current measurement.

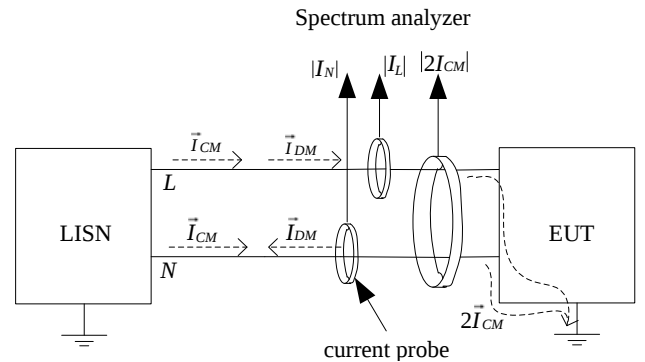


Figure 2. The measurement arrangement.

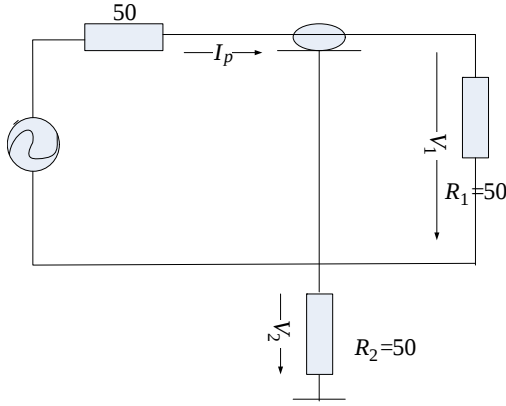


Figure 3. Schematic diagram.

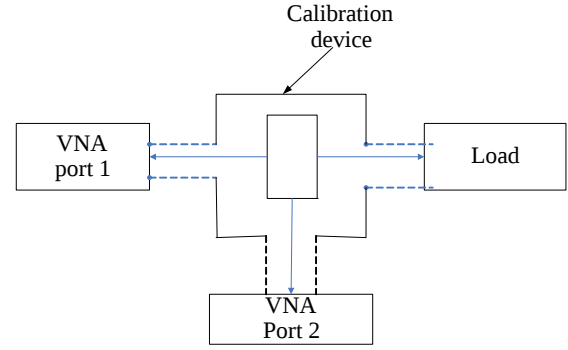


Figure 4. Calibration setup.

2.2. Calibration of the Current Probe

In order to obtain the noise spectrum of the current on the wires, we need to calibrate the measurement system consisting of the used current probe and coaxial cables. The schematic diagram and testing diagram for calibrating are shown in Figure 3 and Figure 4, respectively. In Figure 3, V_2 and V_1 represent the voltage drop on R_2 ($50\ \Omega$) and R_1 ($50\ \Omega$), respectively. I_P is the current flowing through the calibration device, which is the measurement variable. The admittance can be defined by the following equation

$$Y_t = \frac{I_P}{V_2} \quad (1)$$

The S parameter S_{21} obtained from Vector Network Analyzer (VNA) can be defined by the following equation

$$S_{21} = \frac{V_2}{V_1} \quad (2)$$

The current flowing through R_1 is I_P ; therefore, the voltage drop V_1 on R_1 equals $50I_P$. Combining Equations (1) and (2), the admittance Y_t can be defined by the following equations

$$Y_t = \frac{I_P}{V_2} = \frac{I_P}{50I_P S_{21}} = \frac{1}{50S_{21}} \quad (3)$$

Equation (3) can be shown in dB, as below

$$Y_t \text{ (dB)} \approx -S_{21} \text{ (dB)} - 34 \quad (4)$$

where in Equation (4) the units of Y_t and S_{21} are dB, and the coefficient 34 is the dB value of the $50\ \Omega$ impedance.

If the admittance Y_t has been calculated, the interference current can be described by the following equation:

$$I_p = V_2 + Y_t \quad (5)$$

Here I_p , V_2 and Y_t are in dB unit.

So the essence of current probe calibration is actually to measure current probe transmission admittance Y_t .

2.3. Software Separation Method

In this part, software separation method is given. When the line is so hard to bend, we cannot obtain the DM interference current directly through a current probe. In order to solve this problem, we refer to the computer-aided software. Firstly, we can obtain noise current amplitude spectra of I_L , I_N and I_{CM} . Secondly, I_{DM} is calculated by the software program.

The current distribution on lines is shown in Figure 2. The signal on either L line or N line is the vectored sum of CM and DM noises. The CM noise on both L and N lines is in phase, while the DM noise is out of phase. So the interference currents on the lines can be described by the following equations:

$$\vec{I}_L = \vec{I}_{CM} + \vec{I}_{DM} \quad (6)$$

$$\vec{I}_N = \vec{I}_{CM} - \vec{I}_{DM} \quad (7)$$

Assuming that the phase difference between CM signal $\vec{I}_{CM}$ and DM signal $\vec{I}_{DM}$ is θ . Both sides of Equations (6) and (7) are squared, and these equations can be modified to:

$$|\vec{I}_L|^2 = |\vec{I}_{CM}|^2 + |\vec{I}_{DM}|^2 + 2\vec{I}_{CM} \cdot \vec{I}_{DM} \cos \theta \quad (8)$$

$$|\vec{I}_N|^2 = |\vec{I}_{CM}|^2 + |\vec{I}_{DM}|^2 - 2\vec{I}_{CM} \cdot \vec{I}_{DM} \cos \theta \quad (9)$$

According to Equations (8) and (9), the DM current component is defined by the current signals I_L , I_N and I_{CM} .

$$|\vec{I}_{DM}| = \sqrt{\frac{|\vec{I}_L|^2 + |\vec{I}_N|^2 - 2|\vec{I}_{CM}|^2}{2}} \quad (10)$$

where the DM current amplitude spectrum can be calculated avoiding considering the phase difference θ .

3. MEASUREMENT RESULTS AND ANALYSIS

To validate the measurement system for CM and DM interference noises, a 150 w switch mode power supply was measured. Under the quantity of sampling points, measurement results had two different frequency bands. One was from 150 kHz to 1 MHz and the other from 1 MHz to 30 MHz. Noises on phase line and neutral line have been measured directly through the current probe as well as CM signal. According to the algorithm of software separation method, we have calculated the DM signal. At last, the calculated results were compared with the experimental ones.

The measurement setup is shown in Figure 5. A three-phase LISN working in single phase function has been introduced in order to decouple and standardize the switch mode power supply input from the ac source. The adopted measuring system was a ZN23101 current probe (bandwidth from 0.01 MHz to 60 MHz) connected with a Agilent N9000 spectrum analyzer working in peak detection mode. The measuring points and arrangements are represented in Figure 2. In order to ensure the test repeatability, the spectrum analyzer worked in peak detection mode, and its sampling-point number was constant. The whole measurement equipment was on a grounded aluminum plate keeping 0.85 meter above the earth.



Figure 5. Measuring setup.

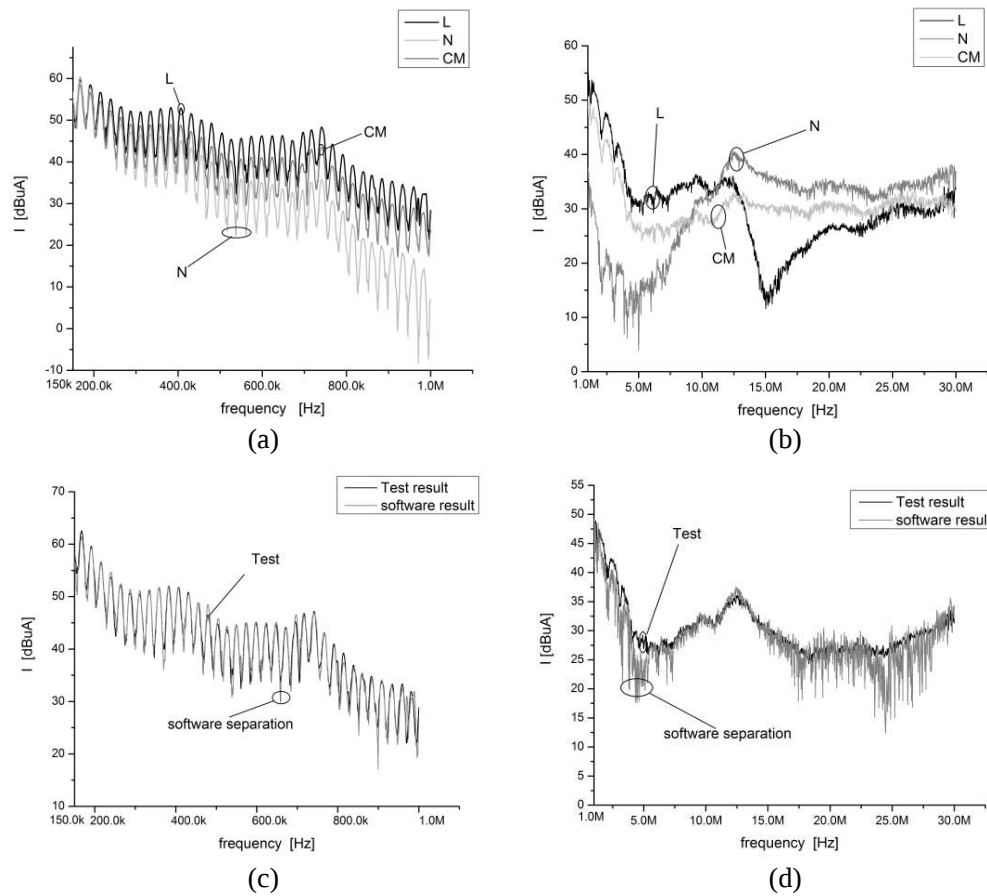


Figure 6. Experimental results: (a) I_L , I_N and I_{CM} with bandwidth from 150 kHz to 1 MHz; (b) I_L , I_N and I_{CM} with bandwidth from 1 MHz to 30 MHz; (c) I_{DM} and compute result with bandwidth from 150 kHz to 1 MHz; (d) I_{DM} and compute result with bandwidth from 150 kHz to 1 MHz.

3.1. Separation Method Validation

The CM signal has been directly recorded by the spectrum analyzer as well as signals on L and N lines. The direct measurement results are shown in Figures 6(a) and (b). The bandwidths of interference current spectrum in Figures 6(a) and (b) are from 150 kHz to 1 MHz and from 1 MHz to 30 MHz, respectively. A good concordance is shown in terms of peak frequencies even if the amplitudes of the three signals are different. In Figure 6(a) at any frequency point the component on L line is almost the largest. Along with the increase in frequency, the amplitudes of these go down. However, the gap between the signals on L and N lines has become bigger. At frequency range from about 700 kHz to 1 MHz, the interference flows through L line rather than N line. And CM signal falls in between them. In Figure 6(b), the trends of the signal spectrum are unlike what happens in Figure 6(a). As we can see in Figure 6(b), the signals on L and N lines have tremendous changes with the increase in frequency; however, the change of CM noise is comparatively gentle.

Figures 6(c) and (d) represent DM signals at the frequent ranges from 150 kHz to 1 MHz and from 1 MHz to 30 MHz, respectively. The dotted lines represent the results calculated by software program. The solid lines represent the experimental results obtained by the current probe. The comparison results show a good concordance in terms of peak value in both Figures 6(c) and (d). So the software separation method is valid. Therefore, we have adopted the measurement system to obtain the interference current spectrum on L and N lines, and the CM signal and DM signal have been separated successfully.

In another situation, if the DM signal rather than the CM signal is known, we can separate CM

signal by using the same Equation (8). Only a little change is needed. CM signal can also be obtained from software program. Here, we have used the data obtained from the measurement of switch mode power supply. The agreement in terms of peak value between the software and experimental results is good. The software separation method applies to these two kinds of situations.

3.2. Converting Current to Voltage

In Figure 6(d), there exist many spikes in the results obtained by software program, which happen in the case that the detected current amplitude is small. In the two pictures, we can see the spikes appearing when the current value is less than about $30 \text{ dB}\mu\text{A}$. The current probe is a device that can convert the current under test into voltage. When the noise current is small, the accuracy of measurement is poor. So the calculation value is much less than the experimental result. Furthermore, for CISPR and FCC specifications, the noise voltage is the concern. It is a simple procedure to convert noise current to noise voltage.

Figures 7(a) and (b) represent the noise voltage spectra corresponding to CM and DM current spectra shown in Figure 6. Here, the input impedance of the spectrum analyzer is 50Ω . So the CM or DM voltage drop on a 50Ω resistance is defined as CM or DM noise voltage. The black broken lines are the Quasi-peak (QA) limits of the EN5008-1 standard. At the frequency range from 150 kHz to 1 MHz, CM signal voltage is larger than DM. In Figure 7(b), the dominant component changes with the frequency. It is necessary to understand the dominant component, and therefore, the filter design can be done by directly measuring the noise spectra referring to this novel separation system.

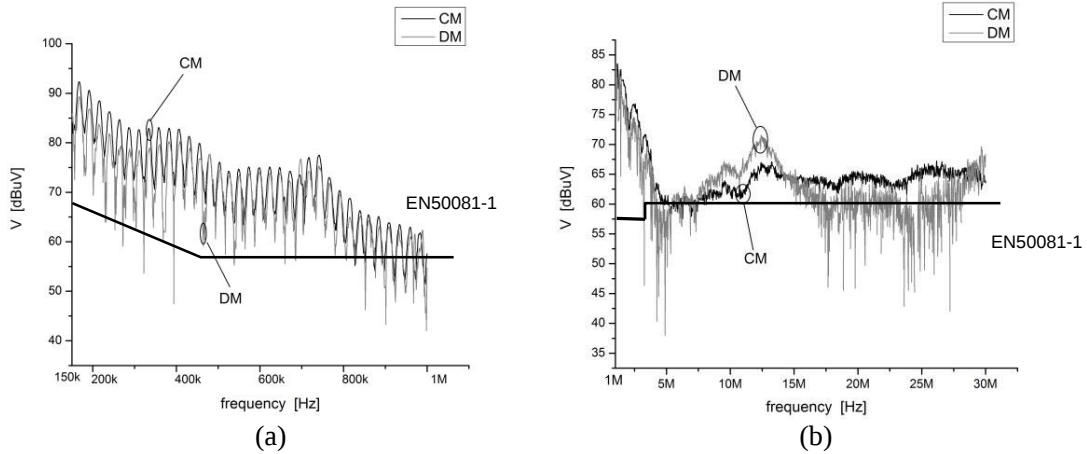


Figure 7. The CM and DM voltage spectrum at the frequency range, (a) from 150 kHz to 1 MHz, (b) from 1 MHz to 30 MHz.

4. CONCLUSION

This paper presents a novel measurement system for separating common- and differential-mode conducted interferences. The separation method of software program was validated by measuring a 150 w switch mode power supply. The CM and DM current amplitude spectrums were successfully separated from total noise on lines by adopting the proposed measurement system. At the same time, in order to satisfy the standards limits, the voltage spectra can be obtained straightforwardly.

It is possible to understand which of the two interference mode components is in dominance, and therefore, the filter design can be done straightforwardly by directly measuring the noise produced by the power electronics under test. This measurement system covers the shortage that DM signal cannot be obtained directly due to the dimension of the current probe or wires. The measurement system can be adopted to get the CM and DM currents or voltages avoiding an additional analog circuitry that can limit the bandwidth.

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