Separation of the Common-Mode and the Differential-Mode Conducted Electromagnetic Interference Noise

by

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(Abstract)

One of the difficulties in solving EMI problems is the lack of diagnostic tools available. In this thesis work, a tool, called Noise Separator, is developed, which can be used to decipher the differential-mode (DM) noise and the common-mode (CM) noise from the total noise. A noise separator hardware is built and tested. The results show that at least 50 dB rejection to either DM or CM noise is achieved for frequency ranging from 10 KHz to 30 MHz. With the aid of the Noise Separator, EMI filter design is made easier.
Acknowledgments

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Chapter I
Introduction

Switched-mode power supply (SMPS) is widely used in modern power supplies. It features small size, light weight and high efficiency. However, it generates serious electromagnetic interference (EMI) problem. EMI emission is always a great concern for power electronic engineers because without passing government EMI emission regulation, the product can not be sold in the market.

One of the difficulties in dealing with EMI problem is the lack of diagnostic tools available. When the noise emission of a piece of equipment fails to pass regulation, it is often very difficult to trace the origin of the noise sources. In a conducted emission test, for example, emission measured is a mixture of both differential mode (DM) and common mode (CM) noises. These two modes of noise come from different sources and coupled through different paths, and must be dealt with separately in the EMI filter design. Therefore, it is advantageous to be able to discern the two modes of noise source in order to design a good line filter.

There have been techniques reported for measuring the two modes of noise from a mixture of noises. Nave introduced a Differential-mode Rejection Network (DMRN), but it can only be used to measure the CM noise [1]. Current probes can also be used to measure both modes of noise current. However, it requires a sophisticated current probe, and even with it, the maximum rejection of noise attainable is only 35 dB [2]. Furthermore, for the government regulations, the noise voltage is the concern, and it is not straightforward to convert the measured noise current to noise voltage. A differential
amplifier has high common mode rejection ratio (CMRR) and could be used to measure DM noise, but it takes a very high-bandwidth differential amplifier to cover the frequency of interest (10 KHz - 30 MHz). High performance differential amplifier is not only costly but it also requires additional power supply which may interfere with the measurement.

It is evident that a new device is needed to achieve accurate and convenient separation of the DM and the CM noises. Based on this motivation, a "Noise Separator" has been developed in the research that has led to this thesis. The Noise Separator can be used to separate both the CM noise and the DM noise from a mixture of noises for the frequency range of interest (10 KHz - 30 MHz). It contains only passive elements.

In this thesis, Chapter II gives a background information about conducted EMI test setup and government regulations. Two noise types, differential-mode and the common-mode, are described using a power supply circuits as an example. In Chapter III, the working principle of the Noise Separator is described. Detailed information about the Noise Separator hardware construction is also given. Chapter IV details the performance test of a Noise Separator constructed. Two approaches are used to measure the same performance, one using network analyzer and the other using a pulse generator and a spectrum analyzer. Both results confirm each other. Chapter V presents results from power supply conducted EMI measurement using a Noise Separator. Ten tests were conducted to demonstrate the usefulness of a Noise Separator. Chapter VI concludes the thesis.
Chapter II
Conducted EMI Test and Noise Types

This chapter reviews general background information about the conducted EMI test and the associated governmental regulations. In addition, the CM and DM noise sources and their coupling paths in a switching power supply will be discussed in the chapter.

2.1 EMI Measurement Setup

Figure 2.1 shows a diagram for the measurement of conducted EMI emission. A switched mode power supply (SMPS) is the Equipment Under Test (EUT) which generates the CM and DM noises. The block "LISN" represents a Line Impedance Stabilization Network that will be discussed in the following section. The noise voltage measured across the 50 ohm resistor inside LISN, usually displayed in frequency domain, is by definition the conducted EMI emission of the switching power circuit. When Line side EMI is measured, the other side must be terminated with a 50-ohm resistor or vice versa. FCC (Federal Communications Commission) and VDE (Verband Deutsche Elektrotechnischer) use the measurement setup requirement of the International Special Committee on Radio Interference.

2.1.1 Line Impedance Stabilization Network (LISN)
Figure 2.1 Conducted EMI Test Setup
FCC and VDE specify precisely of how to obtain noise voltage spectrum that could be used to evaluate conducted EMI. Specifically, the conducted EMI noise current of an SMPS, either from the Line or Neutral side, goes through a 50 ohm resistor to the ground. The noise spectrum should be measured across the resistor. The result should meet corresponding governmental regulations.

In the EMI measurement, a LISN plays a very important role. It guarantees a stabilized 50 ohm impedance from both Line and Neutral to the ground. Meanwhile it provides little insertion loss to the main power going through it. The basic operation of the LISN can be seen from Figure 2.1. At the power line frequency, 50 or 60 Hz, the capacitor in the LISN shows high impedance. The main power passes the inductors without much interference. To the frequency range of the EMI measurement (450 KHz to 30 MHz), the high impedance of the inductors isolates the test setup from the variation of off-line impedance. The Line and Neutral sides are both grounded by 50 ohm resistors, one from the input impedance of the spectrum analyzer and the other from a built-in resistor. The LISN shows 100-ohm equivalent impedance to the DM noise sources and 25-ohm to the CM noise sources.

2.1.2 Governmental Regulations

All electronic products that use digital techniques and whose clock frequencies exceed 10 KHz have to satisfy the FCC specification on conducted and radiated EMI in order to be sold in the United States. If the products are planned to be marketed in Europe, they must meet a corresponding regulation VDE. The specifications concerning conducted EMI that are expressed in the form of spectrum requirement are shown in Figure 2.2. It should be noted that VDE includes low band (10 KHz to 150 KHz) and
Figure 2.2 FCC and VDE Specification on Conducted EMI
high band (150 KHz to 30 MHz), whereas FCC is only concerned with 450 KHz to 30 MHz band. The reason for distinguishing low band and high band is that the resolution bandwidths (RBWs) in spectrum analyzer are different, 200 Hz for low band and 9 KHz for high band. In the FCC specification, RBW is set to 9 KHz. Class "A" of FCC specification is applicable to industrial products and Class "B" to residential electronic appliances. From 30 MHz to 1 GHz is radiated EMI measurement range, which is beyond the scope of the thesis.

2.2 Noise Sources and Coupling Path in a Switching Mode Power Supply

A forward converter configuration shown in Figure 2.3 is used to illustrate the noise sources and the coupling paths in a switching power supply. According to the explanation given earlier, any current going through the LISN 50 ohm resistors causes conducted EMI noises. There are two types of noise current going through the 50 ohm resistors. One is due to the differential mode current $i_{DM}$, and the other is the common mode current $i_{CM}$. A switching device, MOSFET, draws pulsating current as shown in the diagram. The part of the current goes through the filter capacitor $C_B$, and the remaining part flows to the 50-ohm LISN resistor. The DM noise is caused by the unfiltered portion of the MOSFET pulsation current through the 50 ohm resistor. It can be seen that the equivalent series resistance (ESR) and inductance (ESL) of the bulk capacitor $C_B$ are directly related to the DM noise. The larger the ESR and ESL, the larger the DM noise. The CM noise is caused by displacement current flowing through the 50-ohm resistor. Due to switching, there is a high voltage swing between the drain and source of the MOSFET, which induces current by the $dv/dt$ effect. The displacement
Figure 2.3 Noise Sources and Coupling Paths in a Forward Converter
current is coupled through parasitic capacitors, such as $C_d$, $C_q$, and $C_t$. The $C_d$ and $C_q$ are the parasitic capacitance between the semiconductor devices and the chassis, and the $C_t$ is the transformer inter-winding capacitance. In most cases, the capacitances between switching devices and heat sinks are identified as a major CM noise source. The CM noise current flows through the two 50-ohm resistors in parallel, i.e., through both the Line and Neutral to the Ground, while the DM current flows through the two 50 ohm resistors in series. It is therefore expected that the measured EMI voltages on the Line and the Neutral are different. One is CM + DM, and the other is CM - DM.
Chapter III

Noise Separator

In this chapter, the basic principle of the Noise Separator is discussed first. An implementation of the Noise Separator is then described. Experimental measurements are conducted to determine the effectiveness of the separator.

3.1 Basic Principle

The basic concept of the Noise Separator is straightforward. Figures 3.1 and 3.2 show the diagrams depicting this concept, in which the two signals (A and B) derived from the LISN, consist of both the CM and DM noises. However, one of the signals is a vector addition of the two modes of noise (C\(\bar{M}\) + D\(\bar{M}\)), and the other signal is a vector difference of the two modes of noise (C\(\bar{M}\) - D\(\bar{M}\)). In Figure 3.1 the block "Adder" is a device that cancels out the DM component and lets through the CM component. It will be discussed in the next section that the output of the "adder" is \(\sqrt{2}CM\) rather than 2CM. In Figure 3.2 the block "Subtractor" cancels out the CM component and lets through the DM component. The "adder" is called the DM rejecter (DMR), and the "subtractor" is called the CM rejecter (CMR) in the thesis. By using the DMR, one would measure the CM signal and vice versa. This is the basic principle of the Noise Separator. The challenge of implementing the basic concept described above is to maintain the proper rejection for the frequency ranging from 10 KHz to 30 MHz. A small error of phase or magnitude
Figure 3.1 Block Diagram of Differential Mode (DM) Rejecter
Figure 3.2 Block Diagram of Common Mode (CM) Rejecter
introduced in the process of summing or the phase subtracting leads to a large percentage of error for the separator.

3.1.1 Power Combiner

A device that can be used as the "adder" and the "subtractor" is the power combiner. Power combiners are usually used to combine the outputs from a number of RF amplifiers into one signal so that high power output can be obtained. The number of inputs could be from 2 to 48. Sometimes, a power combiner is also called a power splitter when it is used in reverse. For a two-input power splitter, an input signal can be equally divided into two signals with certain phase difference, \( \theta^\circ \), \( 90^\circ \) or \( 180^\circ \). What does the phase lag mean if the device is used as a combiner? The analysis is given as follows [3]:

for a \( \theta^\circ \) power combiner,

\[
P_o = \frac{P_1 + P_2}{2} + \sqrt{P_1 P_2} \cos \theta;
\]

\( P_1, P_2 \): input power;

\( P_o \): output power;

\( \theta \): phase difference between the two inputs;

If \( \theta = 0^\circ \), \( P_1 = P_2 = P_{\text{in}} \);

\( P_o = 2P_{\text{in}} \);

\[
V_o^2 R_o = 2 V_1^2 R_i
\]

Since \( R_o = R_i = 50 \, \text{ohm} \);

\( V_o = \sqrt{2} \, V_{\text{in}} \);

If \( \theta = 180^\circ \),

\( P_o = 0 \);

For a \( 180^\circ \) power combiner,
\[ P_o = \frac{P_1 + P_2}{2} - \sqrt{P_1 P_2 \cos \theta}; \]

If \( \theta = 0^\circ \),

\[ P_o = 0; \]

If \( \theta = 180^\circ \),

\[ P_o = 2P_{in}; \]

\[ V_o^2 R_o = 2 V_i^2 R_i; \]

Since \( R_o = R_i = 50 \text{ ohm} \)

\[ V_o = \sqrt{2} \ V_{in} \]

The above analysis shows that a \( 0^\circ \) power combiner can be used as an "adder" to cancel the DM signal, and a \( 180^\circ \) power combiner can be used as a "subracter" to cancel the CM signal.

Because of parasitic effect and permeability reduction, conventional transformers cannot be used at high frequency range. A well-designed high frequency transformer will also alter its characteristics over 10 MHz. In order to work in a very wide frequency range, a power combiner is made of short transmission lines wound in a core that has a linear B-H curve, high permeability and low loss. At low frequency range, coupling is realized mainly by the magnetic field, as in ordinary transformers, whereas transmission coupling will gradually become dominant with the permeability of the core decreasing at high frequency range. A proper design of the length of transmission line and permeability of the core will guarantee that the transformer offers a flat response curve over a desired frequency range. A detailed discussion of the design criteria can be found in reference [4].

Figure 3.3 is a simplified \( 0^\circ \) power combiner circuit. \( T_1 \) is a center-tapped auto-transformer, which is used for combining input signals from A and B. \( T_2 \) is designed for impedance matching. If the input signals have the same phase and same amplitude, \( V_i \), the
Figure 3.3  A 0° Power Combiner Circuit
output of $T_1$ is $V_i$. Then, the output of $T_2$ is $\sqrt{2}V_i$. If the two input signals are the same amplitude but out of phase, the output of $T_1$ is zero. Thus, no output from $T_2$.

The isolation between the port A and B is another feature of the power combiner, which means that when one channel failed and shorted, the other one should not be disturbed. Figure 3.4 is used to explain the principle. $R_{\text{int}}$ is designed to provide isolation between the port A and B. An input current, $I_{\text{in}}$, is divided into $I_r$ and $I_t$. The same amount of the $I_r$ will induced at the other end of the $T_1$. If $I_r$ is equal to $I_t$, the voltage at the B port, $V_B$, will be zero. Assuming $V_B = 0$, it can be seen from the equivalent circuit in Figure 3.4 that when $R_{\text{int}} = 4R_O = 100$ ohm, $I_r = I_t$. In this situation, the isolation between the port A and B is realized.

According to the description of the standard measurement given in Section 2, 50 ohm impedance should be presented to both from the Line and Neutral. When a power combiner is used with the LISN as indicated in Figure 3.1 and 3.2, the input impedance of the power combiner should be 50 ohm for both input terminals. Otherwise, measurement error will be introduced. Let's examine if the circuit meets the requirement. A load impedance, 50 ohm, is transformed into 25 ohm by $T_2$. Then, $T_1$ boost the impedance to 50 ohm to the each port. This statement is not intuitively clear. Figure 3.5 is used to illustrate it. When two signals with the same amplitude and phase are applied to port A and B respectively, the voltage across the $T_1$ is zero. As a result, it can be treated as a short circuit. Therefore, for each port:

Input impedance: \[ R_i = V_i/I_i = V_o/(I_o/2) = 2R_o = 50 \text{ ohm} \]

Figure 3.6 is a simplified 180° power combiner diagram. The DM signal is picked up across an autotransformer, $T_1$, and sent to a load. The CM signal is prevented from going to the load by a CM choke, $T_3$. The discussion about the isolation and input
Figure 3.4 Illustration of Isolation of the $\theta^\circ$ Power Combiner
Figure 3.5 Illustration of the Input Impedance of the 0° Power Combiner
Figure 3.6 A 180° Power Combiner Circuit
impedance of the 180° power combiner is similar to 0° power combiner's, which will not be repeated here. More detail description about power combiner is given in Reference [3].

In order to have significant cancellation of the CM and DM signals, the accuracy of combining must be maintained over a larger frequency range. Phase unbalance and amplitude unbalance between the two inputs are the major factors affecting the accuracy. The power combiners chosen are a 2-input, 0°, 50-ohm power combiner (ZFSC-2-6-75) and a 2-input, 180°, 50-ohm power combiner (ZFSCJ-2-i), manufactured by Mini-Circuits [5]. The maximum amplitude unbalance for both combiners is less than 0.3 dB, and the maximum phase unbalance is less than 4 degrees over the frequency of 10 KHz to 30 MHz. Since the phase unbalance is very critical to the measurement accuracy, a couple of tests have been done to verify the specification. Figure 3.7 shows the test circuit. A HP4194A Impedance/Gain-Phase Analyzer is used for the tests. Figures 3.8 and 3.9 exhibit the test results of phase unbalance for 0° and 180° power combiner respectively. The tests show that real phase unbalance for either of the combiners is less than 1 degree. Later experiments show that the power combiners satisfy the cancellation requirement. Their main specifications are listed in Table 3.1.

3.1.2 Impedance Matching

In using a Noise Separator to measure the DM or CM noise, the Noise Separator must be inserted. To avoid disturbing the EMI measurement, the Noise Separator must provide proper 50-ohm input impedance. According to the analysis in previous section, the combiner can provide proper input impedance, 50 ohm. To verify this, the input impedance of the power combiners used has been tested. Figure 3.10 shows the test diagram and Figures 3.11 shows the input impedance of the 0° power combiner, and
<table>
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<tr>
<th>MODEL NO.</th>
<th>FREQUENCY RANGE (MHz)</th>
<th>INSERTION LOSS (dB (max.))</th>
<th>PHASE UNBALANCE (Degree (max.))</th>
<th>AMPLITUDE UNBALANCE (dB (max.))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° Combiner</td>
<td>0.004-60</td>
<td>1.0</td>
<td>3.0</td>
<td>0.3</td>
</tr>
<tr>
<td>ZFSC-2-6-75</td>
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</tr>
<tr>
<td>180° Combiner</td>
<td>1-500</td>
<td>1.5</td>
<td>4.0</td>
<td>0.2</td>
</tr>
<tr>
<td>ZFSCJ-2-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1 Specifications of the Two Commercial Combiners

Used in the Experiment (Mini-Circuits Co.)
Figure 3.7 Test Diagram of Phase Unbalance
Figure 3.8 Phase Unbalance of a $0^\circ$ Power Combiner
Figure 3.9 Phase Unbalance of an 180° Power Combiner
Figure 3.10 Test Diagram of the Input Impedance of the Power Combiner
Figure 3.11 Input Impedance of a 0° Power Combiner
Figure 3.12 shows the input impedance of the 180° power combiner. Indeed, 50-ohm input impedance is kept over the frequency range of interest for both 0° and 180° power combiners.

There are two kinds of LISN, double-line and single-line. The double-line LISN combines the Line and Neutral line together in one box. There is a two-throw switch in the LISN which is used to measure the EMI noise of either the Line or the Neutral side. When the switch set in the Line side, a 50 ohm resistor will be connected to the Neutral side, and vice versa. In order to use the Noise Separator, the two-throw switch should be replaced by a three-throw-switch which has a position with both the Line and Neutral side open, i.e., no internal resistor connected. Figure 3.13 shows the measurement setup using the modified double-line LISN. Compared with the standard setup shown in Figure 2.1, the internal resistor has been removed. The single-line LISN only is used for one line. Two LISNs are needed for the Line and the Neutral line. There is no internal resistor in this kind of LISN. When the Noise Separator is used, each input of the Noise Separator is connected to each LISN directly. Figure 3.14 shows the measurement setup. In order to measure the total noise, the spectrum analyzer is connected to one LISN. And the other LISN is terminated by an external 50-ohm terminator.

### 3.2 Construction of the Noise Separator

A Noise Separator has been constructed using the power combiners according to the basic principles described in the previous sections. The noise separator is built by connecting a DMR (0° power combiner) and a CMR (180° power combiner) with two switches, and installed in a shielded box. Inside connection uses thin coax cables. The connection diagram is shown in Figure 3.15, and the photograph of the Noise Separator in
Figure 3.12 Input Impedance an 180° Power Combiner
Figure 3.13 Measurement Setup Using Double-Line LISN
Figure 3.14 Measurement Setup Using Single-Line LISN
Figure 3.15 Diagram of the Noise Separator
Figure 3.16. The size of the Noise Separator is 6"(W) X 1.6"(H) X 2.8"(D). It has to be noted that the wiring of the construction of the Noise Separator hardware should be kept as balanced as possible to maintain high performance. In other words, wiring symmetry between the two input signals to either CMR or DMR should be maintained as much as possible. It was observed that unbalanced wiring contributes to a large error. This will be discussed in Section 4.1.1.
Figure 3.16 Photo of the Noise Separator
Chapter IV
Performance Test of a Noise Separator

Since the Noise Separator is based on the principle of rejection of unwanted noise from the mixture noise, the rejection characteristics of the Noise Separator must be investigated. In this chapter, the rejection characteristics of the Noise Separator are tested. Two methods are used. One uses a phase-gain network analyzer to measure the attenuation characteristic of the Noise Separator, and the other uses a pulse signal to examine the attenuation of the signal due to the Noise Separator. The results obtained from the two methods should agree with each other.

4.1 Measurement Using Phase-Gain Network Analyzer

A phase-gain network analyzer is used in the test. A CM (or DM) signal $V_i$ is injected at the input of the Noise Separator and its output $V_o$ is measured. The ratio $V_o/V_i$ represents the rejection of the CM (or DM) noise by the Noise Separator.

4.1.1 Test setup and results

The test setup for measuring the rejection of a CMR to the CM signal is shown in Figure 4.1. A HP4194A Impedance/Gain-Phase Analyzer is used for the test. The signal provided by the analyzer sweeps from 10 KHz to 30 MHz. This signal is applied to both inputs of the CMR. The output of the CMR is fed back to the analyzer. The rejection
Figure 4.1 Measurement of CM Rejection for the Common-Mode Rejecter
ratio, $V_o/V_i$, is automatically calculated and displayed in the analyzer. Figure 4.2 shows the test results of a CMR rejection. As shown in Figure 4.2, the curves A and B represent the signals to Reference channel ($V_i$) and Test channel ($V_o$). The difference between the two curves is the rejection or the attenuation. It can be seen from Figure 4.2 that at least 50 dB rejection is attained for the frequency ranging from 10 KHz to 30 MHz. Figure 4.3 shows test setup of measuring the rejection of the DMR to a DM signal. Notice that the DM signal to DMR is obtained by using a $180^\circ$ power splitter that splits the signal provided by the phase-gain analyzer. Figure 4.4 shows the test results. Similar rejection capability is obtained for the DMR. It is noted that the test has been conducted to make sure that the $180^\circ$ power splitter does not introduce any significant error into the measurement.

The noise separator should reject one mode of noise, and let the other mode of noise through intact. Using the setups of Figures 4.1 and 4.3, insertion loss of the DMR to the CM signal and the CMR to the DM signal are shown in Figures 4.5 and 4.6 respectively. As discussed in Section 3.1.1, due to the combining effect, output voltage should be 3 dB higher than input voltage in a combiner. Figure 4.5 does show that the output is higher than the input. With the increase of frequency, the combining effect is lessened by the insertion loss of the combiner. In Figure 4.6, Combining gain of the CMR is canceled by the power splitter used to generate a DM signal. Therefore, only insertion losses are shown. It can be seen that the insertion losses are negligible.

It is mentioned in Section 3.2 that the symmetry of wiring is critical to the Noise Separator's performance. An experiment was conducted to verify the point. Two cables with different lengths were used to demonstrate the effect. When two cables of unequal lengths (one is 20 inches, the other 40 inches) are used as the input cables to the CMR and
Figure 4.2 CM Rejection of the Common-Mode Rejecter
Figure 4.3 Measurement of DM Rejection for the Differential-Mode Rejecter
Figure 4.4 DM Rejection of the Differential-Mode Rejecter
Figure 4.5 The Insertion Loss of the DMR to the CM Signal
Figure 4.6 The Insertion Loss of the CMR to the DM Signal
tested, the CM rejection is degraded severely, as shown in Figure 4.7. Compared with the result shown in Figure 4.2, the attenuation is reduced from 50 dB to 15 dB at 30 MHz.

4.2 Measurement Using a Signal Generator

Another method, a pulse generator and a spectrum analyzer were used to verify the rejection characteristics of the Noise Separator. It is discussed in this section.

4.2.1 Test setup and results

The test circuit diagrams for CMR and DMR are shown in Figures 4.8 and 4.9. A TEKTRONIX Function Generator, Model FG 510A, is used to produce a 2 MHz square-wave signal. The spectrum of the signal is shown in Figure 4.10. Its harmonics cover a very wide frequency range. Since the square-wave signal is not exact 50% duty cycle, small even harmonics are also shown in Figure 10, which were found unstable. Setting the output of the generator at the maximum, the square wave signal originally exhibits about 50-dB amplitude range. The HP8568B Spectrum Analyzer is chosen for the measurements. The working frequency of the equipment extends from 100 Hz to 1.5 GHz. All "Function Selection" on the front panel of the spectrum analyzer, including Resolution Bandwidth, Video Bandwidth, Sweep Time, Input Attenuation, and Center Frequency Step Size, are set in the "coupled mode" that is designed to maintain absolute amplitude and frequency calibration of the signal displayed [6]. Similar to test setups of the previous test, a CM signal is generated by connecting the two inputs of CMR or DMR to the signal source in parallel, whereas a DM signal is generated by the 180° power splitter. Figure 4.11 shows the output spectrum of CMR to CM input. It can be seen that
Figure 4.7 CMR Performance When Two Unbalanced Cables Are Used
Figure 4.8 CM Rejection Test Diagram Using a Signal Generator
Figure 4.9 DM Rejection Test Diagram Using a Signal Generator
Figure 4.10 Spectrum of the 2 MHz Square Wave Signal
Figure 4.11 Output Spectrum of the CMR To CM Signal
the CM signal is attenuated. Figure 4.12 shows the output of the CMR when a DM signal
is applied. It can be seen that the DM signal is essentially untouched by the CMR.
Figures 4.13 and 4.14 show the output spectrum of a DMR to a DM and a CM inputs,
respectively. Compared with the original signal shown in Figure 4.10, Figure 4.11 shows
that the rejection of the CMR (to the CM signal) reaches about 50 dB. Similar results are
obtained for the rejection of the DMR (to the DM signal) shown in Figure 4.14. Figure
4.12 show that the DM signal passes through the CMR with no noticeable change. Figure
4.14 shows that the CM signal passes through the DMR with no noticeable change. All
results in this experiment agree well with the tests discussed in Section 4.1.
Figure 4.12 Output Spectrum of the CMR To DM Signal
Figure 4.13 Output Spectrum of the DMR to DM Signal
Figure 4.14  Output spectrum of the DMR to CM Signal
Chapter V
Use of a Noise Separator in Power Supply
EMI measurement

A number of conducted EMI tests were performed on a commercial power supply using the Noise Separator described in previous chapters. The results will be presented in this chapter. In all of tests, the total noise as well as the two modes (both DM and CM) of noise are measured. The results allow the designers to see the working of each filter component and provide a guidance of filter design. Since the discussion is related to EMI filter, a brief review of a typical EMI filter is given.

5.1 Introduction of EMI Filter

An EMI input filter basically is a low pass filter. It prevents conducted high frequency noise from going through both ways and allows the low frequency AC power flowing with the least insertion loss. A typical EMI filter diagram is shown in Figure 5.1, where $L_1$ is a common-mode choke, $L_2$ is a differential-mode choke, $C_{x1}$ and $C_{x2}$ are DM capacitors as sometimes called "X" capacitors, $C_y$ is a common-mode capacitor or sometimes called "Y" capacitor. The common-mode choke $L_1$ has two identical windings wound on the same core. Ideally, a CM choke has no effect on DM noise due to canceling effect of the two identical windings. However, its leakage inductance due to unperfected coupling provides filtering effect to the DM noise. Usually the leakage inductance is about 0.5% to 2% of common-mode inductance.
L1: Common core inductor

L2: Independent inductors

Figure 5.1 A Basic EMI Filter Diagram
It is noted that not every component in the filter has an effect on the DM noise. Same statement can be made for the CM noise. Figure 5.2 shows the filter equivalent circuit for the CM noise and Figure 5.3 for the DM noise. It can be seen from Figure 5.2 that the two "X" capacitor disappears, and the CM noise sees two "Y" capacitors in parallel (resulting in $2 \text{ } C_y$) and two $L_2$s in parallel (resulting in $L_2/2$). In Figure 5.3, the common-mode choke $L_1$ disappears, but the leakage of $L_1$ provides DM filtering, and the two "Y" capacitors are connected in series across the Line and Neutral (resulting in $C_y/2$).

### 5.2 Description of Test sample

A switched-mode power supply made by LAMBDA is chosen as a test sample. The specifications are listed as follows:

- **Model:** LLS9300
- **Output voltage:** 0 - 300 VDC
- **Output current:** 2.8 A
- **Input voltage:** 85 - 132 VAC
- **Maximum input power:** 1100 WATTS
- **Switching Frequency:** 110 KHz
- **Passed FCC Class "A" specification**

Because the input filter in the power supply is built by individual elements rather than a sealed module filter, component evaluation and change in the process of testing become relatively easy. As shown in Figure 5.4, LLS9300 power supply adopts a very typical input filter configuration except there is no physical DM inductors. The leakage inductance of CM choke $L_1$ plays the role instead. The CM and DM equivalent circuits are shown in Figure 5.5 and 5.6 respectively.
Figure 5.2 CM Equivalent Circuit of the Circuit Shown in Figure 5.1
Figure 5.3  DM Equivalent Circuit of the Circuit Shown in Figure 5.1
Figure 5.4 Input Filter Diagram in the Tested Power Supply

L1: 3.7 mH, Leakage inductance: 20 uH
Figure 5.5 The Equivalent Circuit for CM Noise
Figure 5.6 The Equivalent Circuit for DM Noise
5.3 Description of Test setup

Figure 5.7 shows the test setup diagram. The LISN has been modified as discussed in Section 3.1.2. Using the switch on the Noise Separator, both the CM and the DM conducted EMI noise spectra can be obtained respectively. To measure total noise, the Noise separator should be bypassed. Then the spectrum analyzer should be connected directly to the LISN. It is noted that when the Neutral side EMI is measured, the Line side should be grounded by a 50-ohm resistor, and vice versa. Due to the combining effect, the test results are always 3 dB over true value as described in Section 3.1.1. This error should be taken into account in final analysis. In order to separate the two modes of noise effectively, the lengths of cables connecting the Noise Separator and the LISN should be the same, and all the connection cables should be coaxial cables.

According to FCC EMI test specification, the display mode of spectrum analyzer should be set in quasi-peak mode. The spectrum analyzer (Model 8568B) used in the measurements has no such selection but peak detector mode. However, the error between the two detection modes is about 2 dB maximum that is insignificant in normal tests [7]. Also, the peak detector mode gives the higher value that represents worse case.

5.4 Test Results

A sequence of ten tests was conducted. It begins with a test without using any EMI filter and then a filter component is added at one time to see the effect of such addition on the DM, the CM, and the total noise. Test frequency range covers from 450 KHz to 30 MHz (FCC). Due to the restriction of the spectrum analyzer used, resolution bandwidth (RBW) is set in 10 KHz instead of specified 9 KHz.
Figure 5.7 Test Setup
5.4.1 Test # 1 (Figure 5.8)

In this test, no filter is used. Therefore, test results show the maximum noise levels. FCC Class "A" limit is indicated in Figure 5.8(b) as a reference. Ambient noise level also is indicated which shows about 25 dBuV. It can be seen that without EMI filter, this power supply can not pass the FCC limit. It can also be seen that except at low frequency end, CM noise dominates.

5.4.2 Test # 2 (Figure 5.9)

In this test, a common-mode choke of 3.7 mH is used. Figure 5.9 shows the test results. It was mentioned in Section 5.1 that a common-mode choke should ideally provide no filtering effect on the DM noise. However, leakage inductance of the CM choke (20 uH in this case) becomes the DM choke and should provides some attenuation on the DM noise. Figure 5.9(c) shows such effect. The dotted curve indicates the envelope of the DM noise of Test #1. The attenuation on the CM noise is evident as shown in Figure 5.9(d). Notice that the total noise is dominated by the CM noise except around 450 KHz.

5.4.3 Test # 3 (Figure 5.10)

In this test, one DM capacitor $C_{X1}$ (X-capacitor), 0.15 uF, is added. As expected, the DM noise is attenuated but the CM noise is unchanged. As compared to previous test, it can be clearly seen that the total noise level is about the same as the CM noise level. After insertion of the capacitor $C_{X1}$, the DM noise is well below the CM noise for the
entire frequency range. It can be predicted that increasing the $C_{x1}$ value or adding DM filter components at this point will not improve the total noise reduction. The Noise Separator allows the designers to see the next step to further reduce the total noise level.

5.4.4 Test # 4 (Figure 5.11)

Adding $C_{x2}$, a 0.47 uF X-capacitor in the left side of the $L_1$ significantly attenuates the DM signal but leaves the CM noise unchanged. Figure 5.11 shows the filter circuit and test results. Since the CM dominates, the total noise level is also unchanged. This result confirms the statement made in Test #3, i.e., adding DM filter components at this stage will not improve the total noise level.

5.4.5 Test # 5 (Figure 5.12)

Test has shown that the total noise level does not go down even though DM noise level has been greatly suppressed. To reduce the total noise, the CM noise needs to be attenuated further. One way to do it is to add two "Y" capacitors. In this test two CM capacitors (Y-capacitor), 0.01 uF, are used as shown in Figure 5.12(a). The addition of the Y-capacitors effectively decreases the CM noise and the Total noise accordingly. The solid line in Figure 5.12(b) represents the spectrum requirement for FCC Class "A". It surely passes the specification with great margin. It is noted that normally, a Y-capacitor is limited to 3300 pF because of leakage current limit imposed by safety rules. In this test, larger Y-capacitors are used to show the effect of Y capacitors.

5.4.6 Test # 6 (Figure 5.13)
In this filter configuration, DM filtering is provided by the leakage inductance of $L_1$ and the combined 0.005 uF capacitance. CM filtering is relatively effective due to $L_1$ and Y-capacitors. It can be seen that the DM noise dominates the total noise. Therefore, without using DM filtering components in the filter, the total noise can not be reduced further.

5.4.7 Test # 7 (Figure 5.14)

Addition of a 0.47 uF X-capacitor to the previous filter greatly reduces the DM noise. Now that the DM noise is greatly reduced, the total noise in this case is dominated by the CM noise.

5.4.8 Test # 8 (Figure 5.15)

Compared with Test #3, the only difference is that the 0.15 uF X-capacitor is on the line side instead of the power supply side. As can be seen, the difference on the DM noise attenuation is very pronounced. However, since CM noise dominates in this case, the total noise shows no difference. Without the use of the Noise Separator, one would have made the wrong statement that the location of the X-capacitor makes no difference. But in situation where DM noise dominates, then it would have made difference.

5.4.9 Test # 9 (Figure 5.16)

Compared to Test #7, the X-capacitor is reduced from 0.47 uF to 0.15 uF. Since the total noise is dominated by the CM noise except at 450 KHz, the decrease of the X-
capacitor makes little difference in the total noise except at 450 KHz. In fact, by looking at the results obtained in Test #7, one can predict that using a smaller X-capacitor will not make much difference in total noise.

5.4.10 Test # 10 (Figure 5.17)

Compared with Test #9, the only difference is that the 0.15 uF X-capacitor is on the Line side instead of the power supply side. Unlike the results shown in Test #7 and #8, in which the location of the X-capacitor makes no difference in the total noise, the total noise in this case is indeed grossly affected by the change of the X-capacitor location. This is because DM dominates the noise and X-capacitor affects the DM noise. Therefore, without looking at the DM and CM separately, one would have made the statement that the location of X-capacitor makes no difference in total noise in one situation and made opposite statement in another situation.
Test #1:

There is no input filter. The total, DM and CM noise are presented.

![Figure 5.8(a) Test 1 Diagram](image)

![Figure 5.8(b) Total Noise](image)

![Figure 5.8(c) DM Noise](image)

![Figure 5.8(d) CM Noise](image)
Test # 2:

CM noise is not suppressed significantly by the CM choke L1. The leakage inductance of L1 provides some attenuation to the DM noise.

L1: 3.7mH, Leakage inductance: 20uH

Figure 5.9(a) Test 2 Diagram

Figure 5.9(b) Total Noise

Figure 5.9(c) DM Noise

Figure 5.9(d) CM Noise
Test # 3:

Compared with previous test results, the DM noise is attenuated by the X capacitor (0.15u). CM noise remains the same.

Figure 5.10(a) Test 3 Diagram  

Figure 5.10(b) Total Noise  

Figure 5.10(c) DM Noise  

Figure 5.10(d) CM Noise
Test # 4:

Compared with previous test results, adding one more X-capacitor (0.47u), the DM noise is reduced significantly. The CM noise has no change and the total noise is not changed.

![Test 4 Diagram](image1)

**Figure 5.11(a) Test 4 Diagram**

![Total Noise](image2)

**Figure 5.11(b) Total Noise**

![DM Noise](image3)

**Figure 5.11(c) DM Noise**

![CM Noise](image4)

**Figure 5.11(d) CM Noise**
Test #5:

Compared with previous test results, the CM noise has been attenuated effectively by $L_1$ and $Y$ capacitors (0.01u). The DM noise is also suppressed by the $X$ capacitors.

**Figure 5.12(a) Test 5 Diagram**

**Figure 5.12(b) Total Noise**

**Figure 5.12(c) DM Noise**

**Figure 5.12(d) CM Noise**
Test #6:

CM noise is effectively attenuated. DM noise dominates the total noise.

Figure 5.13(a) Test 6 Diagram

Figure 5.13(b) Total Noise

Figure 5.13(c) DM Noise

Figure 5.13(d) CM Noise
Test # 7:

Compared with previous test results, the total noise is down when the CM and DM noise are attenuated effectively at the same time.

Figure 5.14(a) Test 7 Diagram

Figure 5.14(b) Total Noise

Figure 5.14(c) DM Noise

Figure 5.14(d) CM Noise
Test # 8:

Compared with Test #3, the X capacitor (.15u) gives better attenuation to DM noise at the left of L1 than the right of L1.

Figure 5.15(a) Test 8 Diagram

L1: 3.7mH, Leakage inductance: 20uH

Figure 5.15(b) Total Noise

Figure 5.15(c) DM Noise

Figure 5.15(d) CM Noise
Test #9:

Reducing the X-capacitor value in Test #7 makes little difference in the total noise.

Figure 5.16(a) Test 9 Diagram

Figure 5.16(b) Total Noise

Figure 5.16(c) DM Noise

Figure 5.16(d) CM Noise
Test # 10:

By moving the 0.15 uF X-capacitor from the Line side to the power supply side makes big difference in the total noise.

Figure 5.17(a) Test 10 Diagram

Figure 5.17(b) Total Noise

Figure 5.17(c) DM Noise

Figure 5.17(d) CM Noise
Chapter VI
Conclusions and Future Research

Several conclusions were drawn from the research effort leading to this thesis. Those will be described in this chapter. Future research directions are also recommended.

6.1 Conclusions

1. A practical Noise Separator has been developed. It can be used to decipher both the DM and the CM noise from a total combined conducted EMI noise. The device consists of only passive elements and is relatively inexpensive to build.

2. The noise separation of the device is achieved by using the principle of rejection of the unwanted mode of noise from the combined noise. Measurement of the Noise Separator built has shown that at least 50 dB rejection is achieved for the frequency ranging from 10 KHz to 30 MHz.

3. In a conventional conducted EMI measurement, the line impedance stabilization network (LISN) provides proper impedance termination. In using the Noise Separator for measurement, same impedance termination should be provided to avoid disturbing the measurement. This can be achieved by either using two separate LISNs for the Line and the Neutral, or by modifying the existing LISN. The details of the change have been documented in the thesis.
4. The Noise Separator has been used to investigate the conducted EMI of a switching power supply. The results demonstrate its usefulness as a diagnostic tool for EMI filter problems. It provides insight into the inner working of each filter component and removes some mystery about EMI filter design.

6.2 Future Research

Several areas of research are recommended for extending the work described in this thesis:

1. The Noise Separator described in this thesis is for a single-phase system. It should be explored to extend the concept to a three-phase system.

2. In the Chapter V of this thesis, a number of tests were conducted to demonstrate the usefulness of the Noise Separator. It is recommended that effort along this line should continue to take full advantage of the Noise Separator capability.

3. Resonance between filter components and noise source impedance can degrade EMI performance of a power supply [8]. It is often suspected but not easy to confirm whether a resonance observed in the spectrum is indeed caused by such a phenomenon. By using the Noise Separator, one should be able to observe the resonance peaking in a DM spectrum but not in a CM spectrum. Working along this line can be pursued. If this phenomenon can be confirmed by using the Noise Separator, then the results can lead to proper measures to correct it and save the cut-and trial effort.
References


APPENDIX
User's Guide

USER'S GUIDE

A Noise Separator is a diagnostic tool for solving conducted EMI noise problem. It can be used to separate both the differential-mode (DM) and the common-mode (CM) noise from a combined total noise. With both the DM and CN information available, EMI filter design can be made easier.

In order to use the Noise Separator, slight modification to the conventional EMI measurement setup is necessary. Figure 1 and 2 show two setup diagrams. In both setups, the Noise Separator is inserted in between the LISN and the Spectrum Analyzer. However, in Figure 1, a modified double-line LISN is used. In a conventional double-line LISN, there is a two-throw switch which can be selected to measure either the Line side or the Neutral side of EMI. When the switch is set to the Line side, a 50 ohm resistor will automatically be connected to the Neutral side, and vice versa. A modified LISN is not available commercially. It can be achieved by replacing the two-throw switch in a conventional LISN by a three-throw switch, which adds a position with both Line and Neutral open, i.e., no internal resistor connected. In Figure 2, two single-line LISNs are used. This type of LISN contains no internal resistor and is available commercially.

Measurement

For Double-line LISN setup:

1. Total noise: Set the switch in LISN at LINE or Neutral position. Connect respective port LINE or Neutral in LISN to a spectrum analyzer. The Noise Separator is not used.
2. CM noise: Connect the Noise Separator's input to LISN and output to the spectrum analyzer. Set the switch in the LISN at OPEN, and the switches in the Noise Separator at "CM".
3. DM noise: Same as CM noise test except setting the switches in the Noise Separator at "DM".

For the single-line LISN setup:

Fig. 1 Double-line LISN Setup

1. Total noise: Connect the LISN either Line or Neutral to the spectrum analyzer. When measuring the Line side EMI, the Neutral side must be terminated by a 50-ohm terminator. The Noise Separator is not used.
2. CM noise: Connect the inputs of the Noise Separator to the two LISNs. Set the switches in the Noise Separator at "CM".
3. DM noise: Same as CM noise test except setting the switches in the Noise Separator at "DM".
VITA

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