Trade-off between EMI Separator and RF Current Probe for Conducted EMI Testing

D. Sakulhirirak\textsuperscript{1}, V. Tarateeraseth\textsuperscript{2}, W. Khan-ngern\textsuperscript{1}, and N. Yoothanom\textsuperscript{3}

\textsuperscript{1}Research Center for Communications and Information Technology (ReCCIT), Faculty of Engineering, King Mongkut’s Institute of Technology Ladkrabang (KMITL), Bangkok, Thailand.
\textsuperscript{2}Srinakharinwirot University, Faculty of Engineering, Ongkharak, Thailand.
\textsuperscript{3}Sripatum University, Faculty of Engineering, Bangkok, Thailand.
E-mail: s8060210@kmitl.ac.th\textsuperscript{1}, vuttipon@swu.ac.th\textsuperscript{2}, kkveerac@kmitl.ac.th\textsuperscript{1}, nyt@spu.ac.th\textsuperscript{3}

Abstract—This paper presents the trade-off between EMI separator and the RF current probe for conducted EMI measurement. EMI toolkit is used as a noise source for investigating effects from differential-mode (DM) and common-mode (CM). Paul-Hardin noise separation network or EMI separator is used as a benchmark to compare with the RF current probe. The conducted electromagnetic interference between RF current probe and EMI separator is compared by the experiment. Finally, the trade-off between two measurement methods is verified by both theoretical and experimental results.

I. INTRODUCTION

Electromagnetic Compatibility (EMC) is an electronic system which is able to function compatibly with other electronic systems and not produce or be susceptible to interference with its environment [1]. The interference can be divided widely into two groups: conducted and radiated interferences. In this paper, the conducted emission is emphasized and mentioned to separate noise components (Differential-Mode: DM and Common-Mode: CM) for electromagnetic environment. It is very useful to know noise components in every interested circuit [2]. Generally, there are two methods, often used for separating noise components. The first method is a classical measurement using radio frequency current probe (RF current probe). The second method is measurement CM and DM by using separating devices such as CM/DM discrimination network [3], Paul-Hardin noise separation network [4] and noise separator [5] etc. However, all separation networks in this paper are called as the EMI separator.

The Equipment Under Test (EUT) in this paper is EMI toolkit, used for conducted EMI studying in terms of theory and practice. Fig. 1 shows outside of EMI toolkit. Boost converter is a main part which generates EMI. In addition, a lot of study functions are combined in the toolkit and it can be selected functional operation such as self-resonant frequency (SRF) of the passive components, reverse recovery time of diodes, switching frequencies, and gate drive control [6].

To understand noise behaviors in a boost converter, Fig. 1 can be rewritten to Fig. 2 which includes Line Impedance Stabilization Network (LISN) schematic and two 50 Ohm terminators. These terminators are connected to the RF output ports of LISN when measuring by RF current probe but when using Paul-Hardin network these terminators are input impedance of the network. \(V_P\) and \(V_N\) stand for phase and neutral voltage signal, respectively. \(C_S\) is a parasitic capacitance caused by MOSFET (\(Q\)) between drain and frame ground via its heat-sink.

Figure 1. Top view of EMI toolkit configuration.

Figure 2. Schematic of LISN and boost converter under consideration.

II. CONDUCTED EMI MEASUREMENTS: RF CURRENT PROBE AND EMI SEPARATOR CONCEPTS

Conducted EMI emission is measured using a LISN as a 50 Ohm impedance. The DM noise current \(I_{DM}\) flows out from line and returns via neutral while the CM noise current \(I_{CM}\) flows out from line and neutral and returns via ground wire as shown in Fig. 3 Eqns. (1)-(3) are line, neutral and ground current and Eqns. (4)-(5) are line and neutral voltages, respectively [7].
Figure 3. DM and CM currents from LISN.

\[ I_{\text{Line}} = I_{\text{CM}} + I_{\text{DM}} \]  \hspace{1cm} (1)

\[ I_{\text{Neutral}} = I_{\text{CM}} - I_{\text{DM}} \]  \hspace{1cm} (2)

\[ I_{\text{Ground}} = 2 \cdot I_{\text{CM}} \]  \hspace{1cm} (3)

\[ V_{\text{Line}} = 50 \cdot (I_{\text{CM}} + I_{\text{DM}}) \]  \hspace{1cm} (4)

\[ V_{\text{Neutral}} = 50 \cdot (I_{\text{CM}} - I_{\text{DM}}) \]  \hspace{1cm} (5)

A. RF Current Probe

RF current probe is a clamp-on RF current transformer designed for use with EMI Test Receivers/Spectrum Analyzers, or with any similar instrument having a 50 \( \Omega \) input impedance, to determine the intensity of RF current present in an electrical conductor or group of conductors [7]. Fig. 4 shows the RF current probe within bandwidth 10 kHz - 250 MHz. The maximum primary current from DC - 400 Hz is up to 100 A and the transfer impedance \( (Z) \) is 5 \( \Omega \) [8]. The performance of the RF current probe may be expressed in terms of sensor transfer impedance: Eqn. (6). Where \( V_{\text{out}} \) is the voltage developed across a 50 \( \Omega \) termination on the output and \( I_{\text{cond}} \) is the current flowing through the conductor being measured. The probe transfer impedance is often expressed in terms of dB which can be calculated the measured current from Eqn. (7) [9].

\[ Z_T = \frac{V_{\text{out}}}{I_{\text{cond}}} \]  \hspace{1cm} (6)

\[ I_{\text{cond}} (\text{dB} \mu A) = V_{\text{out}} (\text{dB} \mu V) - Z (\text{dB}) \]  \hspace{1cm} (7)

B. EMI separator

Many papers have been discussed and proposed EMI separators [3-5], [10-11]. They can be separated roughly in two groups based on magnitude of output signal, single and double output noise. Moreover, in group of double output [4] has no guarantee that it can be used representative of RF current probe.

Fig. 5 shows the Paul-Hardin noise separation network schematic. There are two important elements; two wideband transformers (1:1 ratio) and single-pole-double-throw (SPDT) switch, which operate simultaneously [7].

The line-ground voltage \( (V_{\text{LG}}) \) and neutral-ground voltage \( (V_{\text{NG}}) \) are connected to EMI separator, using Eqns. (8) and (9) for voltage across switch at A and B position respectively.

\[ |V_{\text{LG}} - V_{\text{NG}}| = |V_{\text{CM}} + V_{\text{DM}}| - |V_{\text{CM}} - V_{\text{DM}}| = |2V_{\text{DM}}| \]  \hspace{1cm} (8)

\[ |V_{\text{LG}} + V_{\text{NG}}| = |V_{\text{CM}} + V_{\text{DM}}| + |V_{\text{CM}} - V_{\text{DM}}| = |2V_{\text{CM}}| \]  \hspace{1cm} (9)

\[ |2V_{\text{DM}}| = |V_{\text{LG}} - V_{\text{NG}}| = 50 \cdot |2I_{\text{DM}}| \]  \hspace{1cm} (10)

\[ |2V_{\text{CM}}| = |V_{\text{LG}} + V_{\text{NG}}| = 50 \cdot |2I_{\text{CM}}| \]  \hspace{1cm} (11)

The output is \( |V_{\text{LG}} - V_{\text{NG}}| \) for \( 2V_{\text{DM}} \) defined by Eqn. (8) and \( |V_{\text{LG}} + V_{\text{NG}}| \) for \( 2V_{\text{CM}} \) defined by Eqn. (9) and lastly, leakage between the DM and CM at the output should be small because noise measurement between the DM and CM must be guaranteed small interference [5]. The impedance of two inputs are 50 \( \Omega \) within 20 percent tolerance according to CISPR 16-1 standard because both of them have to connected with LISNs. The CM output impedance of network is very closed to 50 \( \Omega \) (in range 45 \( \Omega \) – 50 \( \Omega \) at 150 kHz – 30MHz) but for DM output impedance is nearly 20% tolerance from 50 \( \Omega \) (35 \( \Omega \) – 50 \( \Omega \)) as shown in Fig. 7. The performance of EMI separator can be described in term of rejection attenuation value of both modes; some papers call “CM/DM rejection ratio” [2], [10] as shown in Fig. 8.
III. MEASUREMENT METHODS

A. RF Current Probe Measurement

Figs. 9 (a)-(b) show basically method to measure DM and CM noise, respectively. However, the measured results of DM and CM are double ($2I_{DM}$ and $2I_{CM}$) caused by sum of current vectors in same direction. The current probe is usually clamped between the EUT and the LISN as near as possible. In some EMC standard current probes, such as the DEF STAN 59-41 DCE01, have to away 5 cm from the LISN connection on the power lead [7].

B. EMI separator Measurement

The second method to measure DM and CM noise components are displayed in Fig. 10. LISN-1 couples voltage from line-ground while LISN-2 couples voltage from neutral-ground. Output of separator is connected with 50 Ω525 terminal of spectrum analyzer. In addition, coaxial cables (50 Ω) with BNC connector are connected with two RF output terminals of LISNs for coupling line-ground and neutral-ground signal simultaneously.

IV. EXPERIMENTAL RESULTS

In this section, noise floor between the RF current probe and EMI separator are measured first for using as reference levels. There are three noise floors: RF current probe, CM EMI separation and DM EMI separation which are the same level of noise floors about 25 dB.

Measured results of $2V_{CM}$ and $2V_{DM}$ are divided into three sections by comparison results between RF current probe and EMI separator. Firstly, noise source is measured without filter components this is a full noise condition as shown in Figs. 11-12. Secondly, adding two X-capacitors between line and neutral, 0.47 μF, as shown in Figs. 13-14, which show DM and CM comparing between RF current probe and EMI separator with and without filter components. A dash line prefers to EMI measured result when filter components are added in the circuit. Finally, two Y-capacitors are added across line-ground and neutral-ground, 0.2 μF, as shown in Figs. 15-16.
From Eqn. (6), the transfer impedance of the current probe \( Z_{I} \) is 5 \( \Omega \) and the measured current \( I_{\text{cond}} \) is represented by \( 2I_{\text{DM}} \) or \( 2I_{\text{CM}} \) as follows;

\[
V_{\text{out(CM)}} = (5) \cdot (2I_{\text{CM}}) \quad \text{and} \quad V_{\text{out(DM)}} = (5) \cdot (2I_{\text{DM}}) \quad (12)
\]

Where \( V_{\text{out(CM)}} \) and \( V_{\text{out(DM)}} \) are common mode and differential mode output voltage measured by RF current probe respectively.

Then, multiplication Eqn. (12) by two to compare with Eqns. (10)-(11) and inverting them to dB values using logarithm function.

The compared results show the different value between using RF current probe and EMI separator about 13.98 dB.

The experimental results as shown in Figs. 11-12, can be realized by the theoretical expression as mention. Fig. 13 shows the performance of X capacitor filters. The DM EMI is decreased about 20 dB while the CM EMI has a little changed as shown in Fig. 14 and the difference between RF current probe and EMI separator still about 14 dB. Figs. 15-16 show EMI results which are mitigated by Y capacitors. The performance of \( C_{y} \) can suppress noise about 5 dB for common mode and nearly 0 dB for differential mode.

VI. CONCLUSIONS

The separation of conducted EMI measurement, measured by RF current probe and EMI separator, is compared. The attenuation value between RF current probe and EMI separator is about 14 dB, realized by the theoretical and experimental results. The performance of EMI separator has been realized using the convenient EUT as EMI toolkit. However, it should be noted that the EMI separator, which is low cost, can be used at low-medium power level because the saturation of wideband transformer while the RF current probe can be covered the high level.

REFERENCES

II. EXPERIMENTAL

Ceramic sample of Gd 1:2:3 were prepared by conventional powder processing from high-purity oxides and carbonates, calcining at 930°C, the powder were pressed into pellets with a pressure of 1 ton/cm². The pellets were sintered at 900°C, 920°C, 925°C, 930°C, 935°C, 940°C, 945°C, 950°C, 955°C, 960°C, 965°C and 970°C for 10 hours.

We had experimentally investigated the following effect of external magnetic field on current-voltage characteristics and magnitude of negative resistances. The current-voltage characteristics were measured by the four probe technique with indium electrodes at 77 K. The magnetic field is applied to samples perpendicular with the direction of current flow.

III. EXPERIMENTAL RESULTS

A. The optimum condition of critical current for the occurrence of negative resistance

From Fig. 2 shown the relationship between sintering temperature and critical current (I_c). It’s found that, the highest I_c is 2.2 A at sintering temperature 930°C. At the highest I_c sample must be applied external magnetic field (B_EXT) higher than the low I_c sample, to destroy the superconducting state. However the negative resistance could not be observed at this highest I_c. But negative resistance obviously occurred as I_c is reduced from maximum point.

The maximum magnitude of difference voltage(ΔV) is obtained at I_c = 1.05 A. ΔV will be to zero while I_c is decreased to zero as shown in Fig. 2 and Fig. 3. Thus, it can be seen that the negative resistance phenomena is apparently found in the range of low I_c.

B. The effect of magnetic field on magnitude of negative resistance

The influences of B_EXT on the magnitude of differential voltage (ΔV) are studied. Sample used here show the various values of critical currents which are 1.55A, 1.3A, 1.05A, 0.78A, 0.52A, 0.39A and 0.12A respectively. Current-voltage relations and the dependences of ΔV on B_EXT are shown in Fig.4. It’s found that the magnitude of ΔV depends on B_EXT [4]. For example, for the sample with I_c = 1.05 A, when we applied B_EXT from 0 to 0.2 mT, ΔV was increased. However if applied B_EXT exceeded 0.2 mT, then ΔV was decreased continuously. The maximum ΔV (ΔV_MAX) was obtained at 1.4 mV.

Fig. 5 shows ΔV versus B_EXT relations obtained from sample with various critical current. It is found from Fig. 6 that the sample with I_c = 1.05 A shows the highest value of ΔV_MAX comparing with other I_c samples.
IV. DISCUSSIONS

The experimental results can be explained by the macrostructure model of Gd-Ba-Cu-O. Since the high-\(I_c\) sample exhibits superconducting state more completely than the low-\(I_c\) sample, then the connection of weak point region must be stronger than the low-\(I_c\) sample as shown in Fig. 7.

From Fig. 8, when the applied current (\(I\)) is equal to (or less than) its critical current (\(I_c\)) value, both sides of the sample are connected by the superconduction parts. Then, the resistance of sample does not appear. But when \(I > I_c\), superconduction part will be cut-off, because weak point region is destroyed. The resistance appears in this condition. Because the volume of upper destroyed parts are less than lower destroyed parts, all current will flow over the upper part only. Then, the small voltage drop will appear across the upper part. When the current reaches \(I_N\), the upper superconduction part, where has magnetic substance, is destroyed. Thus, overall cut-off region of the upper part is more than lower part. The resistance of upper part increases quickly. Then all current flows to lower part, which has low resistance. Therefore, the voltage drop across sample decreases immediately. This phenomenon is called Negative-resistance. The magnitude of differential voltage (\(\Delta V\)) is about 0.71 mV.

**Figure 5.** The plot of \(\Delta V\) vs \(B_{EXT}\) at various \(I_c\)

**Figure 6.** The relationship between \(\Delta V_{MAX}\) and \(I_c\)

**Figure 7.** Illustration of a macrostructure model at various \(I_c\)

**Figure 8.** Illustration of current-voltage characteristics of sample with \(I_c = 1.05\) A

a) Sample with \(I_c = 2.2\) A  
b) Sample with \(I_c = 1.55\) A  
c) Sample with \(I_c = 1.05\) A  
d) Sample with \(I_c = 0.52\) A
We will consider the effect of $B_{\text{EXT}}$ on $\Delta V$ as follows. In the case of the sample showing $I_C=1.55\,\text{A}$, $\Delta V$ was increased by $B_{\text{EXT}}$ in the range of $0 \sim 0.23\,\text{mT}$, as shown in Fig. 5. This phenomenon can be explained by considering the macrostructure model as shown in Fig. 9 a). Since the cut-off region which has magnetic substance, was broadened by $B_{\text{EXT}}$, $\Delta V$ increases, that is, current path changes from the upper high resistance path to the lower low resistance path. When the external magnetic flux $B_{\text{EXT}}$ exceeds $0.23\,\text{mT}$, $\Delta V$ was decreased. Since $B_{\text{EXT}}$ also destroys partially the lower superconduction part as shown in Fig. 9 a), the difference of electrical resistance between the upper path and the lower path became small. Then, $\Delta V$ decreases. For sample $I_C = 1.05\,\text{A}$, when $B_{\text{EXT}} = 0.2\,\text{mT}$, the highest $\Delta V$ is obtained. Consequently, the cut-off region, containing magnetic substance, is broadened until magnetic substance is uncovered completely.

In the case of sample showing $I_C = 0.52\,\text{A}$, when $B_{\text{EXT}} = 0.16\,\text{mT}$, $\Delta V_{\text{MAX}}$ is obtained. Due to the cut-off region, which has magnetic substance, is broadened until magnetic substance is uncovered completely. Nevertheless, $B_{\text{EXT}}$ will also destroy partially the lower part similarly as shown in Fig. 9 c). Then, $\Delta V_{\text{MAX}}$ in this case less than the sample with $I_C = 1.05\,\text{A}$ as shown in Fig. 6. 

Some experimental results can be quite explained by the macrostructure model of GdBa$_2$Cu$_3$O$_{7-x}$ superconducting ceramic materials.

**ACKNOWLEDGMENT**

We are indebted to A. Keawcharoen and C. Suriyaamaranont for technical assistance.

**REFERENCES**


