

Practical Papers, Articles and Application Notes

Flavio Canavero, Technical Editor

This issue contains two contributions whose authors are from Asian Countries - a testimony to the growing interest and activity in EMC emerging in that part of the world.

The first paper is entitled "Measurement of EMI Suppression of a Ferrite Core Under Realistic Operating Conditions" by Bo Hu, Kye Yak See, and Weng Yew Chang from Nanyang Technical University (first two authors) and DSO National Lab (last author) in Singapore. In this paper, the authors discuss the suppression performance of ferrite cores on power cords, evaluated by means of a novel measurement method based on the use of two inductive probes. The relevant contribution of this paper is the possibility of common-mode suppression estimation of ferrites, as placed in their actual working position. This represents a great advantage for the designer who can better judge the final impact of different design solutions. The second paper is entitled "Do-it-Yourself Fabrication of an Open TEM Cell for EMC Pre-compliance," by S. M. Satav and V. Agarwal from the Indian Institute of Technology in Bombay. In this paper, the authors illustrate a prototype of an open TEM cell they fabricated and tested in their laboratory. The interest of this realization resides in the low cost and weight of the fabricated cell and makes it appealing for education and for designers wishing to easily, quickly and cheaply test pieces of equipment during their development phase.

In conclusion, I encourage (as always) all readers to actively contribute to this column, either by submitting manuscripts they deem appropriate, or by nominating other authors having something exciting to share with the Community. I will follow all suggestions, and with the help of independent reviewers, I hope to be able to provide a great variety of enjoyable and instructive papers. Please communicate with me, preferably by email at canavero@ieee.org.

Measurement of EMI Suppression of a Ferrite Core Under Realistic Operating Conditions

Bo Hu

Electromagnetic Effects Research Lab, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, E-mail: hubo0001@ntu.edu.sg

Kye Yak See

Electromagnetic Effects Research Lab, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, E-mail: ekysee@ntu.edu.sg

Abstract—Based on a two-probe approach, a novel measurement method is proposed to evaluate the commonmode (CM) suppression performance of any ferrite core on a power cord under the actual operating configuration. The proposed measurement method allows the CM impedance of a ferrite core placed onto a power cord be measured so that true CM radiation suppression performance of the selected ferrite core can be assessed.

Key Words—Ferrite core, common-mode impedance measurement, switched-mode power supplies, line impedance stabilization network.

Weng Yew Chang Guided System Division, DSO National Laboratories, Singapore, E-mail: cwengyew@dso.org.sg

I. INTRODUCTION

Due to mandatory international electromagnetic interference (EMI) regulations, all electrical and electronic products have to comply with specific EMI limits. One of the major sources of radiated EMI is the radiation from common-mode (CM) current flowing on the power cord and interfacing cables of the equipment-under-test (EUT). Ferrite cores have been used extensively to suppression CM current on these attached cables.

Ferrite core manufacturers usually provide EMI suppression performance of ferrite cores under pre-defined source and load terminations. However, the actual source and load impedances where the ferrite core is supposed to be employed are usually not readily available. Some research work has been carried out on the impedance characteristics of a ferrite core and its loading effects on various types of the transmission lines [1], [2]. However, it still cannot quantify the EMI suppression characteristics of a ferrite core in the actual operating configuration. For example, a parallel-line measurement jig consisting of a cylindrical metal rod and a metal ground plane [3] has been proposed to investigate ferrite core characteristics, but the measurement test jig is still restricted to a 50 Ω test system. Hence, it does not reflect the true EMI suppression characteristics of the ferrite core in the actual operating configuration, where the impedance can be very different from 50 Ω .

In this paper, a more realistic measurement approach is proposed to assess the ferrite core's EMI suppression performance in its actual operating condition. Using one probe as an injecting probe and another probe as a receiving probe, the CM impedance of the ferrite core can be measured accurately when it is slipped onto a power cord under the powered up condition. The proposed measurement method allows the designer to evaluate and to choose the most suitable ferrite core for the power cord of a specific electronic product to suppress CM radiation from the cable effectively, without the usual trial-and-error process. With a pre-measurement characterization process, the parasitic effect of the two-probe measurement setup can be easily eliminated and therefore good measurement accuracy of the proposed method is preserved.

II. THEORETICAL BACKGROUND

The method of measuring unknown impedance using the twoprobe approach was first reported for power mains impedance measurements [4]. To briefly describe the method, Fig. 1 shows the basic measurement setup to measure the unknown impedance Z_X . The setup involves an injecting probe, a receiving probe, and a vector network analyzer (VNA). A coupling capacitor is employed so that the two probes can be coupled to Z_X at high frequency without direct electrical connection, as Z_X could be a component in a high-voltage circuit. Port 1 of the network analyzer induces a signal through the injecting probe and Port 2 of the VNA measures the resultant induced signal voltage with the receiving probe.

Figure 2 shows the equivalent circuit of the measurement setup. V_{p1} is the output signal source voltage of port 1 connected to the injecting probe and V_{d2} is the resultant signal voltage measured at port 2 with the receiving probe. Z_{p1} and Z_{p2} are output and input impedances of ports 1 and 2, respectively, which are usually 50 Ω . L_1 and L_2 are the primary self-inductances of the injecting and receiving probes, respectively, and Lis the self-inductance of the coupling circuit loop formed by the two probes, the capacitor and the connecting wires. M_1 is the mutual inductance between of injecting probe and the coupling circuit loop, and M_2 is the mutual inductance between the receiving probe and the coupling circuit loop. The final equivalent circuit of the measurement setup seen by the unknown impedance Z_X is given in Fig. 3. Port 1 of the VNA is reflected into the coupling circuit loop through the injecting probe with an equivalent voltage source VM1 and an equivalent source impedance Z_{M1} , as seen from a-a'. Port 2 of the VNA is reflected into the coupling circuit loop through the receiving probe with equivalent impedance Z_{M2} .

Given the final equivalent circuit in Fig. 3, the resultant induced current in the circuit loop due to the injecting signal is



Fig. 1. Measurement setup of the two probes method.



Fig. 2. Equivalent circuit of the measurement setup shown in Figure 1.



Fig. 3. Final equivalent circuit of Figure 2.

given by

$$I = \frac{V_{M1}}{Z_{M1} + Z_{M2} + j\omega L + \frac{1}{j\omega C} + Z_X},$$
 (1)

where

$$Z_{M1} = \frac{(\omega M_1)^2}{Z_{p1} + j\omega L_1}, \quad Z_{M2} = \frac{(\omega M_2)^2}{Z_{p2} + j\omega L_2}$$

and

$$V_{M1} = j\omega M_1 \left(\frac{V_{p1}}{Z_{p1} + Z_1}\right).$$

To simplify the equivalent circuit further, the measurement setup can be represented by an equivalent voltage source V_{M1} in series with an equivalent source impedance Z_{setup} , where

 $Z_{setup} = Z_{M1} + Z_{M2} + j\omega L + 1/j\omega C$. So (1) can be rewritten as

$$I = \frac{V_{M1}}{Z_{setup} + Z_X}.$$
(2)

From (2), the unknown impedance Z_X can be obtained by

$$Z_X = \frac{V_{M1}}{I} - Z_{setup} \,. \tag{3}$$

The current *I* measured by the receiving probe can be determined by

$$I = \frac{V_{p2}}{Z_{T2}},\tag{4}$$

where Z_{T2} is the calibrated transfer impedance of the receiving probe provided by the probe manufacturer.

Substituting

$$V_{M1} = j\omega M_1 \left(\frac{V_{p1}}{Z_{p1} + Z_1}\right)$$

and (4) into (3) leads to

$$Z_{X} = \left(\frac{j\omega M_{1} V_{p1}}{Z_{p1} + Z_{1}}\right) \frac{Z_{T2}}{V_{p2}} - Z_{setup}.$$
 (5)

Let $k = \frac{j\omega M_1 Z_{T2}}{Z_{p1} + Z_1}$, then (5) can be expressed as

$$Z_X = \frac{kV_{p1}}{V_{p2}} - Z_{setup} \,. \tag{6}$$

The ratio V_{p1} / V_{p2} can be obtained through S-parameter measurement using the VNA as follows:

$$\frac{V_{p1}}{V_{p2}} = \frac{S_{11} + 1}{S_{21}}.$$
(7)

By keeping V_{p1} at constant, k is a frequency-dependent coefficient. If Z_X is replaced with a known precision standard resistor R_{std} , the coefficient k at a specific frequency can be determined by

$$k = \frac{(R_{std} + Z_{setup})}{\frac{V_{pl}}{V_{pl}}\Big|_{Z_X = R_{std}}}.$$
(8)

Before measuring Z_X , Z_{setup} can be measured directly with an impedance analyzer with Z_X replaced with a short circuit. Once Z_{setup} is found, the two-probe measurement setup is ready to measure any unknown impedance Z_X as follows:

$$Z_{X} = k \frac{V_{p1}}{V_{p2}} \Big|_{Z_{x} = unknown} - Z_{setup},$$

$$Z_{X} = \frac{(R_{std} + Z_{setup})}{\frac{V_{p1}}{V_{p2}} \Big|_{Z_{x} = R_{std}}} \frac{V_{p1}}{V_{p2}} \Big|_{Z_{x} = unknown} - Z_{setup}.$$
(9)

III. VALIDATION

Because of its length (1 to 1.5 m), CM radiation from power cord usually dominates in the frequency range of 30 to 200 MHz. Hence, the proposed measurement method will be validated in this frequency range. In the validation, the Tektronix CT-1 (5 mV/mA, bandwidth 25 kHz to 1 GHz) and CT-2 (1 mV/mA,



Fig. 4. Measurement setup to characterize ferrite core's EMI suppression performance.

bandwidth 1.2 kHz to 200 MHz) probes are selected as the injecting and receiving probes, respectively. The HP 8573C VNA is used for the measurement of S-parameters. Z_{setup} is measured using the HP 4396B impedance analyzer with the HP 43961A RF impedance test adaptor. The measured Z_{setup} is given in Fig. 7. It is found to be inductive in nature in the said frequency range due to the inductance of the coupling circuit loop and the equivalent series inductance (ESL) of the coupling capacitor (the self resonant frequency of the capacitor is below 30 MHz).

To obtain the frequency-dependent coefficient k for the twoprobe measurement setup, a precision 470 Ω (stated resistance value) surface mount resistor R_{std} is measured using the twoprobe setup with two 3300 pF coupling capacitors in parallel. The coefficient k is evaluated in accordance with (8). Once k and Z_{setup} are found, the coupling circuit is now ready to measure any unknown impedance connected to high voltage.

For validation purposes, a few other precision surface mount resistors of known values (stated resistance values: 100Ω , 200Ω and 620Ω) are treated as unknown Z_X to be measured. In the frequency range of 30 to 200 MHz, all resistance values are checked using the impedance analyzer, the measured values of these surface mount resistors using the impedance analyzer agree very well with the stated resistance values. The measured values using the proposed two-probe approach are compared with the measured results using the impedance analyzer and the differences are found to be less than 9% in the frequency range of 30 to 200 MHz.

IV. COMMON-MODE EMI SUPPRESSION OF FERRITE CORE

To assess the EMI suppression performance of a ferrite core on a power cord under a realistic operating condition, the measurement setup as shown in Fig. 4 is adopted. Figure 5 shows a photograph of the setup in a shielded enclosure. The whole setup is placed on an aluminum metal ground plane of size 1.2 m by 0.9 m. The alternating current (AC) power is connected to the mains through a line impedance stabilization network (LISN), as in the standard EMI measurement setup. The model of the LISN is MIL 5–25/2 (ELECTRO-METRICS, frequency range 100 kHz–65 MHz, 5 μ H/50 Ω per line). The power cord is connected to a switched-mode power supply (SMPS) (AC Input: 100–240 V, 2 A, 50–60 Hz; DC output: +12 V, 2.1 A;



Fig. 5. Photograph of the measurement setup shown in Figure 4.

rated power: 25 W), which is usually the case for nearly all electronic products. The load of the DC output of SMPS is 7.5 Ω (two 15 Ω resistors connected in parallel).

The two-line power cord consists of line and neutral wires (12 AWG, 80 cm in length). The height of the wires to the ground plane is maintained at 7 cm throughout the full length of the power cord. A ferrite core is slipped onto the line and neutral wires bundle. Using an impedance analyzer, the impedance of the ferrite core is measured and its real (resistive) and imaginary (inductive) parts are shown in Fig. 9. It clearly shows that the resistive part is dominant. The earth terminal of the LISN is bonded to the metal ground plane through a copper strip and the metal frame of the SMPS is connected to the metal ground plane through a short length of wire. The metal frame of the SMPS (8.5 cm \times 11.5 cm) has a 7 mm gap with reference from the metal ground plane. The coupling circuit consists of two 3300 pF coupling capacitors (one between line and ground plane and another between neutral and ground plane), two probes and connecting wires, which are mounted on a printed-circuit board (PCB), as shown in Fig. 6. The wire in the coupling circuit has a length of 9 cm, which is much shorter than the wavelength of the highest measurement frequency of 200 MHz. Hence, the transmission-line effect of the coupling circuit can be neglected.

The probes are located at 10 cm with reference from the LISN, as indicated in Fig. 4. The CM impedance at the given location of the power cord, where the coupling circuit is con-



Fig. 6. Implementation of the two-probe coupling circuit.

nected, is measured. The ferrite core can be placed at any location along the power cord. To check the impact of different positioning of the ferrite core, we have chosen to place the ferrite core at three locations, 10 cm, 40 cm and 80 cm with reference from the LISN. To evaluate the EMI suppression performance of the ferrite core, the ratio of CM impedance with and without the ferrite core added, serves as a good EMI suppression performance indicator of the ferrite core, as given in (10),

EMI Suppression Indicator
$$= \frac{Z_{lisn} + Z_{cable+smps} + Z_F}{Z_{lisn} + Z_{cable+smps}},$$
(10)

where Z_{lisn} is the CM impedance of the LISN in powered up condition, $Z_{cable+smps}$ is the CM impedance seen by the LISN with the power cord connected to SMPS in actual working condition, and Z_F is the CM impedance of the added ferrite core.

A. Measurement of Common-Mode Impedance of LISN, SMPS and Ferrite Core

To determine the CM impedance of the LISN under powered up condition, the power cord and the SMPS are removed. With the two-probe measurement setup, the CM impedance of the LISN is measured. The measured CM impedance magnitude and phase of the LISN are given in Fig. 7. The measured magnitude and phases of Z_{setup} are also plotted in Fig. 7 for reference purposes. It clearly shows that Z_{setup} is much lower than Z_{lisn} . Similarly, the input impedance of SMPS is also measured



Fig. 7. Measured common-mode impedance of LISN and Z_{setup} : (a) magnitude, (b) phase.



Fig. 8. Measured common-mode impedance of the SMPS with loads: (a) magnitude, (b) phase.

with the two-probe measurement setup. The magnitude and phase of the impedance are shown in Fig. 8. The impedance characteristic shows two prominent resonant peaks at around 80 MHz and 145 MHz, where the impedance is highest (>1 $k\Omega$).

B. Measurement of Common-Mode Impedance of Power Cord with SMPS (With and Without Ferrite Core)

When the SMPS is connected to the LISN through the power cord, the measured impedance from the setup of Fig. 4 is actually Z_{lisn} and $Z_{cable+smps}$ in parallel. With the ferrite core added, the measured impedance is Z_{lisn} and $(Z_{cable+smps} + Z_F)$ in parallel. Since Z_{lisn} is known, with the measured Z_{lisn} and



Fig. 9. Measured impedance of the ferrite core.



Fig. 10. Common-Mode impedance $(Z_{lisn} + Z_{cable+smps} + Z_F)$ of the actual setup.

 $Z_{cable+smps}$ in parallel, we could determine $(Z_{lisn} + Z_{cable+smps})$ easily. Similarly, with the measured Z_{lisn} and $(Z_{cable+smps} + Z_F)$ in parallel, we could also determine $(Z_{lisn} + Z_{cable+smps} + Z_F)$. Using the impedance $(Z_{lisn} + Z_{cable+smps})$ as a reference, the impedances of $(Z_{lisn} + Z_{cable+smps} + Z_F)$ with ferrite core located at l = 10 cm, 40 cm and 80 cm are plotted in Fig. 10. The impedance characteristic of $(Z_{lisn} + Z_{cable+smns})$ shows that at lower frequencies, the impedance is very much dominated by Z_{smps} . However, above 100 MHz, the transmission lines effect of the power cord kicks in (the quarter-wavelength is about 107 MHz for 70 cm length of power cord seen from the twoprobe measurement point) and the impedance behavior is rather complex with resonances due to Z_{smps} as well as transmission line effect. Three resonant peaks at around 80 MHz (due to SMPS), 160 MHz and 170 MHz (due to both SMPS and transmission line effect of power cord) are clearly observed. We expect the EMI suppression performance at these three frequencies to be poor.

To provide a better picture of EMI suppression performance of the ferrite core, (10) can be used to determine the EMI suppression performance indicator of the ferrite core. Let $Z = Z_{lisn} + Z_{cable+smps}$ and let Z_1 , Z_2 and Z_3 be the impedance $Z_{lisn} + Z_{cable+smps} + Z_F$ with the ferrite core located at l = 10 cm, 40 cm and 80 cm, respectively. Figure 11 shows the EMI suppression performance of the ferrite core in terms



Fig. 11. EMI suppression performance of the ferrite core, with the ferrite core placed at three different locations $(Z_1/Z \text{ for } l = 10 \text{ cm}, Z_2/Z \text{ for } l = 40 \text{ cm and } Z_3/Z \text{ for } l = 80 \text{ cm}).$

of ratios Z_1/Z , Z_2/Z and Z_3/Z , in the frequency range of 30 to 200 MHz.

With Fig. 11, the EMI suppression performance across the whole frequency range with the ferrite core placed at three different locations can be seen clearly. For the given length of power cord and the given SMPS, the dips in the EMI suppression performance around 80 MHz, 160 MHz and 170 MHz are expected because the impedance of $(Z_{lisn} + Z_{cable+smps})$ is very high due to the resonances explained earlier. Figure 11 also shows that the placement of the ferrite core has a strong influence on the EMI suppression performance.

V. CONCLUSION

Based on a two-probe measurement approach, a measurement setup is proposed to evaluate the EMI suppression performance of a ferrite core under realistic working configuration. The proposed method provides a more accurate assessment of the EMI suppression performance of a ferrite core slipped onto a power cord under its actual operating condition. We have also found that the impedance of SMPS and the transmission line effect have strong influence on the ferrite core EMI suppression performance. The proposed method allows us to find out the frequencies when the ferrite core does not work well, where the conventional 50 Ω measurement system is unable to detect. In addition, the positioning the ferrite core along the power cord also plays an important factor in EMI suppression performance. Further work will be carried out to study the positioning of the ferrite core on the CM radiation from the power cord.

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BIOGRAPHIES



Bo Hu received the B.Eng. degree in electronic engineering from Southeast University, Nanjing, China, in 1997. Currently, he is pursuing his Ph.D. degree at the School of Electrical and Electronic Engineering, Nanyang Technological University. From 1997 to 2003, he was a hardware engineer with Nanjing Fujitsu Computer Products Company Ltd., China. His current research interests

are in the areas of electromagnetic compatibility measurement techniques and simulations.



Kye Yak See received his B. Eng degree from the National University of Singapore in 1986 and his Ph.D. degree from Imperial College, United Kingdom, in 1997. He is currently an Associate Professor in the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. He also holds a concurrent appointment of Director of Electro-

magnetic Effects Research Laboratory in the same university. Prior to his academic career, he spent eight years in the industry in various senior technical and management positions in Singapore, the United Kingdom and Hong Kong. He has published close to 70 technical papers in the areas of EMC and computational electromagnetics. He is a senior member of the IEEE, the founding chairman of the IEEE EMC Society Singapore Chapter, a technical assessor of the Singapore Accreditation Council and a member of the Technical Committee on EMC. He was also the Organizing Committee Chair for the 2006 EMC Zurich Symposium and 2008 Asia Pacific EMC Conference in Singapore.



Weng Yew Chang obtained his B. Eng and M. Sc degrees from Nanyang Technological University in 1994 and 2001, respectively. He joined DSO National Laboratories in 1994, started as a designer under the Weapon Electronics Lab involved in the development of airborne embedded digital processing systems and later as project lead in numerous hardware

designs involving embedded DSP digital systems and airborne radar digital systems. His last appointment was the Group Head for the Airborne Radar Digital Electronics Team under the Division of Guided Systems. He was awarded a scholarship from DSO National Laboratories in 2005 to pursuit his Ph.D. degree. His research interests are signal integrity for high-speed digital circuit design, high-speed measurements, practical design techniques for EMI/EMC consideration and airborne embedded digital design.