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Evaluation of Ferrite Core EMI Suppression under Realistic Working Conditions

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Abstract— A novel measurement method is proposed to evaluate the performance of a ferrite core on a power cord under actual operating condition. The proposed method allows the common-mode impedance of a ferrite core under in-circuit condition to be measured so that it provides a more realistic assessment of the noise suppression capability of the ferrite core. With a pre-measurement characterization process, possible error due to parasitic effects of the measurement setup can be determined and eliminated. Hence, good accuracy is achieved for the proposed measurement method.

I. INTRODUCTION

Due to international electromagnetic interference (EMI) regulatory requirements, all electrical and electronic equipments have to comply with specific EMI limits. One of the major sources of radiated EMI is the common-mode (CM) current flowing in the power cord and interfacing cables connected to the equipment-under-test. Ferrite cores are usually used to reduce the CM current on the cable.

Ferrite core manufacturers provide ferrite core impedance under well-defined source and load terminations. However, the actual source and load impedances in an actual ferrite-core application are usually unknown. Some research work has been done on the impedance characteristics of a ferrite core and loading effects on various types of the transmission lines [1-2]. However, it still could not quantify the EMI suppression characteristics of the ferrite cores in actual electronic product configurations. Recently, a parallel-line measurement jig consisting of a cylindrical metal rod and a metal ground plane [3] has been used to investigate ferrite core characteristics. However, the measurement jig is restricted to a 50 Ω test system and does not reflect the actual impedance of actual operating configurations.

In this paper, ferrite core EMI suppression performance is evaluated in an actual in-circuit operating condition. A two-probe measurement approach is proposed. Using one current probe as an injecting probe and another current probe as a receiving probe, the CM impedance of the ferrite core in the frequency range of 30 MHz – 200 MHz can be determined accurately for a varying load in its actual application

configuration. With a pre-measurement characterization process, the parasitic effect of the measurement setup can be easily eliminated and therefore the good measurement accuracy of the proposed method is preserved.

II. TWO PROBES MEASUREMENT APPROACH

The concept of measuring an unknown impedance using the two-probe approach was first reported for power network impedance measurements [4-5] and subsequently modified for noise source impedance measurements of switched-mode power supplies (SMPS) [6]. The measurement setup consists of an injecting current probe, a receiving current probe, and a vector network analyser (VNA). The two probes and the coupling capacitor form a coupling circuit to avoid direct connection to the high-voltage circuit. Port 1 of the network analyzer induces a signal in the coupling loop through the injecting current probe and Port 2 of the network analyzer measures the resultant circulating current in the coupling loop with the receiving current probe.

Fig. 1. Equivalent circuit of the two current probes measurement setup.

Fig. 1 shows the equivalent circuit of the two current probes measurement setup. Z_X is the unknown impedance to be measured. C is the coupling capacitor and V_{M1} is the induced signal voltage from the injecting current probe to the coupling loop. Z_{M1} and Z_{M2} are the reflected impedances of the injecting probe and receiving probe to the coupling loop,

respectively. The total resultant impedance in the coupling circuit is Z_{setup} . The unknown impedance Z_x can be determined through [6]:

$$Z_x = \frac{kV_{p1}}{V_{p2}} - Z_{setup}, \quad (1)$$

where V_{p1} and V_{p2} are the source voltage at the injecting probe and the signal voltage received by the receiving probe, respectively, and k is a frequency-dependent coefficient. Z_{setup} can be measured using an impedance analyzer.

The ratio of V_{p1} and V_{p2} can be measured by the network analyzer as follows:

$$\frac{V_{p1}}{V_{p2}} = \frac{S_{11} + I}{S_{21}}, \quad (2)$$

where S_{11} and S_{21} are S-parameters measured at the injecting probe and receiving probe, respectively. To obtain the coefficient k , the unknown impedance is replaced by a known standard precision resistor, where Z_{std} is the impedance of the standard resistor:

$$k = \frac{Z_{setup} + Z_{std}}{\left(\frac{V_{p1}}{V_{p2}} \right) \Big|_{Z_x = Z_{std}}}. \quad (3)$$

III. EXPERIMENTAL VALIDATION

To validate the two-probe measurement setup in the frequency range of 30 MHz – 200 MHz, Tektronic CT-1 (5 mV/mA, bandwidth 25 kHz to 1 GHz) and CT-2 (1 mV/mA, bandwidth 1.2 kHz to 200 MHz) current probes are chosen as the injecting and receiving current probes, respectively. An HP 8573C network analyzer is used for the measurement of the S-parameters. Z_{setup} is measured using an HP 4396B impedance analyzer with 43961A RF impedance test adaptor. The impedance of the coupling circuit Z_{setup} is inductive in nature in the above frequency range due to the loop inductance of the coupling circuit and the equivalent series inductance of the coupling capacitor (series resonant frequency of the capacitor = 30 MHz).

To obtain the frequency-dependent coefficient k for the two-probe measurement setup, a 470 Ω surface mount resistor R_{std} is measured using the two-probe setup with two 3300 pF coupling capacitors in parallel. The coefficient k is evaluated in accordance with (3). Once k and Z_{setup} are found, the

coupling circuit is now ready to measure any unknown impedance.

For validation purposes, a few other surface mount resistors of known values (100 Ω , 200 Ω and 620 Ω) are treated as unknown resistors and measured using (1). The measured resistance values are compared with the results of the impedance analyzer measurement and the errors were found to be less than 9% in the frequency range of 30 MHz–200 MHz.

IV. IN-CIRCUIT MEASUREMENT OF FERRITE CORE

To emulate the actual operating condition for a ferrite core on a power cord, the measurement setup as shown in Fig. 2 is adopted. The whole setup is placed on an Aluminium metal ground plane of size 1.2 m $\times$ 0.9 m. The AC power is connected to the mains through a line impedance stabilization network (LISN). The LISN model is MIL 5-25/2 (ELECTROMETRICS, Inductance: 5 μ H, Impedance: 50 Ω). The power cord is connected to a SMPS, which is usually the case for nearly all electronic products.

Fig. 2. Measurement setup to characterize ferrite core EMI suppression performance under in-circuit operating condition.

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 (220 Ω @ 100 MHz) encircles the line and neutral wires together. The earth terminal of the LISN and the metal frame of the SMPS are bonded to the metal ground plane. The coupling circuit consists of two 3300 pF coupling capacitors (one between line and ground and another between neutral and ground) and the two current probes.

The probes are located 10 cm from the LISN, as indicated in Fig. 2. The CM impedance at the given location along the power cord is measured. The ferrite core can be placed at any location of along the power cord. We have chosen to place the

ferrite core at 10 cm, 40 cm and 80 cm from the LISN, which means that the ferrite core is located at the two ends and the middle of the power cord. To evaluate the EMI suppression performance of the ferrite core, the ratio of CM impedance with and without ferrite core added serves as a good EMI suppression performance indicator, as given in (4),

$$\text{EMI Suppression} = \frac{Z_{\text{lisn}} + Z_{\text{cable+smps}} + Z_F}{Z_{\text{lisn}} + Z_{\text{cable+smps}}}, \quad (4)$$

where Z_{lisn} is the CM impedance of the LISN in actual power up condition, $Z_{\text{cable+smps}}$ 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

To determine the CM impedance of the LISN under power up condition, the power cord and the SMPS are removed. With the two-probe measurement setup, the CM impedance of the LISN is measured as an unknown impedance. The measured LISN CM impedance in the frequency range 30-200 MHz is given in Fig. 3. The impedance of the measurement setup is also given for reference purposes.

Fig. 3. The common-mode impedance of LISN and Z_{setup} .

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. 2 is actually Z_{lisn} and $Z_{\text{cable+smps}}$ in parallel. With the ferrite core added, the measured impedance is Z_{lisn} and $(Z_{\text{cable+smps}} + Z_F)$ in parallel. The measured impedance without the ferrite core and with the ferrite core located at $l = 10$ cm, 40 cm and 80 cm are plotted in Fig. 4.

Fig. 4. Common-mode impedance measurement of actual setup.

With the measured Z_{lisn} and Z_{lisn} and $Z_{\text{cable+smps}}$ in parallel, we could determine $Z_{\text{lisn}} + Z_{\text{cable+smps}}$ easily. Similarly, with the measured Z_{lisn} and Z_{lisn} and $(Z_{\text{cable+smps}} + Z_F)$ in parallel, we could also determine $Z_{\text{lisn}} + Z_{\text{cable+smps}} + Z_F$. Finally, (4) can be used to determine the EMI suppression performance of the ferrite core. Let $Z = Z_{\text{lisn}} + Z_{\text{cable+smps}}$. Let Z_1 , Z_2 and Z_3 be the impedance $Z_{\text{lisn}} + Z_{\text{cable+smps}} + Z_F$ with the ferrite core located at $l = 10$ cm, 40 cm and 80 cm, respectively. Fig. 5 shows the EMI suppression performance of the ferrite core Z_1/Z , Z_2/Z and Z_3/Z in the frequency range of 30 MHz – 200 MHz.

Fig. 5. The EMI suppression performances of the ferrite core with the ferrite core placed at three different locations (Z_1/Z for $l = 10$ cm, Z_2/Z for $l = 40$ cm and Z_3/Z for $l = 80$ cm).

Fig. 5 shows that the EMI suppression performance with the ferrite placed at three different locations. At low frequencies the performance of the ferrite core are nearly the same. As frequency increases, the performance becomes highly dependent on the location of the ferrite core as the length of the cable becomes comparable to the wavelength. For the given length of power cord and the given SMPS, the performance of the ferrite core located at $l = 10$ cm and 80 cm are much better than that at $l = 40$ cm.

C. Measurement of CM Noise Current

The two current probes coupling circuit is removed from the measurement setup. Now a radio frequency clamp-on

current probe is clamped onto the power cord at $l = 10$ cm. The model of the current probe is R & S ESV-Z1. The measured CM noise current due to the SMPS, without ferrite core added, is shown in Fig. 6. Let I_0 be the measured CM noise current without the ferrite core added. Let I_1 , I_2 and I_3 be the measured CM noise currents with the ferrite core located at $l = 10$ cm, 40 cm and 80 cm, respectively. Fig. 7 shows the reduction of CM noise current in terms of ratios I_0/I_1 , I_0/I_2 and I_0/I_3 . Comparing Fig. 7 with Fig. 5, the reduction of CM noise current correlates very well with the EMI suppression based on impedance ratio.

Fig. 6. CM noise current measured at $l = 10$ cm without ferrite core added (I_0).

Fig. 7. Reduction of CM noise after ferrite core is added at three different locations.

V. CONCLUSION

A two current probe measurement approach was proposed to evaluate ferrite core EMI suppression performance under realistic working conditions. Using a LISN and a SMPS, the EMI suppression performance of a ferrite core on a power cord has been evaluated. The measured performance agrees well with actual CM current measurements. Such an evaluation provides more meaningful EMI suppression information as compared to an evaluation based on either 50 Ω measurement system or a manufacturer's data sheet. With the proposed approach, the correct ferrite core that fits a specific EMI suppression performance for a specific electronic product can be easily selected without the usual trial-and-error approach.

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