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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 [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 analyzer (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 shows the equivalent circuit of the two current probes measurement setup. Z0 is the unknown impedance to be measured. C is the coupling capacitor and Vdc is the induced signal voltage from the injecting current probe to the coupling loop. Zl and Zr are the reflected impedances of the injecting probe and receiving probe to the coupling loop.

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

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respectively. The total resultant impedance in the coupling circuit is $Z_{\text{setup}}$. The unknown impedance $Z_{x}$ can be determined through (6):

$$Z_x = \frac{kV_p}{V_p} - Z_{\text{setup}}, \tag{1}$$

where $V_p$ and $V_p'$ 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. $Z_{\text{setup}}$ can be measured using an impedance analyzer.

The ratio of $V_p$ and $V_p'$ can be measured by the network analyzer as follows:

$$\frac{V_p}{V_p'} = \frac{S_{11}}{S_{21}}, \tag{2}$$

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 $Z_{\text{std}}$ is the impedance of the standard resistor:

$$k = \frac{V_p}{V_p'} \frac{Z_{\text{setup}}}{Z_{\text{std}}}. \tag{3}$$

### III. Experimental Validation

To validate the two-probe measurement setup in the frequency range of 30 MHz – 200 MHz, Tektronix 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. $Z_{\text{setup}}$ is measured using an HP 4396B impedance analyzer with 43961A RF impedance test adaptor. The impedance of the coupling circuit $Z_{\text{setup}}$ 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 $\Omega$ surface mount resistor $R_k$ 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 $Z_{\text{setup}}$ 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 $\Omega$, 200 $\Omega$ and 620 $\Omega$) 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 μH, Impedance: 50 $\Omega$). The power cord is connected to a SMPS, which is usually the case for nearly all electronic products.

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 $\Omega$ @ 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),

\[ \text{EMI Suppression} = \frac{Z_{\text{lisn}} + Z_{\text{cable+smps}}}{Z_{\text{lisn}} + Z_{\text{cable+smps}} + Z_{F}} \quad (4) \]

where \( Z_{\text{lisn}} \) 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.

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 \( Z_{\text{lisn}} + Z_{\text{cable+smps}} \) in parallel. With the ferrite core added, the measured impedance is \( Z_{\text{lisn}} + (Z_{\text{cable+smps}} + Z_{F}) \) 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.

With the measured \( Z_{\text{lisn}} \) and \( Z_{\text{cable+smps}} \), we could determine \( Z_{\text{lisn}} + Z_{\text{cable+smps}} \) easily. Similarly, with the measured \( Z_{\text{lisn}} \) and \( Z_{\text{cable+smps}} \), 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. 3. The common-mode impedance of LISN and \( Z_{\text{setup}} \)

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

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 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.

**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 \( \Omega \) 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.

**REFERENCES:**


