Assessment of EMI Chokes under Realistic Loading Conditions

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***Abstract*—A novel measurement method has been developed to characterize the common-mode (CM) and differential-mode (DM) impedances of power line EMI chokes under realistic loading conditions. With a proper pre-measurement calibration process, all parasitic effects in the measurement setup can be eliminated. The measurement allows designer to assess the EMI suppression performance of these chokes with reasonable accuracy under various loading conditions. With the measurement results, a proper choke with optimum EMI suppression performance could be selected for a specific loading condition.**

I. INTRODUCTION

The effectiveness of a power line EMI filter in switched mode power converters depends to a great extent on the characteristics of the power line filter components, especially the EMI chokes such as CM choke and DM choke under actual loading condition. Besides parasitic parameters, different magnetic core materials may cause two apparently identical chokes to behave very differently under a specific operating condition [1].

Exiting measurement methods measure the chokes under either steady-state dc or ac loading with defined source and load impedance [2][3]. In reality, for EMI filters in power conversion applications, the current carried by the EMI chokes is usually a pulsed dc current, the source and load impedance is also varying [4][5]. To characterize an EMI choke, either a CM choke or a DM choke, under realistic working 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 RF impedance of the EMI choke in the EMI regulated frequency range of 150 kHz – 30 MHz can be determined accurately under varying load in its actual application configuration. With a pre-measurement characterization process, the effect of the measurement setup can be easily eliminated and therefore good measurement accuracy of the proposed method is preserved.

II. THEORITICAL BACKGROUND

The concept of measuring unknown impedance using the two-probe approach was first reported for power mains impedance measurement [6]. To illustrate the concept, Fig. 1 shows the basic measurement setup to measure any unknown impedance Z_X. The measurement setup consists of an injecting current probe, a receiving current probe and a network analyser. The two probes and the coupling capacitor form a coupling circuit to avoid direct connection to Z_X, which may be a component of a high-voltage circuit. Port 1 of the network analyser induces a signal in the coupling loop through the injecting current probe. Port 2 of the network analyser measures the resultant circulating current in the coupling loop with the receiving current probe.

Fig. 2 shows the equivalent circuit of the setup. V_1 is the output signal source voltage of port 1 connected to the injecting probe and V_2 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 L is the self-inductance of the coupling loop. M_1 is the mutual inductances of injecting probe and the coupling loop, M_2 is the mutual inductance between the receiving probe and the coupling loop. By reflecting the primary circuits of the injecting and receiving probes in the coupling circuit loop, the simplified equivalent circuit of the measurement setup is illustrated in Fig. 3. The resultant current in the coupling loop due to the injecting signal is given by

$$I = \frac{V_{M1}}{Z_{M1} + Z_{M2} + j\omega L + \dfrac{1}{j\omega C} + Z_X} \tag{1}$$

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

$$V_{M1} = j\omega M_1\left(\frac{V_1}{Z_{p1} + Z_1}\right).$$

Finally, the coupling circuit can be replaced 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 equation (1) can be rewritten as

$$I = \frac{V_{M1}}{Z_{setup} + Z_X} \tag{2}$$

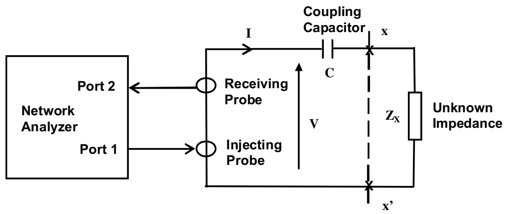

Fig. 1 Basic setup of the two current probes approach

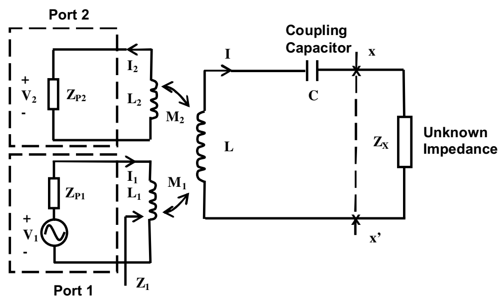

Fig. 2 The equivalent circuit of the two current probes measurement setup

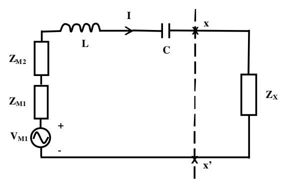

Fig. 3 Simplified equivalent circuit of the two current probes measurement setup

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

$$Z_X = \frac{V_{M1}}{I} - Z_{setup} \quad (3)$$

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

$$I = \frac{V_2}{Z_{T2}} \quad (4)$$

where Z_{T2} is the calibrated transfer impedance of the receiving probe. Substituting $V_{M1} = j\omega M_1\left(\frac{V_1}{Z_{p1}+Z_1}\right)$ and equation (4) into equation (3) leading to

$$Z_X = \left(\frac{j\omega M_1 V_1}{Z_{p1}+Z_1}\right)\frac{Z_{T2}}{V_2} - Z_{setup} \quad (5)$$

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

$$Z_X = \frac{kV_1}{V_2} - Z_{setup} \quad (6)$$

By maintaining V_1 at a fixed magnitude, kV_1 is a frequency-dependent constant. If Z_X is replaced with a known precision standard resistor R_{std}, the constant coefficient kV_1 can be determined by

$$kV_1 = \left(R_{std} + Z_{setup}\right)V_2\big|_{Z_X = R_{std}} \quad (7)$$

If Z_X is replaced with a short circuit, one gets

$$kV_1 = Z_{setup} V_2\big|_{Z_X=0} \quad (8)$$

From equations (7) and (8), the impedance due to the coupling circuit Z_{setup} can be obtained through:

$$Z_{setup} = \frac{V_2\big|_{Z_X=R_{std}}}{V_2\big|_{Z_X=0} - V_2\big|_{Z_X=R_{std}}} R_{std} \quad (9)$$

Once Z_{setup} is found, the coupling circuit is ready to measure any unknown impedance Z_X as follows

$$Z_X = \frac{kV_1}{V_2\big|_{Z_X=unknown}} - Z_{setup}$$

$$Z_X = \frac{\left(R_{std}+Z_{setup}\right)V_2\big|_{Z_X=R_{std}}}{V_2\big|_{Z_X=unknown}} - Z_{setup} \quad (10)$$

In most practical situations, Z_{setup} is small and can be neglected. Then, equation (10) can be simplified to

$$Z_X = \frac{R_{std} V_2\big|_{Z_X=R_{std}}}{V_2\big|_{Z_X=unknown}} \quad (11)$$

However, if the unknown impedance Z_X to be measured is small and comparable to Z_{setup}, then Z_X must be evaluated according to equation (10) to ensure good measurement accuracy.

III. CM IMPEDANCE MEASUREMENT

A CM choke consists of two identical windings sharing the same magnetic core. The windings are wound in such a way that the magnetic fluxes generated by the two windings cancel for differential-mode (DM) operation but add for CM operation. In reality, it is impossible for the net magnetic flux to be cancelled totally when the DM current passes through the CM choke. If the net magnetic flux is significant enough, it may saturate the magnetic core and results in drastic reduction of CM inductance of the choke [1]. Hence, the expected performance of CM choke in the actual circuit can be different from that obtained with a conventional measurement system under no load or low-current dc biasing condition.

With the proposed two-probe measurement approach, it is possible to measure the impedance of a CM choke under in-circuit operating condition. By varying the load current, the CM impedance behaviour of the choke can be easily observed. Fig. 4 shows the measurement setup to characterize the CM choke. The circuit where the CM choke is inserted resembles that of a typical SMPS. The differential-mode (DM) load circuit consists of a bridge rectifier, a 220 μF electrolytic capacitor and a 100 Ω wire-wound resistor with a maximum power rating of 300 W. By connecting the DM load circuit to the programmable ac power source, repetitive dc current pulses are generated so that it emulates the actual operating condition where the CM choke supposed to work. The magnitude of the DM current pulse can be varied with the programmable ac power supply.

The two 1 μF capacitors (one between live-to-ground and another between neutral-to-ground) and the injecting and receiving current probes form the CM coupling circuit for the CM choke-under-test. In order to complete the CM signal path, two 2200 pF capacitors (one between live-to-ground and another between neutral-to-ground) are added on the other end of the CM choke. The RF signal is injected into the CM signal path through the injecting current probe, which is connected to port 1 of the network analyser. The resulting RF signal in the CM signal path is measured by port 2 of the network analyser via the receiving current probe. The CM impedance of the CM choke-under-test can be obtained using the procedure described in Section II. Firstly, without the CM choke-under-test, the CM impedance of the measurement setup (Z_{setup}) is measured. Then, the CM choke-under-test is inserted and the CM impedance is measured again. If the effect of Z_{setup} cannot be ignored, it should be subtracted from the second set of measurement.

IV. DM IMPEDANCE MEASUREMENT

The DM impedance of a CM choke is due to the imperfect compensation of differential mode magnetizing force in the core. This DM impedance can be used for DM noise suppression. When load current is higher, the imperfect cancellation of DM magnetic flux will cause the core to saturate and the DM impedance will decrease drastically, especially in the frequency range near its self-resonant frequency, mainly due to the core losses such as hysteresis losses and eddy current losses. Similarly, with the two current probes, the DM impedance of a CM choke under loading condition can be measured over a wide frequency range. Fig. 5 shows the DM impedance measurement setups for a CM choke. It is recommended to use the same RF coupling circuit that used in the CM impedance measurement in order to eliminating the duplicating work in the system calibration and measurement of Z_{in}. The load which consists of a bridge rectifier, a bulk capacitor C_d and a load R_d can also be replaced by an actual application circuit such as a switched mode power supply. The two inductors L_Bs are used to eliminating the effects from the variable ac source and the load circuit. The total inductive reactance of the two L_B should be much greater than that of the L_{DM} in order to provide good isolation. The L_B must be chosen such that it is not saturated throughout the measurement. Same as the CM impedance measurement, the amplitude of load current can be adjusted by changing the amplitude of the input ac voltage.

The same measurement setup can be applied to the DM impedance measurement of normal DM choke, as shown in Fig. 6.

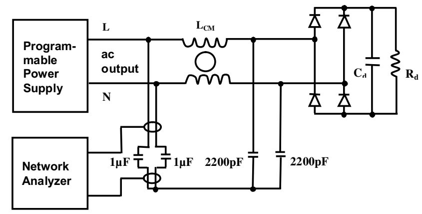

Fig.4 Measurement setup to characterize CM impedance of a CM choke

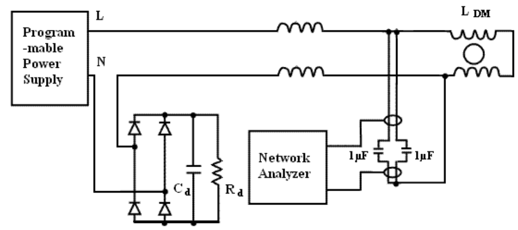

Fig. 5 Measurement setup to characterize the DM impedance of a CM choke

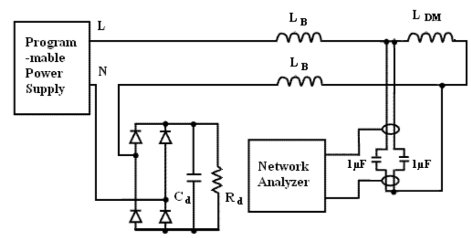

Fig. 6 Measurement setup to characterize the DM impedance of a DM choke

V. EXPERIMENTAL RESULTS

In the actual measurement in laboratory, Tektronic CT-1 (5mV/mA, bandwidth 25 kHz to 1000 MHz) and CT-2 (1mV/mA, bandwidth 1.2 kHz to 700 MHz) current probes are chosen as the injecting and monitoring current probes, respectively; together with a Agilent 4395A Network Analyser and an ELGAR SW 5250A programmable power supply. A CM choke, model: Tokin SS24V-R15080, is chosen for evaluation. The loading current of the CM choke is adjusted by changing the output voltage amplitude of the programmable power supply during the measurement. As before, the CM coupling circuit is calibrated with a standard known resistor and followed by characterization of the measurement setup. Then, the CM choke is added to the measurement setup as shown in Fig. 4. Fig. 7 shows the measured CM impedance of the choke under varying load current condition. When the peak magnitude of the current pulse is less than 5.21A, the CM choke provides excellent CM impedance, with at least 1kΩ up to 5 MHz. As usual, a self-resonate frequency of at 336 kHz is observed. If the peak current is higher than 5.21A, the CM impedance of the choke begins to decrease as a sign of core saturation. This behaviour is clearly observed when the peak current is increased to 6.11A. At this loading condition, the highest CM impedance has dropped from 24.5kΩ to about 8.1 kΩ. Further increase in peak current, for examples, at 7.10A, the choke practically offers no CM impedance at all.

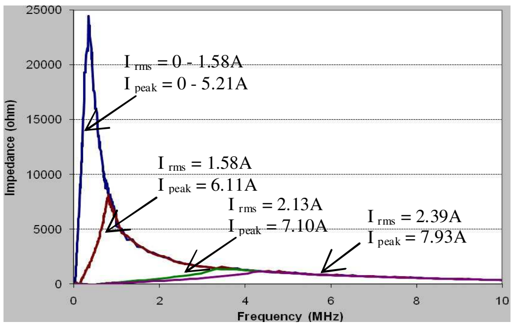

Fig. 7.The CM impedance of the CM choke

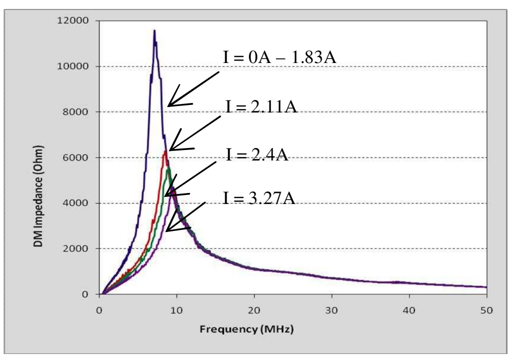

Fig. 7.The DM impedance of the CM choke

With the measurement setup shown in Fig 5, the DM impedance of this CM choke was measured using the same set of equipment and circuit. Fig. 8 shows the results of the DM impedance measurement. From the results, it can be found that the self-resonate frequency is at 7.273MHz when the load current is below 1.83A. When the load current is greater than 1.83A, the amplitude of DM impedance will decrease significantly with the increasing of the load current, the self-resonate frequency will also increase in the same time.

The experiment is made on a CM choke when it is operating with its typical load. The similar measurement can also be made for a normal DM choke with the measurement setup shown in Fig 6.

VI. CONCLUSIONS

Based on a two-probe measurement approach, the impedance of either a CM or DM EMI choke can be measured under in-circuit condition with its actual operating configuration. The pre-measurement calibration and characterization processes allow the measurement error contributed by the setup to be accounted for and eliminated. Hence, good measurement accuracy can be preserved. The ability to observe the EMI choke characteristic under varying load current provides the designer a more complete picture of the EMI suppression performance of the chokes, without the usual trial-and-error approach.

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