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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 can 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 operating conditions. Besides parasitic parameters, different magnetic core materials may cause two apparently identical chokes to behave very differently under a specific operating condition [1].

Existing 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 to 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 $Z_e$. The measurement setup consists of an injecting current probe, a receiving current probe and a network analyzer. The two probes and the coupling capacitor form a coupling circuit to avoid direct connection to $Z_e$, which may be a component of a high-voltage circuit. Port 1 of the network analyzer induces a signal in the coupling loop through the injecting current probe. Port 2 of the network analyzer measures the resultant circulating current in the coupling loop with the receiving current probe.

Fig. 2 shows the equivalent circuit of the setup. $V_i$ is the output signal source voltage of port 1 connected to the injecting probe and $V_i$ is the resultant signal voltage measured at port 2 with the receiving probe. $Z_{in}$ and $Z_{out}$ are the input impedances of ports 1 and 2, respectively, which are usually 50Ω. $L_1$ and $C_1$ are the primary self-inductances of the injecting and receiving probes, respectively. $L_0$ is the self-inductance of the coupling loop. $M_i$ is the mutual inductance of injecting probe and the coupling loop, $M_o$ 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

$$I = \frac{V_i}{Z_{in} + Z_{out} + \frac{1}{j\omega C_1} + Z_e}$$

(1)

where $Z_{in} = \frac{1}{j\omega M_i}$ and $Z_{out} = \frac{1}{j\omega M_o}$, $\omega$ is angular frequency, $M_i$ is the coupling inductance between the injecting probe and coupling loop with the receiving current probe, $M_o$ is the coupling inductance between the receiving probe and the coupling loop.

Finally, the coupling circuit can be replaced by an equivalent source impedance $Z_{equ}$ in series with an equivalent source impedance $Z_{equ}$, where $Z_{equ} = Z_{in} + Z_{out} + \frac{1}{j\omega C_1} + Z_e$. So equation (1) can be rewritten as

$$I = \frac{V_i}{Z_{equ}}$$

(2)

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 µH electrolytic capacitor and a 100 Ω wire-wound resistor with a maximum frequency-dependent constant. If $Z_M$ is replaced with a known precision standard resistor $R_{std}$, the constant coefficient $kV$ can be determined by

$$kV = \frac{V_{1std}}{V_{1,cm}}$$

If $Z_M$ is replaced with a short circuit, one gets

$$Z_M = \frac{Z_{setup}V_1}{V_{1,cm}}$$

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

$$Z_{setup} = \frac{V_{1,cm}V_{1std}}{V_{1,cm}V_{1std} - kV}$$

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

$$Z_M = \frac{Z_{setup}V_1}{V_{1,cm} + kV}$$

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

$$Z_M = \frac{R_{std}V_1}{V_{1std}}$$

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

$$Z_M = \frac{kV}{Z_{setup}}$$

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

$$kV = \frac{V_{1std}}{V_{1,cm}V_{1std} - kV}$$

$$Z_M = \frac{Z_{setup}V_1}{V_{1,cm} + kV}$$

Let $k = \frac{\mu_0 M Z_{setup}}{Z_{setup} + Z_{setup}}$, then equation (5) can be expressed as

$$Z_M = \frac{4V_1}{Z_{setup} + Z_{setup}}$$

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

$$Z_M = \frac{V_{1,cm}}{Z_{setup}V_1}$$

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

$$I = \frac{V_1}{Z_{setup}V_1}$$

where $Z_{setup}$ is the calibrated transfer impedance of the receiving probe. Substituting $V_{1,cm} = \mu_0 M \left( \frac{Z_{setup}}{Z_{setup}} \right)$ and equation (4) into equation (3) leading to

$$Z_M = \frac{\mu_0 M V_1}{Z_{setup}V_1} \frac{Z_{setup}}{Z_{setup} + Z_{setup}}$$

Let $k = \frac{\mu_0 M Z_{setup}}{Z_{setup} + Z_{setup}}$, then equation (5) can be expressed as

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However, if the unknown impedance $Z_M$ to be measured is small and comparable to $Z_{setup}$, then $Z_M$ must be evaluated according to equation (10) to ensure good measurement accuracy.
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. Finally, without the CM choke-under-test, the CM impedance of the measurement setup (Zsetup) is measured. Then, the CM choke-under-test is inserted and the CM impedance is measured again. If the effect of Zsetup 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 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.

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 Zup. 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 Bs should be much greater than that of the L DM in order to provide good isolation. The L Bs 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.

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 an Agilent 4395A Network Analyzer 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 1 kΩ 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 24.3 kΩ to about 8.1 kΩ. Further increase in peak current, for example, at 7.10A, the choke practically offers no CM impedance at all.

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.

REFERENCES


