In-circuit characterization of common-mode chokes

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Fig. 5. Lightning-induced voltages on a 1-km-long overhead line for different channel base currents. (a) Line center. (b) Line end.

than the other but a slower front. This is exactly the case of curves MCS.SUB and MSS.SUB, as the former has a peak value of 16.0 kA and a maximum time derivative of about 30 kA/μs, whereas the latter presents a peak value of around 12.0 kA and a maximum time derivative of around 40 kA/μs (differences of 33% in both parameters; see Table V for details).

To provide a basis for comparing both current waveforms, and to illustrate the application of the subsequent stroke currents presented in Section III-C, Fig. 5 shows lightning-induced voltages on a 1-km-long 10-m-high single-phase overhead line matched at both ends. In the analysis, currents MCS.SUB and MSS.SUB were assumed to be injected at the channel base, adopting the TL return-stroke model with a propagation speed of 1.3×10^8 m/s [8]. A stroke location 50 m away from the line center and equidistant from the line extremities was chosen. The calculation of electromagnetic fields assumed the representation of the lightning channel as a vertical antenna over a perfectly conducting ground [8]. Finally, Agrawal's coupling model was applied to evaluate the interaction of lightning electromagnetic fields with the illuminated line [3].

Comparing the curves presented in Fig. 5, it is apparent that, if median characteristics are considered, subsequent stroke currents measured at Morro do Cachimbo station lead to much severer overvoltages than subsequent stroke currents measured at Mount San Salvatore, with differences of about 24% in the peak values. This indicates, in this particular case, a prevalence of the channel-base current amplitude upon the maximum current steepness in the determination of critical induced-voltage levels, although the higher time derivative of current waveform MSS.SUB is responsible for a reduction in the difference expected in the peak values of the calculated voltages. If waveforms MSS.SUB and MCS.SUB had the same average steepness, such difference would be in the same range observed for the peak values of the injected currents, i.e., around 33%. It is to be noted that the observed differences and the relative importance of the evaluated parameters also depend on factors such as ground conductivity, stroke location, nonlinear phenomena, line configuration, etc., which were not investigated in the given example for the sake of simplicity.

V. CONCLUSION

Waveforms, which are able to represent typical first and subsequent stroke currents measured at short instrumented towers, are proposed. Such waveforms are obtained analytically and present continuous-time derivatives. The main advantage of the proposed method is the possibility of representing double-peaked lightning currents in computational analysis.

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In-Circuit Characterization of Common-Mode Chokes

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Abstract—The two current probes measurement method was employed by other researchers to measure the radio-frequency impedance of ac power mains. In this paper, with a modified measurement setup, the method is extended to measure the common-mode (CM) impedance of a CM choke under in-circuit condition. With a premeasurement characterization process, the effect of the measurement setup can be determined and eliminated. The proposed measurement provides a more realistic assessment of the CM impedance characteristic of any CM choke under actual operating condition.

Index Terms—Electromagnetic compatibility, filters, impedance measurement, measurement, power filters.

I. INTRODUCTION

Common-mode (CM) chokes are crucial components in power line electromagnetic interference (EMI) filters for power-conversion products, such as switched-mode power supplies (SMPS) and uninterruptible power supplies (UPS). Besides parasitic parameters, different magnetic core materials may cause two apparently identical CM chokes to behave very differently under a specific operating condition [1].

Existing measurement methods measure the CM choke 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 CM choke is usually a pulsed dc current, the source and load impedance are also varying [4], [5]. To characterize a CM choke under a 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 CM impedance of the CM 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 premeasurement characterization process, the effect of the measurement setup can be easily

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Fig. 1. Basic setup of the two-current probe approach.

Fig. 2. Equivalent circuit of the two-current probe measurement setup.

eliminated, and therefore, good measurement accuracy of the proposed method is preserved.

II. THEORETICAL 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 analyzer. 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 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 measurement 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, and 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

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

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

where

$$Z_{M1} = \frac{(\omega M_1)^2}{Z_{p1} + j\omega L_1} \quad Z_{M2} = \frac{(\omega M_2)^2}{Z_{p2} + j\omega L_2} \quad V_{M1} = j\omega M_1 \left(\frac{V_1}{Z_{p1} + Z_1} \right).$$

Finally, the coupling circuit can be replaced by an equivalent voltage source V_{M1} in series with an equivalent source impedance Z_{setup} , where $Z_{\text{setup}} = Z_{M1} + Z_{M2} + j\omega L + (1/j\omega C)$. So, (1) can be rewritten as

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

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

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

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 $V_{M1} = j\omega M_1 V_1 / (Z_{p1} + Z_1)$ and (4) into (3) leads to

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

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

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

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

$$kV_1 = (R_{\text{std}} + Z_{\text{setup}}) V_2 |_{Z_X = R_{\text{std}}}. \quad (7)$$

If Z_X is replaced with a short circuit, one gets

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

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

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

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

$$Z_X = \frac{kV_1}{V_2 |_{Z_X = \text{unknown}}} - Z_{\text{setup}} \quad (10)$$

$$Z_X = \frac{(R_{\text{std}} + Z_{\text{setup}}) V_2 |_{Z_X = R_{\text{std}}} - Z_{\text{setup}} V_2 |_{Z_X = \text{unknown}}}{V_2 |_{Z_X = \text{unknown}}} - Z_{\text{setup}}.$$

Fig. 4. Measurement of large-resistance resistors.

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

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

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 (10) to ensure good measurement accuracy.

III. VALIDATION

To validate the proposed measurement method, Tektronic CT-1 (5 mV/mA, bandwidth 25 kHz–1000 MHz) and CT-2 (1 mV/mA, bandwidth 1.2 kHz–700 MHz) current probes are chosen as the injecting and monitoring current probes, respectively. The Agilent 4395A network analyzer is employed for the measurement. To obtain the frequency-dependent constant kV_1 for the two-probe measurement setup, a precision resistor R_{std} ($600 \Omega \pm 1\%$) is measured using the two-probe setup with a coupling capacitor of $2.2 \mu\text{F}$. After that, without any resistor, Z_{setup} is evaluated in accordance with (9). Once kV_1 and Z_{setup} are found, the coupling circuit is now ready to measure any unknown impedance. For validation purposes, a few resistors of known values are treated as unknown resistors and measured using the proposed method. Fig. 4 shows that, for resistors with resistance 600 Ω , 1, 5, and 10 k Ω , the measured resistance is in close agreement with the stated resistance of these resistors. For 5- and 10-k Ω resistors, the roll-off above 10 MHz is expected due to the parasitic capacitance that is inherent to resistors of large resistance. For comparison purposes, the magnitude of Z_{setup} is also plotted in Fig. 4. Based on the trend of impedance variation with frequency, the impedance of the coupling circuit Z_{setup} is capacitive in nature at low frequency because of the coupling capacitor. However, it becomes more inductive as frequency increases, which is due to the loop inductance of the coupling circuit. The inductive reactance can be as high as 40 Ω at 30 MHz. Hence, if the unknown impedance to be measured is low, it should be measured and determined in accordance with (10), so that Z_{setup} can be eliminated for better accuracy.

For resistors with resistance 2, 5, 10, and 25 Ω , the error due to the coupling circuit cannot be ignored, and Z_{setup} has to be subtracted from the measurement results for better accuracy. By subtracting Z_{setup} from the measurement results, the measured resistance has agreed very well with the stated resistance of these resistors, as

Fig. 5. Measurement of small-resistance resistors.

demonstrated in Fig. 5. Hence, the premeasurement characterization of the measurement setup serves as a good means to eliminate measurement error, due to the coupling circuit.

IV. IN-CIRCUIT MEASUREMENT OF CM CHOKE

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 a 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 behavior of the choke can be observed easily. Fig. 6 shows the measurement setup to characterize the CM choke. The circuit where the CM choke is inserted resembles that of a typical SMPS. The DM load circuit consists of a bridge rectifier, a 220- μF electrolytic capacitor, and a 100- Ω aluminum 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 is 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 value of 2200 pF is chosen because this is the typical value commonly used in SMPS or UPS for EMI filtering purposes. The radio-frequency (RF) signal is injected into the CM signal path through the injecting current probe, which is connected to port 1 of the network analyzer. The resulting radio-frequency (RF) signal in the CM signal path is measured by port 2 of the network analyzer via the receiving current probe. The CM impedance of

Fig. 6. Measurement setup to characterize CM choke under in-circuit operating condition.

the CM choke under test can be obtained using the procedure described in Section II. To ensure the impedance of the measurement setup of the CM signal path Z_{setup} is stable and repeatable, all the capacitors are mounted on a printed circuit board (PCB). Also, two fixed positions on the PCB are labeled for the placements of the injecting and receiving current probes. The wire connections on the PCB have been made as short as possible to minimize the loop inductance of the coupling circuit. 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.

Again, Tektronic CT-1 and CT-2 current probes are chosen as the injecting and monitoring current probes, respectively, and the Agilent 4395A network analyzer is employed for the measurement. The ac source used in the measurement is 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 a characterization of the measurement setup. Then, the CM choke is added to the measurement setup, as shown in Fig. 6. The CM impedance of the choke is measured in the frequency range from 50 kHz–10 MHz. In the frequency range of interest, the impedance of the measurement setup Z_{setup} is much smaller than the CM impedance of the choke, as shown clearly in Fig. 7. Fig. 8 shows the measured CM impedance of the choke under varying load current condition. When the peak magnitude of the current pulse is less than 5.21 A, the CM choke provides excellent CM impedance, with at least 1 k Ω up to 5 MHz. As usual, a self-resonate frequency of 336 kHz is observed. If the peak current is higher than 5.21 A, the CM impedance of the choke begins to decrease as a sign of core saturation. This behavior is clearly observed in Fig. 8, when the peak current is increased to 6.11 A. At this loading condition, the highest CM impedance has dropped from 24.5 to about 8.1 k Ω . Further, for an increase in peak current, for example, at 7.10 A, the choke practically offers no CM impedance at all.

V. CONCLUSION

Based on a two-probe measurement approach, the impedance of any CM choke can be measured under in-circuit condition with its actual operating configuration. The premeasurement calibration and characterization processes allow the measurement error contributed by the setup to be accounted for and eliminated. Hence, a good measurement accuracy can be preserved. The ability to observe the CM choke

Fig. 7. CM impedance and Z_{setup} .

Fig. 8. CM impedance of the CM choke under measurement.

characteristic under varying load current provides the designer a more complete picture of the EMI suppression performance of the CM choke, without the usual trial-and-error approach.

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