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A Dual-Current-Probe Method for Characterizing Common-Mode Loop Impedance

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Abstract **– The definition of common-mode loop impedance is proposed instead of the ambiguous definition of common-mode impedance. Moreover, a non-invasive measurement method to characterize the common-mode loop impedance using dual clamp-on current probe is presented herein. The frequency responses of the current probes are de-embedded through a calibration procedure. Independent direct measurements using a network analyzer corroborate the validity of the Dual-Current-Probe Method.**

I. INTRODUCTION

For a multi-wire transmission line above ground, the common-mode impedance looking into a load is the impedance that is seen if all wires are connected to each other. In real systems, the wires are not shorted to each other. As consequence, there is no unique common-mode impedance definition. Still, there is a unique common-mode current definition, i.e., the sum of all currents in the multi-wire transmission line is defined as the common-mode current, and is the current returning through the ground plane.

Although not uniquely defined, the common-mode impedance is used in a multitude of papers [1], [2], [3], [4] and EMC standards [5]. Dual current probe methods for measuring power line impedances and input impedances of electronic equipment under normal active conditions have been reported in [1], [2], and [3]. A method using two clamp-on current probes was developed in [4] to measure the common-mode and differential-mode noise source impedance of a switched-mode power supply (SMPS). Clause C.2 of CISPR 22 (1997) indicates that the ratio of the current in a 50 Ω loop to the current in a loop formed by the ITE cable bundle and the ground plane times 50 Ω yields the common-mode impedance of the ITE cable bundle [5]. This standard measurement requires the cable bundle to be disconnected from the EUT, and common mode grounded to the reference ground plane. However, these papers disregard the problems associated with the uniqueness of the definition.

The common-mode loop impedance is defined in this paper as opposed to the common-mode impedance. The problems of concern include in which cases the common-mode loop impedance and the common-mode impedance can be related, and how the common-mode loop impedance can be measured. The loop impedance is actually the impedance looking at one point into a setup consisting of a set of load impedances, a multi-wire or single-wire transmission line above ground, and a set of source impedances. The Dual-Current-Probe Method is proposed herein to measure the loop impedance, and the source and load impedance can be determined under some conditions, e.g., a single-wire case, or a balanced three-phase system.

This paper proposes a definition of the common-mode loop impedance of a single wire system and a multi-wire transmission line system in Section II and Section III, respectively. Section IV provides a transformer model for a dual current probe measurement setup and calibration procedure. The applications of this method to a single wire are described in Section V, while the application to a 3-phase cable in Section VI. Conclusions and more discussions are given in Section VII.

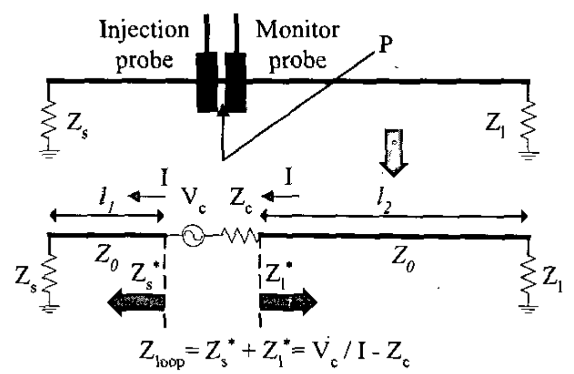

Figure 1. Circuit model employing lumped voltage source and impedance for the dual current probe clamped on a single wire.

II. LOOP IMPEDANCE OF A SINGLE WIRE SYSTEM

A single wire above ground terminated with a source and load impedance at the ends is illustrated in Figure 1, where V_c is the equivalent voltage generator, and Z_c is the series impedance introduced by current probes located along the single conductor at the approximate position of the clamps

[8], [9]. Further details about this circuit model are described in Section IV. Using transmission line theory, the loop impedance as seen from point P can be determined as

$$Z_{cm,loop} = Z_s^{*} + Z_l^{*} = \frac{V_c}{I} - Z_c, \qquad (1)$$

where the asterisk indicates that the termination at one end (Z_s or Z_l) has been transformed from its original location along the transmission line to the location P of the probes. If two current probes are attached to a wire-resistor loop, as shown in Figure 2, a network analyzer can be used to determine the loop impedance. If the transmission line parameters are known, i.e., the characteristic impedance Z_0, then the source and load impedances can be extracted when the Dual-Current-Probe measurement is made at two different locations along the wire.

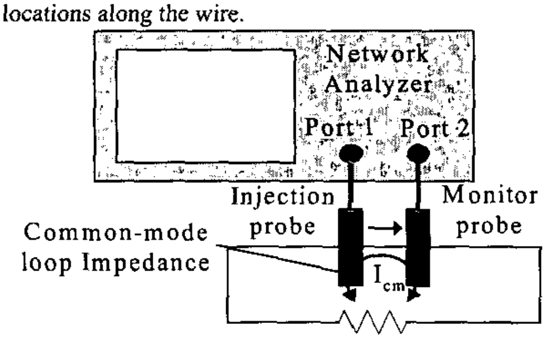

Figure 2. Common-mode loop impedance measurement setup for a single wire using the Dual-Current-Probe Method.

III. LOOP IMPEDANCE OF A MULTI-WIRE TRANSMISSION LINE SYSTEM

A multi-wire transmission line above ground is terminated with a set of source and load terminations at ends, as shown in Figure 3. The voltage sources exciting the line conductors and the introduced impedances into the lines are arranged into the excitation vector $\mathbf{V}_c$ and impedance vector $\mathbf{Z}_c$, since all the wires are closely spaced. The monitor current probe measures the common-mode current, which is defined as the summation of all the currents on each wire. Then the measured common-mode loop impedance of the multi-wire transmission line is

$$Z_{cm,loop} = \frac{V_c}{I_{cm}} - Z_c. \qquad (2)$$

In general, for a multi-conductor cable bundle, it is not possible to extract the equivalent common-mode source and load impedances, which are only a function of the set of source and load impedances ($\mathbf{Z}_s$ and $\mathbf{Z}_l$). Herein the common-mode loop impedance is not only a function of the set of sources and load impedances of the cable bundle, but also of the connecting wires.

A simple example illustrates the point. Assuming there are two identical black boxes A and B, both boxes have two identical wires (Wire 1 and Wire 2), as shown in Figure 4. In each box, Wire 1 is floating, and Wire 2 is shorted to the chassis. In the first measurement, as shown in Figure 4(a), Wire 1 of the Box A is connected to Wire 1 of the Box B, and Wire 2 of the Box A is connected to Wire 2 of the Box B. Assuming the length of the connecting wires are very short, then the measured common-mode loop impedance using the dual current probe should be equal to 0 Ω (or very small). However, in the second measurement, as shown in Figure 4(b), Wire 1 of the Box A is connected to Wire 2 of the Box B, and Wire 2 of the Box A is connected to Wire 1 of the Box B. In this case, since the common-mode current on the two wires is negligible, the measured common-mode loop impedance should be infinite (or very large) based on (2). Therefore, it clearly indicates that the result of common-mode loop impedance depends on not only the original source and load terminations of a multi-conductor cable bundle, but also the wiring connection. If the common-mode impedance is defined as the impedance when all wires are shorted to each other, then the true common-mode impedance of both black boxes is 0 Ω.

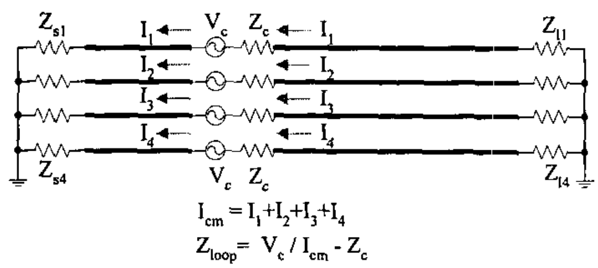

Figure 3. Circuit model employing lumped voltage sources and impedances for the dual current probe clamped on a multi-conductor cable.

As consequence, care needs to be taken in using the term common-mode impedance in a multi-wire transmission line. Not only the measurement is problematic, but also there is no unique definition of the common-mode impedance, although the common-mode current is still uniquely defined. This applies e.g., to EMC test standards like CISP22 and IEC 61000-4-6. In applying the work reported in [1], [4], and [5], care should to be exercised to ensure that the wires are all shorted to each other for the frequency of interest.

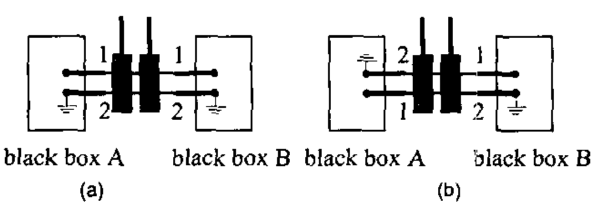

Figure 4. Schematic representation of a measurement setup for the common-mode loop impedance of a multi-wire cable: (a) The first measurement; and (b) the second measurement.

IV. PROPOSED MEASURING METHOD AND CALIBRATION PROCEDURE

The measurement of common-mode loop impedance uses two current probes clamped on the attached cable of the EUT, as shown in Figure 2. An injection current probe is connected to Port 1 of a network analyzer to drive a loop under test, while a monitor current probe connected to Port 2 of the network analyzer is used to measure the current in the loop. The two current probes are placed adjacent to each other, so the current measured with the monitor probe is assumed to be equal to the current injected into the loop by the injection probe. However, the injection impedance is not equal to the transfer impedance of the monitor probe in general. Consequently a calibration procedure is necessary to de-imbed the injection impedance from the measured results.

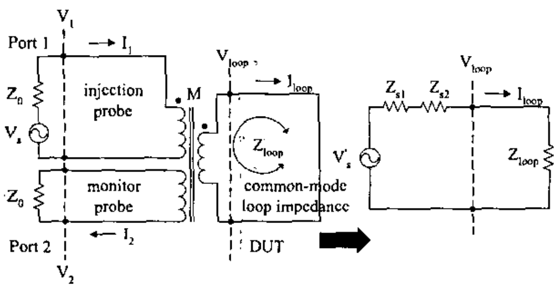

Figure 5. (a) Transformer model for the dual current probe measurement setup; (b)Thevenin equivalent circuit for the setup.

The injection current probe can be modeled as a transformer, as shown in Figure 5(a). Z_{loop} is an unknown common-mode loop impedance to be determined, Z_0 is the characteristic impedance of the network analyzer, 50-Ω, V_s is the internal voltage source inside the network analyzer, V_1 is the drive voltage applied at the terminal of the injection current probe by the network analyzer, I_1 is the current flowing in the coil of the injection current probe, I_{loop} is the current injected into the loop by the injection probe, I_2 is the current flowing in the coil of the monitor current probe, and M is a mutual inductance between the coil of the injection probe and the loop. Therefore, the system with two clamp-on current probes can be simplified to a Thevenin equivalent circuit shown in Figure 5(b), where $V'_s = j\omega MI_1$ is the Thevenin equivalent voltage source, Z_{s1} is the equivalent series impedance introduced into the loop by the injection current probe, Z_{s2} is the equivalent series impedance introduced into the loop by the monitor probe, and $Z_s = Z_{s1} + Z_{s2}$ is the Thevenin equivalent source impedance. The relation between these parameters can be expressed as

$$V_{loop} = j\omega MI_1 - (Z_{S1} + Z_{S2})I_{loop} \quad (3)$$
$$= V'_S - Z_S I_{loop} = Z_{loop} I_{loop}$$

Since I_1 and I_{loop} can be represented as

$$I_1 = \frac{V_1}{Z_{in}} = \frac{V_1}{Z_0}\frac{1-S_{11}}{1+S_{11}} \quad (4)$$

$$I_{loop} = V_2 / Z_T \ , \quad (5)$$

where Z_T is the transfer impedance of the monitor current probe. Substituting (4) and (5) into (3), a new equation is derived as

$$(Z_{loop} + Z_s)\frac{V_2}{V_1}\frac{1+S_{11}}{1-S_{11}} = j\omega M\frac{Z_T}{Z_0} = K(f) \quad (6)$$

where Z_0=50 Ω, and Z_{in} is the equivalent injection impedance of the injection probe. Since the mutual inductance M is approximately constant, and the transfer impedance of the monitor probe Z_T is defined for a specified current probe, the right hand side of (6) can be considered as a purely frequency-dependent parameter $K(f)$. Because the ratio of voltages at Port 1 and Port 2 can be expressed as

$$\frac{V_2}{V_1} = \frac{V_2^-}{V_1^+(1+S_{11})} = \frac{S_{21}}{1+S_{11}} \ , \quad (7)$$

(4) can be simplified as

$$(Z_{loop} + Z_s)\frac{S_{21}}{1-S_{11}} = K(f) \quad (8)$$

Two unknown parameters Z_s and $K(f)$ in (6) are associated only with the properties of current probes for a given frequency, thus, a calibration procedure is proposed to de-embed the two parameters. A 15-cm long and 1.5-cm wide copper tape forms a small calibration ring, which can be tightly wrapped around the two current probes, as shown in Figure 6. Two standard SMA terminations SHORT and LOAD (50 Ω) can be used in the procedure to construct two independent equations for extracting Z_s and K. For convenience, define

$$S = \frac{S_{21}}{1-S_{11}} . \quad (9)$$

An assumption is made that the loop impedance of the small calibration loop is negligible. More cares must be taken for the frequency range above 100 M Hz because this assumption is easily violated, as explained in the last section of this paper. Based on this assumption, the loop impedance of an unknown system can be determined as

$$Z_{loop} = (50\ \Omega)\frac{S_{50\Omega}}{S_{short} - S_{50\Omega}}(\frac{S_{short}}{S_{loop}} - 1) \quad (10)$$

where $S_{50\Omega}$ and S_{short} are the measured values of S when the terminations for the calibration ring are LOAD (50 Ω) and SHORT respectively, and S_{loop} is the measured value of S when the two current probes are clamped on the loop under test. A summary of the measurement procedure is:

- measure the S_{21} and S_{11} when the two current probes are clamped on the calibration ring terminated with the SHORT load, and calculate S_{short} using (9);

- measure the S_{21} and S_{11} when the two current probes are clamped on the calibration ring terminated with the LOAD (50 Ω), and calculate $S_{50\Omega}$ using (9);
- measure the S_{21} and S_{11} when the two current probes are clamped on the loop under test, and calculate S_{loop} using (9);
- obtain the common-mode loop impedance Z_{loop} of the unknown system using (10).

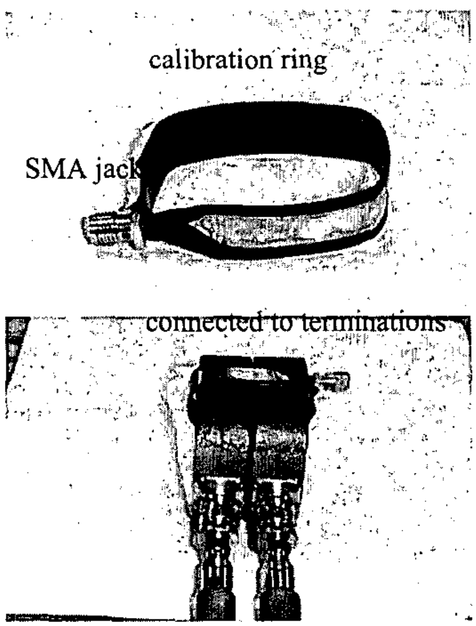

Figure 6. Photos of the calibration setup for de-imbedding the inherent parameters of the current probes.

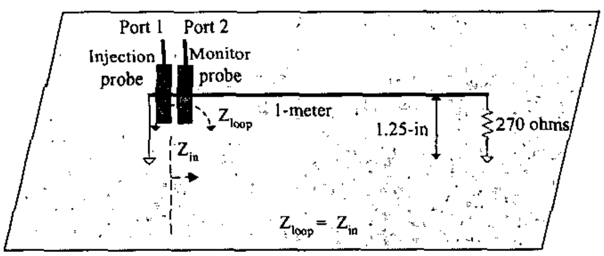

Figure 7. The common-mode loop impedance measurement setup using the Dual-Current Probe Method when the termination is 270-Ω resistive load.

V. APPLICATIONS TO A SINGLE WIRE

A transmission line was built by placing a 1-meter long wire (12 AWG) 1.25 inches above a large aluminum plate, as shown in Figure 7. The Dual-Current-Probe Method was used herein to avoid shortcomings of an invasive direct measurement, where the short end of the transmission line has to be disconnected and soldered to an SMA jack, and an impedance analyzer or network analyzer is connected to the jack. The measured impedance by the non-invasive Dual-Current-Probe Method agrees well with a direct measurement at the frequency range from 1 MHz to 60 MHz, as shown in Figure 8. Above 60 MHz, the magnitude difference is up to 2~3 dB Ω, and there is frequency shift at resonance peaks.

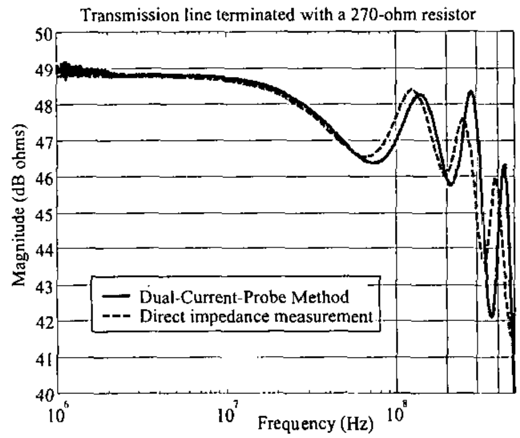

Figure 8. Common-mode loop impedance of the transmission line with a 270-Ω load.

The Dual-Current-Probe Method was applied to measure the common-mode loop impedance of the transmission line terminated with a capacitive load instead of the 270-Ω resistor. Figure 9 shows good agreement within 0.5 dB of the results obtained by the Dual-Current-Probe Method and direct measurement. However, above 100 MHz, there is a slight upward frequency shift at resonance peaks.

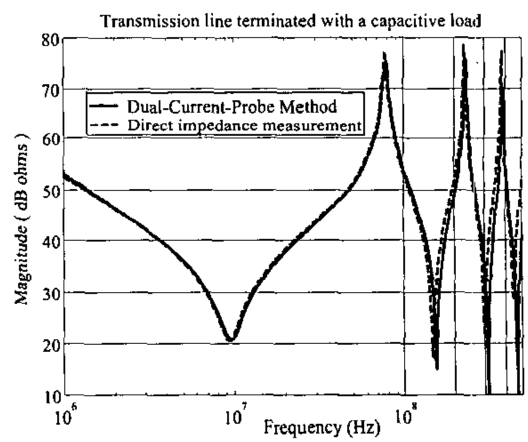

Figure 9. Common-mode loop impedance of the transmission line with a capacitive load.

The Dual-Current-Probe Method was also applied to a non-uniform transmission line, which was constructed by soldering a section of flat copper strip in series with a 12 AWG wire. This non-uniform transmission line had a total length of 1-meter and was spaced 1.25-inch above the large aluminum ground plane. In a resistive case, the transmission line was terminated with a 90-Ω resistor at the copper strip end and a 270-Ω resistor at the wire end, while two SMT capacitors were terminated at both ends in another capacitive case. Then, direct measurements were made for comparison by cutting the copper strip at the location of the injection current probe and soldering a short piece of semi-rigid coaxial cable in series with Port 1 of the network analyzer. The results of the Dual-Current-Probe Method and the direct measurements are shown in Figure 10 and Figure 11. The results agree favorably in the capacitive load case. However, for the resistive load case, the ripples in the result from the direct method are not seen in that from current probe method, though in general the difference is 1 dB or less. The Fisher F-61 current probe may be not sensitive enough at this frequency range. In addition, the upward frequency shift is noticeable in the results measured by the Dual-Current-Probe Method.

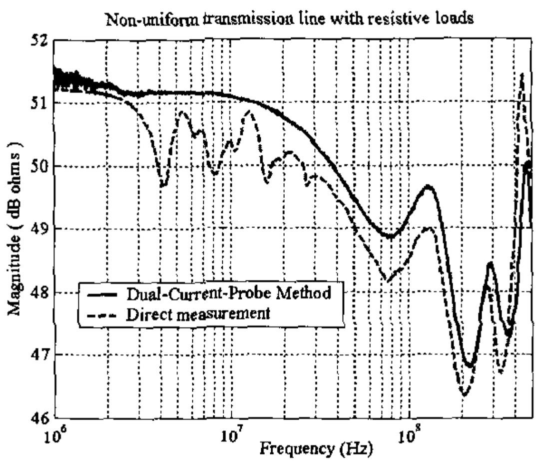

Figure 10. Common-mode loop impedance of the non-uniform transmission line with resistive loads.

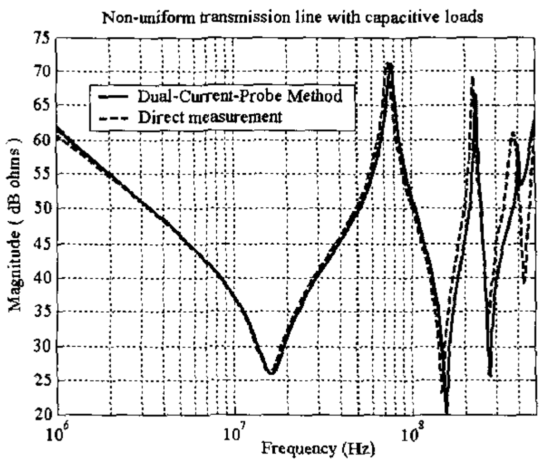

Figure 11. Common-mode loop impedance of the non-uniform transmission line with capacitive loads.

The effect of the current probes on the loop impedance of the transmission line was also investigated. The loop impedances of the non-uniform transmission line with and without the clamp-on current probes were measured directly by an impedance analyzer for both resistive load and capacitive load cases, as shown in Figure 12. The current probe does shift the resonance frequencies somewhat and also results in some differences in the measured impedance results.

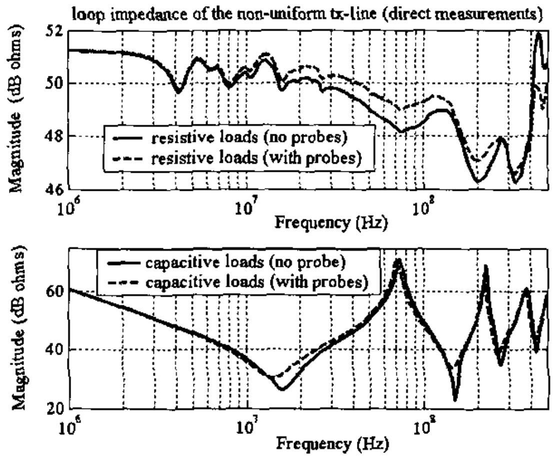

Figure 12. Loop impedance of the non-uniform transmission line terminated with resistive and capacitive loads measured by an impedance analyzer.

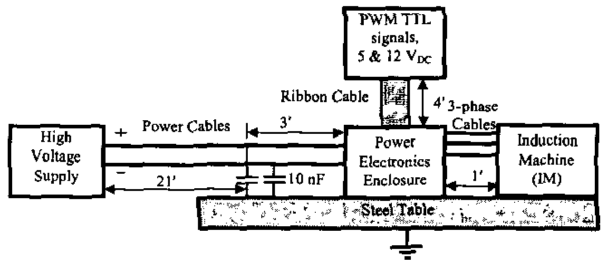

Figure 13. Schematic representation of a traction drive test setup.

VI. APPLICATION TO A 3-PHASE CABLE

The Dual-Current-Probe Method for determining the common-mode loop impedance was applied to a traction drive system, as illustrated in Figure 13. A 100V DC voltage provided from a Sorenson voltage supply was converted to 3-phase AC for driving an induction machine (IM) through a power electronic inverter. When the two current probes were clamped on the 3-phase cable at the power electronic enclosure end, the measured common-mode loop impedance is actually the cascade connection of three parts: a common-mode input impedance looking into the power electronics enclosure, a segment of 3-phase cable, and a common-mode input impedance looking into the induction machine. In addition, only a single current probe was also clamped on the 3-phase cable at the power electronic enclosure end for measuring the common-mode current. Both results are shown *in Figure 14, and minima of the common-mode loop* impedance correlate with maxima of the common-mode current.

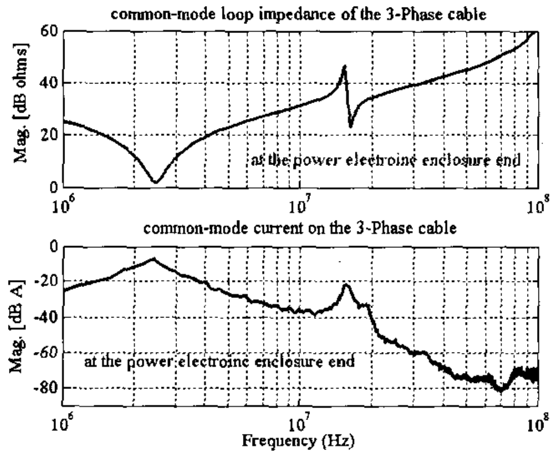

Figure 14.The common-mode loop impedance and common-mode current on the 3-phase cable at the power electronic enclosure end.

VII. CONCLUSIONS AND DISCUSSIONS

The Dual-Current-Probe Method has been experimentally verified to be an effective and non-invasive technique for measuring the common-mode loop impedance of an unknown system. However, it should be noted that the method is based on the transformer model of current probes and some higher order effects of current probes have not been considered, such as parasitic capacitance between wire and probes or coax cables, position of the wire within the clamp-on current probes, disturbance of the fields on the wire, etc. It indicates some aspects of the current probes need to be taken into account carefully with increasing frequency.

The calibration procedure for the Dual-Current-Probe Method is based on Equation (6). Herein for convenience, two standard SMA terminations SHORT and LOAD (50-Ω) were used to extract the two inherent parameters. Since the small calibration ring has approximately several nano-Henry self-inductance, the loop impedance can not be ignored above 100 M Hz (about several ohms at 100 M Hz). Further improvements in the calibration procedure are needed for achieving better results for the frequency range above 100 M Hz.

Finally, it is emphasized herein, that there is no unique definition of the common-mode impedance, although the common-mode current is uniquely defined. When only one wire is used, this is a true common-mode case. For a multi-wire transmission line having a set of source and load terminations, this can only be directly applied if all wires are shorted to each other. Instead of the ambiguous definition of the common-mode impedance, the definition of the common-mode loop impedance is clearly proposed in this paper.

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