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Transfer impedance simulation and measurement methods to analyse shielding behaviour of HV cables used in Electric-Vehicles and Hybrid-Electric-Vehicles

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Abstract. In the power drive system of the Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs), High Voltage (HV) cables play a major role in evaluating the EMI of the whole system. Transfer impedance (Z_T) is the most commonly used performance parameter for the HV cable. To analyse and design HV cables and connectors with better shielding effectiveness (SE), appropriate measurement and simulation methods are required. In this paper, Ground Plate Method (GPM) with improvements has been proposed to measure Z_T. Use of low-frequency ferrites to avoid ground-loop effects has also been investigated. Additionally, a combination of analytical model with a circuit model has been implemented to simulate limitations (frequency response) of the test setup. Also parametrical studies using the analytical model have been performed to analyse the shielding behaviour of HV cables.

1 Introduction

The Transfer impedance (Z_T) of a cable shield is considered as a benchmark of shielding performance, which has been used by communication cable industries for many decades now. It quantifies the immunity of a communication cable. In recent years, since the shielded cables are being used in EV and HEV, it has become important to measure the shielding performance against disturbances from the inner conductor(s). Established measurement methods (IEC-62153-4-1) such as Triaxial Method (IEC-62153-4-3) and Line Injection Method (LIM)(IEC-62153-4-6) are commonly used to measure Z_T. Triaxial Method requires for different dimensions of the cable, to rebuild a large partition of the test structure. Line Injection Method (LIM) is easier to apply, but Z_T measurement results are sometimes sensitive to different positions of the injection line, especially in case of non-symmetrical cables and connectors. To overcome some of these limitations in the measurements, Ground Plate Method (GPM) was developed to measure Z_T of high voltage cables and cable-connector systems (Mushtaq et al., 2013). Although, it had the flexibility to measure various types of shielded cables and cable-connector systems with different sizes and lengths using same test-setup, still some points had to be improved e.g. wider measurable frequency range and simple method of making the termination connections at far-end were required. Usually in the standards (e.g. IEC-62153-4) for 1 m DUT the maximum measureable frequency of Z_T is required to be up to 30 MHz, but to analyse Z_T of HV-cables and connectors, it is important to reach a higher cut-off frequency. FM radio reception is very important in automotive EMC and connectors can add inductances which are dominant at higher frequencies.

In this paper, further improvements in the GPM have been proposed. To increase the measureable frequency range of Z_T, use of matched terminations for the inner and outer circuits in the test setup has been suggested. Additionally, the GPM measurement precision has been increased, by using a simple method to create termination connections. Comparison of all three test-methods has been made and the results are discussed.

Apart from the measurement of Z_T, analytical methods to simulate Z_T of shielded cables using simple braid parameters are also very useful to predict shielding behaviour and improve the design of the HV cable and connectors systems.

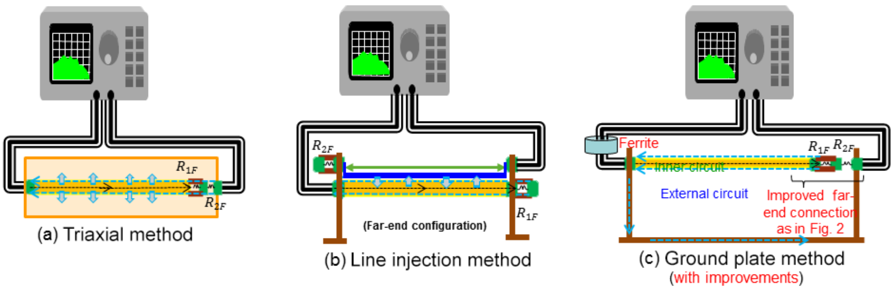

Figure 1. Comparison of test setups for **(a)** Triaxial Method, **(b)** Line Injection Method and **(c)** Ground Plate Method (GPM).

In this paper, an approach to build a simulation model based on cable geometry, cable materials, and transmission line theory has been proposed. Additionally, the simulation models have been used to show the effect of geometric variations, i.e. braid parameters (e.g. braid-wire thickness and weave angle on Z_T). The presented investigations are necessary for in depth electromagnetic analysis, improvements in the shield designs and for better understanding of the shielding behaviour of the HV cable-connector systems.

In this paper, Sect. 2 compares the existing measurement methods and gives details of the improved GPM, Sect. 3 describes the combination of analytical and circuit models, and Sect. 4 gives suggestions to improve Z_T of the HV cable and optimize GPM measurement setup, followed by concluding remarks in Sect. 5.

2 Transfer impedance measurement methods

Due to the complex structure of the braided shield, analytical models are not sufficient to describe Z_T (Qi et al., 2006). The most accurate method for determining Z_T is the measurement of complex braided shields (Sali, 2004). Commonly used test methods to measure Z_T as mentioned earlier are Triaxial Method and Line Injection Method (LIM) (ref. IEC-62153-4-1, 4-3, 4-6, 4-7 and 4-15). To use the Triaxial Method for measuring Z_T of the DUTs with different sizes and shapes, large test structures have to be rebuild (i.e. variable diameters and shapes of cables and connectors require variation in the tube size or cell size), which makes it a bit complex. Whereas the LIM is comparatively simpler method to apply, but due to variable positioning of the injection line (parallel wires) especially in case of non-symmetrical DUT (cables and connectors), inaccuracy could be a problem. Martin and Mendenhall (1984) proposed to use an additional braid (i.e. milked on braid method) to make outer conductor of the outer coaxial system instead of using an outer tube (IEC 62153-4 Annex C). But it is not applicable to large and non-symmetrical cable-connector system as the construction would be difficult and not easy to repeat. Among other research articles, Korovkin et al. (2003) and Hofmeister et al. (2013), proposed slight variation or improvements in Triaxial method, which may be used for variable lengths of cable (DUT). But the main issue of complex structure and termination connections for variable size of cables and connectors remains the same as in the standard Triaxial Method (IEC-62153-4-1, -4-3, -4-6, -4-7 and -4-15). Among other alternative methods, Krauthäuser et al. (2005) proposed a method to determine Z_T up to 1 GHz using a loop-method and adequate Green's function (analytical expressions) for the description of loop in the field inside the GTEM cell. This method can be used to measure Z_T for braided shield cables and semi-rigid cables but application to large and non-symmetrical automotive cable connector systems is difficult as Green's functions for each DUT needs to be defined in order to measure Z_T. To measure Z_T without the GTEM cell or Triaxial Tube for both HV cable and HV cable connector systems the Ground Plate Method, (GPM) was proposed (Mushtaq et al., 2013). For validation, improved GPM has been compared with Triaxial Method and Line Injection Method. The three methods have similar inner-circuits. As shown in Fig. 1, they differ mainly in the construction of the return path. Triaxial Method uses cylinder/tube (Fig. 1a), LIM uses parallel wires/injection line (Fig. 1b) and GPM uses ground-plane (copper-plate) as return path (Fig. 1c).

2.1 Ground Plate Method (GPM)

The two-port measurement setup of GPM can be seen in Fig. 1c. The cable shield is fixed to metal brackets, which are connected to the ground plane (copper-plate). It is important that all connections have very low impedance. The source port is connected to the HV-cable on the left-side (referred as "Near-End") and the receiver port is connected to the HV-cable on the right-side (referred as "Far-End"). To have maximum possible measureable frequency i.e. cut-off frequency ($f_\mathrm{CUT\text{-}OFF}$) for Z_T measurements, matched-matched configuration has to be used (IEC 62153-4-3, Annex E). This means the terminations R_1F and R_2F in Fig. 1c, should be selected to match the characteristic impedance of the source circuit Z_{01} and the receiver circuit Z_{02} respectively (i.e. $R_\mathrm{1F} = Z_{01}$ and $R_\mathrm{2F} = Z_{02}$). For GPM, in case of a symmetrical shielded cable (and in-line connectors), Z_{01} and Z_{02} may be calculated using the analytical formulae (Tesche et al., 1997), i.e.

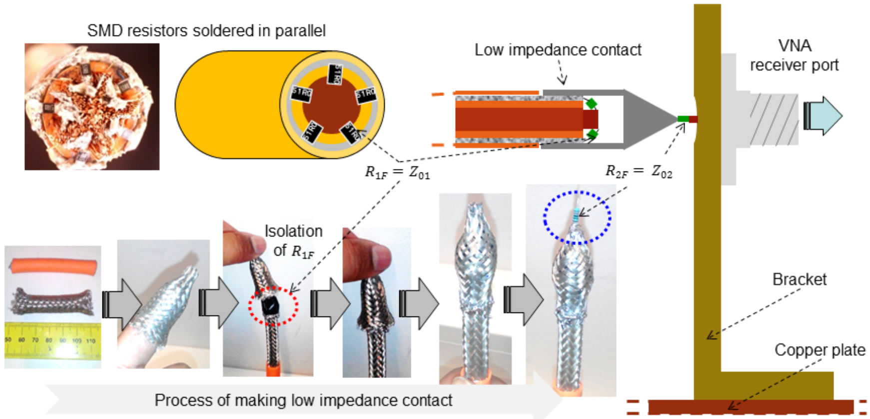

Figure 2. GPM: Improved way of making Far-end connection.

Eqs. (1) and (2), respectively.

$$Z_{01} = \sqrt{\frac{L_{\text{COAX}}}{C_{\text{COAX}}}}; \tag{1}$$

where $L_{\text{COAX}} = \frac{\mu_1}{2\pi} \ln\left(\frac{d_2}{d_1}\right)$ and $C_{\text{COAX}} = 2\pi\varepsilon_1 / \ln\left(\frac{d_2}{d_1}\right)$,

$$Z_{02} = \sqrt{\frac{L_{\text{WIRE-GND}}}{C_{\text{WIRE-GND}}}}; \tag{2}$$

where $L_{\text{WIRE-GND}} = \frac{\mu_2}{2\pi} \ln\left(\frac{4h_2}{d_2}\right)$

and $C_{\text{WIRE-GND}} = 2\pi\varepsilon_2 / \ln\left(\frac{4h_2}{d_2}\right)$,

where d_1, d_2 and h_2 are the diameter of the inner conductor, diameter of shield, and height of shield above ground plane respectively. Z_{01} and Z_{02} of the inner and the outer circuits may also be measured using VNA (Agilent E5061B, available at: http://cp.literature.agilent.com/litweb/pdf/5965-7917E.pdf) for Open/Short S-parameters measurements or TDR (Reflection measurements) (ref. IEC-62153-4-3, Annex A). After determining the required values of Z_{01} and Z_{02}, the termination loads R_{1F} and R_{2F} are connected physically as shown in Fig. 2. First R_{1F} is realised by connecting the Surface Mounted Device (SMD) resistors in parallel as they have less inductance. Individual value of the SMD resistor is: $R_{\text{SMD}} = m \cdot Z_{01}$; where m is the number of SMD resistors used in parallel. Five SMD resistors have been used to realize R_{1F} in GPM measurements as shown at the top-left corner on Fig. 2. After soldering and isolating the R_{1F} resistor, to make a low impedance contact (Bradley and Hare, 2009), an extra piece of braid from the same DUT is cut (3–4 cm) and used (as shown at the bottom of Fig. 2). Leads of the resistor (R_{2F}) are cut to reduce the series inductance in the external loop.

Z_T has been calculated from measured S-parameters using Eq. (3):

$$Z_{\text{T-GPM}} = \frac{V_{\text{Shield}}}{I_{\text{Source}} \cdot l_{\text{shield}}} = \left(\frac{(R_0 + R_{1\text{F}}) \cdot (R_0 + R_{2\text{F}})}{2 \cdot R_0 \cdot l_{\text{shield}}}\right) \cdot S_{21}, \tag{3}$$

where $R_0 = 50\,\Omega$, is the port impedance of the VNA (Agilent E5061B). In order to get a higher frequency range in the measurements, DUT with shorter length may be used, here $l_{\text{shield}} = 50$ cm has been used for all measurements. Whereas, for better sensitivity at lower frequency (as $Z_T = R_{\text{DC shield}}$), longer cables may be used to limit the dominance of the connectors (Morriello et al., 1998).

2.2 Comparison of Z_T measurement methods

Transfer impedance of a HV shielded cable (Coroplast 35 mm^2: braided-shield-diameter, $D_0 = 11.4°$ mm; Thickness of the braid-wire, $d = 0.2$ mm; number of wires in a carriage, $n = 8$; Number of carriages, $N = 24$; Weave-angle, $\psi = 30°$; Optical coverage min. 85 %) has been measured using a VNA (Agilent E5061B). In Fig. 3 results for transfer impedance measured using all three methods i.e. LIM (blue), Triaxial Method (green) und GPM (red), are shown. To show the effect of using matched terminations, Triaxial Method is shown twice, i.e. (1) Triaxial Method TUDO with matched-matched configuration and (2) Triaxial Method from the company Bedea with matched-short configuration using equipment described in Halme and Mund (2013).

Figure 3 shows, at low frequency measured Z_T is equal to the DC resistance of the shield ($R_{\text{DC shield}} \cong 3.6\,m\Omega/m$) up to f_{DC}, i.e. the frequency at which the ratio of the thickness of the braid-shield (Δ) and skin depth (δ) is much less than 1, i.e. $\Delta/\delta \ll 1$ (Vance, 1975). Above f_{DC} there is a decrease in Z_T up to minimum Z_T point ($Z_{\text{T-MIN}}$) i.e. $f_{\text{MIN}} =\sim 1.5$ MHz. As Z_T is a complex quantity at $Z_{\text{T-MIN}}$ Real$|Z_T| \geq$ Imag$|Z_T|$ and is usually present for shields with optimum

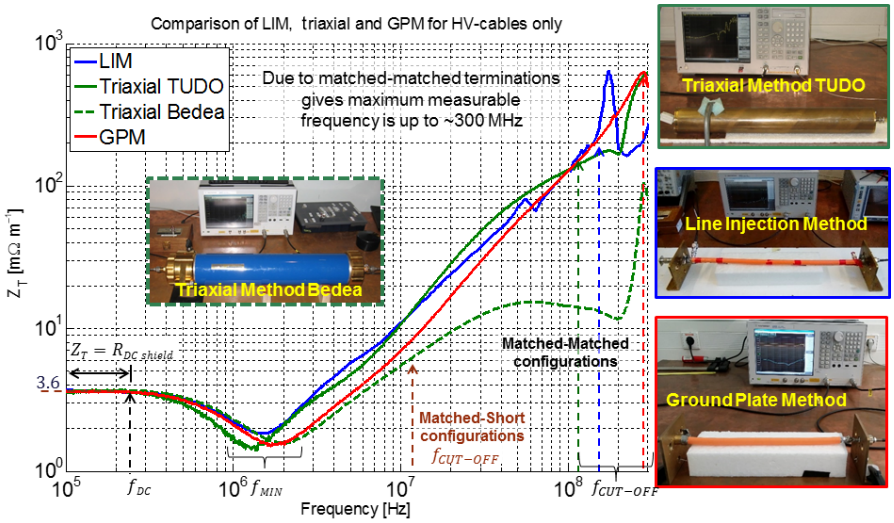

Figure 3. Comparison of Z_T measurement methods for HV-cable.

optical coverage (Sali, 1991). Minimum Z_T is achieved by reducing the difference between the hole (L_{HOLE}) and the braid (L_{BRAID}) inductances (Benson et al., 1992). After f_{MIN}, Z_T depends mainly on the braid inductances i.e. $Z_T \cong j\omega(L_{HOLE} \pm L_{BRAID})$ and Z_T rises again with 20 dB decade^{-1}.

Over the entire measured frequency range, the results from all three methods show qualitatively equal trend with little differences at higher frequencies except for Bedea Triaxial method (which has $f_{CUT\text{-}OFF} \cong 10$ MHz due to matched-short configuration). With matched-matched configurations, measurement results for HV cables up to $f_{CUT\text{-}OFF} = \sim 300$ MHz are achievable, above this frequency resonances start to occur due to physical dimensions of the test setup. As mentioned by Breitenbach et al. (1998) and Hohloch et al. (2010), mismatches in the outer circuit result in resonances at the receiver port. To overcome these, it is recommended to design the mechanical dimensions of the outer circuit such that, $Z_{02} = R_{port}$ (Breitenbach et al., 1998). With a simplified test setup maximum measurement is achieved up to $f_{CUT\text{-}OFF} = \sim 300$ MHz. Alternatively, method proposed by Krauthäuser et al. (2005) can be used, to estimate Z_T at higher frequency using the combination of field measurements in GTEM cell and green functions (analytical expressions).

3 Transfer impedance simulation methods

Due to complex structure of the braided shield, the measurements are the most reliable method of determining the Z_T (Sali, 2004), but the analytical models of Z_T are also useful for shielding analysis. Based on braid parameters, various analytical models have been developed for Z_T, like Tyni (1976), Demoulin et al. (1981), Sali (1991), Kley (1993), and Beatric Model (Schippers et al., 2011), etc. to predict the shielding characteristics of coaxial cables. These models have slight variations and modifications, based on the construction of the shield and mathematical simplifications. Modelling of Z_T may be divided into low and high frequency parts. At low frequencies, the mechanism for the linkage between the fields inside and those outside are due to diffusion of the magnetic currents induced in the shield and can be modelled as diffusion impedance (Z_d) (Vance, 1975; Sali, 1991; also shown in Eq. 5). With the increase in frequency, braid inductances become dominant. Based on the physical parameters of the shield hole and porpoising inductances can be calculated using analytical expressions (Eqs. 6 and 7, respectively) given by Tyni (1976) and Demoulin et al. (1981). It has been found in previous investigations (Mushtaq et. al., 2013) that comparatively Demoulin model (Demoulin et al., 1981; Demoulin and Kone, 2010, 2011), as per Eqs. (4)–(7), gives good approximation for HV shielded cable.

$$Z_{T\_DEMOULIN} = Z_d + j\omega \cdot (L_{HOLE}) - j\omega \cdot (L_{BRAID}) + k\sqrt{\omega}e^{+j\frac{\pi}{4}} \tag{4}$$

$$Z_d = R_{SHIELD}\frac{(1+j)\Delta/\delta}{\sinh\left[(1+j)\Delta/\delta\right]} \tag{5}$$

$$\text{and } R_{SHIELD} = \frac{4}{\pi d^2 n N \sigma \cos\psi};$$

Diffusion impedance

$$L_{HOLE} = \frac{2\mu_0 N}{\pi \cos\psi}\left(\frac{b}{\pi D_M}\right)^2 e^{-\left(\frac{\pi d}{b}+2\right)}; \tag{6}$$

Hole inductance

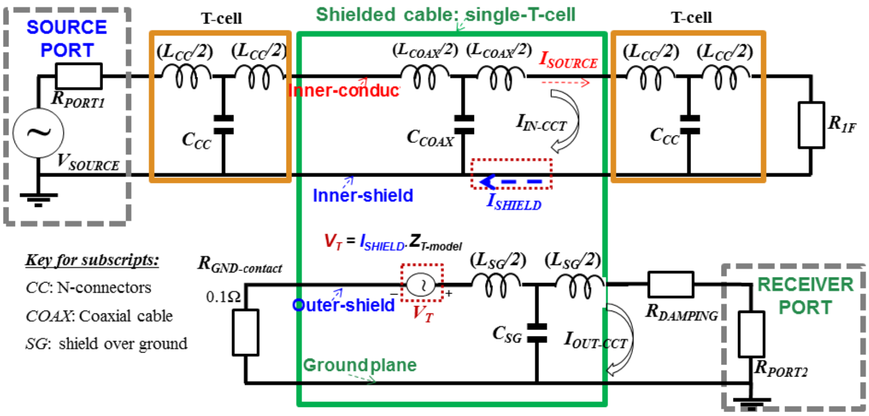

Figure 4. Combined analytical and circuit model for a shielded cable.

$$L_{\mathrm{BRAID}} = \frac{\mu_0 h_1}{4\pi D}\left(1 - \tan^2\psi\right) \tag{7}$$

and $k = -\dfrac{1.16}{nNd} \arctan \dfrac{N}{3} \sin\left(\dfrac{\pi}{2} - 2\psi\right)\sqrt{\dfrac{\mu}{\sigma}}$;

Porpoising inductance

Analytical models show an ideal behavior for Z_{T} i.e. Z_{T} increases at 20 dB decade^{-1} as $Z_{\mathrm{T}} = j\omega \cdot (L_{\mathrm{HOLE}} \pm L_{\mathrm{BRAID}})$ at higher frequencies without any limits, whereas in practice at higher frequencies, due to mismatches and higher modes of propagations, resonance is measured at the receiving port (summarized in coupling equations IEC-62153-4-1 and 4-3). Z_{T} may be estimated up to very high frequencies as proposed by Demoulin and Kone (2010, 2011) using mathematical expressions to add the effect of multiple wave propagation into analytical expressions. In this paper, circuit model has been proposed to simulate the variation in Z_{T} due to measurement setup at higher frequencies.

3.1 Circuit models to simulate measurement limitations

Transfer impedance analytical models are combined with circuit models. It simulates the variation in measured results due to measurement setup. The combined circuit model for shielded cable is implemented in the circuit simulation program QUCS (Quite Universal Circuit Simulator, http://qucs.sourceforge.net/). The circuit model shown in the Fig. 4, simulates the inner and outer circuits of the GPM test setup. For the inner circuit, the connecting cables and connectors have been added as lumped T-models. The value of inductances (L_{CC} and L_{COAX}) and capacitances (C_{CC} and C_{COAX}) for N-type-connectors and the coaxial cable are calculated using Eq. (1). For the external circuit the voltage at outer-shield is calculated using an analytical expression for Z_{T} from Demoulin et al. (1981) and the inner circuit current (I_{SHIELD}), i.e. $V_{\mathrm{T}} = I_{\mathrm{SHIELD}} \cdot Z_{\mathrm{T}}$. The value of the inductance (L_{SG}) and

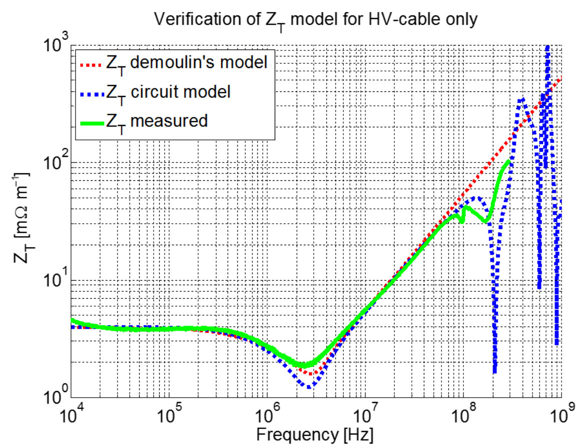

Figure 5. Verification of shielded cable model.

capacitance (C_{SG}) in the external circuit are estimated by using Eq. (2) for the shield over ground (Tesche et al., 1997).

Additionally, errors in the measurement setup due to imperfect connections can also be modelled using proposed circuit model.

Comparison of ideal analytical model, combined circuit model from 10 kHz to 1 GHz and measured results from 10 kHz to 300 MHz are shown in Fig. 5. Above $f_{\mathrm{CUT\text{-}OFF}} = 100$ MHz, resonance starts to appear in the measured and combined circuit simulation model. The benefit of combined circuit simulation model is to identify the limiting factors and physical effects of the test setup in measuring the Z_{T}. In future works, effects of HV connectors may be simulated using combined circuit model.

4 Analysis and optimization

In this section, use of analytical model and measurements to do shielding analysis for improving shielding designs are discussed.

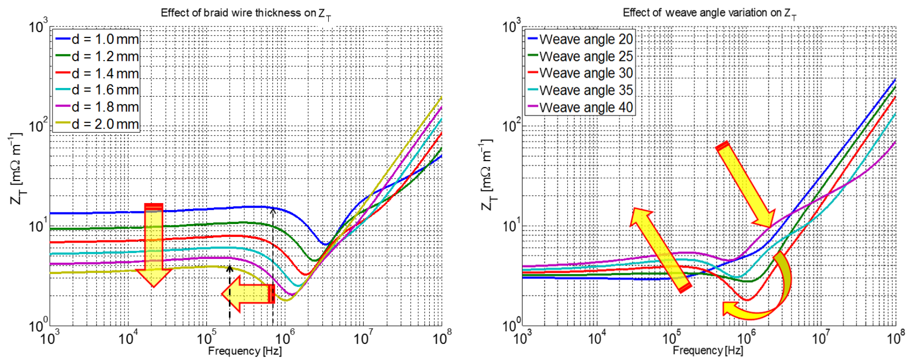

Figure 6. Effects of braid-wire thickness and variation in weave angle on Z_T. **(a)** $\Delta d = 0.1$ to 0.2 mm; **(b)** $\Delta\psi = 20$ to 40°.

4.1 Shielding design improvements using simulations

Based on the analytical model of Demoulin et al. (1981, i.e. Eqs. 4–7), effects of varying shield parameters (i.e. braid wire diameter (d) and weave angle (ψ)) on the shielding behaviour of the cables have been investigated individually. Braid thickness is kept small in order to keep the weight and material costs low, whereas weave angle is varied usually when optimizing the optical coverage of the shield. Both parameters are very important to get the optimized trade-off between cost and performance. To perform parametrical analysis, analytical model as per Eqs. (4)–(7), have been used for a shielded cable with $D_0 = 11.4°$ mm; $n = 8$; and $N = 24$ as constant and with variable braid-wire thickness and weave angle (as $\Delta d = 0.1$ to 0.2 mm and $\Delta\psi = 20$ to 40°, respectively).

As shown in Fig. 6a, variation of the single braid wire thickness affects the low frequency region, i.e. the resistive part of Z_T. With the increase in the thickness of braid-wire, Z_T decreases linearly. At higher frequencies, as the inductances are dominant, variation in braid thickness affects Z_T as per Eq. (6), (i.e. $L_{HOLE} \propto d^2$). Whereas variation in weave angle ψ, has a non-linear effect on Z_T, because weave angle varies the resistive as well as the inductive properties of the shield, (Eqs. 5–7). Variation in weave angle means difference in optical coverage of the shield and difference in length of individual braid wires used to build a shield. Usually, it is adjusted to give lowest dip in the Z_T curve (Sali, 1991), as shown in Fig. 6b, minimum Z_T is achieved when weave angle of 30° is used (i.e. $L_{HOLE} - L_{BRAID} \approx 0$),

4.2 Optimization of Z_T measurement

As discussed in current standards (IEC 62153-4-3, Annex-F), while using VNA (or when both source and receiver have the ground at same point), presence of ground loops affect the measurements results especially at low frequency ($f < 100$ kHz). In GPM, to overcome these measurement errors while using VNA (Agilent E5061B), low-frequency ferrites (i.e. Epcos B64290L40X830; see http://de.tdk.eu/inf/80/db/fer_13/R5830x4080x1760.pdf) have been used around the connecting cables on both the source and the receiver sides. Measurements of HV cable Coroplast 35 mm^2 using GPM are shown in Fig. 7.

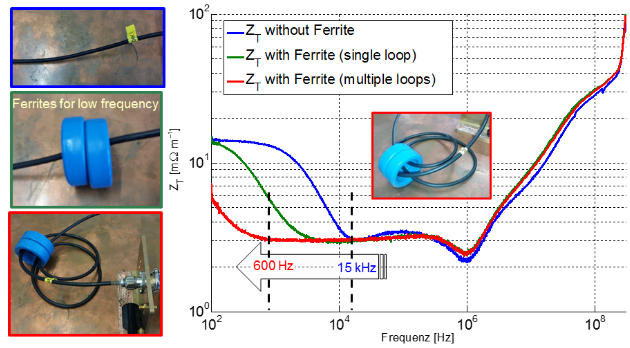

Figure 7. Improvements in the low frequency measurements using low-frequency ferrites.

Use of three windings through two ferrites lowers the starting measurable frequency down to 600 Hz. It was also observed that use of ferrites on either source or receiver side of the connecting cables (i.e. only on one side) is sufficient.

5 Conclusions

An alternative method, called Ground Plate Method (GPM), has been proposed with improvements for Transfer impedance measurements and is compared with Triaxial and Line Injection methods. Triaxial Method works well but with variable size of cables and connectors different sizes of measurement tubes or Triaxial cells are required. On contrary, Line Injection Method (LIM) gives a simple test setup but is not well suited for measuring Z_T of non-symmetrical cables and connectors. GPM can overcome the existing limitations. It could be shown that the GPM provides good measurement results up to approximately 300 MHz. Afterwards setup resonances appear due to the outer circuit structure. In order to cover the important FM frequency range a cut-off frequency above 100 MHz was needed. With consequent usage of matching circuits for the terminations, a cut-off frequency of close to 300 MHz could be reached.

For low-frequency measurements the influence of ground-loops could be reduced by using low-frequency ferrites. Apart from measurements an analytical Z_T model has been applied and was combined with a circuit model. It predicts the measurement setup limitations. Furthermore it has been shown, that the analytical model may be used for improving the shielding designs.

For future works and integration into existing standard like e.g. IEC 62153-4, additional steps to characterize and finalize physical dimensions of the test setup and measurement of different types of DUTs are required.

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