Alternative Methods to Measure Transfer Impedance of Shielded HV-Cable-Connector Systems for EV

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***Abstract*—In order to understand and design better shielding effectiveness (SE) of HV cables and connectors for electric vehicles (EV) and hybrid electric vehicles (HEV), appropriate measurement methods are required. Due to complexity and limitations in established methods, like Triaxial Method and Line Injection Method (LIM), alternative methods are required. Especially the connectors are difficult to handle in Triaxial Method. Equipment becomes extremely bulky and heavy. Line Injection Method (LIM) is sensitive to placement of the injection line along the connector. In this research alternative methods have been proposed to measure Z_T of shielded HV-cables and cable-connector systems. Two improved measurement methods, Ground Plate Method (GPM) and Capacitive Voltage Probe Method (CVP) have been developed to measure Z_T of both HV-cables and HV-cable-connector system. The methods have been verified by comparisons to Z_T measurements using Triaxial and Line Injection Methods. For comparative shielding analysis, Z_T of different HV-cable-connector systems have been evaluated. Performance and limitations of the methods for both cable and cable-connector systems are discussed.**

Keywords—Shielded HV-cable-connector system; Transfer Impedance measurement; Coaxial cable.

I. Introduction

In EV and HEVs, HV cables have been considered as one important structure for radiation caused by HV power electronics. Commonly, Transfer Impedance (Z_T) is used as a measure of shielding performance analysis for the shielded cables and connectors [1]. Z_T for shielded cable can be evaluated using existing analytical models, like, Vance, Tyni, Kley, and Demoulin models etc [3], but still the measurements are considered to give the most accurate values of Z_T [1]. For measuring Z_T, standard measurement methods are Triaxial Method [6] and Line Injection Method [7]. But due to non-symmetrical and variable sizes of HV-cable and HV-connectors used in modern EV and HEV, these methods have some limitations. Like for Triaxial Method, for variable sizes and shapes of cables and connectors, different size and structure of the Triaxial tube and Triaxial cell is required which makes it quite complex and expensive. Whereas in LIM, for non-symmetrical cables and connectors, different positioning of the injection lines over the DUT gives different Z_T results, due to which repeated measurements are required (at least 3 different positions as per [7]). This gives limitations of accuracy and makes the procedure time-consuming. Apart from these factors, usually for research purposes, it is difficult and expensive to follow complete standardized procedures. So, it is desirable to have some simplified Z_T pre-compliance evaluation methods which are accurate and easy to implement at laboratory level.

In this research, Ground Plate Method (GPM) [4] [5] with improvements and Capacitive Voltage Probe (CVP) Method have been implemented which overcome the limitations of existing methods. With the proposed methods it is easily possible to analyze bulky connectors. The test-setups can further be used and correlated with other measurements, like e.g. antenna or BCI. In this paper, first the Transfer Impedance and the influencing parameters are analyzed and discussed with a simulation model. Then, the proposed methods have been compared with existing methods. Z_T measurement analysis on shielded HV-cable-connector systems has been performed to demonstrate shielding improvements for HV-connectors.

II. Transfer Impedance

Alternative techniques to measure Z_T can be understood once the shielding mechanism and role of Z_T is clear. In this section, equivalent circuit of a shielded cable is shown which depicts the role of Z_T. Transfer Impedance (Z_T), is the intrinsic electromagnetic shielding property of cable, connector and backshells, defined by (1), dependent only on the physical properties and geometry of the shield and independent of the termination loads attached to the shielded cable [1] which makes it very important for EMC at component-level (i.e., improvements in shielding of cable and connectors).

$$Z_T = \frac{1}{I_{Shield}} \frac{dV_{Shield}}{dl_{Shield}} \ (\Omega/\text{m}) \Big\} \text{ Transfer Impedance} \qquad (1)$$

Lower value of Z_T means lesser induced voltage, meaning the shielding is better in avoiding the EM interference noise or vice versa. Figure 1 shows the equivalent circuit for a shielded cable with one end of the shield connected to the ground. The current flowing on the inner-shield is related to voltage induced on the outer-shield by Transfer Impedance Z_T of the shield (i.e., $V_T = I_{SOURCE}.Z_T$). This voltage is dependent only on the I_{SOURCE} (i.e., $I_{SOURCE} = V_{SOURCE}/Z_{INPUT\text{-}IMPEDANCE}$), and Z_T (i.e. dependent on the physical parameters and geometry of the shield only). As the external loop is open (except a capacitive coupling at higher frequencies), it can be assumed that there is no external ground current ($I_{OUT\text{-}CCT} = I_{GROUND}=0$).

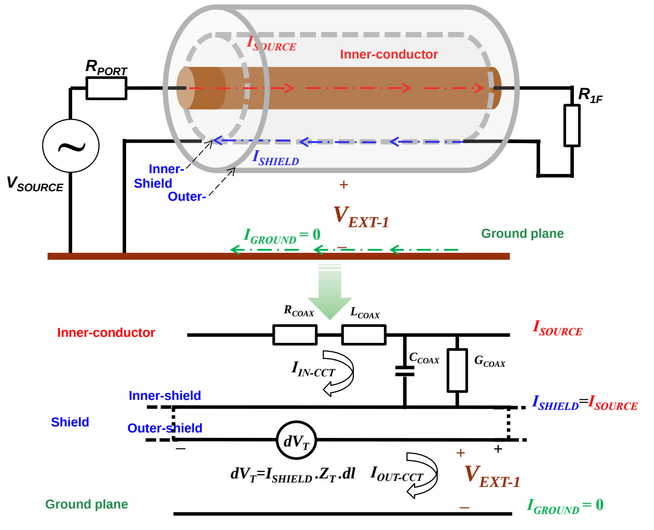

Fig. 1 Equivalent circuit-model for shielded cable

To predict the Z_T results using geometrical parameters for different shielded cables, various analytical models exist [3] [4]. Demoulin Z_T model [3] described by (2) to (6) has often been used to understand the Z_T characteristics.

$$Z_{T-DEMOULIN} = Z_{DIFFUSION} + j\omega\left(L_{HOLE} \pm L_{BRAID}\right) + k\sqrt{w}e^{+j\frac{\pi}{4}}; \tag{2}$$

$$Z_{DIFFUSION} = R_{SHIELD}\frac{(1+j)d/\delta}{\sinh[(1+j)d/\delta]}; \text{where } \delta = \sqrt{2/\omega\mu\sigma} \tag{3}$$

$$L_{HOLE} = \frac{\mu_0 2N}{\pi\cos\psi}\left[\frac{b}{\pi D_M}\right]^2 \exp^{\left[\frac{-\pi d}{b}-2\psi\right]}; \text{ where } D_M = D + 2d \tag{4}$$

$$L_{BRAID} = \frac{\mu_0 h}{4\pi D_M}\left(1-\tan^2\psi\right); \text{ where } \begin{cases} h = \dfrac{2d}{1+\left(w_h/d\right)} \\ w_h = \dfrac{2\pi D_M}{N}(\cos\psi - nd) \end{cases} \tag{5}$$

$$k = -\frac{1.16}{nNd}\cdot\arctan\frac{n}{3}\sin\left(\frac{\pi}{2}-2\psi\right)\cdot\sqrt{\frac{\mu_0}{\sigma}} \tag{6}$$

Figure 2, shows Z_T model, from Demoulin [3], for Coroplast 25 mm^2, a HV-cable (with shield-inner-dia. 'D_0'= 9.45mm; braid thickness 'd'=0.2 mm; No. of braid filaments 'n'= 7; No. of carriers 'N'= 24; Weave angle, 'ψ'= 34°), compared to a measurement with Triaxial Method [6]. For very low frequencies, current flow is uniformly distributed over the cross-section of the shielding conductor (braid-wire). As shown by region 1 (in grey) that Z_T is same as DC resistance of the shield [1]. The current density in braided shield is diffused in a similar way as in a solid cylindrical shield. With increasing frequency, the current density within the shield becomes non-uniform and depends on square-root of frequency due to skin-effects decreasing the Z_T as indicated by region 2 (in blue) i.e. $Z_{DIFFUSION}$ in [3] and [1]. With increasing frequency, eddy currents in the braid produce tangential E-field as shown by region 3 (in purple). After $f_{min\text{-}ZT}$ = ~2 MHz, Z_T is dominated mainly by the shield inductances (L_{HOLE} (4) and L_{BRAID} (5)) as shown by the region 4 (in red). Frequency point at which $Z_{T\text{-}min}$ occurs is different for each shield as it depends on respective shield inductances.

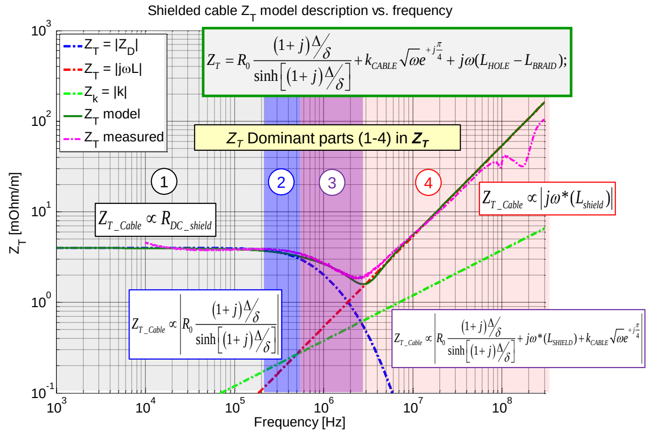

Fig. 2 Z_T Demoulin-model decomposed and compared to measurement

Due to complex structure of the braided shields, existing analytical models [3] give approximations for Z_T, but still the most accurate way is to measure Z_T which is described in the next section.

III. Z_T MEASUREMENT METHODS

The two established Z_T measurement methods are shortly discussed in this section and are compared to new methods which are described more in detail.

A. Triaxial Method and Line Injection Method

Established measurement methods like Triaxial Method [6] and Line Injection Method (LIM) [7] are commonly used test methods to measure Z_T. Triaxial Method is a complex test method as for 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). Whereas for LIM, inaccurate Z_T measurement results can be acquired due to variable positioning of the injection line (parallel wires) especially in case of non-symmetrical DUT (cables and connectors). For details refer to [6] and [7].

B. Ground Plate Method (GPM)

To overcome these limitations and problems, an alternative method "Ground Plate Method" (GPM) [4], [5] was proposed. Comparison of GPM circuit schematic with established methods has been shown in fig. 3. Source-circuit is same for all three methods, whereas in the receiver-circuit, Triaxial Method uses cylinder/tube, LIM uses parallel lines/injection lines and GPM uses ground-plane (copper-plate) as return path. Use of copper-plate in GPM, gives the test setup advantage of measuring Z_T of variable size/shape of cable and connectors. GPM has the flexibility to use same test-setup to measure both HV-cable and HV-cable-connector systems and it's easy to observe individual effects of cable and connectors separately.

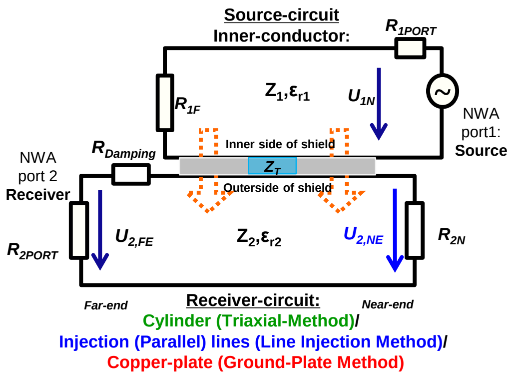

Fig. 3 Circuit schematics for Z_T measurement methods

In this paper, GPM with improved measuring conditions has been suggested. It has been proposed to use low frequency ferrites to allow Z_T measurements at very low frequencies (below 10 kHz) to overcome the influence of ground loops [6]. Whereas, in order to have highest possible measureable frequency for Z_T, terminations R_{1F} and $R_{Damping}$ should be selected to match the characteristic impedance of the source circuit Z_1 and receiver circuit Z_2 respectively i.e. $R_{1F} = Z_1$ and $R_{Damping} = Z_2$.

$$Z_1 = \sqrt{\frac{L'_{COAX}}{C'_{COAX}}};\text{where}\begin{cases} L'_{COAX} = \dfrac{\mu}{2\pi}\ln\left[\dfrac{d_{inner}}{d_{external}}\right] & \text{(H/m)} \\ C'_{COAX} = 2\pi\varepsilon_1 \Big/ \ln\left[\dfrac{d_{inner}}{d_{external}}\right] & \text{(F/m)} \end{cases} \quad (7)$$

$$Z_2 = \sqrt{\frac{L'_2}{C'_2}};\text{where}\begin{cases} L'_2 = \dfrac{\mu}{2\pi}\ln\left[\dfrac{4h}{d_{external}}\right] & \text{(H/m)} \\ C'_2 = 2\pi\varepsilon_2 \Big/ \ln\left[\dfrac{4h}{d_{external}}\right] & \text{(F/m)} \end{cases} \quad (8)$$

For GPM, Z_1 and Z_2 have been calculated using analytical formulae for coaxial cable (7) and for wire (shield) over ground (8) (with dimensions of the shield as hollow wire) respectively, as per fig.4.

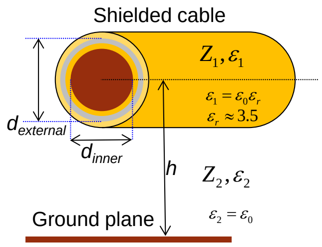

Fig. 4 Calculation of Z_{INNER} and Z_{OUTER} analytically

Another alteration in GPM test setup for HV-cable-connector system as DUT, is that, instead of using single cable-connector pair, two cable-connectors pairs in mirror configuration mounted over a connector-box (housing) have been used to easily make termination connections (with cables) at both sides (near- and far-ends) as shown in fig. 5. Agilent E5061B Network Analyser has been used to measure $S_{21\text{-}MEAS}$ for the test setup. With this GPM setup, Z_T has been calculated from measured S-parameters using (9), where $R_{Port1} = R_{Port2} = 50\ \Omega$, $R_{1F} = Z_1$ and $R_{Damping} = Z_2$.

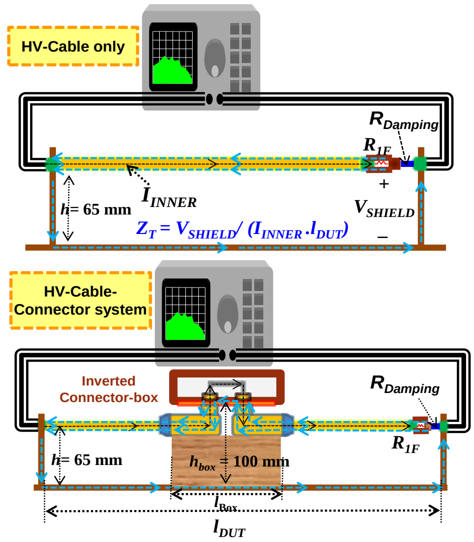

Fig. 5 GPM Test setups for HV-cable and HV-cable-connector system

The equation (9) can be derived from equivalent circuit of the complete test setup as well [4].

$$Z_{T\_GPM} = \frac{V_{shield}}{I_{source}\, l_{shield}} = \left(\frac{(R_{Port1} + R_{1F})(R_{Port2} + R_{Damping})}{2 \cdot R_{Port2} \cdot l_{shield}}\right) \cdot S_{21\text{-MEAS}} \quad (9)$$

C. Capacitive Voltage Probe (CVP) Method

For measuring directly the voltage over shield, Capacitive Voltage Probe (CVP) measurements (according to CISPR 16) can be performed. It functions similar to active-rod antenna, but with the flexibility to measure at any specific point along the shield, and with reduced influences of table or chamber.

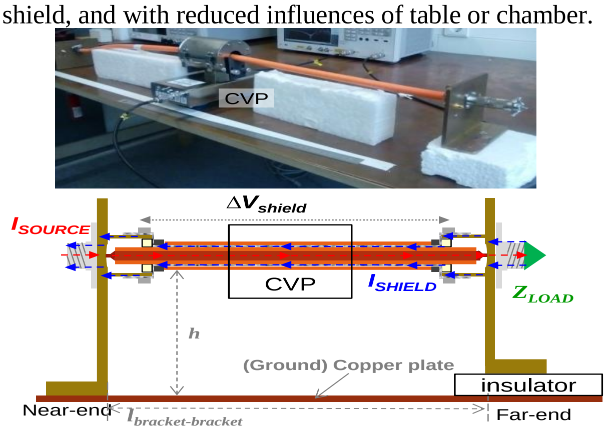

Fig. 6 Z_T measurement setup used for CVP

CVP measurements have been performed using the configurations shown in fig. 6, with CVP placed at the center of the DUT (cable) and insulator at far-end to get $I_{SHIELD} = I_{SOURCE}$ (so that: measured $V_{SHIELD\text{-}CVP} = I_{SHIELD} * Z_T$)

$$Z_{T\_CVP} = \left(\frac{Z_{port} + Z_1}{l_{shield}/2}\right) \cdot S_{21\_CVP}; \quad (10)$$

IV. Results and Analysis

A. Shielded HV-Cable analysis

Comparison of Z_T measurement results for shielded cable (Coroplast 35mm2), have been shown in fig. 7. GPM gives same Z_T results as that of Triaxial Method and LIM. Due to flexibility in matching the inner and outer circuits, GPM shows highest measurable Z_T. As discussed for Z_T model, measured Z_T shows, DC resistance of the shield at lower frequencies and later due to the skin effect, described by $Z_{DIFFUSION}$ in (3) shows the decrease in Z_T. After reaching minimum point at f~2MHz, Z_T rises again with 20 dB/decade due to the $j\omega(L_{HOLE}-L_{BRAID})$ as described by (4) and (5).

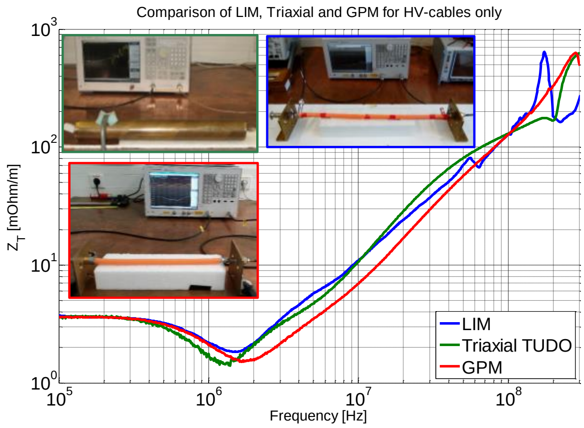

Fig. 7 Comparison of Z_T measurement methods for HV-cable

B. *Shielded HV-Cable-Connector system analysis*

After verification of GPM, shielding analysis of HV-cable-connector system has been performed using Z_T (GPM) (up to 300 MHz) for connector A, B and Dummy-box shown in fig. 8.

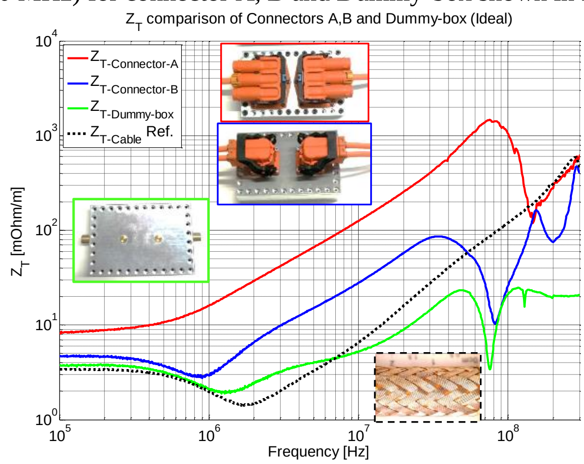

Fig. 8 Comparison of Z_T for different connector-systems

As per the results, compared to cable only, Z_T for cable-connector system has higher Z_T (higher overall shield resistance due to the additional contact points) at lower frequencies and as the frequency increases there is an early rise in Z_T due to additional inductance (i.e. due to non-symmetrical structure and larger structure of the connectors). Ideal dummy-box, showing lowest Z_T has been constructed with low-impedance and symmetrical shield contact points.

C. *Z_T using CVP Method*

CVP measures similarly voltage distribution (dV_T/dl) over the shield (as by GPM) upto 100MHz. For shielded cable RG58 (with shield-dia 'D_0'= 4.4mm; braid thickness 'd'=0.15 mm; No. of braid filaments 'n'= 5; No. of carriers 'N'= 24; Weave angle, 'ψ'= 21°), Z_T using CVP (shown in fig. 9), has been calculated from $S_{21\text{-}MEAS\text{-}CVP}$ using (10). Due to CVP frequency limitation and presence of parasitic effects in CVP, Z_T up to f~50MHz is measurable.

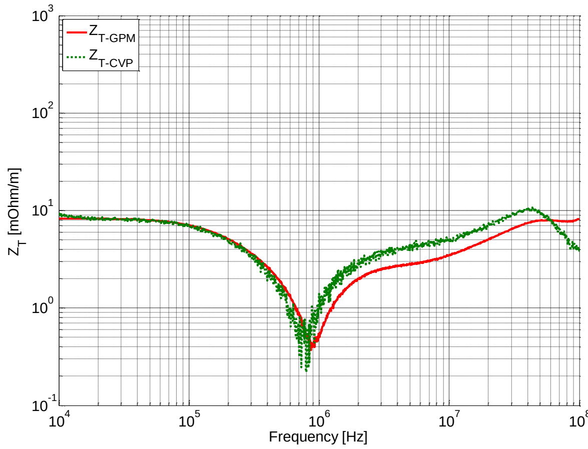

Fig. 9 Z_T using GPM and CVP

V. Conclusion

Shielding analysis of the HV-cable and HV-cable-connector systems has been performed with Ground Plate Method (GPM) and Capacitive Voltage Probe (CVP) Method. Z_T measurable frequency can be improved with suggested matched-matched terminations for both inner and outer circuits. Improvements in connector shielding designs have been suggested and verified by comparisons with ideal connector. Both proposed analysis techniques described in this paper may be used to predict, evaluate and improve the shielding performance of individual or overall HV-cable-connector systems.

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