Analysis of Shielding Effectiveness of HV Cable and Connector Systems used for Electric Vehicles

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***Abstract*—In order to understand and design better shielding effectiveness (SE) of HV cables and connectors for electric vehicles (EV), appropriate measurement methods are required. The Transfer Impedance Z_T is usually measured using Triaxial or Line Injection method. Based on a simplification of Triaxial method, a Ground Plate measurement method has been proposed to evaluate SE of cables and the cable-connector system. Results of proposed method have been compared to Triaxial method for cable only and Line Injection methods for the cable-connector system. Different approaches to analytically model the transfer impedance Z_T have been discussed. Dependency of weave angle and braid wire thickness on the shield performance has been simulated in order to better understand cable shield design. The document gives an overview of mathematical modeling techniques and existing measurement methods for Z_T. It proposes a simplified approach for evaluating Z_T for the complete HV cable connector system used in EV.**

Keywords— shielded cables, shielding effectiveness; elecrical vehicle; HV system; transfer impedance; EM modeling

I. INTRODUCTION

Cable and connector system for Electric Vehicles HV-applications should have an effective shielding. Various measurement setups have already been proposed to determine the shielding effectiveness of a HV cables. Most of them like the Line Injection method and the Triaxial method [1] originate from the testing of communication cables. HV-connectors are difficult to measure due to the large size. In order to find appropriate methods for HV automotive cable-connector systems, the known methods are systematically compared in this paper. Triaxial and Line Injection methods have been used to measure transfer impedance. Based on typical automotive measurement setups a Ground Plate method was developed and investigated. Its measurement results are compared with Triaxial method and Line Injection method for cable only and Line Injection method for the cable-connector system. It could be shown that the Ground Plate method can be a simple and robust possibility to specify the shielding properties of a cable connector system.

To support the measurement results, investigations in analytical models based on Vance, Tyni and Demoulin have been performed. The effect on the transfer impedance by varying the shield parameters was investigated. The simulation results have been compared with existing and proposed EMC test methods.

II. BASICS OF SHIELDED CABLES

As per [2] simple shielded cable can be electromagnetically modeled and represented using inner and outer circuits as shown in fig. 1.

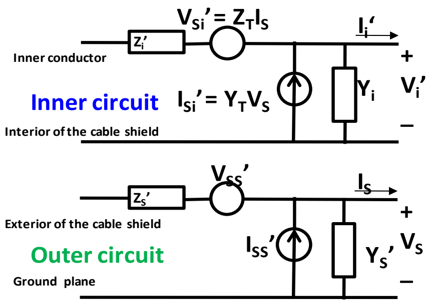

Fig. 1. Electromagnetic model of a shielded cable

It can be seen that inductive coupling can be represented as transfer impedance Z_T, whereas the capacitive coupling can be represented as transfer admittance Y_T. Electrical (capacitive) coupling and magnetic (inductive) coupling can be defined as (1, 2):

$$Z_T^{'} = \frac{1}{I_S} \frac{\partial V_i}{\partial x}\bigg|_{I_i=0} \quad (\Omega/\mathrm{m}) \Big\} \text{Transfer impedance} \tag{1}$$

$$Y_T^{'} = -\frac{1}{V_S} \frac{\partial I_i}{\partial x}\bigg|_{V_i=0} \quad (S/\mathrm{m}) \Big\} \text{Transfer admittance} \tag{2}$$

Often transfer admittance is assumed to be small. But for cables with braid shields, transfer admittance might be important. When frequency increases both the electric and magnetic fields can penetrate through the apertures thus both Z_T and Y_T are important to be considered. The apertures in the braid shield can be seen as small dipoles excited through the combination of electric and magnetic fields occurring inside the shield. Further details of such aperture polarizabilities due to electric and magnetic coupling are discussed in [2]. Out of two standard measurement methods described further in section III, Line Injection method has the ability to measure combined effect due of inductive and capacitive coupling.

III. Measurement Setups for HV Systems

The most commonly used measurement setups are the Triaxial method and the Line Injection method [1, 13] which are described shortly in the following subsections.

A. *Triaxial Method*

According to [1] Triaxial method can be used for measuring the transfer impedance of shielded cables at least up to 30 MHz. Figure 2 shows the equivalent circuit of the triaxial test setup. Outer circuit labeled with subscript 2, consists of outer shield surface and triaxial tube (cylinder) and measures the coupled signal at port 2.

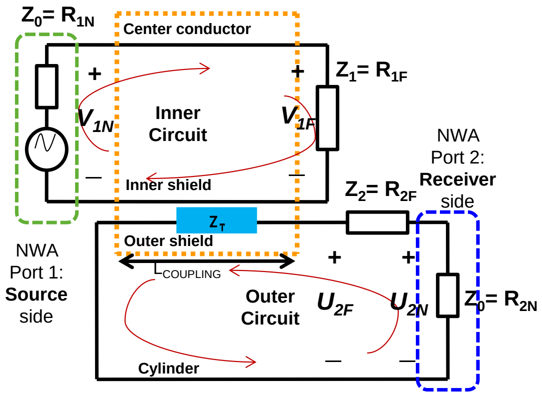

Fig. 2. Equivalent circuit of Triaxial test setup

Where:

R_{1N}, R_{1F}: Load resistance of inner circuit at the near and far end

R_{2F}, R_{2N}: Load resistance of outer circuit at the far and near end

U_{1N}: Voltage fed into the inner circuit at the near end

U_{2N}, U_{2F}: Voltage coupled into the outer circuit at near and far end

$$U_{2N} = \frac{R_{2N}}{R_{2N}+R_2}U_{2F} \rightarrow U_{2F} = \frac{R_{2N}+R_{2F}}{R_{2N}}U_{2N}$$
$$I_1 = \frac{U_{1N}}{R_{1N}} = \frac{k_m U_{1F,Meas}}{R_{1N}} \tag{3}$$

The inner circuit (including cable under test), labeled with subscript 1, is fed from source port labeled 1 of network analyzer (NWA). From fig. 2 and using (3-5) it can be seen how S_{21} parameters are used to find Z_T.

$$Z_T = \frac{U_2}{I_1 L_C} = \frac{R_{1F}\left(R_{2N}+R_{2F}\right)}{R_{2N}k_m L_C}\frac{U_{2N}}{U_{1F,meas}}$$
$$Z_T = \frac{R_{1F}\left(R_{2N}+R_{2F}\right)}{R_{2N}k_m L_C}10^{-\left[\frac{S_{21}(dB)}{20}\right]} \tag{4}$$

For simplicity and non-reference measurements, R_{2F} can be neglected and R_{1F} can be taken as 50 Ω for matched load. Then (4) gets simplified to:

$$Z_T = \frac{50}{k_m L_C}10^{-\left[\frac{S_{21}(dB)}{20}\right]} \tag{5}$$

B. *Line Injection Method*

As shown in fig. 3, the outer circuit, labeled by subscript 2, comprises of Line Injection circuit (Line Injection wire and outer shield of the cable under test). It is fed from source port 2 of NWA. The inner circuit labeled by subscript 1, consists of the cable under test is terminated with a matched load, where the induced voltage is measured at NWA port 1.

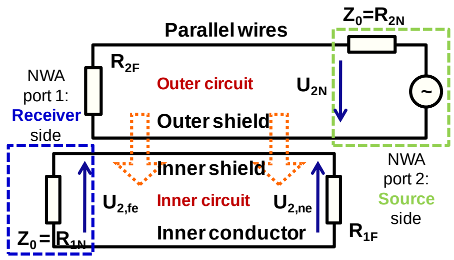

Fig. 3. Equivalent circuit of Line Injection measurement setup

The main difference between Line Injection and Triaxial setup is that, in Triaxial method the transfer admittance (through capacitance) is short circuited at the near end of the outer circuit. Whereas in the Line Injection both Z_T and Y_T are acting on the cable, we can measure equivalent transfer impedance Z_{TE}. Using the measurement process described in [1, 13], after matching both inner and outer circuits, we have:

$$Z_{TE_f^n} L_c = \frac{2U_{1_f^n}}{k_m I_2} = \left(Z_F \pm Z_T\right)$$
$$I_2 = \frac{U_{2,n}}{R_{2,f}} \text{ for } Z_T L_c \ll R_1 \tag{6}$$

$$Z_{TE_f^n} L_c = \frac{2U_{1_f^n}}{k_m U_{2,n}} R_2 = \left(Z_F \pm Z_T\right) \tag{7}$$

$$Z_{TE_f^n} = \frac{2R_2}{L_c k_m}10^{\left(\frac{-A_{T_f^n}}{20}\right)} \tag{8}$$

Usually the cable shields are not uniform, so it is recommended to perform the measurements at different angles. Here three angles 0°, 120° and 240° were used.

C. *Ground Plate method*

Based on the simplification of Triaxial method, a ground Plate method has been proposed which is explained in this section. In Triaxial method, a hollow cylinder is used which completes the outer circuit. Based on every DUT's size and shape, cylinder has to be customized i.e., re-designed and manufactured along with complex connections in order to accommodate the DUT properly, which can make Triaxial method costly and time consuming. So to overcome this problem, to consider voluminous connectors, and to comply more with standard automotive EMC set ups it is proposed to replace cylinder with ground plate. This does not change the network circuit as shown in fig. 2.

Mathematical analysis of the network circuit has been derived considering input and reflected waves at NWA ports and using fig. 2.

$$Z_T = \frac{V_{2F}}{I_1 L_{Coupling}} \Rightarrow$$

$$\frac{V_{2F}}{I_1 L_{Coupling}} = \frac{\left[\dfrac{2\sqrt{Z_0}}{2\left(R_{2N}/\left(R_{2N}+R_{2F}\right)\right)}\right]}{\left[\dfrac{2\sqrt{Z_0}}{Z_0+R_{1F}}\right]}\frac{b_2}{a_1} \quad (9)$$

where S_{21} (S-parameter)= b_2/a_1

$$Z_T = \frac{V_{2F}}{I_1 L_{Coupling}} = \frac{1}{L_{coupling}}\left(\frac{R_{1N}+R_{1F}}{2}\right)\left(\frac{R_{2N}+R_{2F}}{R_{2N}}\right)S_{21} \quad (10)$$

Generic formulation for Z_T is given in (10). Additional simplification of Ground plate method has been suggested by varying termination loads.

$$Z_T = \frac{1}{L_{coupling}}\left(\frac{R_{1N}+R_{1F}}{2}\right)\left(\frac{R_{2N}+\cancel{R_{2F}}}{R_{2N}}\right)S_{21} \Rightarrow \quad (11)$$

$$Z_T = \frac{1}{L_{coupling}}\left(\frac{R_{1N}+R_{1F}}{2}\right)S_{21}$$

If R_{2F} = 0, Z_T is calculated using (11) and if both R_{2F} and R_{1F}=0, then (12) can be used.

$$Z_T = \frac{1}{L_{coupling}}\left(\frac{R_{1N}+\cancel{R_{1F}}}{2}\right)\left(\frac{R_{2N}+\cancel{R_{2F}}}{R_{2N}}\right)S_{21} \Rightarrow \quad (12)$$

$$Z_T = \frac{1}{L_{coupling}}\left(\frac{R_{1N}}{2}\right)S_{21}$$

TABLE I. PARAMETERS OF THE INVESTIGATED HV CABLE

Geometrical parameter	***Symbol***	***Value***
Cross section of the inner conductor	A	35 mm²
Diameter of the braid	D_0	11.4 mm
Diameter of single braid wire	d	0.2 mm
Number of wires in carrier	n	8
Number of carriers	N	24
Weave angle	Ψ	30 degrees
Conductivity	σ	5.8x10^7 S/m
Coupling lengths used	Lc	0.4 m & 1.0 m

Figure 4 shows DUT used for cable-connector system measurement. Specifications of the measurement setup can be found in table 2.

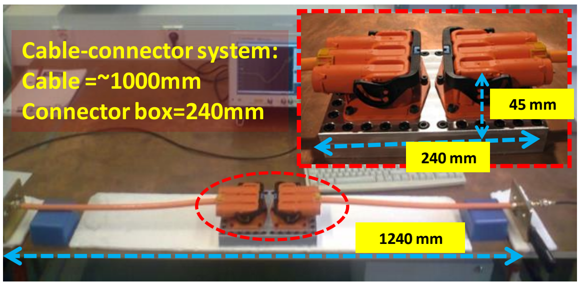

Fig. 4. Cable-connector system

TABLE II. SPECIFICATIONS FOR THE MEASUREMENT SETUP

<table>
<tr><th colspan="2">Measurement setup</th><th>Symbol</th><th>Value</th><th rowspan="2">Length</th></tr>
<tr><td colspan="2">For all measurements (Port input impedance)</td><td>R_{1N} & R_{2N}</td><td>50 Ω</td></tr>
<tr><td colspan="2" rowspan="3">Triaxial method</td><td>km</td><td>0.216</td><td rowspan="3">0.4 m & 1 m cable only</td></tr>
<tr><td>R_{1F}</td><td>13 Ω</td></tr>
<tr><td>R_{2F}</td><td>80 Ω</td></tr>
<tr><td colspan="2" rowspan="2">Line Injection method</td><td>R_{1F}</td><td>13 Ω</td><td rowspan="2">1 m cable only & 1.24 m cable-connector system</td></tr>
<tr><td>km</td><td>0.216</td></tr>
<tr><td rowspan="4">Ground Plate method</td><td rowspan="2">Matched setting</td><td>R_{1F}</td><td>50 Ω</td><td rowspan="4">0.4 m cable only & 1.24 m cable-connector system</td></tr>
<tr><td>R_{2F}</td><td>0</td></tr>
<tr><td rowspan="2">Short-circuit setting</td><td>R_{1F}</td><td>0</td></tr>
<tr><td>R_{2F}</td><td>0</td></tr>
</table>

IV. RESULTS & DISCUSSION

A. *Measurement results*

With Triaxial method for 1 m cable without a connector, two measurements were made, one without R_{2F} (simple / open) and other measurement result with R_{2F}. Using Line Injection method for 1 m cable only, measurements at three different angles (0°, 120° and 240°) were performed.

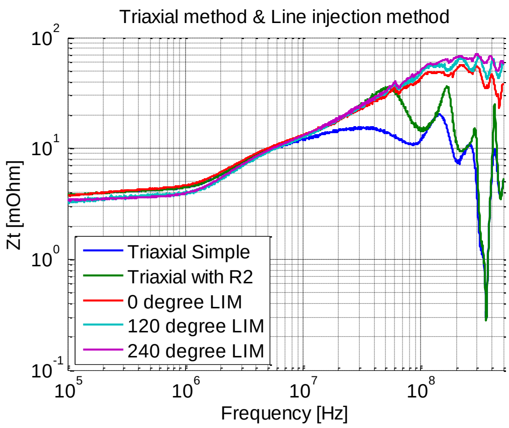

Fig. 5. Triaxial method and Line Injection comparison

In fig. 5 it is shown that the transfer impedance measured from the Triaxial method can be used up to 60 MHz maximum with impedance matching at R_2 and up to 20 MHz with Triaxial (simple), whereas transfer impedance measured from Line Injection results gives correct result up to 200 MHz after which first resonance take place.

From the difference in results for Triaxial measurements (simple and with R_2) it can be seen that mismatches cause decrease in frequency range of accurate results. For Line Injection method it can be seen, measurements with different angles have very slight variation, especially in this case, when the DUT has symmetrical structure. It can be deduced that, at lower frequencies, both Triaxial method and Line Injection method results are equally appropriate, whereas at higher frequencies, Line Injection method is better as at higher frequencies electric fields (capacitive coupling) can also penetrate through the apertures of the braid. To verify Ground plate method, its measured results for 400 mm cable were compared with reference Triaxial method and an 1240 mm cable-connector system was compared to Line Injection method.

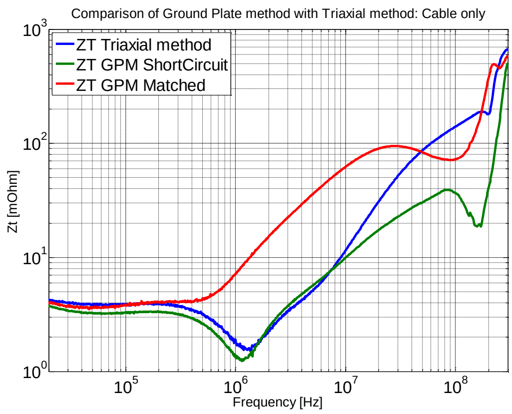

Fig. 6. Comparison of Ground plate method with Triaxial method

Figure 6 shows comparison of Ground plate method with Triaxial method for a cable with 0.4 m length only. It can be observed that Ground plate method with short circuit setting can produce similar results as Triaxial method.

Fig. 7. Line Injection measurement setup on cable-connector system

To investigate Ground Plate method on cable-connector assemblies, first Line Injection method is implemented on cable-connector system as shown in fig. 7, this is assumed as a reference measurement result.

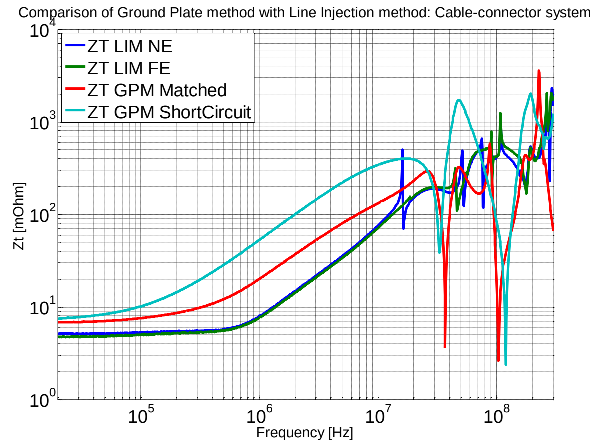

Fig. 8. Comparison of Ground Plate method with Line Injection method on cable-connector system (1240 mm)

In fig. 8, it can be observed that, both settings of Ground plate method have higher measured value for Z_T than the Line Injection method. Also the DC resistance seems to be higher, indicating a mechanical connection problem. It is assumed there is a solution, but more analysis is required in order to improve Ground Plate method.

V. Transfer Impedance Calculation

As the HV cables used are braided shield cables, only models for the braided shield are considered. In this section, models for simulating the braided shield cables, based on Vance, Tyni and Demoulin are presented and discussed [4-6]. The effects of particular geometrical parameters which affect the measurements of shield performance are shown. Before analyzing the models, it is necessary to understand the basics of braided shields used for electromagnetic shielding purpose. As analyzed in [3], a metallic braid can be described completely by 6 parameters of a cable shield, these are Braid shield diameter (D_0), braid wire diameter (d), number of carriers in shield (C), number of wires in single carrier (n), conductivity of the braid material (σ), and weave angle (α).

A. *Vance Model*

As shown by Vance [7], transfer impedance of a braided shield can be calculated as:

$$Z_t = Z_d + j\omega L_h \tag{13}$$

Where Z_d covers the diffusion of magnetic fields through the sheath and hole inductance L_h covers the penetration of magnetic fields through the apertures in the metal braids.

$$Z_d = R_0 \frac{(1+j)d/\delta}{\sinh[(1+j)d/\delta]} \tag{14}$$

Where d is braid-wire diameter and R_0 is the per-unit-length braid resistance, skin depth (δ) as described by (15):

$$\delta = \sqrt{2/\omega\mu_0\sigma} \tag{15}$$

$$R_0 = \frac{4}{\pi d^2 n C \sigma \cos\alpha} \quad (16)$$

In [8, 14] a simplified relationship for L_h has been used:

$$L_h = \frac{\mu_0 2C}{\pi \cos\alpha}\left[\frac{b}{\pi D_M}\right]^2 \exp^{\left[\frac{-\pi d}{b}-2\right]} \quad (17)$$

Where b is the hole width.

B. Tyni Model

In addition to Vance model, [9, 10] Tyni proposed (18), in which an additional term is added for considering the effects of braid inductance.

$$Z_t = Z_d + j\omega(L_h - L_b) \quad (18)$$

Where L_b is the transfer inductance which arises due to the woven nature of the braid. It is the magnetic leakage occurring at the junction of the braids composing the carrier wires.

$$L_b = \frac{\mu_0 h}{4\pi D_M}\left(1-\tan^2\alpha\right) \quad (19)$$

Where D_M is the mean braid diameter i.e., $D_M = D_0+2d$ and h is the radial spindle separation.

C. Demoulin Model

In [11, 12], Demoulin has proposed (20), a generic model for the braided shield cable transfer impedance, which consist of four terms where the additional term is further defining porpoising effect with depending of Z_T on $\sqrt{\omega}$:

$$Z_t = Z_d + j\omega L_h + k\sqrt{\omega}e^{+j\frac{\pi}{4}} \pm j\omega L_b \quad (20)$$

Where sign of L_b is positive for α > 45º and is negative for α < 45º. A real co-efficient k which depends on braid parameters and symmetry was introduced. If α = 45º, the inductance due to the woven nature of the braid is zero i.e., $k \approx 0$. For α < 45º the following simplified model can be used:

$$Z_t = Z_d + k\sqrt{\omega}e^{+j\frac{\pi}{4}} - j\omega L_b \quad (21)$$

where $$k = -\frac{1.16}{nCd}.\arctan\frac{n}{3}.\sin\left(\frac{\pi}{2}-2\alpha\right).\sqrt{\frac{\mu}{\sigma}} \quad (22)$$

D. Comparison of Simulation Models

All three simulation models have been implemented using the parameters given in table 1. Comparison of simulation models is shown in fig. 9. It can be seen that for the investigated particular braided shield cable, both Tyni and Vance models are almost similar whereas Demoulin model has difference due to the additional k and $\sqrt{\omega}$ terms added to represent the opposing eddy currents flowing in the braided shield wire which varies the curve with increasing frequency. After cut-off frequency, diffusion and inductive effects play dominant role causing variation in Z_T. Figure 9 shows also comparison of reference Triaxial method with simulation models.

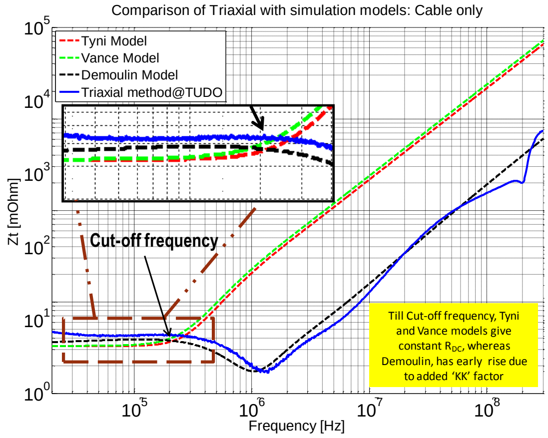

Fig. 9. Comparison of Triaxial method with simulation results

It can be observed that the simulated result for Demoulin model is very similar to the measured results. Figure 10 shows slight difference between Demoulin model, Triaxial and Ground Plate method with short circuit setting.

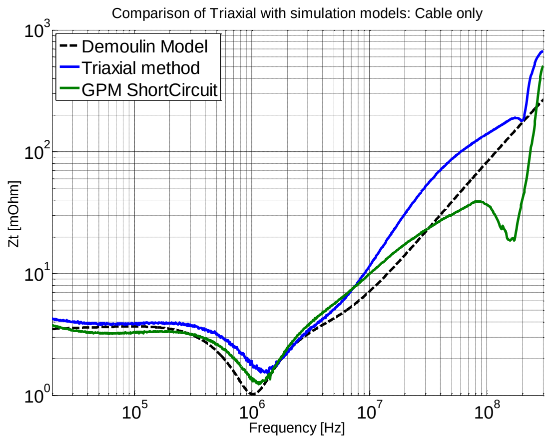

Fig. 10. Comparison of Triaxial and Ground plate with Demoulin)

E. Variation of Geometrical Parameters

In [3] dependency of Z_T on spindle distance variation (h) has been discussed along with other parameters. In this paper the two factors weave angle α and braid wire diameter d, which indirectly affect the cost of the cable, are analyzed. Braid wire thickness was varied from 0.1 mm to 0.2 mm and weave angle from 20° to 35° in the simulation model. As shown in fig. 11 and also evident from (8-14) α plays an important role and can be adjusted to give lowest dip in the Z_T curve for optimized braid. For optimized braids, inductive effects are adjusted in order to cancel out each other to give a lowest value to Z_T. In this DUT case, 29 degree is the optimized value of the weave angle, while keeping all other parameters same.

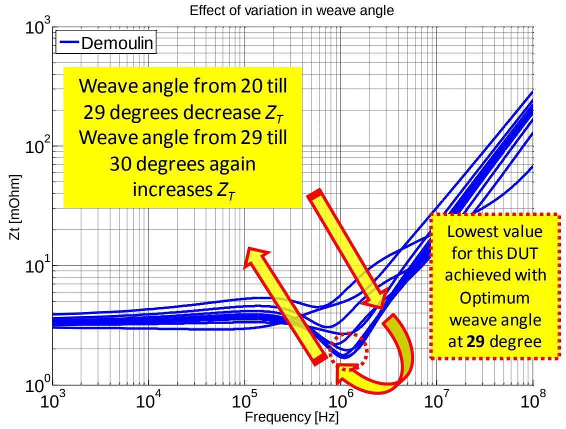

Fig. 11. Effects of variation in weave angle 20º to 35º

Variation of diameter of single braid wire has greater effect on the resistive part and diffusion part (skin effect) of the transfer impedance as shown in fig.12. For good shielding and achieving lower values of Z_T, braid wire diameter can be optimized against the weight and cost requirements.

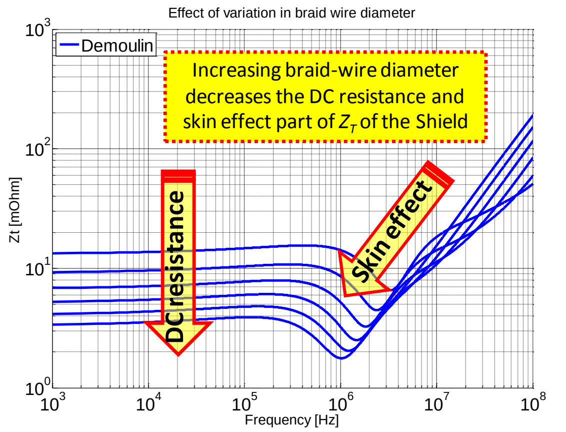

Fig. 12. Effects of variation in braid-wire diameter 0.1 mm to 0.2 mm

VI. CONCLUSIONS

The different measurement methods for shielding performance of shielded cables have been analyzed and compared. In order to cater for both cable and large connector systems, a new Ground Plate method has been proposed, which has been compared with Triaxial and Line Injection methods for both cable only and cable-connector systems. For Triaxial method, measurements up to 60 MHz are possible. For Line Injection method three different angles were investigated for measuring the transfer impedance. As the cable was coaxial having symmetrical field distribution, the measured shield performance at all angles is similar. Method seems to be valid for HV cables up to approximately 200 MHz. When comparing both Triaxial and Line Injection methods together, for lower frequencies below 50 MHz, they give similar results. Above Line Injection method provides better results. Proposed Ground Plane method has been compared with Triaxial method with similar results with short circuit setting for the cable. For cable connector system comparison was done between Groud Plane method and Line Injection method. Here a difference of 2 mΩ till cut-off frequency, and early rise in Z_T with frequency could be observed. It is assumed that there is a connection problem in setup. More analysis is required in order to reduce the differences.

Furthermore simulation models for HV braided shielded cables have been reviewed and verified with measurements. Dependency of transfer impedance on the weave angle and braid-wire diameter has been analyzed.

ACKNOWLEDGMENT

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