Comparative Study of Transfer Impedance (Z_T) Measurement Methods and Simulation Models to Analyze Shielding Behaviour of High Voltage Cables in Electric Vehicles

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- Introduction
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- Measurement methods
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Motivation

Problem Overview

- In Electrical Vehicles (EV) and Hybrid-Electrical Vehicles (HEV)
  - Power drive systems, inverters convert and provide PWM signals at high voltage ($V_{\text{peak-to-peak}} \geq 300V$) to drive the E-motors via HV-cables (shielded power cables)
  - EMI noise signals from these HV-cables may cause malfunction of LV electronics devices, MCUs, vehicular communication networks (LIN, CAN, Flexrays, MOST, etc), AM Radio, etc

- Optimum shielding of the HV-cables and HV-connectors
Motivation

Steps:

■ How to evaluate shielding performance of HV-shielded cables?
  ■ Shielding Effectiveness vs. Transfer Impedance

■ Shielding Effectiveness (SE)
  ■ Is a measure for the not just shielded cable, but also depends on external parameters
  ■ For the same shield, we can get different SE by varying the external parameters
  ■ Good for overall integrated system shielding analysis

■ Transfer Impedance ($Z_T$)
  ■ Is an intrinsic property of the shield, and doesn’t depend on external parameters
  ■ For the same shield, $Z_T$ is independent of external parameters like termination load, external layouts, etc.
  ■ Good for component level shielding analysis

Main focus of this talk is on $Z_T$:

■ Predicting Transfer Impedance using simulation and measurement methods
**Motivation**

**Basic Terminology**

- Transfer Impedance \( Z_T \)
  - It is defined as:
    \[
    Z_T = \frac{dV_{\text{SHIELD}}}{I_{\text{SHIELD}} \cdot l_{\text{SHIELD}}}
    \]

**Measurement method**

Based on above formula, various test setup have been proposed (Triaxial Method and Line Injection Method)

**Simulation methods**

Based on braid parameters, dimensions, \( Z_T \) can be predicted

Based on circuit models
Content

- Introduction
- Measurement methods
  - Existing methods
  - Ground Plate Method (GPM)
  - Capacitive Voltage Probe (CVP) Method
- Simulation methods
- Conclusions
**Measurement methods**

**Existing methods**

- $Z_T$ measurement methods
  - Triaxial Method (IEC 62153-4-3)
    - Complex structure for variable sizes and connectors
    - Variable size of tubes require for different sizes and shapes, specially for connectors
  - Line Injection Method (LIM) (IEC 62153-4-6)
    - For non-symmetrical cables and connector assemblies, different positioning of the injection wires can cause inaccuracy in measured results
Use of alternative methods to measure $Z_T$

- For shielding analysis of HV-cable-connector systems, it should be
  - Flexible to measure $Z_T$ of non-symmetrical samples and large connectors
  - With maximum accuracy and better repeatability/reproducibility

- To overcome these issues in HV-cable-connector analysis, following methods are used:
  - Ground Plate Method (GPM)
    - Overcomes the limitation of the existing methods
    - Flexible to measure $Z_T$ of non-symmetrical samples and large connectors
    - Ability to correlate with Antenna measurements with least variation in test setup
  - Capacitive Voltage Probe (CVP) measurement
    - Direct measurement of Voltage over the shield
    - Transfer Impedance can be approximated using both voltage and input current
    - Ability to correlate with Antenna measurements with least variation in test setup
**Measurement methods**

**Ground Plate Method (GPM)**

- Circuit schematics for all three measurement setups are similar
  - Source circuits are almost same
  - Receiver circuits are different (physically)

- Same GPM test setup for both HV-Cable and HV-Cable-Connector system

\[
Z_T = \frac{dV_{\text{SHIELD}}}{I_{\text{SHIELD}} \cdot l_{\text{SHIELD}}}
\]

Source-circuit

\[R_{1F}\]

\[U_{1N}\]

\[R_{1P}\]

\[U_{2,FE}\]

\[R_{2P}\]

\[R_{2N}\]

**Cylinder (Triaxial-Method)/ Injection (Parallel) lines (Line Injection Method)/ Copper-plate (Ground-Plate Method)**
**Measurement methods**

**Ground Plate Method (GPM)**
- **Test setup**

**Line Injection Method (Far-end configuration)**

**Triaxial Method**

**Ground Plate Method (Far-end configuration)**
- **Alternative method for measuring Transfer Impedance $Z_T$**

\[
Z_T = \frac{V_{\text{SHIELD}}}{I_{\text{INNER}}l_{\text{DUT}}} 
\]

- **HV-Cable only**
- **HV-Cable-Connector system**

- **Inverted Connector-box**

- **Ground Plate Method (GPM)**

- **$h = 65$ mm**
- **$l_{\text{DUT}}$**
- **$l_{\text{box}} = 100$ mm**

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**Ground Plate Method (GPM)**

Compared to the reference cable, the ZT (transfer impedance) for the connectors shows that:

- **ZT-Connector-A**
- **ZT-Connector-B**
- **ZT-Dummy-box**
- **ZT-Cable Ref.**

**Lesser contact points improve shielding**

**Measurement methods**

**Ground Plate Method (GPM)**

Comparative Study of Transfer Impedance (ZT) Measurement Methods and Simulation models to Analyze Shielding Behaviour of High Voltage Cables in Electric Vehicles
**Capacitive Voltage Probe (CVP) test**

- Using basic definition of $Z_T$

\[
Z_T = \frac{dV_{\text{SHIELD}}}{I_{\text{SHIELD}} \cdot l_{\text{SHIELD}}}
\]

\[
V_{\text{CVP}} \rightarrow V_{\text{SHIELD}}
\]

\[
I_{\text{SOURCE}} = \frac{V_{\text{SOURCE}}}{Z_{\text{IN}} - 50\Omega}
\]

For unknown input impedance/mismatched system, it can be measured using reflection measurements using NWA.

Contacts are assumed to be perfect $R=0\Omega$.

Longer DUT length will ensure better $R_{DC}$ measurements.
Measurement methods

Comparative Study of Transfer Impedance (Z_T) Measurement Methods and Simulation models to Analyze Shielding Behaviour of High Voltage Cables in Electric Vehicles

Capacitive Voltage Probe (CVP) test

CVP doesn’t require soldering matched terminations in complex ways, but has lesser measurable Z_T

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=21
Comparative Study of Transfer Impedance (ZT) Measurement Methods and Simulation models to Analyze Shielding Behaviour of High Voltage Cables in Electric Vehicles

Measurement methods

**Capacitive Voltage Probe (CVP) test**

Semi-rigid cable $Z_T$ using CVP

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>$Z_T$ [mOhm/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^4$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>$10^5$</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>$10^6$</td>
<td>$10^0$</td>
</tr>
</tbody>
</table>

**Benefit:**

For semi-rigid cables, very good shielded cables CVP measures directly $Z_T$.

\[
Z_{T-SIM-RG-402} = R_{DC} \frac{(1 + j \Delta \delta)}{\sinh((1 + j \Delta \delta))}
\]
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- Simulation methods
  - Analytical models
  - Circuit models
- Conclusions
Simulation methods

**Analytical Model**

- Using analytical model (Demoulin model) for $Z_T$

\[
Z_T = R_0 \frac{(1+j)\Delta/\delta}{\sinh \left( (1+j)\Delta/\delta \right)} + k_{CABLE} \sqrt{\omega e} + j^4 \omega (L_{HOLE} - L_{BRAID});
\]

Shielded cable $Z_T$ model description vs. frequency

**Simulation methods**

- Analytical Model

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*Braid parameters*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of the braid</td>
<td>$D_0$</td>
</tr>
<tr>
<td>Diameter of single braid wire</td>
<td>$d$</td>
</tr>
<tr>
<td>Number of wires in carrier</td>
<td>$n$</td>
</tr>
<tr>
<td>Number of carriers</td>
<td>$N$</td>
</tr>
<tr>
<td>Weave angle</td>
<td>$\Psi$</td>
</tr>
<tr>
<td>Conductivity</td>
<td>$\sigma$</td>
</tr>
</tbody>
</table>

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Comparative Study of Transfer Impedance ($Z_T$) Measurement Methods and Simulation models to Analyze Shielding Behaviour of High Voltage Cables in Electric Vehicles
Simulation methods

**Analytical Model**

- How $Z_T$ can be improved based on geometrical parameters of the shield?

![Diagram showing geometrical parameters of shield]

- **Geometrical parameters of shield**
  - Carrier $N$
  - Single Braid wire $n$
  - Aperture
  - Weave Angle $\Psi$

**Simulation methods**

- **Analytical Model**
  - How $Z_T$ can be improved based on geometrical parameters of the shield?

![Graph showing effect of braid wire thickness on $Z_t$]

- **Effect of braid wire thickness on $Z_t$**
  - $d = 1.0\text{mm}$
  - $d = 1.2\text{mm}$
  - $d = 1.4\text{mm}$
  - $d = 1.6\text{mm}$
  - $d = 1.8\text{mm}$
  - $d = 2.0\text{mm}$

- **Frequency [Hz]**
- **$Z_t$ [mOhm/m]**

- **Break frequency decreases with increasing shield thickness**

**Comparative Study of Transfer Impedance ($Z_T$) Measurement Methods and Simulation models to Analyze Shielding Behaviour of High Voltage Cables in Electric Vehicles**

- **Inductance is directly dependent on weave angle. Changing weave angle means changing inductance of the shield thus major impact is at higher frequencies where inductance are dominant in $Z_T$**

![Graph showing effect of weave angle variation on $Z_t$]

- **Weave angle**
  - 20
  - 25
  - 30
  - 35
  - 40

- **Frequency [Hz]**
- **$Z_t$ [mOhm/m]**

- **Break frequency decreases with increasing shield thickness**
Simulation methods

**Circuit models**

- Combination of analytical and circuit models
  - give more realistic prediction of shielding behavior

\[ V_T = I_{\text{SHIELD}} Z_{T\text{-model}} \]

- Advantages: Possible to...
  - Add TL models for connecting cables, to predict realistic measurement results
  - Add to other modules, for complex system analysis

![Diagram](image)

Verification of \( Z_T \) model for HV-cable only

\[ V_T = I_{\text{SHIELD}} \cdot Z_{T\text{-model}} \]
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Conclusions

Summary

Overview

- Comparative study of ZT measurement methods and Simulation methods for shielding analysis of HV cables used in EVs

Measurement methods

- Existing methods like Triaxial and Line Injection Methods
- Ground Plate Method (GPM)
- Capacitive Voltage Probe (CVP) Method

Simulation methods

- Analytical models
- Circuit models

Applications:

- Component level shielding analysis of shielded cables and connectors
- Further integration of proposed simulation methods into complex system simulations
- Correlation with Antenna measurements
Thanks for your attention!

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