Analysis of the Shielding Properties of HV-Cable and HV-Cable-Connector Systems using Transfer Impedance $Z_T$ and Antenna Measurements

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- Transfer Impedance ($Z_T$)
- Antenna Measurements
- Correlating measurements
- Analysis of HV-Connector
- Conclusion
Introduction

Motivation

■ Goal
  ■ Electromagnetic shield analysis of HV-Cable and HV-Cable-Connector systems used in EVs and HEVs

■ Overview of research
  ■ Transfer Impedance $Z_T$ analysis (mostly used by Cable and Connector companies)
  ■ Antenna Measurements (used in Automotive EMI tests)
  ■ Both used to analyze shielding performance of cables and connectors
  ■ Investigations to find correlation between $Z_T$ and antenna measurements
  ■ HV-Connector analysis to find critical EMI points

■ Benefit
  ■ Use of correlation between $Z_T$ and Antenna measurements can simplify our measurements
  ■ Predict Antenna measurement results from $Z_T$ measurements or vice versa
  ■ Improvements in the Connector shielding design
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Transfer Impedance ($Z_T$)

**Ground Plate Method (GPM)**

- Existing measurement methods
  - Triaxial Method:
    - Test setup has to be modified for different size of DUT
  - Line Injection Method:
    - Difficult to measure non-symmetrical DUTs

- Alternative Method “Ground Plate Method”
  - 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

- In previous investigations, it has been
  - Used for both HV-Cable and HV-Cable-Connector systems
  - Verified by comparing measurement results with both Triaxial Method and Line Injection Method

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Transfer Impedance \((Z_T)\)

**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

\[
Z_T = \frac{V_{\text{Shield}}}{(I_{\text{inner conductor}} \cdot I_{\text{Coupling}})}
\]

\[
Z_{T^*} = 2x Z_{T,\text{Cable}} + 2x Z_{T,\text{Connector}}
\]

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Transfer Impedance ($Z_T$)

$Z_T$ measurements using GPM (for two types of connectors)

- $Z_T$ measurements for HV-Cable-Connector sample 1 (left) and 2 (right)
- Reference $Z_T$ measurements for corresponding cables are shown
- Connector has higher $R_{contact}$ and adds extra Inductance
- Compared to sample 1, sample 2 has lower $Z_T$, thus better shielding performance

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Antenna Measurements

Field measurements

- Initial investigations
  - Conventional antenna measurement method and different approaches were used for field measurements
- Problems faced were
  - Variable influence of the connecting cables
  - Strong coupling was required for correlating with $Z_T$
- Modification in the setup as per requirements to correlate with $Z_T$

Use of stripline antenna to improve the sensitivity of coupling reception

Conventional antenna measurement setup

ESPI Test Rx
Amplifier
Attenuator
Coupler
Termination resistor

DUT directly connected to chamber wall (ground)

Ferrites used at the receiver cable

Initial investigations
Conventional antenna measurement method and different approaches were used for field measurements

Problems faced were
Variable influence of the connecting cables
Strong coupling was required for correlating with $Z_T$

Modification in the setup as per requirements to correlate with $Z_T$
Antenna Measurements

Measurement setup

- Modifications in test setup were made for development of better correlation
  - Amplifier may be used for increasing the dynamic range and sensitivity of the setup to measure coupling
  - Low frequency ferrites help to limit common-mode currents
  - Direct connection of the DUT into the metallic chamber wall helps to avoid influence of brackets and connecting cables
  - Some effects due to bending and shape variation

![Measurement setup diagram]

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**Power ON Status: OK**

**ESPI Test receiver**

**Amplifier** 100A400 100W CW 100kHz - 400MHz

**Coupler**

**Termination Resistor**

**Attenuator**

**EMI Test Receiver**

**Inside chamber**

**Reference ground (Aluminum table)**

**Metallic Chamber wall (ground)**

**Anechoic-chamber walls (Ferrite tiles)**

**1m Rod-antenna (100kHz-50MHz)**

**DUTs:**

- Unshielded cable
- Shielded-Cable
- Cable-Connector System

**Tx-side**

**Rx-side**

*Both table and chamber ground connected together via metallic copper sheet*
Measurements were done for different samples
- Unshielded cable was also measured as reference for finding Shielding effectiveness
- Similar to ZT measurement results, difference between both samples can be seen (Sample 1 has lower shielding than sample 2)
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Correlating measurements

Correlating using $S_{21}$ (from $Z_T$) and $S_{21}$ (from Antenna measurements)

- Correlation for HV-Cable only
  - For similar test conditions and addition of correct correlation factor, we see good correlation between both measurement results
  - Correlation factor depends on the DUT conditions (shape and height, etc), type of antenna and distance, etc

Addition of correction factor for antenna measurements gives similar results for $f > 1$ MHz
Correlating measurements

Correlating using $S_{21}$ (from ZT ) and $S_{21}$ (from Antenna measurements)

- Correlation factor depends on the DUT conditions (shape and height, etc), antenna factors and distance, etc

Correlation for HV-Cable-Connector system (TYCO)
- For similar test conditions and addition of correct correlation factor, we see good correlation between both measurement results

Resonance difference is due to ($C_{\text{box-Gnd}}$) slight cable length difference and gap difference between connector box and ground plate
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Analysis of HV-Connector

Finding the critical EMI points using $Z_T$ model

- Explanation of the $Z_T$ for both HV cable and cable-connector system
- Connector has higher $R_{\text{contact}}$ and extra Inductance causes no lowest $Z_T$ point (No-dip)
- To make connector $Z_T$ model: $R_{\text{CONTACT}}$ and $L_{\text{CONNECTOR}}$ in $Z_{T,\text{Cable}}$ are added

$Z_T$ Cable model:

$Z_{T,\text{Cable model}} = R_0 \frac{(1+j)d/\delta}{\sinh[(1+j)d/\delta]} + k_{\text{CABLE}} \sqrt{\omega} + e^{i\delta} + j\omega(L_{\text{HOLE}} - L_{\text{BRAID}}) + R_{\text{CONTACT}} + j\omega L_{\text{CONNECTOR}}$

$Z_T$ Cable-Connector Model:

$Z_{T,\text{Cable-Connector}} = R_0 \frac{(1+j)d/\delta}{\sinh[(1+j)d/\delta]} + k_{\text{CONTACT}} \sqrt{\omega} + e^{i\delta} + j\omega(L_{\text{HOLE}} - L_{\text{BRAID}}) + R_{\text{CONTACT}} + j\omega L_{\text{CONNECTOR}}$

For example for sample 1 KOSTAL and 35 mm² Coroplast:

$L_{\text{HOLE}} = 3.65\text{nH} ; L_{\text{BRAID}} = 3.78\text{nH}; k_{\text{CABLE}} = 0.5e^{-7} ; R_0 = 3.3\text{mOhm}$

$L_{\text{CONNECTOR}} = 2.2\text{nH} ; R_{\text{CONTACT}} = 3.5\text{ mOhm} ; k_{\text{CONNECTOR}} = 50^*k_{\text{CABLE}}$

Sample 1: KOSTAL and 35mm² Coroplast cable

Sample 2: TYCO and 25mm² Coroplast cable
Comparison of different HV-Connectors

- Difference is at low-frequency
- Sample 1 has higher DC-resistance compared to Sample 2 connectors
- As there are more contact interfaces

Sample 1 has higher DC-resistance compared to Sample 2 connectors. As there are more contact interfaces.
Analysis of HV-Connector

Comparison of HV-Connector box with an Ideal (dummy) box

- To experimentally compare the shield performance of the HV-Cable-Connector system, we used
  - a dummy box (connecting cables)

- Observations
  - At low frequency, ideal connector has similar $Z_T$ as that of cable
  - After ~1 MHz, additional inductances differentiates the connector-box from cable

![Diagram of HV-Cable, braided shield, and Ideal connector-box (dummy-box)](image)

![Graph showing comparison of $Z_T$ values for different configurations.](image)
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Conclusion

Summary

- Investigations to do electromagnetic shield analysis of HV-Cable and HV-Cable-Connector systems has been presented
- Transfer Impedance measurements have been presented using Ground Plate Method (GPM)
- Antenna measurements have also been performed which were further used to find the shield effectiveness
- Comparison of Ideal (dummy) Connector-box with conventional HV-Connector System has been made to suggest connector design improvements

Benefits:
- The presented work serves as start-up for correlating the $Z_T$ and Antenna measurements
- Correlation helps to simplify the measurements
- Identification of the critical EMI points suggests improvements in connector shield designs

Future tasks

- Correlation between $Z_T$ and Antenna (EMI) measurements
  - Using intermediate measurement setup
  - Using Current and Voltage measurements
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