Analysis, Optimization & Verification of an HV Connector

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Requirements for HV Connectors

Due to the increasing density of electronics and microprocessor technology in electric vehicles, the EMC of energy and communication cabling and the associated components are becoming increasingly important (**Figure 1**).

Fig. 1 — HV-connector PowerStar HPS40-2, Hirschmann Automotive[11].

This applies in particular to the high-voltage or HV connectors. The high switching transients of the electric motors and the high voltages of the power inverters pose a great challenge to the developers. And full functionality is required at voltages up to 1000 V in a temperature range of -40°C to +170°C with low emissions and high interference immunity even after aging. Additional requirements include low weight and inexpensive design.

Another aspect is the reduction of electrosmog in electric vehicles through appropriate shielding of the components to protect the occupants.

EMC-compatible design must therefore be integrated from the beginning of the development of HV connectors, i.e., technical optimization of the connector under EMC, weight and cost aspects.

Instead of elaborate sample designs, suitable 3D electromagnetic simulations of the performance and EMC of the connector can save time and money in the course of development. Both simulation and verification/measurement of the EMC behavior on the finished connector should be carried out with the same test method, in this case with the triaxial method in accordance with *IEC 62153-4-7*.

The approach presented in this article shows the ideal interlinking of simulation and measurement technology in different stages of the product design process of HV connectors for electromobility.

HV-connectors & EMC. The transfer impedance according to *IEC 62153-4-3* is the measure for the screening effectiveness of screened electrical cables, connectors, cable assemblies and components at frequencies up to approximately 30 MHz. Above 30 MHz, the screening attenuation according to *IEC 62153-4-4* is the measure of the screening effectiveness[1,2,8].

For the connection of the connectors and the components, shielded aluminum and copper cables with cross-sections of 16 mm² to 50 mm² are used, which are assembled with appropriate HV connectors.

HV cables and connectors must, for example, have a continuous current carrying capacity of 280 A at 23°C or 195 A at 83°C, while the transfer impedance (also after aging) must be between 2 mΩ and 10 mΩ depending on application. Also, in the range of up to 300 MHz, screening attenuation up to 70 dB is required.

The screening attenuation value of 70 dB on screened cables can be achieved only with a screen construction made of a combination of braiding and foil. Screens made from just one braid achieve a maximum screening attenuation of approximately 45 dB.

Triaxial Test Procedure

Triaxial test procedure per *IEC 62153-4-n* is designed to measure transfer impedance and screening or coupling attenuation on cables, connectors and components.

Since the procedure for determining the transfer impedance is addressed in the following chapters, the most important key points, especially with regard to connectors, are briefly presented here.

Triaxial test procedure for connectors. The measurement or simulation of transfer impedance and screening or coupling attenuation on cables and connectors or cable assemblies can be carried out using the triaxial method according to *IEC 62153-4-7*[4,10].

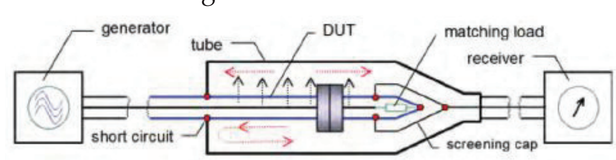


Fig. 2 — Basic triaxial test procedure.

To measure the screening effectiveness of larger components such as HV connectors and HV components, the triaxial cell can be used. The triaxial cell uses the same principles as the basic triaxial procedure according to **Figure 2** with tubes[5,7].

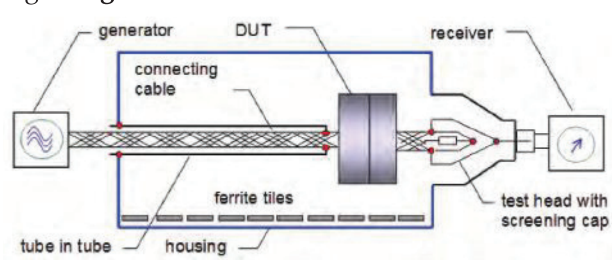


Fig. 3 — Principle of the Triaxial cell with tube in tube and ferrite tiles as absorber.

At higher frequencies the triaxial cell becomes in principle a cavity resonator respectively a rectangular waveguide which exhibits resonances depending on its dimensions. Above these resonance frequencies, propagation of TEM waves is disturbed and the frequency range for measurements of screening attenuation with triaxial test method is limited.

To increase the frequency range, the cell can be equipped with ferrite tiles or with magnetic absorbers[7] (**Figure 3**).

Comparison of the triaxial procedure and the line injection procedure. Transfer impedance of cables, connectors and components can be measured either with the line injection method per *IEC 62153-4-6* or with the triaxial test procedure per *IEC 62153-4-3*[1,3,8] (**Figure 4**).

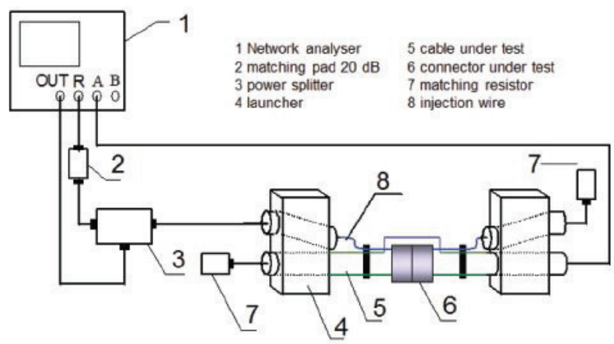


Fig. 4 — Principle of the line injection procedure.

The basic principle of the line injection method is simple; an unscreened wire is placed close to the cable/connector under test (CUT) and "injects" RF energy into the CUT. The energy which couples into the CUT is measured at near and far end as transfer impedance after respective calculation.

Although the principle is simple, one has to perform at least eight different measurements to find the worst case (near and far end and four different positions around the circumference).

The triaxial procedure has various advantages versus the line injection procedure. These can be recognized both in measurement and in simulation and lead to an increase in the accuracy and efficiency of the analysis:

- All problem areas of the connector where electromagnetic fields can escape from the inside of the connector are recorded in the triaxial cell.
- The line injection method, on the other hand, essentially only detects the electromagnetic fields that lie between the shielding of the connector and the feed wire. Measuring cables without connector only, for example, this is not a major limitation. However, if you look at large HV plugs with a side length of up to 100 mm, it is more likely to be left to chance whether you are detecting a potential problem area with a 2 to 5 mm wide copper wire or not.
- Furthermore, a minimum value of the reflection of the inner circuit can be found by an automated parametric variation of the generator impedance in the triaxial method in the simulation environment.
- With the line injection method, however, it is necessary in both cases, measurement and simulation to manually adjust the width of the line injection so that the impedance is approximately 50 Ω.

Another drawback of the line injection method is that it can be used for simulation and measurement of transfer impedance only. The triaxial procedure can be used for both, transfer impedance or screening attenuation in a broad frequency range from DC up to about 9 GHz[8].

Simulation and Analysis

Motivation. The goal of the simulation is:

a) The realistic representation of quantitative results such as screening attenuation and transfer impedance. It must be assessed whether the design meets the requirements of the application with the existing limit values of the above parameters.

b) Visualization of faults and regions in which the shielding is not sufficient. This input is particularly important for the developer so that the shield properties can be improved in a targeted manner in order to achieve the necessary limit values.

Method. A typical approach is to simulate the connector and the measurement environment in an electromagnetic 3D simulation program[9].

When simulating the connector, the CAD data of the construction forms the basis. This data still has to be modified in order to achieve realistic contact within the individual shield parts. As the performance of the simulation programs progresses, more and more complex material properties, such as complex surface coatings, surface roughness, etc., can be realistically simulated.

The structure of the simulation depends on the selected test method. As already mentioned, the triaxial procedure should be used here.

Figure 5 and **Figure 6** illustrate the HV connector in a 140 mm long triaxial cell.

The same components of the cell can be seen as in the description of the principle in the following sections.

The generator can be seen on the left side of the cell, which feeds the measurement signal into the inner circuit of the shielded cable/connector. This is defined as a coaxial cable whose impedance can be easily adapted to the average impedance of the test object.

The connector itself is a 2-pin HV connector. The two lines are interconnected for measurement. The plug is mounted in an adapter, which, in reality, corresponds to a unit, e.g., the air conditioning system in an electric vehicle. If possible, the external shape of the adapter should not deviate too much from the plug in order to avoid jumps in the impedance of the outer circuit.

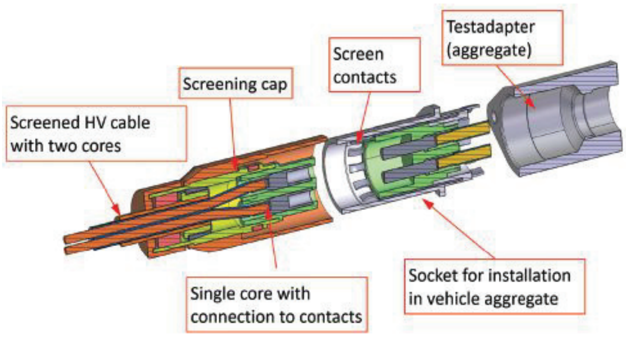


Fig. 5 — Basic replication of a HV connector and installation in the triaxial cell.

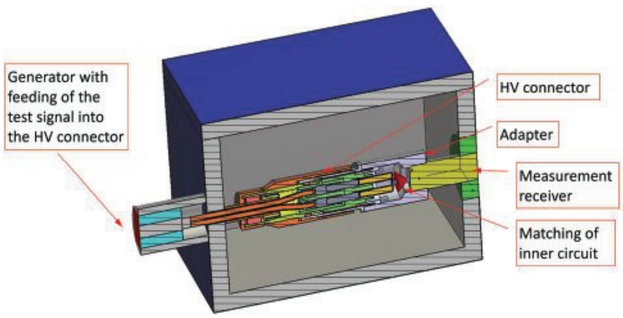


Fig. 6 — Triaxial cell with HV connector.

The measuring receiver on the right side of the cell is simulated by a short coaxial line with 50 Ω system impedance.

Depending on the chosen method, the simulation is performed in the time domain, e.g., with the Finite Integration Technique (FIT) method with subsequent transformation in the frequency domain or in the frequency domain by solving the linear system of Maxwell's equations using an iterative or direct solution algorithm for each frequency point considered[9].

Quantitative analysis. In both cases, as with a measurement with the vector network analyzer, S-parameters are obtained, which can be converted into transfer impedance and screening attenuation with the appropriate relationships.

IEC 62153-4-3 contains three different test methods, A, B and C. The evaluation described here is based on section "7 Test method B: Inner circuit with load resistor and outer circuit without damping resistor", see **Figure 2**[1]. The transfer impedance Z_T is then given by **Equation 1**:

$$Z_T = \frac{R_1 + Z_0}{2 \cdot L_c} \cdot 10^{\left\{-\frac{a_{meas} - a_{cal}}{20}\right\}} \qquad (1)$$

where:

Z_T is the transfer impedance in mΩ/m

Z_0 is the system impedance in Ω

a_{meas} measured attenuation (S21) in dB

a_{cal} attenuation value to be deducted from a calibration measurement. This is not necessary in the simulation and therefore a_{cal} l = 0.

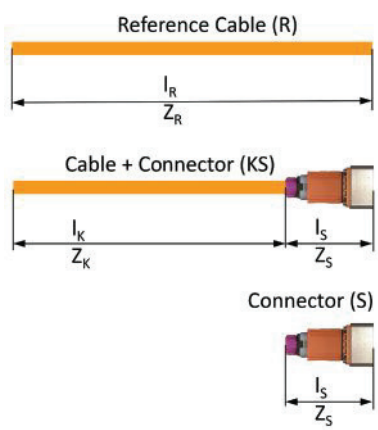
L_c coupling length in m

R_1 matching resistor in the inner circuit (either equal to the Impedance of the inner circuit or the impedance of the generator)

In accordance with *IEC 62153-4-4* the screening attenuation a_S becomes in principle, **Equation 2**:

$$a_S = |S21| \qquad (2)$$

For cables by meter, the transfer impedance according to **Equation 1** is related to a length of 1 m and is usually given in mΩ/m (milliohms per meter). If only the screening effectiveness of a connector is measured, the measuring length L_c is not taken into account and the transfer impedance of the connector is given in mΩ. In this case, the transfer impedances of the adapter and head sleeve of the triaxial set-up are assumed to be zero because they are made of solid, highly conductive metal. The term "delta transfer impedance" is used for many specifications of the limit values for the transfer impedance for connectors (**Figure 7**) where:



$$Z_{TR} = \frac{Z_R}{l_R} \qquad (3)$$

$$Z_{TKS} = \frac{Z_K + Z_S}{l_K + l_S} \qquad (4)$$

$$Z_{TS} = \frac{Z_S}{l_S} \qquad (5)$$

Fig. 7 — Delta transfer impedance.

l_x is the length in m

Z_x is the transfer impedance in mΩ

Z_{Tx} is the length related transfer impedance in mΩ/m

The above illustration shows the geometrical relationships between the measurement setups.

If one consider the transfer impedance Z_T as the addition of the individual resistances of the connector and cable, the following relationship, **Equation 6**, for the delta transfer impedance results from the three configurations in the figures above:

$$Z_{TDiff} = Z_{TKS} - Z_{TR} \qquad (6)$$

$$Z_{TDiff} = \left(\frac{l_K}{l_K + l_S} - 1\right) \cdot Z_{TR} + \frac{Z_S}{l_K + l_S} \qquad (7)$$

As it can be seen from **Equation 7**, the first term is always negative and represents a residual influence of the reference cable. Z_{TDiff} itself can become negative if the transfer impedance of the connector Z_S is significantly lower than that of the reference cable.

In order to show the influence of the connector more clearly, a measurement would certainly be more unambiguous, since only Z_{TS} or Z_S is recorded here.

With the simulation, values comparable to real measurements can be generated in a short time. In the design stage, this approach is much more cost-effective than the time-consuming construction of samples.

Qualitative analysis. In addition to these quantitative results, the advantage of simulation is that processes within the connector can be made visible. The simulated curves show the sum of all effects like a measurement. However, they do not allow any conclusions to be drawn about the causes.

An analysis of the electric and magnetic field distributions is essential for this. The illustration in **Figure 8** shows the maximum value of the magnitude of the E-field in a time domain simulation. The maximum field strength is approximately 20 kV/m.

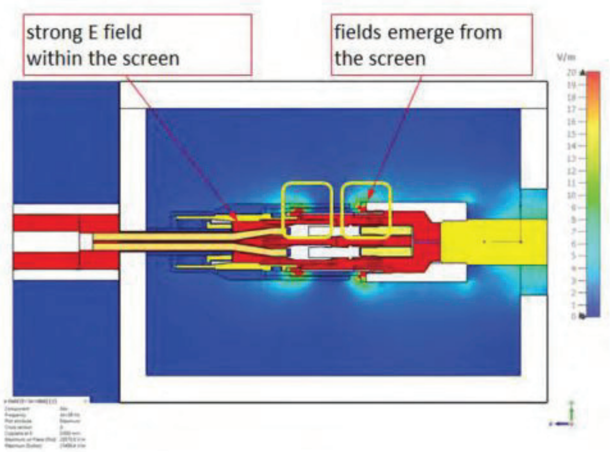


Fig. 8 — Analysis of the weak points of a HV connector due to leaked E-fields.

To visualize the screening effects in the range of approximately 80 dB, however, it is necessary to reduce the scaling very much in order to recognize them. For this reason, the maximum field strength to be displayed was limited by a factor of 80 dB = 1000 to 20 V/m.

It is only in this depiction that the locations at which the fields emerge from the connector can be clearly recognized.

Test Adapter

When measuring a connector, different transitions or transfer impedances are to be considered. Transfer impedances add up! Connections should therefore be made with care and with impedance as low as possible, see **Figure 9**.

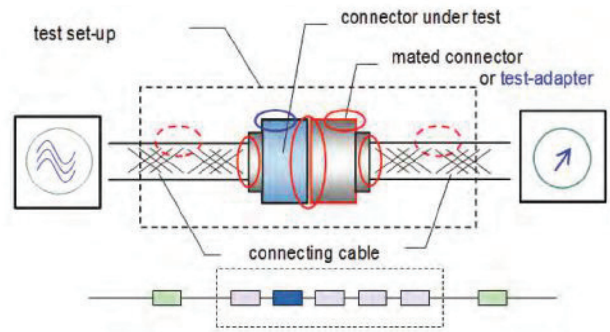


Fig. 9 — Influencing variables when measuring the EMC of a connector.

The measurement of the screening effectiveness of a single connector or a pre-assembled cable is only possible with appropriate mated connectors or with test adapters of high EMC performance. Unsuitable measuring adapters can significantly influence the measurement through own emissions.

Qualification tests should therefore be carried out on the measuring adapters used in order to determine the background noise or the measurement limits of the system. Test adapters should preferably be produced by the manufacturer of the connector to be tested. If this is not possible, the adapter must be made by the measurement laboratory.

To qualify a test adapter, an additional adapter of high quality is needed. Another option is, to optimize test adapter by simulation to guarantee best performance. **Figure 10** shows a TDR (Time Domain Reflectometer) simulation of the impedance of the outer circuit of the test adapter in the triaxial cell.

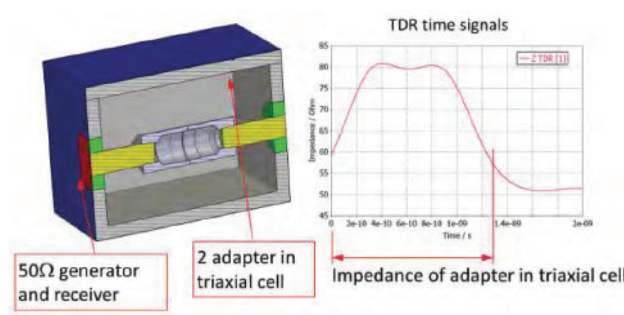


Fig. 10 — Simulation of a test adapter in a triaxial cell .

It can be easily seen that the impedance is approximately 80 Ω and is thus clearly above the system impedance of 50 Ω of the measuring system, as required by the standard[5]. The measuring adapter shows an ideal behavior with regard to the transfer impedance from the inner to the outer circuit, since all components are made of solid metal.

Comparison of Simulation and Measurement

Measurement. The following images show two typical configurations of connectors measured in a triaxial cell. **Figure 11** shows a straight HV connector in a small triaxial cell 140/140/100 with a short piece of connecting cable, the test adapter and the connecting case to the test head. In this case, in principle only the transfer impedance (and the screening attenuation) of the connector under test is measured. The transfer impedance of the short piece of connecting cable, the transfer impedance of the test adapter and the transfer impedance of the connecting case to the test head are considered zero.

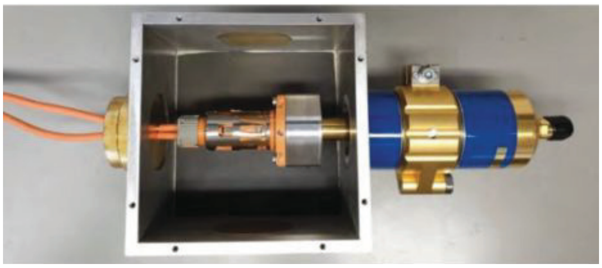


Fig. 11 — Straight HV connector in triaxial cell.

An angled (90°) HV connector is seen in **Figure 12**. The test head which is connected to the measuring receiver is arranged at an outlet of the 1000 mm long triaxial cell on a side wall. This allows the adapter to be made very compact.

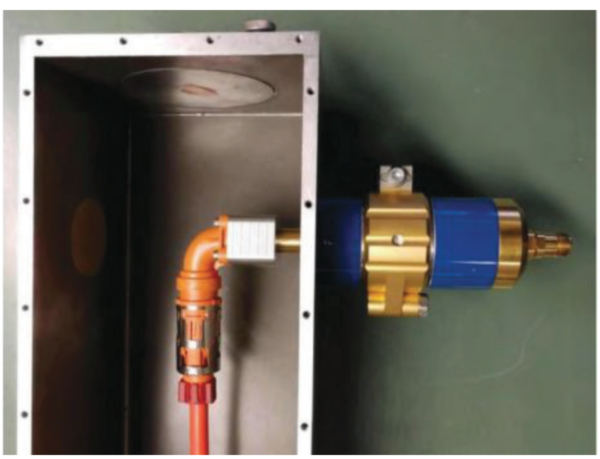


Fig. 12 — Angled HV connector in triaxial cell.

In this case, the transfer impedance of the cable (length of approximately 800 mm) is measured separately. To get the transfer impedance of the connector, the transfer impedance of the cable can be subtracted from the measurement of the cable with connector. Another option is to calculate delta transfer impedance according to **Equation 6** or **Equation 7**.

Comparison between simulation and measurement. **Figure 13** shows the simulated transfer impedance with several design iterations as well as the limit value curve. The variant with the lowest Z_T was implemented, which was also measured on three parts. Both values in simulation and measurement are well below the required limit values and thus offer sufficient security for possible deterioration over the service life.

Figure 14 shows the comparison of the screening effectiveness of measurement and simulation. The measured curves of **Figure 14** show the coupling transfer function (CTF) of three connectors under test and the connecting cable. The coupling transfer function includes both, the transfer impedance at the lower frequency range and the screening attenuation at higher frequencies. As an envelope, the simulated value covers the measured values of the three test objects well.

The prediction shows the screening effectiveness in the range of 30 MHz to 300 MHz for a test length of 1 m with a good correlation to the measured curves. According to *IEC 62153-4-3* and *IEC 62153- 4-4*, this is the range of the transition between transfer impedance and screening attenuation. Nevertheless, measured and predicted values can be extrapolated to other frequencies and/or length.

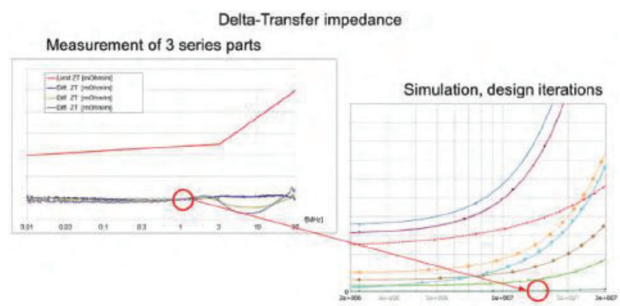


Fig. 13 — Transfer impedance, comparison of measurement (left) and simulation (right).

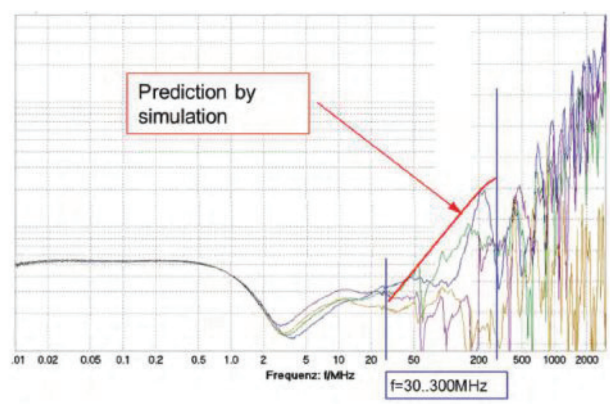


Fig. 14 — Comparison of measurement and simulation.

Conclusions

In the previous sections, the analysis and optimization of an HV connector was presented through the use of simulation methods with subsequent verification by means of a measurement. An identical procedure was chosen for both steps with the triaxial procedure in order to ensure a comparability of the results.

An additional advantage is that with the help of the simulation in a standardized arrangement, reliable figures for the EMC criteria screening attenuation and coupling impedance can be determined at a very early stage of the connector development, thus making a faster, more efficient and cost-optimized design possible.

The additional visualization of faults and regions in which the shielding is not sufficient is the most important input for the development team in order to be able to carry out necessary modifications of a design in a targeted manner.

In addition to confirming compliance with the limit values, a final verification using the same test method then allows important conclusions to be drawn about the quality of the simulation and enables it to be compared with reality.

Due to the increased demand for HV connectors and other components for electromobility, we expect this method to be used more widely in future applications as well. In addition, consideration should be given to measuring the connectors in isolation in order to obtain a meaningful value for the transfer impedance of the connector system.

For further discussion, contact **Dr. Thomas Gneiting** of **AdMOS GmbH** at **thomas.gneiting@admos.de** or **Dipl.-Ing. Bernhard Mund** of **bda connectivity GmbH** at **Bernhard.mund@bda-c.com**.

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[1] *IEC 62153-4-3, Surface transfer impedance - Triaxial method.*

[2] *IEC 62153-4-4, Test method for measuring of the screening attenuation as up to and above 3 GHz, triaxial method.*

[3] *IEC 62153-4-6, Surface transfer impedance, line injection method.*

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[5] *IEC 62153-4-15, Test method for measuring transfer impedance and screening attenuation or coupling attenuation with triaxial cell.*

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After successfully training as a radio and television technician, Dipl.-Ing. Bernhard Mund studied Communications and microprocessor technology at the Giessen-Friedberg University of Applied Sciences. Since 1985 he has been an employee of the cable manufacturer, bda connectivity GmbH (formerly bedea Berkenhoff & Drebes GmbH) in Asslar as R&D manager in the field of communication cables among others. Bernhard is currently responsible for the EMC test engineering and for standardization. In addition to his work for bda connectivity, Bernhard Mund is active in national and international standardization, serving as chairman of the German committee UK 412.3 coaxial cable, as well as secretary of IEC SC 46A and CENELEC SC 46XA, coaxial cable. Further standardization activities include membership of IEC TC 46/WG 5, screening effectiveness, since 1995.

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