Measuring EMC of HV Cables & Components With the "Triaxial Cell" — *Part 1*

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This article describes the capabilities of the newly developed Triaxial Cell. Measurements with the cell are presented and discussed. The question of whether and when transfer impedance can be measured with or without matching is examined and a new test method "unmatch-match-short" for measuring the transfer impedance is presented.

The triaxial test method for measuring transfer impedance and shielding effectiveness was originally designed for communications cables. For power lines and for high-voltage cables (HV cables) for electric vehicles, the measurement of the shielding effectiveness is also required. The mechanical dimensions of power lines and lines and components for electric vehicles are generally larger than typical dimensions of cables and components for telecommunications.

To measure the EMC of those larger elements, the triaxial test method has been expanded with the Triaxial Cell.

In addition to the larger dimensions, impedances of power lines also differ from the impedances of communication cables. While communication cables usually have standardized characteristic impedances of 50 or 75 ohm, the impedances of power lines and HV cables for electric vehicles are in the range of about 10 to 12 ohm. Depending on whether it is measured by short circuit or by matched conditions, interactions may be applied to the system, which can significantly disturb the measurement. This consideration applies to measurements in the tube as well as in the Triaxial Cell.

Part 1 and *Part 2* of this article describe the capabilities of the Triaxial Cell. Measurements with the cell are presented and discussed. The question of whether and when transfer impedance can be measured with or without matching is examined and a new test method "unmatch-match-short" for measuring the transfer impedance is presented.

Principle of the Triaxial Test Procedure

With the triaxial test setup, one can measure both the transfer impedance at the lower frequency range as well as the screening attenuation at higher frequencies.

The test setup consists of a network analyzer (or alternatively a discrete signal generator and a selective measuring receiver) and a tube with terminations to the cable screen and the network analyzer or receiver. The material of the tube will be well conductive and nonferromagnetic, for example brass or aluminum.

The cable under test (CUT), which is centered in the middle of the tube, forms together with the tube a triaxial system (**Figure 1a**). The inner system is the CUT itself and the outer system is formed by the screen under test and the tube. The CUT is terminated with its characteristic impedance at the far end (**Figure 1a**).

The screen under test is short circuited with the tube at the near end of the generator. Due to this short circuit, the influence of capacitive parts is excluded. A generator with the voltage U_1 feeds the inner system. The voltage U_2 is

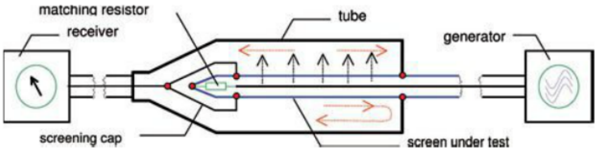

Fig. 1a — Principle test setup to measure transfer impedance and screening attenuation.

measured with a measuring receiver with an input impedance equal to the characteristic impedance of the tube (50 ohm) (**Figure 1b**).

The energy, which couples through the weak screen travels into both directions of the tube, respectively the outer system. At the short circuit at the near end side of the generator, the wave is totally reflected so that the receiver measures the complete energy that couples through the screen.

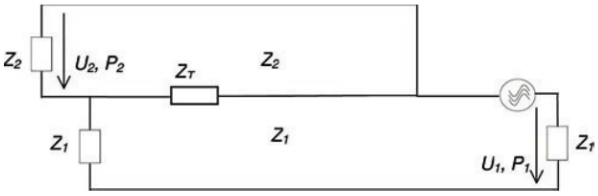

Fig. 1b — Equivalent circuit of the principle test setup in Figure 1a.

At the low frequency range, the transfer impedance Z_T may be calculated from the voltage ratio U_2/U_1:

$$Z_T \cdot l \approx Z_1 \cdot \left|\frac{U_2}{U_1}\right| \qquad \text{if } Z_T << Z_1$$

At high frequencies, the logarithmic ratio of the input power P_1 to the measured power P_2 on the receiver gives the screening attenuation a_S:

$$a_s = 10 \cdot \log\left(\left|\frac{P_2}{P_1}\right|_{max}\right) = 20 \cdot \log\left(\left|\frac{U_2}{U_1}\right|_{max}\right)$$

In order to compare the screening attenuation with other test procedures in accordance with *IEC 62153-4-4*, the measured ratio of power P_2 to P_1 is related to the standardized characteristic impedance of the outer system of 150 Ω:

$$a_s = 20 \cdot \log\left(\left|\frac{U_2}{U_1}\right|_{max}\right) + 10 \cdot \log\left(\frac{2 \cdot Z_s}{Z_1}\right)$$

Where Z_1 is the characteristic impedance of the device under test and the characteristic impedance of the outer system is 150 Ω. The measure of the screening attenuation is the measured maximum value.

Coupling Transfer Function

Depending on the length of the device under test and the frequency, the screening effectiveness is divided into the transfer impedance and the screening attenuation. The coupling transfer function in **Figure 2** shows the transfer impedance Z_T and the screening attenuation a_S of a cable screen versus frequency.

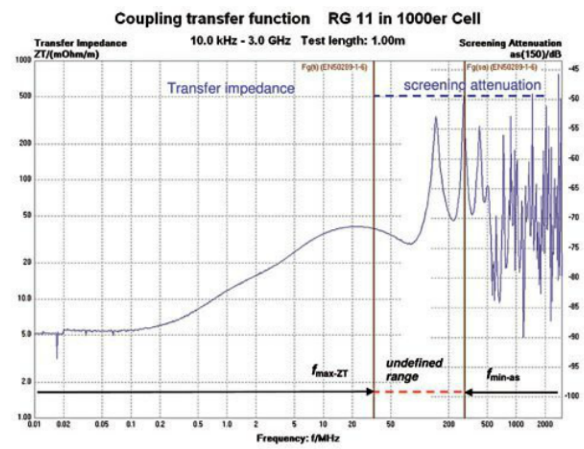

Fig. 2 — Measured coupling transfer function of a braided screen versus frequency with the Triaxial cell.

With the triaxial procedure, the transfer impedance Z_T and the screening attenuation a_S can be measured in one test setup.

In the DC range respectively, at very low frequencies, the transfer impedance of a braided screen is equal to the DC resistance. In the range of about 1 MHz to 10 MHz, the value of the transfer impedance drops down to lower values (at optimized braids) and increases then with about 20 dB per decade towards higher frequencies.

The coupling transfer function $T_{n,f}$ gives the relation between the screening attenuation a_S and the transfer impedance Z_T of a cable screen. In the lower frequency range, where the cable samples are electrically short, the transfer impedance Z_T can be measured up to the cut-off frequencies $f_{cn,f}$. Above these cut-off frequencies, $f_{cn,f}$ in the range of wave propagation, the screening attenuation a_S is the measure of screening effectiveness. The cut-off frequencies $f_{cn,f}$ may be moved towards higher or lower frequencies by variable length of the cable under test.

The upper cut-off frequency $f_{max\text{-}ZT}$ for measuring the transfer impedance is given by:

$$f_{max-ZT} \leq \frac{50 \cdot 10^6}{\sqrt{\varepsilon_{r1}} \cdot L_c}$$

The lower cut off frequency $f_{min\text{-}as}$ for measuring the screening attenuation according to *EN 50289-1-6* is given by:

$$f_{min-as} \geq \frac{c_0}{2 \cdot \left| \sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}} \right| \cdot L_c}$$

Where:

c_0 velocity of light in free space
ε_{r1} relative dielectric constant of the inner system
ε_{r2} relative dielectric constant of the outer system
L_c coupling length

Figure 2 shows the cut-off frequencies of the transfer impedance Z_T and of the screening attenuation a_S according to *EN 50289-1-6*. For a cable of 1 m length and a relative dielectric constant of the inner system ε_r of 2.28, we obtain an undefined range or a "grey zone" in the frequency range from about 30 MHz to about 300 MHz, although this frequency range is of specific interest for different services.

In principle, the undefined range could be covered by varying the length of the device under test. But varying the length of the device under test is not always desired or impossible in case of DUTs with fixed length, e.g., in case of cable assemblies. Hence it should be discussed how the coupling transfer function could be the measure for the screening effectiveness including transfer impedance and screening attenuation.

IEC TC 46/WG 5 revises *IEC 62153-4-7*, transfer impedance and of screening attenuation of connectors and cable assemblies with the triaxial test procedure. During this revision, it should be discussed to introduce the coupling transfer function as shown in **Figure 2**. The length of the test setup could be fixed to 1 m. The value of the minimum of the screening attenuation at $f_{min\text{-}as}$ could be extended to $f_{max\text{-}ZT}$ and is from here the measure of the screening attenuation. With this extension, the screening effectiveness, consisting of transfer impedance and screening attenuation is explicitly described over the complete frequency range.

Furthermore, with the new procedure of *IEC 62153-4-3 Ed.2* described below, the cut off frequency $f_{max\text{-}ZT}$ of the transfer impedance can be moved towards higher frequencies and the undefined range can be reduced.

To compare different devices and for qualification purposes the proposed application of the coupling transfer function is useful in any case.

Triaxial Cell

Larger connectors and cable assemblies do not fit into the commercial available test rigs of the triaxial test procedure, which have been designed originally to measure transfer impedance and screening attenuation on communication cables, connectors and assemblies.

In cooperation with **bedea** and **Rosenberger**, the Triaxial Cell was designed to test larger devices and assemblies, especially for HV cables and components for electromotive vehicles. The principles of the triaxial test procedures can be transferred to rectangular housings. Tubes and rectangular housings can be operated in combination in one test rig. The screening effectiveness of larger connectors or devices can be measured in the tube as well as in the Triaxial Cell. Test results of tube and cell measurements corresponds well (see **Figure 3** and **Figure 4** (on next page)).

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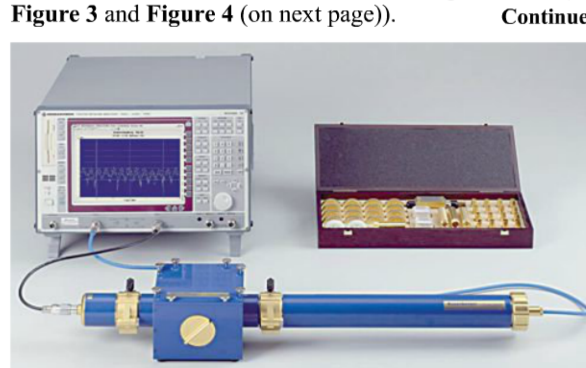

Fig. 3 — Measuring of transfer impedance and screening attenuation of connectors and assemblies with Triaxial Cell and tube-in-tube according to *IEC 62153-4-7*.

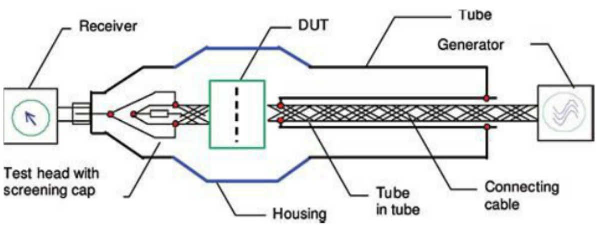

Fig. 4 — Principle depiction of the Triaxial Cell to measure transfer impedance and screening attenuation at HV assemblies with tube-in-tube according to *IEC 62153-4-7*.

Care should be taken at the transition from the tube to the rectangular housing. At this transition, reflections of the transmitted signal may occur (in the outer circuit), due to the deviation of the characteristic impedances. The plane of the short circuit at the near end (generator side) should be therefore direct at the wall of the housing of the cavity without any additional tube. At the receiver side, the transition of the housing to the coaxial 50 ohm system should be also direct at the wall of the housing. Different designs of Triaxial Cells are shown in **Figure 5**.

Fig. 5 — Different designs of Triaxial Cells.

Cut-Off Frequencies, Higher Order Modes

The housing, particularly the triaxial cell is in principle a cavity resonator, which shows different resonance frequencies, depending on its dimensions.

For a rectangular cavity resonator, the resonance frequencies can be calculated according to the equation:

$$f_{MNP} = \frac{c_0}{2}\sqrt{\left(\frac{M}{a}\right)^2 + \left(\frac{N}{b}\right)^2 + \left(\frac{P}{c}\right)^2}$$

Where

M, N, P	number of modes (even, 2 of 3 >0)
a, b, c	dimensions of cavity
c_0	velocity of light in free space

For this calculation, one of the parameters M, N or P may be set to zero. Conductive parts inside the cavity resonator may lead to deviating resonance frequencies or to muting them.

The resonance frequencies for the dimensions of the Triaxial Cells of 136/136/99 mm, 750/250/250 mm and 1000/300/300 mm are provided in **Table 1** up to 3 GHz. Since the device under test is placed inside the cavity, the resonance frequencies during the test may deviate from the calculated frequencies.

Measurements of transfer impedance and screening attenuation of a cable RG 11 with single braid construction with tube and with Triaxial Cell with a length of 1 m shows the same results up to the first resonance frequency of about 720 MHz.

Figure 6a and **Figure 6b** show measurements of transfer impedance and screening attenuation of a cable RG 11 with single braid construction with tube and with Triaxial Cell of a length of 1 m. Up to the calculated first resonance frequency of approximately 720 MHz, no deviation of the measured curves can be observed.

Above the first resonance frequency of the cell of about 720 MHz, deviations of the maximum values of the curves within 3 dB can be found. Measurements of samples with complex geometries are under further study.

Measuring of screening effectiveness of connectors and cable assemblies with the Triaxial Cell is under study relative to *IEC TC 46/WG 5* and will be included as an additional test procedure in the revised version of *IEC 62153-4-7*, Transfer impedance and screening attenuation of connectors and assemblies, Triaxial method.

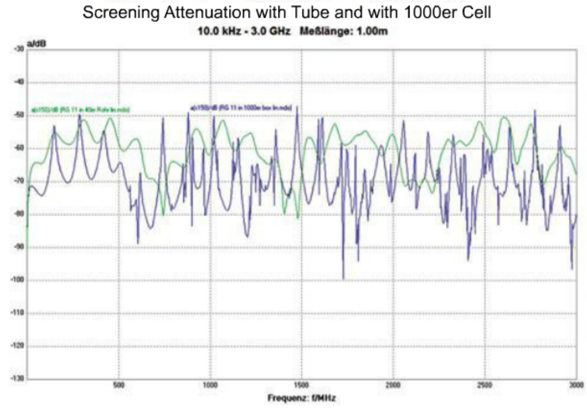

Fig. 6a — Comparison of the measurements with tube and with Triaxial Cell of a RG 11 cable with single braid construction, linear scale.

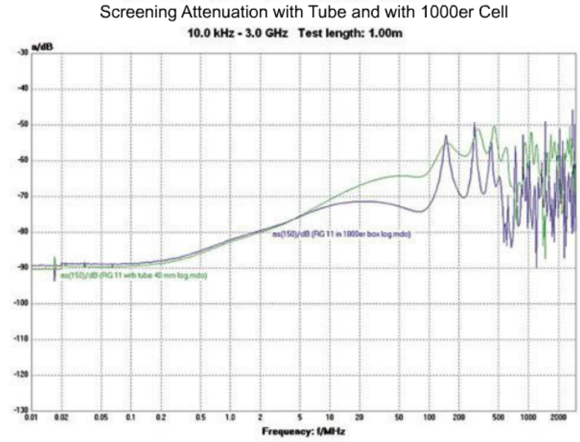

Fig. 6b — Comparison of the measurements with tube and with Triaxial Cell of a RG 11 cable with single braid construction, log scale.

Part 2 of this article, in the next issue of this magazine, will look at the influence of load conditions in the inner system.

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Table 1. Resonance Frequencies of Different Triaxial Cells.

136-er Cell				750-er Cell				1000-er Cell			
a	b	c		a	b	c		a	b	c	
136	136	99		750	250	250		1000	300	300	
m	n	p	f/GHz	m	n	p	f/GHz	m	n	p	f/GHz
1	1	1	2,17	1	1	1	0,87	1	1	1	0,72
1	2	0	2,47	1	2	0	1,22	1	2	0	1,01
0	2	1	2,68	0	2	1	1,34	0	2	1	1,12
1	2	1	2,89	1	2	1	1,36	1	2	1	1,13
2	2	0	3,12	2	2	0	1,26	2	2	0	1,04
0	1	2	3,22	0	1	2	1,34	0	1	2	1,12
1	1	2	3,41	1	1	2	1,36	1	1	2	1,13
2	2	1	3,47	2	2	1	1,40	2	2	1	1,16
0	2	2	3,75	0	2	2	1,70	0	2	2	1,41
1	2	2	3,91	1	2	2	1,71	1	2	2	1,42
2	3	0	3,98	2	3	0	1,84	2	3	0	1,53

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[1] *Bernhard Mund, EMV von Steckverbindern und Verbindungskabeln, 4. Anwenderkongress Steckverbinder 2010, Vogel Verlag, Würzburg.*

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Standards:

- *EN 50289-1-6* Communication cables-Specifications for test methods Part 1-6: Electrical test methods-Electromagnetic performance.
- *IEC 62153-4-1* Introduction to EMC measurements.
- *IEC 62153-4-3* surface transfer impedance-Triaxial method.
- *IEC 62153-4-4* Shielded screening attenuation, test method for measuring of the screening attenuation "as" up to and above 3 GHz.
- *IEC 62153-4-7* Shielded screening attenuation, test method for measuring the Transfer impedance ZT and the screening attenuation as of RF-Connectors up to and above 3 GHz; Tube in Tube method.
- *IEC 62153-4-9* Coupling attenuation, Triaxial method.

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***Part 1** of this article described the principle of the triaxial test method and procedure, the coupling transfer function, the Triaxial Cell and cut-off frequencies and higher order modes. **Part 2** now continues with the influence of load conditions.*

Influence of Load Conditions in the Inner System

The choice of the matching loads within a system has considerable influence regarding the coupling of the inner to the outer system and vice-versa. This is valid for real existing screened electrical systems as well as for test set-ups to measure the screening effectiveness with the triaxial procedure.

At the triaxial system according to **Figure 1** (as seen in *Part 1* of this article), the inner system consists of the DUT (device under test) with inner conductor, dielectric and screen, load resistor and generator. The second system consists of the receiver, airspace, test tube, short circuit (as load of the DUT) and the screen of the DUT. The screen of the DUT is member of both, the inner and the outer system.

The influence of different load impedances of the inner system regarding the test results is discussed below.

In case of screening problems on cables and assemblies, usually the galvanic coupling of the systems via the transfer impedance of the cable screen or the outer conductor of the connector is considered as the dominant effect. The transfer impedance of screens can be determined by:

$$Z_T = \frac{U_2}{I_1}$$

This simple equation shows the underlying screening problem directly. A current I_1 that flows in the inner system through the screen with the transfer impedance Z_T causes a voltage U_2 at the outer system. This voltage acts as the disturbing source in the outer system.

An increasing current through the screen causes increasing emission. If one looks at the current distribution of the inner system (the device under test), simple and easy conditions can only be found in the case of matching. In this case, the current and voltage are in phase and knotted by the impedance of the line by:

$$I_1 = \frac{U_1}{Z_1}$$

This equation is only valid for the special case of matching. In case of changing load conditions, a more general description is required. **Figure 7** shows the general equivalent circuit.

The generator with the internal resistor Z_G is connected to the DUT with the length L. The device under test is depicted by the characteristic impedance Z_1 of the line, the dielectric constant ε_r, the velocity of propagation v and propagation constant γ. The device under test is loaded with the load R_1.

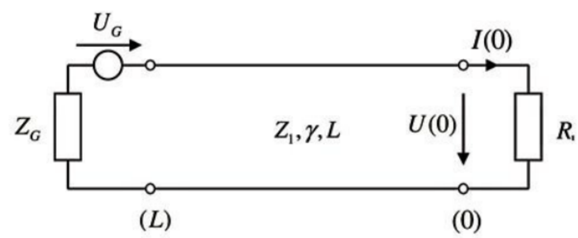

Fig. 7 — Inner system, matched with source and load impedance.

The current $I(0)$ at the load is calculated according to the previous equation as follows:

$$I(0) = \frac{U_G}{R_1 \cdot [\cosh(\gamma L) + \frac{Z_G}{Z_1}\sinh(\gamma L)] + Z_1 \cdot [\sinh(\gamma L) + \frac{Z_G}{Z_1}\cosh(\gamma L)]}$$

With the theory of transmission lines, the current can be calculated now as function x of the length of the DUT:

$$I(x) = I(0) \cdot \cosh(\gamma x) + U(0) / Z_1 \cdot \sinh(\gamma x)$$

In case of short circuit, respectively in case of open circuit of a DUT with low impedance of Z_1 = 10 Ohm (e.g., a HV-cable) with 1 m or 2 m length, the current distribution along the cable length vs. frequency is given in **Figure 8** and **Figure 9**.

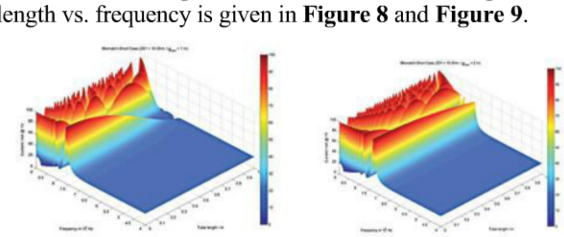

Fig. 8 — Local current distribution vs. frequency with short circuit, left side 1 m length, right side 2 m length.

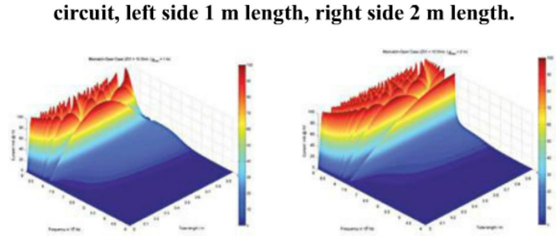

Fig. 9 — Local current distribution vs. frequency with open circuit, left side 1 m length, right side 2 m length.

At certain frequencies, a considerable location-dependent increase of current occurs.

The maximum value of those current peaks related to the matched condition ($Z_1 = Z_G$) is given by:

$$I_{max}(Z_1) / I_{max}(Z_1{=}Z_G) = Z_G / Z_1$$

It is the inverse ratio of the impedances of the generator and the DUT. For an unmatched cable under test with a characteristic impedance of $Z_1 = 10$ Ohm, we get local current maxima with a factor 5.

Impact of Load Conditions to the Measurements

The test results of a real test set-up with a 0.95 m long HV cable under test and with a characteristic impedance of $Z_1 = 10$ Ohm for the load conditions: open circuit, matched and short circuit are shown in **Figure 10**.

Whereas measuring with matched DUT ($R_1 = 10$ Ohm, purple curve) shows a smooth coupling curve (Transmission S_{21}) up to 100 MHz, a first resonance maximum at approximately 40 MHz can be observed at the short circuit. Further maxima can be observed at 3 * 40 MHz and 5 * 40 MHz; that means at uneven multiples of the first resonance maximum of the short circuit. At the open circuit, ($R_1 = \infty$ Ohm, green curve), we find the first resonance at about 80 MHz and a second one at about 160 MHz. A third one is indicated at about 240 MHz; that means, resonances occur at even multiples from the first resonance frequency in case of open circuit.

Expressed in wavelength, which fit into the length of the cable under test, resonances occur as follows:

short circuit: uneven multiples of lambda/4
open circuit: even multiples of lambda/2

The magnitude of those resonance cambers amounts up to +14 dB, which corresponds to the factor 5 (in case of voltage measurement). This value conforms to the theoretic investigated maximum current cambers at the inner system.

Revision of *IEC 62153-4-3*: Measuring of Transfer Impedance

The first draft of revised *IEC 62153-4-3 Ed.2* (*46/371/CD*) already contains the conditions, described above. A third test procedure with the load conditions "unmatch-match-short" is added in the new draft.

This new procedure allows direct feeding of the cable under test from the generator with the inner load R_1 without any matching device. Transfer impedance of HV cables can be measured without any matching device, where resonance cambers as pictured above can be avoided when using the procedure "unmatched-short-short". This is possible by using new calculation rules for the calculation of Z_T from the measured Transmission S_{21}.

The upper cut-off frequency $f_{max\text{-}ZT}$ can be extended towards higher frequencies. The considerations of the new test procedure "unmatch-match-short" are valid for both, measuring the transfer impedance with the well known Triaxial Tube as well as with the Triaxial Cell.

The function "Coupling transfer functio" as well as the changes of the new version of *IEC 62153-4-2 Ed2* are already integrated in the current version of the WinCoMeT software of the CoMeT system of **bedea**/**Rosenberger**.

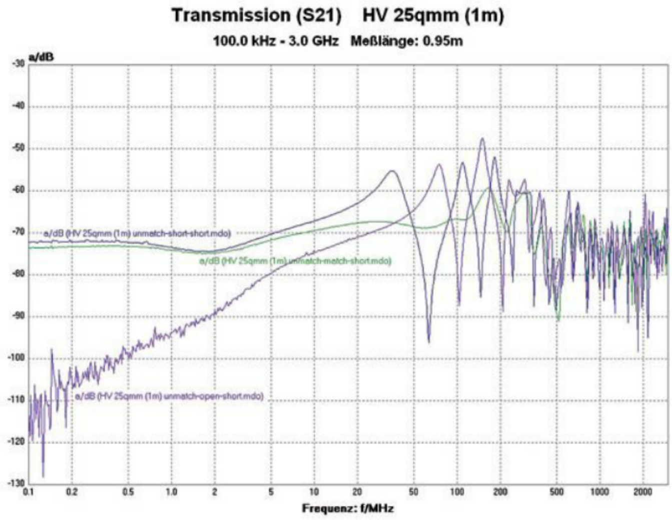

Fig. 10 — Comparison of the screening effectiveness of HV-cables with different load conditions.

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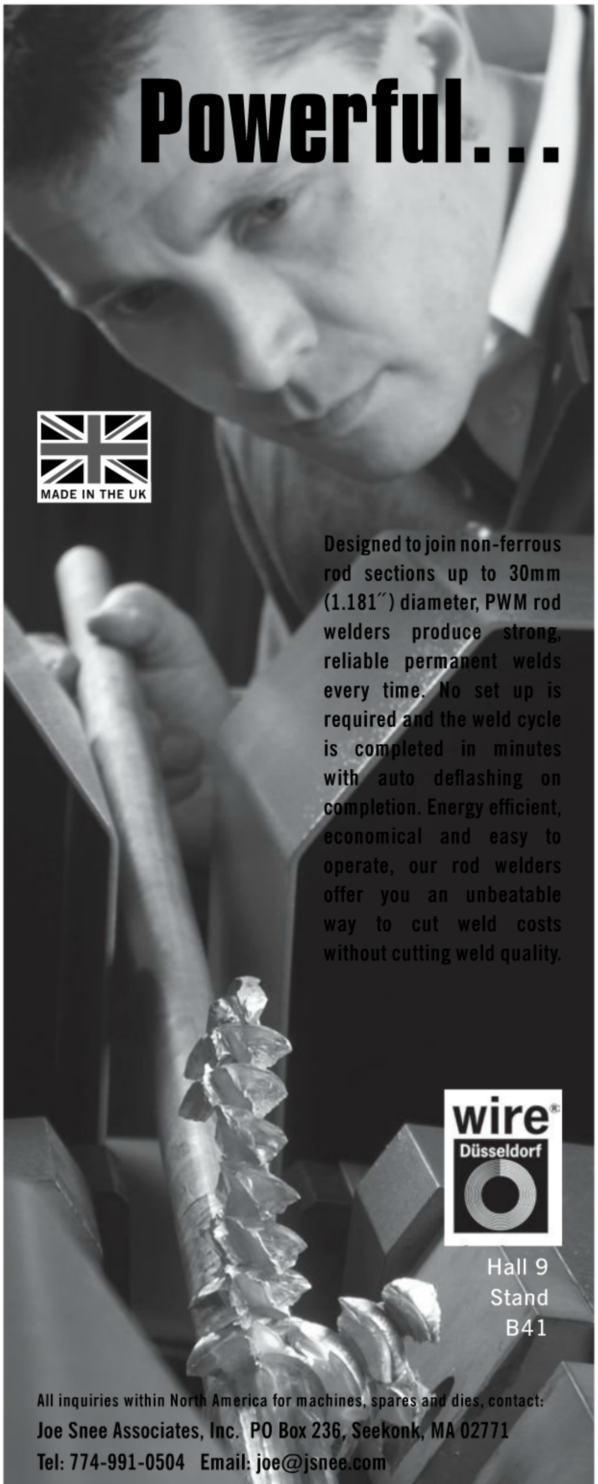

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- *IEC 62153-4-9* Coupling attenuation, Triaxial method.

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