

TECHNICAL REPORT



**Metallic communication cable test methods –
Part 4-1: Electromagnetic compatibility (EMC) – Introduction to electromagnetic
(EMC) screening measurements**

Withhold



THIS PUBLICATION IS COPYRIGHT PROTECTED

Copyright © 2010 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester.

If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

Droits de reproduction réservés. Sauf indication contraire, aucune partie de cette publication ne peut être reproduite ni utilisée sous quelque forme que ce soit et par aucun procédé, électronique ou mécanique, y compris la photocopie et les microfilms, sans l'accord écrit de la CEI ou du Comité national de la CEI du pays du demandeur.

Si vous avez des questions sur le copyright de la CEI ou si vous désirez obtenir des droits supplémentaires sur cette publication, utilisez les coordonnées ci-après ou contactez le Comité national de la CEI de votre pays de résidence.

IEC Central Office
3, rue de Varembe
CH-1211 Geneva 20
Switzerland
Email: inmail@iec.ch
Web: www.iec.ch

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

- Catalogue of IEC publications: www.iec.ch/searchpub

The IEC on-line Catalogue enables you to search by a variety of criteria (reference number, text, technical committee,...). It also gives information on projects, withdrawn and replaced publications.

- IEC Just Published: www.iec.ch/online_news/justpub

Stay up to date on all new IEC publications. Just Published details twice a month all new publications released. Available on-line and also by email.

- Electropedia: www.electropedia.org

The world's leading online dictionary of electronic and electrical terms containing more than 20 000 terms and definitions in English and French, with equivalent terms in additional languages. Also known as the International Electrotechnical Vocabulary online.

- Customer Service Centre: www.iec.ch/webstore/custserv

If you wish to give us your feedback on this publication or need further assistance, please visit the Customer Service Centre FAQ or contact us:

Email: csc@iec.ch
Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00

TECHNICAL REPORT



**Metallic communication cable test methods –
Part 4-1: Electromagnetic compatibility (EMC) – Introduction to electromagnetic
(EMC) screening measurements**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE **XB**

ICS 33.100, 33.120.10

ISBN 978-2-88910-918-0

CONTENTS

FOREWORD.....	5
1 Scope.....	7
2 Normative references.....	7
3 Electromagnetic phenomena.....	8
4 The intrinsic screening parameters of short cables.....	10
4.1 General.....	10
4.2 Surface transfer impedance, Z_T	10
4.3 Capacitive coupling admittance, Y_C	10
4.4 Injecting with arbitrary cross-sections.....	12
4.5 Reciprocity and symmetry.....	12
4.6 Arbitrary load conditions.....	12
5 Long cables – coupled transmission lines.....	12
6 Transfer impedance of a braided wire outer conductor or screen.....	20
7 Test possibilities.....	26
7.1 General.....	26
7.2 Measuring the transfer impedance of coaxial cables.....	26
7.3 Measuring the transfer impedance of cable assemblies.....	26
7.4 Measuring the transfer impedance of connectors.....	27
7.5 Calculated maximum screening level.....	27
8 Comparison of the frequency response of different triaxial test set-ups to measure the transfer impedance of cable screens.....	32
8.1 General.....	32
8.2 Physical basics.....	32
8.2.1 Triaxial set-up.....	32
8.2.2 Coupling equations.....	35
8.3 Simulations.....	35
8.3.1 General.....	35
8.3.2 Simulation of the standard and simplified methods according to EN 50289-1-6, IEC 61196-1 (method 1 and 2) and IEC 62153-4-3 (method A).....	36
8.3.3 Simulation of the double short circuited methods.....	43
8.4 Conclusion.....	51
9 Background of the shielded screening attenuation test method (IEC 62153-4-4).....	52
9.1 General.....	52
9.2 Objectives.....	52
9.3 Theory of the triaxial measuring method.....	53
9.4 Screening attenuation.....	58
9.5 Normalised screening attenuation.....	59
9.6 Measured results.....	60
9.7 Comparison with absorbing clamp method.....	62
9.8 Practical design of the test set-up.....	63
9.9 Influence of mismatches.....	64
Annex A (normative) List of symbols.....	67
Bibliography.....	70

Figure 1 – Total electromagnetic field ($\vec{E}_t, \vec{H}_t$)

Figure 2 – Defining and measuring screening parameters – A triaxial set-up	9
Figure 3 – Equivalent circuit for the testing of Z_T	11
Figure 4 – Equivalent circuit for the testing of $Y_c = j \omega C_T$	11
Figure 5 – Electrical quantities in a set-up that is matched at both ends	12
Figure 6 – The summing function $S\{L \cdot f\}$ for near and far end coupling	16
Figure 7 – Transfer impedance of a typical single braid screen	17
Figure 8 – The effect of the summing function-coupling transfer function of a typical single braid screen cable	17
Figure 9 – Calculated coupling transfer functions T_n and T_f for a single braid – $Z_F = 0$	18
Figure 10 – Calculated coupling transfer functions T_n and T_f for a single braid – $\text{Im}(Z_T)$ is positive and $Z_F = +0,5 \times \text{Im}(Z_T)$ at high frequencies	18
Figure 11 – Calculated coupling transfer functions T_n and T_f for a single braid – $\text{Im}(Z_T)$ is negative and $Z_F = -0,5 \times \text{Im}(Z_T)$ at high frequencies	19
Figure 12 – $L \cdot S$: the complete length dependent factor in the coupling function T	20
Figure 13 – Transfer impedance of typical cables	21
Figure 14 – Magnetic coupling in the braid Complete flux	22
Figure 15 – Magnetic coupling in the braid Left-hand lay contribution	22
Figure 16 – Magnetic coupling in the braid Right-hand lay contribution	22
Figure 17 – Complex plane, $Z_T = \text{Re } Z_T + j \text{Im } Z_T$, frequency f as parameter	23
Figure 18 – Magnitude (amplitude), $ Z_T(f) $	23
Figure 19 – Typical Z_T (time) step response of an overbraided and underbraided single braided outer conductor of a coaxial cable	24
Figure 20 – Z_T equivalent circuits of a braided wire screen	25
Figure 21 – Comparison of signal levels in a generic test setup	28
Figure 22 – Triaxial set-up for the measurement of the transfer impedance Z_T	32
Figure 23 – Equivalent circuit of the triaxial set-up	33
Figure 24 – Simulation of the frequency response for g	37
Figure 25 – Simulation of the frequency response for g	37
Figure 26 – Simulation of the frequency response for g	38
Figure 27 – Simulation of the frequency response for g	38
Figure 28 – Simulation of the 3 dB cut off wavelength (L/λ_1)	39
Figure 29 – Interpolation of the simulated 3 dB cut off wavelength (L/λ_1)	40
Figure 30 – 3 dB cut-off frequency length product as a function of the dielectric permittivity of the inner circuit (cable)	41
Figure 31 – Measurement result of the normalised voltage drop of a single braid screen in the triaxial set-up	42
Figure 32 – Measurement result of the normalised voltage drop of a single braid screen in the triaxial set-up	43
Figure 33 – Triaxial set-up (measuring tube), double short circuited method	44
Figure 34 – Simulation of the frequency response for g	45
Figure 35 – Simulation of the frequency response for g	45
Figure 36 – Simulation of the frequency response for g	46
Figure 37 – Simulation of the frequency response for g	46
Figure 38 – Interpolation of the simulated 3 dB cut off wavelength (L/λ_1)	47

Figure 39 – 3 dB cut-off frequency length product as a function of the dielectric permittivity of the inner circuit (cable)	48
Figure 40 – Simulation of the frequency response for g	49
Figure 41 – Interpolation of the simulated 3 dB cut off wavelength (L/λ_1).....	50
Figure 42 – 3 dB cut-off frequency length product as a function of the dielectric permittivity of the inner circuit (cable)	50
Figure 43 – Definition of transfer impedance.....	52
Figure 44 – Definition of coupling admittance	52
Figure 45 – Triaxial measuring set-up for screening attenuation.....	53
Figure 46 – Equivalent circuit of the triaxial measuring set-up	54
Figure 47 – Calculated voltage ratio for a typical braided cable screen.....	55
Figure 48 – Calculated periodic functions for $\epsilon_{r1} = 2,3$ and $\epsilon_{r2} = 1,1$	56
Figure 49 – Calculated voltage ratio-typical braided cable screen.....	57
Figure 50 – Equivalent circuit for an electrical short part of the length Δl and negligible capacitive coupling.....	58
Figure 51 – a_s of single braid screen, cable type RG 58, $L = 2$ m.....	61
Figure 52 – a_s of single braid screen, cable type RG 58, $L = 0,5$ m	61
Figure 53 – a_s of cable type HF 75 0,7/4,8 02YCY.....	62
Figure 54 – a_s of cable type HF 75 1,0/4,8 02YCY	62
Figure 55 – a_s of double braid screen, cable type RG 223.....	62
Figure 56 – Schematic for the measurement of the screening attenuation a_s	64
Figure 57 – Short circuit between tube and cable screen of the CUT	64
Figure 58 – Triaxial set-up, impedance mismatches.....	65
Figure 59 – Calculated voltage ratio including multiple reflections caused by the screening case.....	66
Figure 60 – Calculated voltage ratio including multiple reflections caused by the screening case.....	66
Table 1 – The coupling transfer function T (coupling function).....	15
Table 2 – Screening effectiveness of cable test methods for surface transfer impedance Z_T ..	30
Table 3 – Load conditions of the different set-ups.....	34
Table 4 – Parameters of the different set-ups	36
Table 5 – Cut-off frequency length product	40
Table 6 – Typical values for the factor v , for an inner tube diameter of 40 mm and a generator output impedance of 50 Ω	44
Table 7 – Cut-off frequency length product	47
Table 8 – Material combinations and the factor n	49
Table 9 – Cut-off frequency length product	50
Table 10 – Cut-off frequency length product for some typical cables in the different set-ups...	51
Table 11 – Δa in dB for typical cable dielectrics	60
Table 12 – Comparison of results of some coaxial cables	63

INTERNATIONAL ELECTROTECHNICAL COMMISSION

METALLIC COMMUNICATION CABLE TEST METHODS –

**Part 4-1: Electromagnetic compatibility (EMC) –
Introduction to electromagnetic (EMC) screening measurements**

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC/TR 62153-4-1, which is a technical report, has been prepared by IEC technical committee 46: Cables, wires, waveguides, R.F. connectors, R.F. and microwave passive components and accessories.

This second edition cancels and replaces the first edition published in 2007. The significant change is a new clause on the background of the shielded screening attenuation test method.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
46/331/DTR	46/350/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 62153 series, under the general title: *Metallic communication cable test methods*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

METALLIC COMMUNICATION CABLE TEST METHODS –

Part 4-1: Electromagnetic compatibility (EMC) – Introduction to electromagnetic (EMC) screening measurements

1 Scope

Screening (or shielding) is one basic way of achieving electromagnetic compatibility (EMC). However, a confusingly large number of methods and concepts is available to test for the screening quality of cables and related components, and for defining their quality. This technical report gives a brief introduction to basic concepts and terms trying to reveal the common features of apparently different test methods. It should assist in correct interpretation of test data, and in the better understanding of screening (or shielding) and related specifications and standards.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60096-1:1986, *Radio-frequency cables – Part 1: General requirements and measuring methods*
Amendment 2 (1993)

IEC 60096-4-1, *Radio-frequency cables – Part 4: Specification for superscreened cables – Section 1: General requirements and test methods*

IEC 60169-1-3, *Radio frequency connectors – Part 1: General requirements and measuring methods – Section 3: Electrical tests and measuring procedures – Screening effectiveness*

IEC 61196-1:1995, *Radiofrequency cables – Part 1: Generic specification – General, definitions, requirements and test methods*

IEC 61726, *Cable assemblies, cables, connectors and passive microwave components – Screening attenuation measurement by the reverberation chamber method*

IEC 62153-4-3, *Metallic communication cables test methods – Part 4-3: Electromagnetic compatibility (EMC) – Surface transfer impedance – Triaxial method*

IEC 62153-4-4, *Metallic communication cable test methods – Part 4-4: Electromagnetic compatibility (EMC) – Shielded screening attenuation, test method for measuring of the screening attenuation a_s up to and above 3 GHz*

IEC 62153-4-5, *Metallic communication cable test methods – Part 4-5: Electromagnetic compatibility (EMC) – Coupling or screening attenuation – Absorbing clamp method*

EN 50289-1-6, *Communication cables – Specification for test methods – Electrical test methods – Electromagnetic performance*

3 Electromagnetic phenomena

It is assumed that if an electromagnetic field is incident on a screened cable, there is only weak coupling between the external field and that inside, and that the cable diameter is very small compared with both the cable length and the wavelength of the incident field. The superposition of the external incident field and the field scattered by the cable yields the total electromagnetic field $(\vec{E}_t, \vec{H}_t)$ in Figure 1. The total field at the screen's surface may be considered as the source of the coupling: electric field penetrates through apertures by electric or capacitive coupling; also magnetic fields penetrate through apertures by inductive or magnetic coupling.

Additionally, the induced current in the screen results in conductive or resistive coupling.

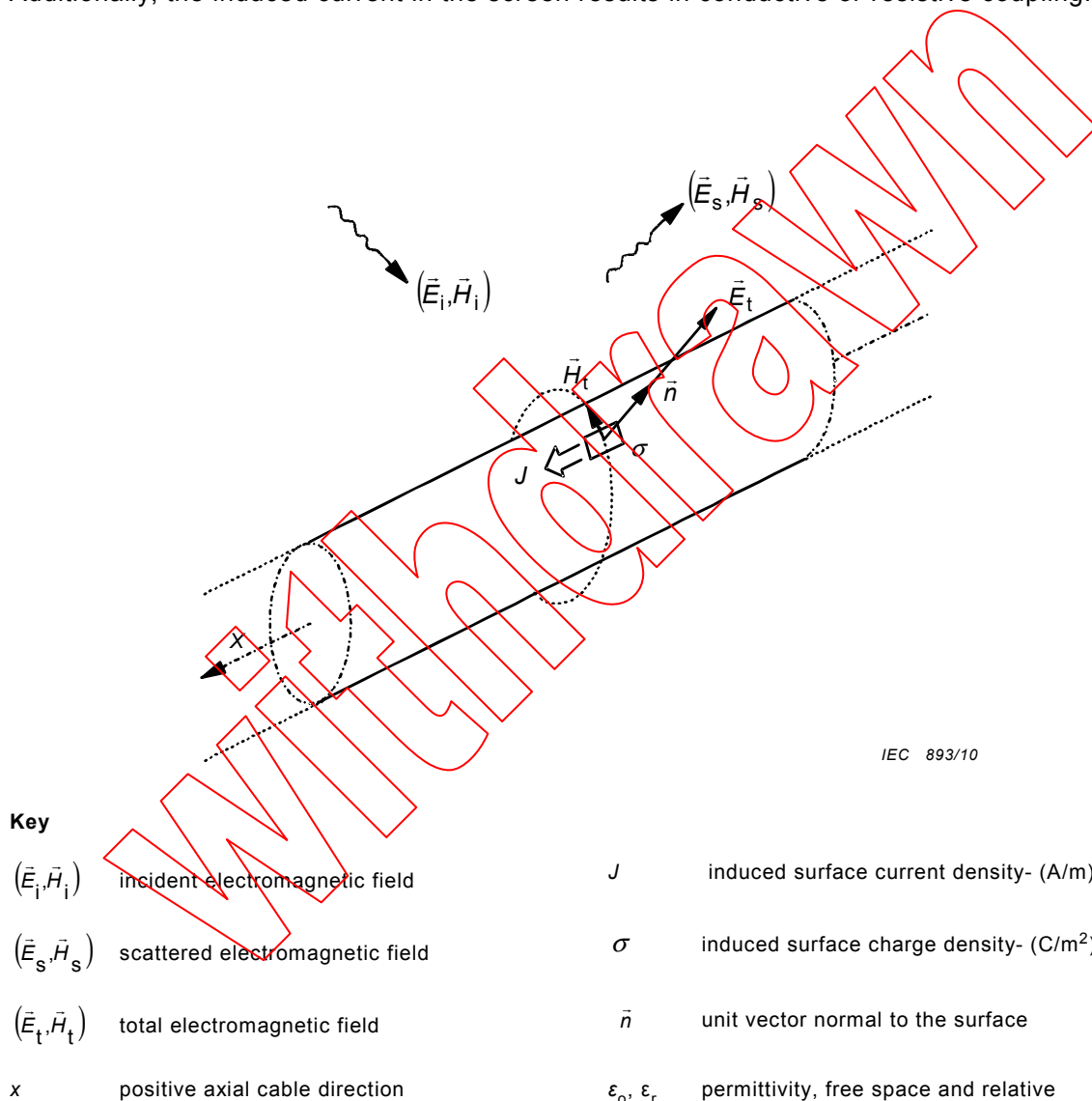


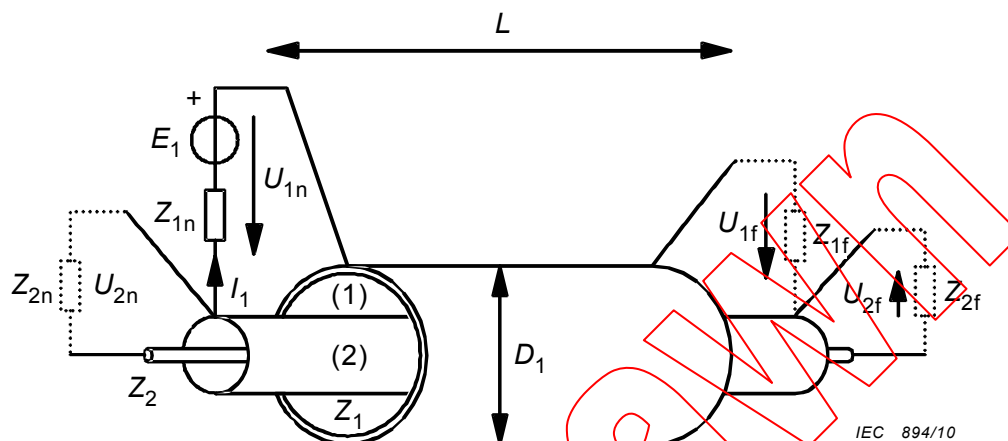
Figure 1 – Total electromagnetic field $(\vec{E}_t, \vec{H}_t)$

$$(\vec{E}_t, \vec{H}_t) = (\vec{E}_i, \vec{H}_i) + (\vec{E}_s, \vec{H}_s) \quad (1)$$

$$J = \vec{n} \cdot \vec{H}_t \quad (2)$$

$$\sigma = \vec{n} \cdot \vec{E}_t \epsilon_0 \epsilon_r \quad (3)$$

As the field at the surface of the screen is directly related to density of surface current and surface charge, the coupling may be assigned either to the total field ($\vec{E}_t, \vec{H}_t$) or to the surface current- and charge- densities (J and σ). Consequently, the coupling into the cable may be simulated by reproducing, through any suitable means, the surface currents and charges on the screen. Because the cable diameter is assumed to be small, the higher modes may be neglected and it is possible to use an additional coaxial conductor as the injection structure, as shown in Figure 2.



Key (for Figures 2,3,4,5)

- (1), (2) Indicates outer circuit(1), tube, respectively inner circuit(2), cable
- $Z_{1,2}$ Characteristic impedance of the outer circuit(1), tube, respectively inner circuit(2), cable
- $\epsilon_{1,2}$ Dielectric permittivity of the outer circuit(1), tube, respectively inner circuit(2), cable
- $\beta_{1,2}$ Phase constant of the outer circuit(1), tube, respectively inner circuit(2), cable
- $\lambda_{1,2}$ Wave length of the outer circuit(1), tube, respectively inner circuit(2), cable
- L Coupling length
- D_1 Diameter of injection cylinder-tube
- V Voltmeter
- A Ammeter
- Z_{1n}, Z_{1f} Load resistance at the near end, respectively far end of the outer circuit(1), tube
- Z_{2n}, Z_{2f} Load resistance at the near end, respectively far end of the inner circuit(2), cable
- E_1 EMF of the generator
- I_1, I_2 Current in the outer circuit(1), tube, respectively inner circuit(2), cable
- U_{1n}, U_{1f} Voltage at the near end, respectively far end of the outer circuit(1), tube
- U_{2n}, U_{2f} Voltage at the near end, respectively far end of the inner circuit(2), cable

Concept of a triaxial set-up

- (1) outer circuit (1), formed by an injection cylinder-tube and the screen under test, with characteristic impedance Z_1 ,
- (2) inner circuit (2), formed by the screen under test, and centre conductor, with characteristic impedance Z_2 ; screening at the ends of circuit (2) is not shown.

Observe the conditions Z_{1f}, Z_{2n}, Z_{2f} and λ in Figure 3 and Figure 4.

NOTE 1 $D_1 \ll L$.

NOTE 2 Both ends of circuit (2) must be well screened.

Figure 2 – Defining and measuring screening parameters – A triaxial set-up

4 The intrinsic screening parameters of short cables

4.1 General

The intrinsic parameters refer to an infinitesimal length of cable, like the inductance or capacitance per unit length of transmission lines. Assuming electrically short cables, with $L \ll \lambda$ which will always apply at low frequencies, the intrinsic screening parameters are defined and can be measured as indicated in the following subclauses.

4.2 Surface transfer impedance, Z_T

As shown in Figure 3, where Z_{1f} and Z_{2f} are zero, the surface transfer impedance (Z_T in Ω/m) is given:

$$Z_T = \frac{U_{2n}}{I_1 \cdot L} \quad (4)$$

The dependence of Z_T on frequency is not simple and is often shown by plotting $\log Z_T$ against $\log$ frequency. Note that the phase of Z_T may have any value, depending on braid construction and frequency range.

NOTE In circuit (2) of Figure 3, the voltmeter and short circuit can be interchanged.

4.3 Capacitive coupling admittance, Y_C

As shown in Figure 4, where Z_{1f} and Z_{2f} are open circuit, the capacitive coupling admittance (Y_C in mho/m) is given by:

$$Y_C = j \cdot \omega C_T = \frac{I_2}{U_{1n} \cdot L} \quad (5)$$

where

C_T is the through capacitance;

ω is the radian frequency;

j is the imaginary operator.

The through capacitance C_T is a real capacitance and has usually a constant value up to 1 GHz and higher (with aperture $a \ll \lambda$).

While Z_T is independent of the characteristics of the coaxial circuits (1) and (2), C_T is dependent on those characteristics. There are two ways of overcoming this dependence:

- a) The normalized through elastance K_T (with units of m/F) derived from C_T is independent of the size of the outer coaxial circuit (2), but it depends on its permittivity:

$$K_T = C_T / (C_1 \cdot C_2) \quad (6)$$

$$K_T \sim 1/(\epsilon_{r1} + \epsilon_{r2}) \quad (7)$$

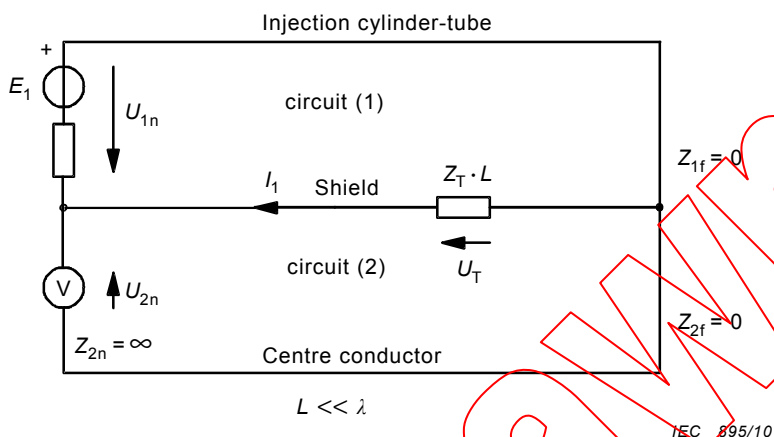
where C_1 and C_2 are the capacitance per unit length of the two coaxial circuits.

- b) The capacitive coupling impedance Z_F (with units of Ω/m) again derived from C_T is also independent of the size of the outer coaxial circuit (2) and, for practical values of ϵ_{r1} , is only slightly dependent on its permittivity:

$$Z_F = Z_1 Z_2 Y_C = Z_1 Z_2 j \omega C_T \quad (8)$$

$$Z_F \sim \sqrt{(\epsilon_{r1} \cdot \epsilon_{r2})} / (\epsilon_{r1} + \epsilon_{r2}) \quad (9)$$

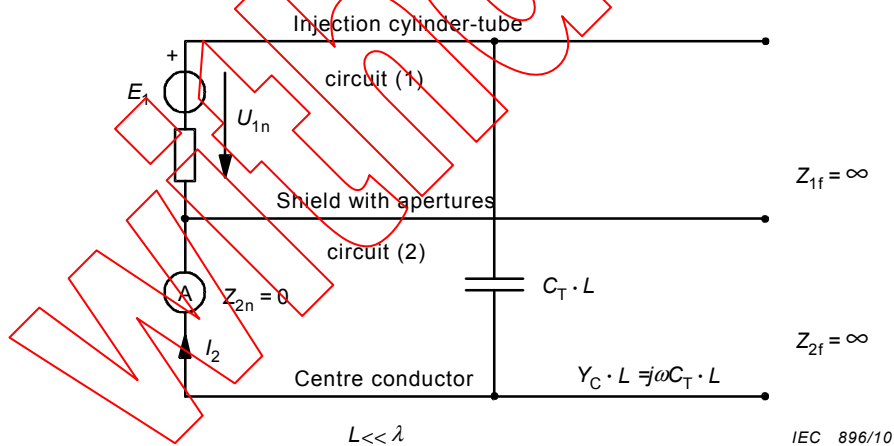
Compared with Z_T , Z_F is usually negligible, except for open weave braids. It may, however, be significant when Z_{2n} and $Z_{2f} \gg Z_2$ (audio circuits).



Key

See Figure 2.

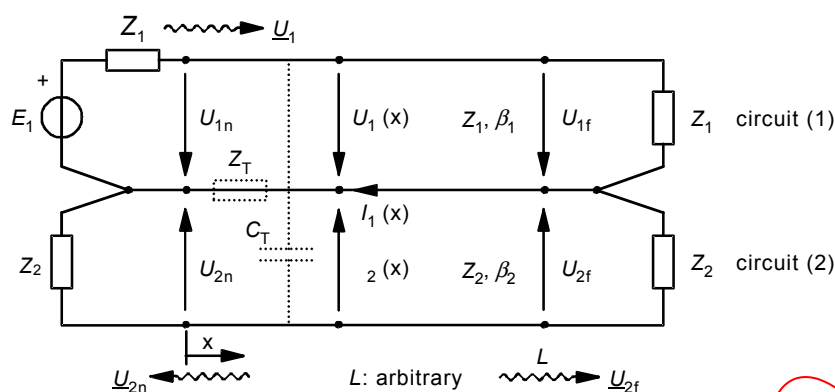
Figure 3 – Equivalent circuit for the testing of Z_T



Key

See Figure 2.

Figure 4 – Equivalent circuit for the testing of $Y_C = j \omega C_T$



Key

See Figure 2.

NOTE Z_T and C_T are distributed (not correctly shown here). The loads Z_1 , Z_2 at the ends may represent matched receivers.

Figure 5 – Electrical quantities in a set-up that is matched at both ends

4.4 Injecting with arbitrary cross-sections

A coaxial outer circuit (2) has been assumed so far in this report, but it is not essential because of the invariance of Z_T and Z_F . Using a wire in place of the outer cylinder, the injection circuit (2) becomes two-wire with the return via the screen of the cable under test. Obviously the charge and current distribution become non-uniform, but the results are equivalent to coaxial injection, especially if two injection lines are used opposite to each other, and may be justified for worst-case testing. Note that the IEC line injection test uses a wire.

4.5 Reciprocity and symmetry

Assuming linear shield materials, the measured Z_T and Z_F values will not change when interchanging the injection circuit (1) and the measuring circuit (2). Each of the two conductors of the two-line circuit can be interchanged, but in practice the set-up will have to take into account possible ground loops and coupling to the environment.

4.6 Arbitrary load conditions

When the circuit ends of Figure 3 and Figure 4 are not ideally a short or open circuit, Z_T and Z_F will act simultaneously. Their superposition is noticeable in the low frequency coupling of the matched circuit (1) and circuit (2), (Figure 5 and Table 1).

5 Long cables – coupled transmission lines

The coupling over the whole length of the cable is obtained by summing up (integrating) the infinitesimal coupling contributions along the cable while observing the correct phase. The analysis utilizes the following assumptions and conventions:

- matched circuits considered with the voltage waves $\underline{U}_1$, $\underline{U}_{2n}$, $\underline{U}_{2f}$, see Figure 5,
- representation of the coupling, using the normalized wave amplitudes $\underline{U}/\sqrt{Z} [\sqrt{\text{Watt}}]$, instead of voltage waves. i.e. the coupling transfer function, in the following denoted by "coupling function", will be defined as

$$T_n = \frac{\underline{U}_{2n} / \sqrt{Z_2}}{\underline{U}_1 / \sqrt{Z_1}} \quad (10)$$

$$T_f = \frac{U_{2f} / \sqrt{Z_2}}{U_1 / \sqrt{Z_1}} \quad (11)$$

NOTE 1 $|T|^2$ is the ratio of the power waves travelling in circuits (2) and (1). Due to reciprocity and assuming linear screen (shield) materials, T is reciprocal, i.e. invariant with respect to the interchange of injection and measuring circuits (1) and (2).

NOTE 2 The quantity $|1/T|^2$, or in logarithmic quantities

$$a_s = -20 \times \log_{10} |T| \quad (12)$$

may be considered as the "screening attenuation" of the cable, specific to the set-up.

Performing the straight forward calculations of coupled transmission line theory, the coupling function T , given in Table 1, is obtained. The term $S\{L \cdot f\}$ is the "summing function" S , being dependent on L and f . (The wavy bracket just indicates that the product $L \cdot f$ is the argument of the function S and not a factor to S). S represents the phase effect, when summing up the infinitesimal couplings along the line, and is:

$$S_n \left\{ \frac{L \cdot f}{f} \right\} = \frac{\sin \frac{\beta L \pm}{2}}{\frac{\beta L \pm}{2}} \exp \left(-j \cdot \frac{\beta L \pm}{2} \right) \quad (13)$$

with

$$\beta L \pm = (\beta_2 \pm \beta_1) \cdot L \quad (14)$$

$$= 2\pi L f \cdot (1/v_2 \pm 1/v_1) \quad (15)$$

$$= 2\pi L f \cdot (\sqrt{\epsilon_{r2}} \pm \sqrt{\epsilon_{r1}}) / c \quad (16)$$

subscript $\pm$ refers to near/far end respectively;
 $+$ refers to both near/far ends.

Note that weak coupling, i.e. $T \ll 1$, has been assumed. This case, including losses, is given in [1]¹⁾.

Equation (17) and the representation in Table 1 illustrate the contributions of the different parameters to the coupling function T :

$$T_n = (Z_F \pm Z_T) \cdot \frac{1}{\sqrt{Z_1 \cdot Z_2}} \cdot \frac{L}{2} \cdot S_n \left\{ \frac{L \cdot f}{f}, \epsilon_{r1}, \epsilon_{r2} \right\} \quad (17)$$

Note especially the following points.

- There may be a directional effect ($T_n \neq T_f$) in the whole frequency range if Z_F is not negligible. (But Z_F is usually negligible except with loose, single braid shields.)
- Up to a constant factor, T is the quantity directly measured in a set-up.

¹⁾ Figures in square brackets refer to the bibliography.

- c) For low frequencies, i.e. for short cables ($L \ll \lambda$), the trivial coupling formula is obtained that is directly proportional to L :

$$T_{nf} = (Z_F \pm Z_T) \cdot \frac{1}{Z_{12}} \cdot \frac{L}{2} \quad (18)$$

where

$$Z_{12} = \sqrt{Z_1 \cdot Z_2}$$

- d) The summing function $S\{L \cdot f\}$ is presented in Figure 6.

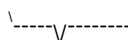
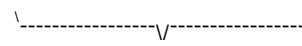
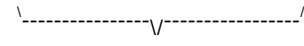
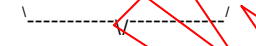
- e) $S\{L \cdot f\}$ has a $\sin(x)/x$ behaviour. A cut-off point may be defined as $(L \cdot f)_c$:

$$(L \cdot f)_{cn} = \frac{c}{\pi \sqrt{\epsilon_{r1} \pm \sqrt{\epsilon_{r2}}}} \quad (19)$$

- f) The exact envelope of $S\{L \cdot f\}$ is

$$\text{Env} \left| S_{nf}\{L \cdot f\} \right| = \frac{1}{\sqrt{1 + \frac{(L \cdot f)^2}{(L \cdot f)_{cn}^2}}} \quad (20)$$

Table 1 – The coupling transfer function T (coupling function)^a

Set-up parameters ^b	
$(Z_1), L, \epsilon_{r1}$	
$T_n = (Z_F \pm Z_T) \cdot \frac{1}{\sqrt{Z_1 \cdot Z_2}} \cdot \frac{L}{2} \cdot S_n \{L \cdot f, \epsilon_{r1}, \epsilon_{r2}\}$	
	
Intrinsic screen parameters	Cable parameters ^b $(Z_2, L), \epsilon_{r2}$
	
"Low-frequency coupling", short cables ^c	"HF-effect", cut-off $(L \cdot f)_c$
	
Length + frequency effect	
^a T^2 is the power coupling from circuit (1) to circuit (2). The stacked subscripts _fⁿ are associated to the stacked operation symbols $\pm$ in the obvious way: upper subscript $\rightarrow$ upper operation, lower subscript $\rightarrow$ lower operation. ^b ϵ_{r1} and ϵ_{r2} contained in S as parameters. ^c for $L \ll \lambda$: $S\{L \cdot f\} \rightarrow 1$.	

g) The first minimum (zero) of $S\{L \cdot f\}$ occurs at

$$(L \cdot f)_{\min} = \pi(L \cdot f)_c \quad (21)$$

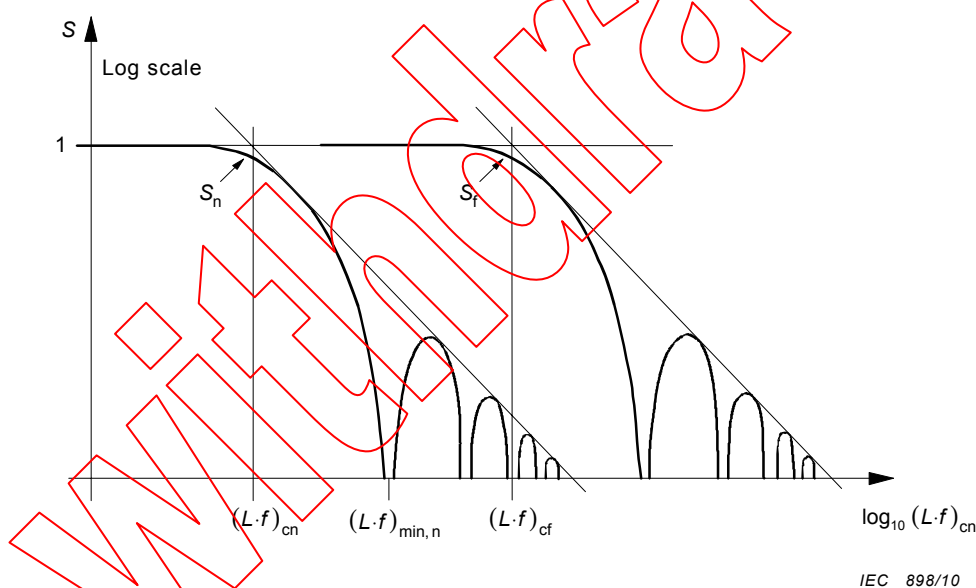
h) As seen from Equations (13) and (20), below the cut-off points $(L \cdot f)_{cn}$ is $S\{L \cdot f\} \approx 1$ and above them it starts to oscillate and its envelope drops asymptotically 20 dB/decade,

$$\text{Env} \left| S_n \{L \cdot f\} \right|_f \approx \frac{\left(\frac{(L \cdot f)_{cn}}{f} \right)}{(L \cdot f)} \quad (22)$$

i) S is symmetrical in L and f , i.e. L and f are interchangeable. For a fixed length a cut-off frequency f_c and vice versa, for a fixed frequency a cut-off length L_c may be defined. Substituting c/λ_0 for f , we obtain the cut-off length as

$$L_{cn} = \frac{\lambda_0}{\pi \sqrt{\epsilon_{r1} \pm \sqrt{\epsilon_{r2}}}} \quad (23)$$

- j) The effect of S in the frequency range ($L = \text{constant}$) is illustrated in Figure 8. The coupling function is proportional to Z_T , only if $f < f_c$. Note also the typical values indicated for f_c .
- k) The minima and maxima of S are not resonances, they are due to cancelling and additive effects of the coupling along the line.
- l) The far end cut-off frequency is significantly influenced by the permittivity of the outer system (ϵ_{r1}). Selecting $\epsilon_{r1} \rightarrow \epsilon_{r2}$ we obtain $(L \cdot f)_{cf} \rightarrow \infty$, i.e. no cut-off at the far end. Due to practical aspects (tolerances, homogeneity, etc.), an ideal phase matching ($\epsilon_{r1} \equiv \epsilon_{r2}$) is not feasible.
- m) The effects of Z_T and Z_F on the coupling transfer functions T_n and T_f are shown in Figure 8.
- n) The total effect of L on the coupling is not contained in S alone, but in the product $L \cdot S\{L \cdot f\}$. The product $L \cdot S$ is presented in Figure 12 for $f = \text{constant}$. The coupling function T which can be measured in a set-up, is proportional to L if $L < L_c$. However, for appropriately long cables ($L > L_c$), the maximum coupling is independent of L and we obtain a length independent shielding attenuation above the cut-off point $(L \cdot f)_c$. But we should remember that $(L \cdot f)_c$ as well as A_s are still dependent on the set-up parameters (ϵ_{r1}, Z_1).



NOTE $S_f > S_n$ above near end cut-off, yielding a directive effect.

$(L \cdot f)_c$: cut-off point

Figure 6 – The summing function $S\{L \cdot f\}$ for near and far end coupling

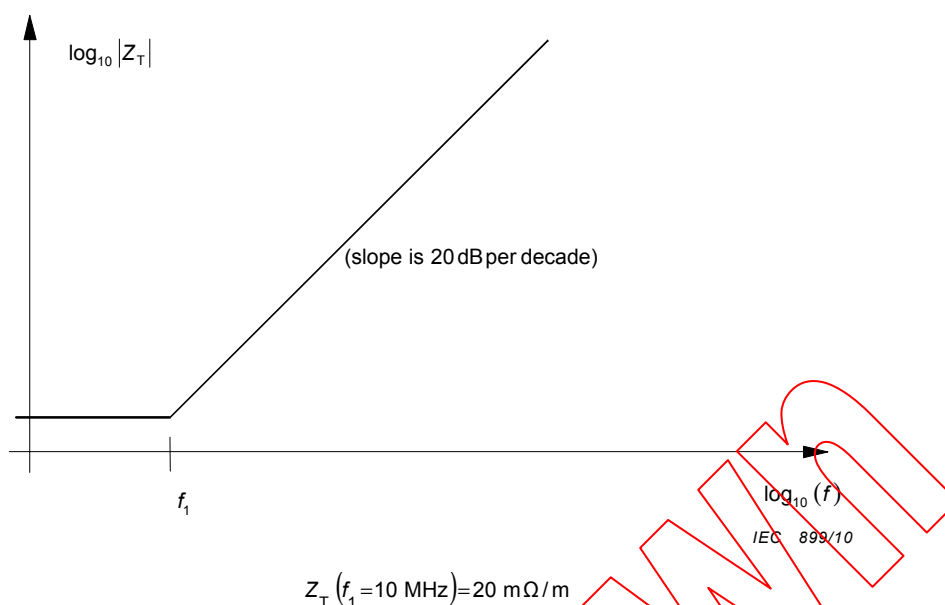
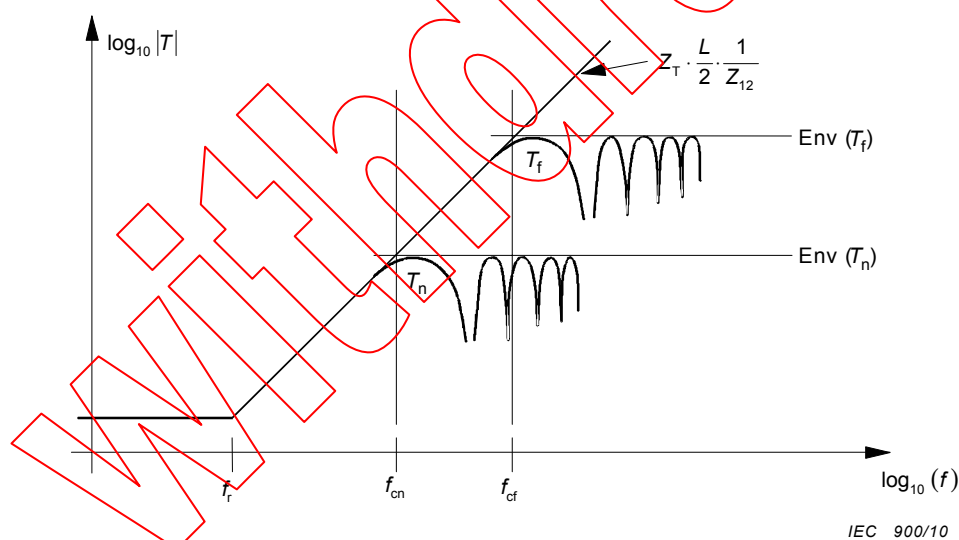


Figure 7 – Transfer impedance of a typical single braid screen

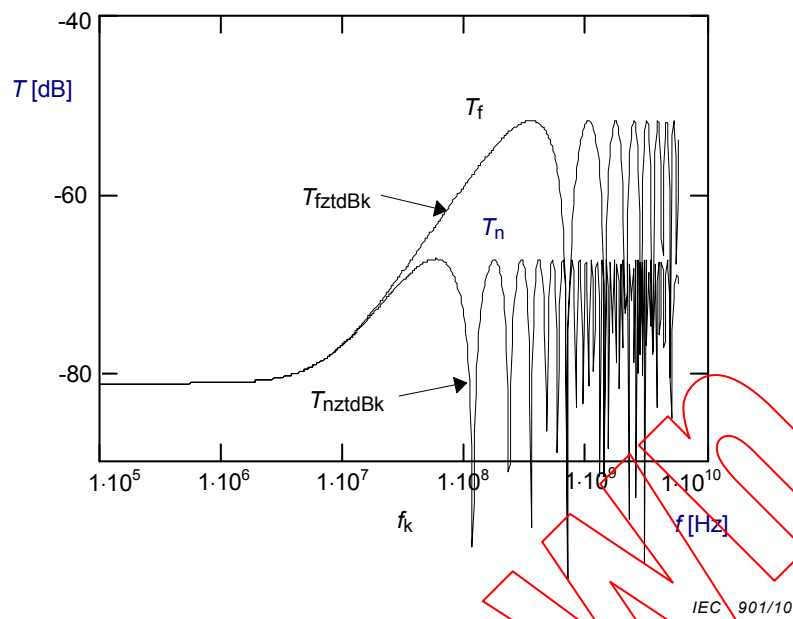
Figure 8 gives the result of adding (on a log scale) the frequency responses from Figure 6 and Figure 7. It is assumed the cable has negligible Z_F ($Z_F \ll Z_T$)



Example: $\epsilon_{r1} = 1$ (set-up), $\epsilon_{r2} = 2.2$ (cable)

$L = 1 \text{ m}$; $f_{cn} = 40 \text{ MHz}$; $f_{cf} = 200 \text{ MHz}$

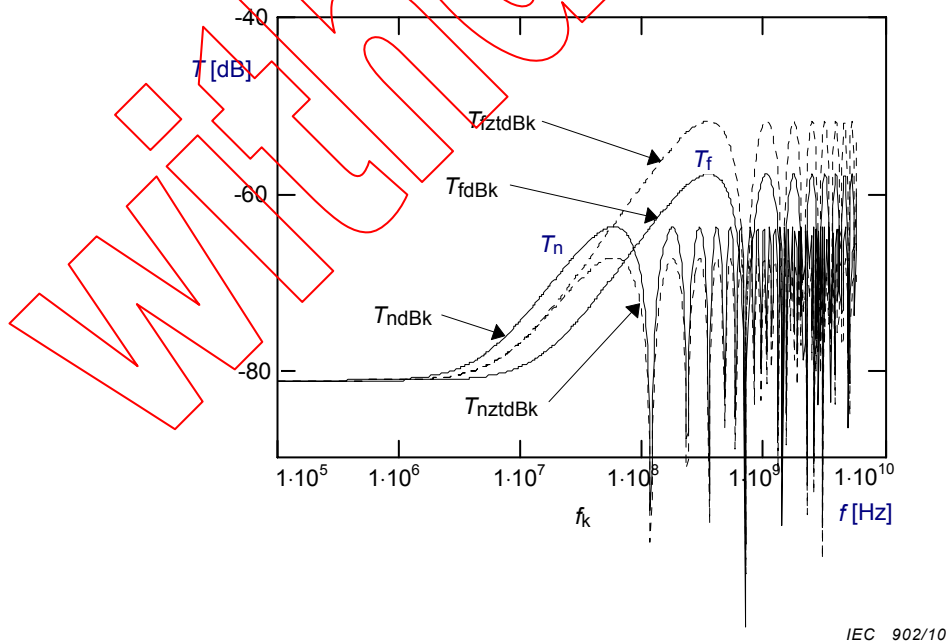
Figure 8 – The effect of the summing function-coupling transfer function of a typical single braid screen cable



In calculations the following parameters are used:

Z_T (d.c.) = 15 mΩ/m and Z_T (10 MHz) = 20 mΩ/m increasing 20 dB/decade (see Figure 7), cable length 1 m, and velocities of the outer and inner line: $v_1 = 200$ Mm/s and $v_2 = 280$ Mm/s corresponding to a velocity difference of 40 %.

Figure 9 – Calculated coupling transfer functions T_n and T_f for a single braid – $Z_F = 0$

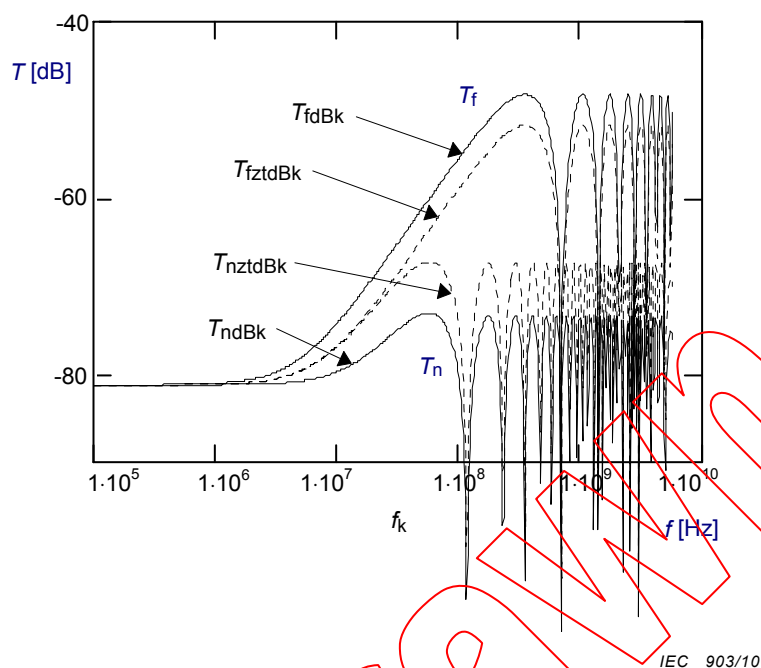


T_n is 3,5 dB higher and T_f is 6 dB lower than in reference Figure 9 because

$$T_n \sim |Z_F + Z_T| = 1,5 \times Z_T \text{ and}$$

$$T_f \sim |Z_F - Z_T| = 0,5 \times Z_T$$

Figure 10 – Calculated coupling transfer functions T_n and T_f for a single braid – $\text{Im}(Z_T)$ is positive and $Z_F = +0,5 \times \text{Im}(Z_T)$ at high frequencies



T_f is 3,5 dB higher and T_n is 6 dB lower than in reference Figure 9 because

$$T_f \sim |Z_F - Z_T| = 1,5 \times |Z_T| \text{ and } T_n \sim |Z_F + Z_T| = 0,5 \times |Z_T|$$

Figure 11 – Calculated coupling transfer functions T_n and T_f for a single braid – $\text{Im}(Z_T)$ is negative and $Z_F = -0,5 \times \text{Im}(Z_T)$ at high frequencies

In Figure 9, $Z_F = 0$ and Z_T is positive.

In Figure 10 and 11, Z_F is significant ($Z_F = (1/2) \times Z_T$).

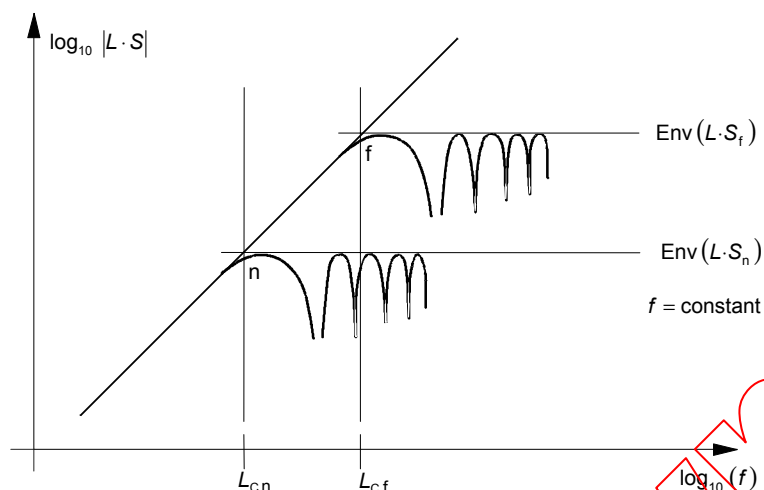
In Figure 11, Z_T is negative at high frequencies.

The following notes apply to Figures 9, 10, and 11.

NOTE 1 T_n for near-end, T_f for far-end and dB means that $T_{n,f}$ are calculated in dB ($20 \times \log_{10} |T_{n,f}|$)

NOTE 2 T_n dB: near-end when $Z_F = (1/2) \times Z_T$ and T_{nzt} dB: near-end when $Z_F = 0$.

NOTE 3 T_f dB: far-end when $Z_F = (1/2) \times Z_T$ and T_{fzt} dB: far-end when $Z_F = 0$.



NOTE 1 For $L > L_c$, the maximum value of T is attained, i.e. the maximum coupling (or the screening attenuation) is not dependent on L .

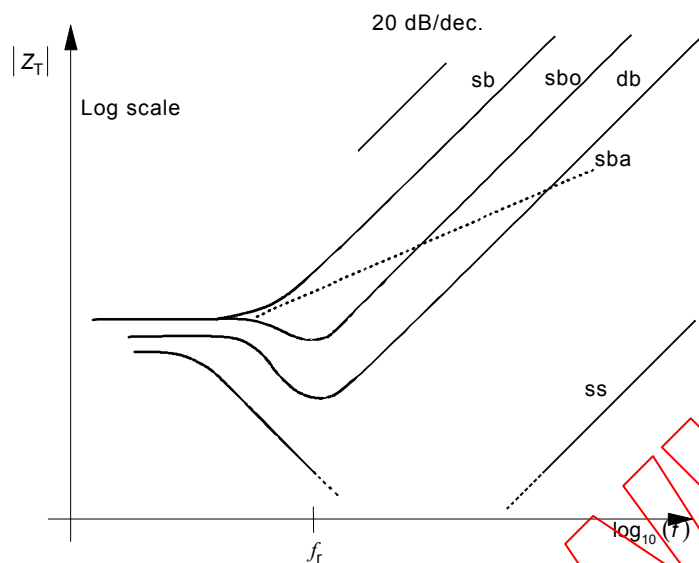
NOTE 2 L_{cf} strongly depends on ϵ_{r1} .

NOTE 3 See also Table 1 and list item n)

Figure 12 – $L \cdot S$: the complete length dependent factor in the coupling function T

6 Transfer impedance of a braided wire outer conductor or screen

Typical transfer impedances of cables with braided wire screens are shown in Figure 13. The constant Z_T value at the low-frequency end is equal to the DC resistance of the screen, the 20 dB per decade rise at the high-frequency end is due to the inductive coupling through the screen and the dip at the middle frequencies is caused by eddy currents or skin effect of the braid. Some braided cables may behave anomalously having less than a 20 dB per decade rise at high frequencies. By using an extrapolation of 20 dB per decade we are in most cases on the conservative side. This extrapolation can be used up to several GHz.



Key

f_r : typically 1....10 MHz

sb: single braid

sbo: single braid optimized

sba: single braid 'anomalous'

db: double braid

ss: superscreen

Figure 13 – Transfer impedance of typical cables

An electrically short piece of braided coaxial cable (2) is considered to be placed in a triaxial arrangement as in Figure 2.

It is assumed that the outer circuit (1) is the disturbing one. As stated a braided cable has a transfer impedance Z_T that increases proportionally to frequency at high frequencies, because of the leakage of the magnetic field through holes in the braid.

The total flux of the magnetic field induced by the disturbing current I_1 is Φ_1 . A part of it, Φ'_{12} leaks directly through the holes and includes a disturbing voltage U'_2 in the inner circuit. However, a part Φ''_{12} of Φ_1 flows in the braid and complicates the mechanism of the total magnetic leakage by the following additional phenomenon:

The braiding wires alternate between the outer and inner layer. It means that the inner and outer braid wires are likewise ingredients of both the inner (2) and outer (1) circuit of Figure 14.