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Transmission properties of cascaded two-ports or quadripols — Background of terms and definitions

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National foreword

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The UK participation in its preparation was entrusted to Technical Committee EPL/46, Cables, wires and waveguides, radio frequency connectors and accessories for communication and signalling.

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TECHNICAL REPORT



Transmission properties of cascaded two-ports or quadripols - Background of terms and definitions

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**BACKGROUND OF TERMS AND DEFINITIONS
OF CASCADED TWO-PORTS**

FOREWORD

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IEC 62152, 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.

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

Enquiry draft	Report on voting
46/283/DTR	46/300/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 second edition cancels and replaces the first edition published in 2004 and constitutes some technical improvements.

Important terms and definitions have been added.

Some of the terms are better described in the German language and also many countries have originally taken terms and definitions from German and translated them into their own language.

Therefore important terms have been added in German in the form of a footnote.

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

The committee has decided that the contents of this publication will remain unchanged until the maintenance result 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- withdrawn,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 edition of this document 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.

BACKGROUND OF TERMS AND DEFINITIONS OF CASCADED TWO-PORTS

1 Scope

It is important and practical that components of a transmission chain can be separated and tested separately. To accomplish this, well-defined interfaces and measuring techniques, including agreed terms and definitions, are required.

This technical report has two main goals. It lays the foundation for agreement on the fundamental terms and definitions to be used world-wide in describing the transmission properties of a two-port or quadripole. The report builds a bridge between the classical quadripole theory and the scattering matrix presentation which is based on incident and reflecting square root of power waves at the input and output of a two-port. Finally, it is shown that the two concepts are bound together through simple equations and are fundamentally identical.

The quadripole theory was originally developed for voice- and carrier-frequency technologies and transmission, and later for microwaves, but both can be used through the whole frequency range.

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 60050-726, *International Electrotechnical Vocabulary – Chapter 726: Transmission lines and waveguides*

IEC 61156-1, *Multicore and symmetrical pair/quad cables for digital communications – Part 1: Generic specification*

IEC/TR 61156-1-2, *Multicore and symmetrical pair/quad cables for digital communications – Part 1-2: Electrical transmission characteristics and test methods of symmetrical pair/quad cables used for digital communications*

3 Terms and definitions, symbols, units and abbreviated terms

For the purposes of this document, the terms and definitions given in IEC 60050-726, IEC 61156-1, IEC/TR 61156-1-2, as well as the following definitions, apply.

3.1 Terms and definitions

3.1.1

complex operational attenuation¹

quotient of the unreflected square root of the power wave fed into the reference impedance R_1 of the input of the two-port and the square root of the power wave consumed by the load R_2 of the two-port expressed in dB and radians

¹ Komplexe Betriebs-Dämpfung.

NOTE By defining a new quantity, operational insertion loss, which is the same as the operational attenuation when the reference impedances on both sides of the two-port are the same $R_1 = R_2$, the problem of insertion loss and operational attenuation is solved in most usual cases.

3.1.2

complex operational insertion loss²

quotient of the unreflected square root of the power wave fed into the reference impedance R_1 of the measurement system and the square root of the power wave consumed by the load R_1 of the two-port expressed in dB and radians

NOTE In the IEV, insertion loss is understood as the loss produced by inserting a two-port into a separated point of the transmission chain. Because of varying impedances along the transmission line, it leads to deviation in the overall losses depending on where in the chain the two-port is inserted. This is called insertion loss deviation (ILD). In “complex operational insertion loss” the reference impedances at both sides of the two-port are equal.

3.2 Symbols, units and abbreviated terms

3.2.1 Two-port electrical symbols, units and related terms

E_0	generator source voltage (V)
R_1, R_2	reference impedance at the two-port input and output, respectively (Ω)
R	reference impedance at the two-port input and output, respectively (Ω)
U_1, U_2	voltage at the two-port input and output, respectively (V)
U_0	voltage at the reference impedance for the condition of matched generator reference impedance (V)
Z_{01}, Z_{02}	complex characteristic impedance at the two-port input and output, respectively
$\sqrt{P_2}$	square root of power wave from the two-port ($W^{1/2}$)
$\sqrt{P_0}$	unreflected square root of power wave from the generator for the condition of matched generator reference impedance ($W^{1/2}$)
$\sqrt{P_{02}}$	reflected square root of power wave coming from the reference impedance at the two-port output ($W^{1/2}$)
T_B	operational transfer function
T	image transfer function
T'_B	insertion transfer function
S_{21}	forward transfer scattering parameter
Γ_B	complex operational attenuation
A_B	real part of Γ_B and is the operational attenuation $A_B = -20 \times \log_{10} S_{21} $ (dB) or $A_B = -\ln S_{21} $ (Np)
B_B	imaginary part of Γ_B and is the operational attenuation phase shift $= -\arg(S_{21})$ (rad)
Γ'_B	complex insertion attenuation or loss
A'_B	real part of Γ'_B (dB) or (Np)
B'_B	imaginary part of Γ'_B (rad)
Γ	complex image attenuation

² Komplexe Betriebs-Einfüge-Dämpfung.

A	real part of Γ (dB) or (Np)
B	imaginary part of Γ (rad)
j	imaginary denominator
$\arg$	argument operator of a complex number
Z_C, Z_0	complex characteristic impedance, or mean characteristic impedance if the pair is homogeneous or free of structure (also used to represent a function fitted result) (Ω)
Z_{CN}	nominal characteristic impedance and resistive part of the mean characteristic impedance Z_C value at a given frequency with tolerance at a given frequency (Ω)
Z_N	nominal impedance of the link and/or terminals (the system) between which the two-port is operating (Ω)
Z_R	(nominal) reference impedance used in measurements, normally, $Z_R = Z_N$. (Ω)
RL	complex operational return loss (dB)
ρ_B	reflection coefficient
SRL	structural return loss (dB)
Z_W	measured input image impedance (Ω)
Re	real part operator for a complex variable
Im	imaginary part operator for a complex variable
R	pair resistance (Ω/m)
L	pair inductance (H/m)
L_∞	pair inductance asymptotic value at high frequencies (H/m)
G	pair conductance (S/m)
C	pair capacitance (F/m)
v_p	phase velocity of cable (m/s)
ω	radian frequency (rad/s)
l	length (m)
Δf	frequency difference between input impedance minima of a short-circuited transmission line (MHz)
S, ρ	complex reflection coefficient of the junction
$\sqrt{P_r}$	reflected square root of power wave at the junction ($W^{1/2}$)
$\sqrt{P_i}$	incident square root of power wave at the junction ($W^{1/2}$)
Z_1, Z_2	line impedance to the left and right of the junction, respectively (Ω)
U_i, U_r	incident and reflected voltage at the junction, respectively (V)
V_i, V_r	incident and reflected voltage at the junction, respectively (V)
I_i, I_r	incident and reflected current at the junction, respectively (A)
Γ_s	complex reflection loss at the junction
A_s	reflection loss

$$A_s = 20 \times \log_{10} \left| \frac{z_N + 1}{2 \times \sqrt{z_N}} \right| \text{ (dB)}$$

A_r return loss

$$A_r = 20 \times \log_{10} \left| \frac{z_N + 1}{z_N - 1} \right| \text{ (dB)}$$

z_N normalized impedance given by $z_N = \frac{Z_2}{Z_1} = r + jx$

r x-axis ordinate

x y-axis ordinate

Γ_m mismatch loss of a junction (not recommended)

3.2.2 Transmission line equation electrical symbols and related terms

α attenuation coefficient (Np/m)

β phase coefficient (rad/m)

γ propagation coefficient (Np/m, rad/m)

v_P phase velocity of cable (m/s)

v_G group velocity of cable (m/s)

τ_P phase delay time (s/m)

τ_G group delay time (s/m)

Z_C complex characteristic impedance, or mean characteristic impedance if the pair is homogeneous or free of structure (also used to represent a function fitted result) (Ω)

$\angle Z_C$ angle of the characteristic impedance in radians

Z_∞ high frequency asymptotic value of the characteristic impedance (Ω)

l length (m)

ω radian frequency (rad/s)

f frequency (Hz)

R' first derivative of R with respect to ω

C' first derivative of C with respect to ω

L' first derivative of L with respect to ω

R_0 d.c. resistance of a round solid wire with radius r (Ω/m)

R_C constant with frequency component of resistance which is about one-quarter of the d.c. resistance (Ω/m)

R_S square-root of frequency component of resistance (Ω/m)

L_E external (free space) inductance (H/m)

L_I internal inductance whose reactance equals the surface resistance at high frequencies (H/m)

σ specific conductivity of the wire material (S/m)

ρ resistivity of the wire material (Ω/m^2)

μ permeability of the wire material (H/m)

r radius of the wire (m)

δ skin depth (not to be confused with the dissipation factor $\tan \delta$) (m)

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

$\tan \delta$ dissipation factor

$$\tan \delta = G/(\omega C)$$

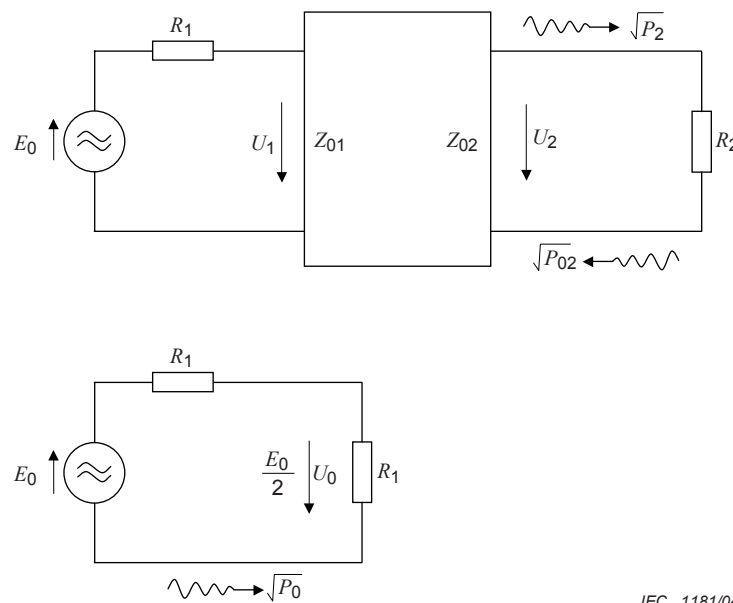
q forward echo coefficient at the far end of the cable at a resonant frequency

p	reflection coefficient measured from the near end of the cable at a resonant frequency, $p = 10^{-PSRL/20} = \left \frac{Z_{CM} - Z_C}{Z_{CM} + Z_C} \right $
A_Q	forward echo attenuation at a resonant frequency (dB) $A_Q = -20 \times \log_{10} q $
$PSRL$	structural return loss at a resonant frequency (dB), $PSRL = -20 \times \log_{10} p $
K	$= 2 \times \alpha l - 1$ when $2 \times \alpha l \gg 1$ (Np)
A_Q	$= 2 \times PSRL - 20 \times \log_{10} (2 \times \alpha l - 1)$ (dB) where $2 \times \alpha l$ is in Np
Z_{OC}	complex measured open circuit impedance (Ω)
Z_{SC}	complex measured short circuit impedance (Ω)
Z_{CM}	characteristic impedance as measured (with structure) (Ω) $Z_{CM} = \sqrt{Z_{SC} Z_{OC}}$
Z_{MEAS}	complex measured impedance (open or short) (Ω)
Z_{IN}	input impedance of the cable when it is terminated by Z_L (Ω)
Z_{OUT}	output impedance of the cable when the input of the cable is terminated by Z_G (Ω)
Z_T	terminated impedance measurement made with the opposite end of the cable pair terminated in the reference impedance Z_R (Ω)
ς	reflection coefficient measured in the terminated measurement method $\varsigma = \frac{Z_R - Z_C}{Z_R + Z_C}$
Z_G	termination at the cable input when defining the output impedance of the cable Z_{OUT} (Ω)
Z_L	termination at the cable output when defining the input impedance of the cable Z_{IN} (Ω)
L_0, L_1, L_2, L_3	least squares fit coefficients for angle of the characteristic impedance
K_0, K_1, K_2, K_3	least squares fit coefficients of the characteristic impedance
$ Z_C $	fitted magnitude of the characteristic impedance (Ω)
$ Z_{CM} $	measured magnitude of the characteristic impedance (Ω)
$\angle(V_{1N})$	input angle relative to a reference angle in radians
$\angle(V_{1F})$	output angle relative to the same reference angle in radians
k	multiple of 2π radians;
S_{11}	reflection coefficient measured with an S parameter test set

4 Transfer functions and complex attenuations or losses of a two-port

4.1 General remarks

Figure 1 indicates the variables and their relationships for defining the transfer functions of a two-port. E_0 is the generator source voltage in Figure 1.



IEC 1181/04

Figure 1 – Defining the transfer functions of a two-port**4.2 Operational transfer function (T_B)**

Referring to Figure 1, the operational transfer function T_B is defined as the ratio of the square root of the power wave into the load (equal to reference impedance R_2) of a two-port $\sqrt{P_2}$ with the unreflected square root of power wave $\sqrt{P_0}$ from the generator with a source impedance equal to the reference impedance R_1 . See Equation (1).

$$T_B = \frac{\sqrt{P_2}}{\sqrt{P_0}} = \frac{U_2 / \sqrt{R_2}}{U_0 / \sqrt{R_1}} = S_{21} = \left. \frac{\sqrt{P_2}}{\sqrt{P_0}} \right|_{\sqrt{P_{02}}=0} \quad (1)$$

4.2.1 Image transfer function (T)

The operational transfer function becomes the image transfer function T when the reference impedance becomes equal to the input and output characteristic impedances Z_{01} and Z_{02} of the two-port.

4.2.2 Insertion transfer function (T'_B)

The operational transfer function becomes the insertion transfer function T'_B when $R_1 = R_2 = R$.

4.3 Complex attenuation**4.3.1 Complex operational attenuation (Γ_B)³**

The complex operational attenuation is given by Equation (2):

³ Komplexe Betriebs-Dämpfung.

$$\Gamma_B = A_B + j \cdot B_B = \ln \frac{1}{T_B} = -20 \times \log_{10} |T_B| - j \cdot \arg(T_B) \quad (2)$$

4.3.2 Complex image attenuation (Γ)⁴

The complex image attenuation is given by Equation (3):

$$\Gamma = A + j \cdot B = \ln \frac{1}{T} = -20 \times \log_{10} |T| - j \cdot \arg(T) \quad (3)$$

4.3.3 Complex insertion attenuation or loss (Γ'_B)⁵

The complex insertion attenuation or loss is given by Equation (4):

$$\Gamma'_B \Big|_{R1=R2=R} = A'_B + j \cdot B'_B = \ln \frac{1}{T'_B} = -20 \times \log_{10} |T'_B| - j \cdot \arg(T'_B) \quad (4)$$

⁴ Komplexe Wellen-Dämpfung.

⁵ Komplexe Einfüge-Dämpfung.

Annex A (normative)

Concepts of normalized voltage waves, square root of power waves and operational attenuation and losses

A.1 General

It is advantageous to operate, by the square root of a reference impedance (normally application impedance of the system), with normalized voltage waves corresponding to the square root of power waves.

In this way the scattering parameters are defined. For example, S_{21} is the forward operational transfer function and S_{11} is the operational reflection coefficient.

Two primary reasons for using the square root of the impedance normalized voltage waves or the square root of the power waves are

- a) that the network analyser is measuring voltages, and
- b) because the natural logarithm, $\ln$, of a complex quantity $z = x + j \cdot y = |z| \cdot e^{j \arg(z)}$ is directly $\ln(z) = \ln|z| + j \cdot \arg(z)$ and $\ln|z|$, in nepers, can be expressed in decibels $20 \times \log_{10} |z|$ and the imaginary part still remains $\arg(z)$ in radians, as, for example,

$$\Gamma_B = A_B + j \cdot B_B = -20 \times \log_{10} |S_{21}| - j \times \arg(S_{21})$$

(see Equations (A.1) and (A.2)).

Furthermore, usage of operational quantities means the measurements are always made between resistive terminations in well-defined circumstances.

This means that the impedances at a reference plane between the cascaded units of the system are specified.

Individual units can be specified and tested separately and made by different manufacturers.

This makes open systems, networks and cabling possible.

A.2 Complex operational attenuation or operational propagation coefficient (Γ_B)

The complex operational attenuation (complex operational loss) introduced by a two-port component, cascade of components, link, cable assembly, etc. into a system is defined by using the scattering parameter S_{21} as

$$\Gamma_B = A_B + j \cdot B_B = \ln(1/S_{21}) = -\ln|S_{21}| - j \cdot \arg(S_{21}) \quad (\text{A.1})$$

$$\Gamma_B = A_B + j \cdot B_B = -20 \times \log_{10} |S_{21}| - j \cdot \arg(S_{21}) \quad (\text{A.2})$$

NOTE 1 A_B is equal to the ratio of the unreflected complex power (voltage $\times$ current) sent into a two-port, to the complex power consumed by the load of the two-port, in decibels. The load is normally a resistance equal to the application impedance of the system Z_N . When the generator and load impedances are the same, complex operational attenuation becomes complex operational insertion loss.

NOTE 2 From the theory of complex functions:

$$\ln z = \ln|z| + j \cdot \arg(z)$$

where

$$z = x + j \cdot y = |z| \cdot e^{j\arg(z)}$$

and, by using the square root of power waves, we can write, for the natural logarithms of the ratio of two square root of complex power waves:

$$\ln \frac{\sqrt{P_1}}{\sqrt{P_2}} = \ln \left| \frac{\sqrt{P_1}}{\sqrt{P_2}} \right| + j \cdot \arg \left(\frac{\sqrt{P_1}}{\sqrt{P_2}} \right) = \Gamma = A + j \cdot B$$

where A is in nepers and B in radians.

When A is expressed in decibels, B will not be affected; it remains in radians.

A.3 Impedances

The different kinds of impedances are defined as follows:

- a) the nominal characteristic impedance⁶ Z_{CN} (of a two-port) is the resistive part of the mean characteristic impedance Z_C specified with a tolerance at a given frequency;
- b) Z_N is the nominal impedance of the system terminals between which the two-port is operating;
- c) Z_R is the (nominal) reference impedance used in measurements, normally $Z_R = Z_N$.

A.4 Operational reflection coefficient (S_{11})

The operational reflection coefficient of a two-port is equal to the scattering parameter S_{11} of the two-port. It equals the reflection coefficient ρ_B at the input when the two-port is terminated with its reference impedances Z_{R1} normally equal to the nominal impedance of the system terminals.

$$S_{11} = \rho_B = \frac{Z_{in} - Z_{R1}}{Z_{in} + Z_{R1}} \quad (\text{A.3})$$

A.5 Return loss

A.5.1 Complex operational return loss of a transmission line (RL_B)

The complex operational return loss, RL_B of a transmission line is given in Equation (A.4):

⁶ Nominale Wellen-Widerstand.

$$\begin{aligned}
 RL_B &= \ln \frac{1}{\rho_B} = -\ln(\rho_B) = -\ln|\rho_B| - j \cdot \arg(\rho_B) \\
 &= -20 \times \log_{10}|\rho_B| - j \cdot \arg(\rho_B)
 \end{aligned}
 \tag{A.4}$$

A.5.2 Structural return loss of a transmission line (*SRL*)

SRL is the return loss where the mismatch effects at the input and output of transmission line have been eliminated (compare with the continuous wave (CW) burst measurement method). This quantity is obtained by calculation (Equation (A.5)) using the measured input image input impedance⁷ and measured, calculated (Equation (A.6)) and curve fitted mean characteristic impedance⁸ where both are complex quantities. The structural return loss is as follows:

$$SRL = -20 \times \log_{10} \left| \frac{Z_W - Z_0}{Z_W + Z_0} \right| - j \cdot \arg \left(\frac{Z_W - Z_0}{Z_W + Z_0} \right) \tag{A.5}$$

See Clauses A.6 and A.7.

The complex characteristic impedance⁹ of a homogeneous transmission line is as follows:

$$Z_0 = \operatorname{Re}(Z_0) + j \cdot \operatorname{Im}(Z_0) \approx \sqrt{\frac{L_\infty}{C}} \left(1 + \frac{R}{2\omega L} \right) - j \cdot \sqrt{\frac{L_\infty}{C}} \frac{R}{2\omega L} \tag{A.6}$$

$$\operatorname{Re}(Z_0) \approx \sqrt{\frac{L_\infty}{C}} \left(1 + \frac{R}{2\omega L} \right) \approx \frac{1}{v_p C} = \frac{1}{2\Delta f l C} \tag{A.7}$$

$$-\operatorname{Im}(Z_0) \approx \sqrt{\frac{L_\infty}{C}} \left(\frac{R}{2\omega L} \right) = \operatorname{Re}(Z_0) - \sqrt{\frac{L_\infty}{C}} \tag{A.8}$$

where v_p and l are the phase velocity and length of the transmission line and C the capacitance of the low dielectric loss line measured at such a low frequency that the length is electrically short, $l < \lambda/40$. Δf is the distance in frequency between two input impedance minima of the short-circuited measured transmission line; and L_∞ the asymptotic value of the inductance reached at high frequencies. See Annex B.

NOTE It is important to distinguish between the two return losses *RL* and *SRL* although they are normally not measured separately.

A.5.3 Reflection loss of a junction

The quantities that determine the reflection loss of a junction are shown in Figure A.1. Normalized plots of reflection loss and return loss are given in Figure A.2.

$$\begin{aligned}
 &\sqrt{P_i} \rightarrow \\
 &\leftarrow \sqrt{P_r}
 \end{aligned}$$

⁷ Eingangs- Wellen-Widerstand, Z_W .

⁸ Mittlerer Wellen-Widerstand, Z_0 .

⁹ Komplexe Wellen-Widerstand.

**Figure A.1 – Reflection at a junction**

$$S = \rho = \sqrt{\frac{P_r}{P_i}} = \frac{V_r}{V_i} = \frac{U_r}{U_i} = -\frac{I_r}{I_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (\text{A.9})$$

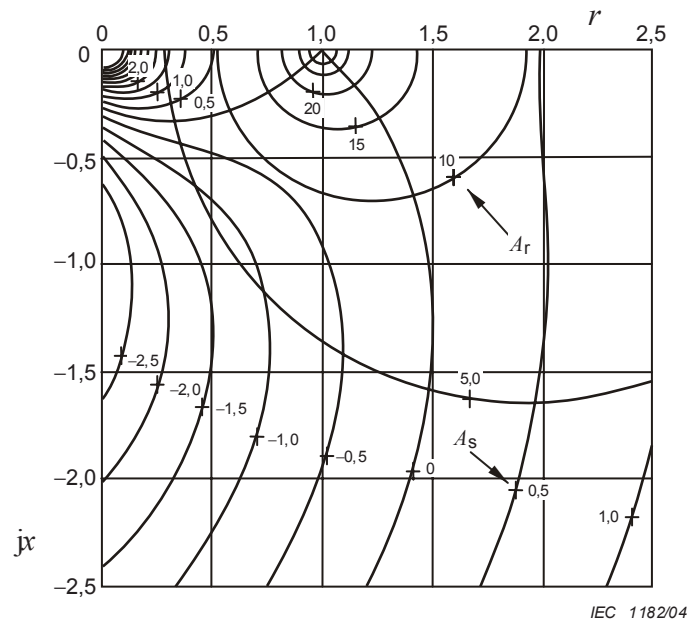
S is the complex reflection coefficient of the junction. See Annex C.

$$\Gamma_S = -\ln\sqrt{1-S^2} = -\ln\left|\sqrt{1-S^2}\right| - j \cdot \arg\left(\sqrt{1-S^2}\right) \quad (\text{A.10})$$

or

$$\Gamma_S = -\ln\sqrt{1-S^2} = -20 \times \log_{10}\left|\sqrt{1-S^2}\right| - j \cdot \arg\left(\sqrt{1-S^2}\right) \quad (\text{A.11})$$

$$\Gamma_S = -\ln\sqrt{1-S^2} = -10 \times \log_{10}\left|1-S^2\right| - j \times \frac{1}{2} \times \arg(1-S^2) \quad (\text{A.12})$$



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Key

A_s is the reflection loss given by $A_s = 20 \times \log_{10} \left| \frac{z_N + 1}{2 \times \sqrt{z_N}} \right|$ expressed in dB;

A_r is the return loss given by $A_r = 20 \times \log_{10} \left| \frac{z_N + 1}{z_N - 1} \right|$ expressed in dB;

z_N is the normalized impedance given by $z_N = \frac{Z_2}{Z_1} = r + jx$ (see Figure A.1);

r is the x-axis ordinate;
 x is the y-axis ordinate.

Figure A.2 – Constant value A_s and A_r curves on a complex plane $z = r + jx$

A.5.4 Mismatch loss of a junction (Γ_m)(not recommended)

Mismatch loss of a junction is expressed as a function of S the complex reflection coefficient, as follows:

$$\Gamma_m = -\ln\sqrt{1-|S|^2} = -\ln\left|\sqrt{1-|S|^2}\right| - j \cdot \arg\left(\sqrt{1-|S|^2}\right) \quad (\text{A.13})$$

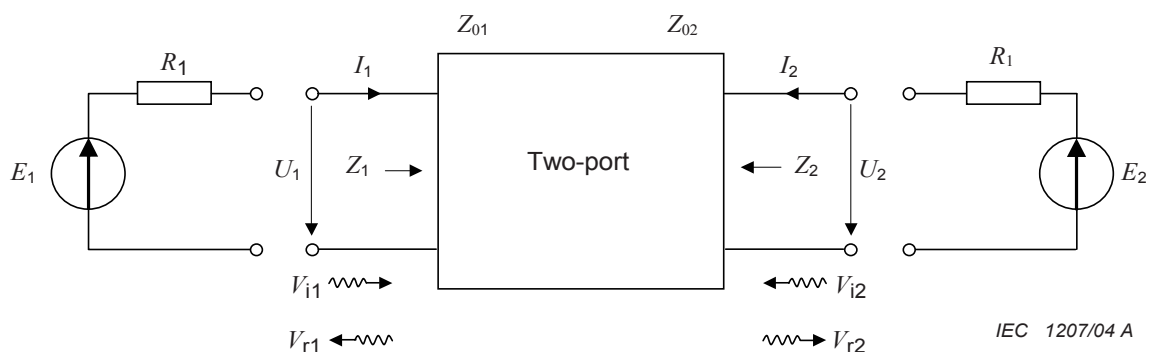
or

$$\Gamma_m = -\ln\sqrt{1-|S|^2} = -20 \times \log_{10}\left|\sqrt{1-|S|^2}\right| - j \cdot \arg\left(\sqrt{1-|S|^2}\right) \quad (\text{A.14})$$

$$\Gamma_m = -\ln\sqrt{1-|S|^2} = -10 \times \log_{10}\left(1-|S|^2\right) - j \times \frac{1}{2} \times \arg(1-|S|^2) \quad (\text{A.15})$$

A.6 Definition of the characteristic input impedance of a transmission line (cable pair)

The important variables associated with the two-port representation of a transmission line are given in Figure A.3. V_i and V_r are the incident and reflected square root of power waves.



Key

E_1, E_2	network analyser at input, output, respectively	V_{i1}, V_{i2}	incident square root of power waves at input and output, respectively
R_1	reference impedance at input and output	V_{r1}, V_{r2}	reflected square root of power waves at input and output, respectively
I_1, I_2	current at input and output, respectively	Z_1, Z_2	impedance at input and output, respectively
U_1, U_2	voltage at input and output, respectively	Z_{01}, Z_{02}	characteristic input impedance or complex image input impedance ¹⁰

Figure A.3 – Two-port representation of a transmission line

The characteristic input impedance or complex image input impedance¹¹ is given by Equation (A.16):

$$Z_{01} = R_1 \frac{1 + S_{W11}}{1 - S_{W11}} = \sqrt{Z_{\text{shortc}} \cdot Z_{\text{openc}}} \quad (\text{A.16})$$

¹⁰ Komplexe eingangs-wellenwiderstand.

where

S_{W11} is the the complex image reflection factor at the input when there are no reflections from the far-end, $V_{i2} = 0$ (see note);

Z_{shortc} is the the measured impedance at the input when the output is terminated in a short-circuit;

Z_{openc} is the the measured impedance at the input when the output is terminated in an open circuit.

The complex image reflection factor¹¹ at the input may also be expressed by Equation (A.17):

$$\rho_{W11} = S_{W11} = \frac{Z_{01} - R_1}{Z_{01} + R_1} \quad (\text{A.17})$$

where

$\rho_{W11} = S_{W11}$ is the complex image reflection factor at the input when there are no reflections from the far-end, ($V_{i2} = 0$) (see note).

NOTE The condition $V_{i2} = 0$ can be simulated by a long line terminated with its nominal impedance. When the roundtrip attenuation of the line added with the return loss at the far end is not less than 40 dB (see Equation (A.18)) the maximum uncertainty in Z_{01} is less than 2 %. With more than 60 dB round-trip attenuation the maximum uncertainty in Z_{01} is less than 0,2 %.

$$(2 \times \alpha \cdot L - 20 \times \log_{10} |\rho_{W22}|) \geq 40 \quad (\text{A.18})$$

A.7 General coupling transfer function, crosstalk and echoes

A.7.1 General

Figure A.4 indicates the key variables and their relationships for defining the coupling transfer function between two systems.

¹¹ Komplexe Eingangs-Wellen-Reflexions-Faktor.