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TECHNICAL REPORT

colour inside

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

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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

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- withdrawn,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

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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 defintions, apply.

3.1 Terms and definitions

3.1.1
complex operational attenuation[1]
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 loss[2]

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 (W½)
$\sqrt{P_0}$	unreflected square root of power wave from the generator for the condition of matched generator reference impedance (W½)
$\sqrt{P_{02}}$	reflected square root of power wave coming from the reference impedance at the two-port output (W½)
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 $A_B = -20 \times \log_{10}\lvert S_{21}\rvert$ (dB) or $A_B = -\ln\lvert S_{21}\rvert$ (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 ($W^{½}$)
$\sqrt{P_i}$	incident square root of power wave at the junction ($W^{½}$)
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

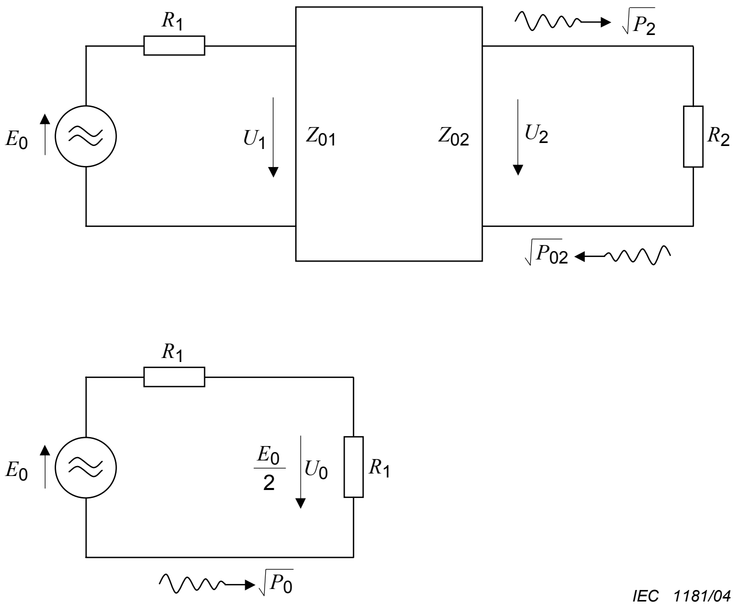
α	attenuation coefficient (Np/m)
β	phase coefficient (rad/m)
γ	propagation coefficient (Np/m, rad/m)
v_P	phase velocity of cable (m/s)
v_G	group velocity of cable (m/s)
τ_P	phase delay time (s/m)
τ_G	group delay time (s/m)
Z_C	complex characteristic impedance, or mean characteristic impedance if the 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 δ) (m) $\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$
tan δ	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 $2 \times \alpha l >> 1$ (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).

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

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.

$$\mathit{\Gamma}_\mathrm{B} = A_\mathrm{B} + \mathrm{j} \cdot B_\mathrm{B} = \ln \frac{1}{T_\mathrm{B}} = -20 \times \log_{10} \left| T_\mathrm{B} \right| - \mathrm{j} \cdot \arg\left(T_\mathrm{B} \right) \qquad (2)$$

4.3.2 Complex image attenuation ($\mathit{\Gamma}$)[4]

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

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

4.3.3 Complex insertion attenuation or loss ($\mathit{\Gamma}'_\mathrm{B}$)[5]

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

$$\left. \mathit{\Gamma}'_\mathrm{B} \right|_{R1 = R2 = R} = A'_\mathrm{B} + \mathrm{j} \cdot B'_\mathrm{B} = \ln \frac{1}{T'_\mathrm{B}} = -20 \times \log_{10} \left| T'_\mathrm{B} \right| - \mathrm{j} \cdot \arg\left(T'_\mathrm{B} \right) \qquad (4)$$

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[4] Komplexe Wellen-Dämpfung.

[5] Komplexe Einfüge-Dämfung.

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 $z = x + \mathrm{j} \cdot y = |z| \cdot \mathrm{e}^{\mathrm{j} \cdot \arg(z)}$ is directly $\ln(z) = \ln|z| + \mathrm{j} \cdot \arg(z)$ 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,

$$\Gamma_\mathrm{B} = A_\mathrm{B} + \mathrm{j} \times B_\mathrm{B} = -20 \times \log_{10}|S_{21}| - \mathrm{j} \times \arg(S_{21})$$

(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

$$\Gamma_\mathrm{B} = A_\mathrm{B} + \mathrm{j} \cdot B_\mathrm{B} = \ln(1/S_{21}) = -\ln|S_{21}| - \mathrm{j} \cdot \arg(S_{21}) \tag{A.1}$$

$$\Gamma_\mathrm{B} = A_\mathrm{B} + \mathrm{j} \cdot B_\mathrm{B} = -20 \times \log_{10}|S_{21}| - \mathrm{j} \cdot \arg(S_{21}) \tag{A.2}$$