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INTERNATIONAL STANDARD

colour inside

Coaxial communication cables –
Part 1-112: Electrical test methods – Test for return loss and voltage standing wave ratio

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COAXIAL COMMUNICATION CABLES –

Part 1-112: Electrical test methods – Test for return loss and voltage standing wave ratio

FOREWORD

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IEC 61196-1-112 has been prepared by subcommittee 46A: Coaxial cables, of IEC technical committee 46: Cables, wires, waveguides, RF connectors, RF and microwave passive components and accessories. It is an International Standard.

This second edition cancels and replaces the first edition published in 2006. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) added "voltage standing wave ratio" in the title;
b) added 3.1 voltage standing wave ratio (VSWR) and 3.2 return loss (RL);
c) revised Clause 4 "Principle";

d) added Figure 1 and Figure 2;

e) revised Clause 7 "Number of measuring points";

f) added Clause 8 "Test procedure";

g) added Clause 10 "Information to be given in the relevant specification";

h) added Annex B.

The text of this International Standard is based on the following documents:

Draft	Report on voting
46A/1704/FDIS	46A/1715/RVD

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

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

This document is to be read in conjunction with IEC 61196-1:2005.

A list of all parts in the IEC 61196 series, published under the general title *Coaxial communication cables*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

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COAXIAL COMMUNICATION CABLES –

Part 1-112: Electrical test methods – Test for return loss and voltage standing wave ratio

1 Scope

This part of IEC 61196 applies to coaxial communications cables. It specifies test methods for determining return loss (RL) and voltage standing wave ratio (VSWR) of coaxial cables for use in communications systems.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 61196-1:2005, *Coaxial communication cables – Part 1: Generic specification – General, definitions and requirements*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61196-1 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1
voltage standing wave ratio
VSWR
ratio, along a transmission line, of a maximum of the voltage to an adjacent minimum magnitude of the voltage of a standing wave, expressed as the following:

$$VSWR = \frac{|V_{max}|}{|V_{min}|} = \frac{|V_i + V_r|}{|V_i - V_r|} \tag{1}$$

where

$VSWR$ is the voltage standing wave ratio;

V_{max} is the maximum magnitude of the voltage;

V_{min} is the minimum magnitude of the voltage;

V_i is the voltage of incident wave;

V_r is the voltage of reflected wave.

3.2
return loss
RL
ratio of the power of the reflected wave to the power of the incident wave at a specified port or transverse cross-section of a transmission line, expressed as follows:

$$RL = -10\log_{10}\frac{P_\mathrm{r}}{P_\mathrm{i}} = -20\log_{10}\left|\frac{Z_\mathrm{T}-Z_\mathrm{R}}{Z_\mathrm{T}+Z_\mathrm{R}}\right| = -20\log_{10}\frac{VSWR-1}{VSWR+1} \quad (2)$$

where

RL is the return loss;

P_i is the power of incident wave;

P_r is the power of reflected wave;

Z_t is the measured complex impedance, in ohms (Ω), obtained from terminated cable measurements where the distant end is terminated in Z_R;

Z_R is the reference impedance of a transmission line, in ohms (Ω), (50 Ω, 75 Ω, or as appropriate);

$VSWR$ is the voltage standing wave ratio.

4 Principle

At lower frequencies, physical length of the test sample is less than $\lambda/10$, where λ is the wavelength, and the test values of the voltage/current on the test sample are independent of the test position. At higher frequencies, physical length of the test sample is bigger than $\lambda/10$, and the characteristic impedance reflects its transmission characteristics. The voltage/current on the test sample differs at different positions.

It is assuming that the shielding effect of the test sample is good enough with no interference from outside and no signal leaking out. The input signal a_1 of the test sample will transmit one part of signal b_2 to the load and also a portion of the signal b_1; a_2 is reflected back at both the input port 1 and the output load port 2 respectively, as shown in Figure 1.

The signal transmission and reflection characteristics in test sample can be represented by the S-parameter in Figure 1.

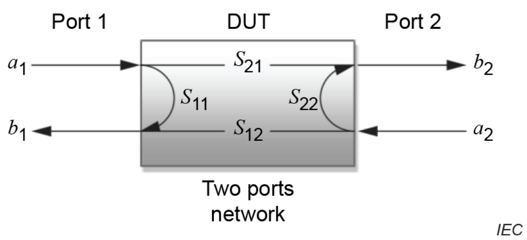

Figure 1 – S-parameter representing transmission and reflection characteristics

The definition of S-parameter is based on the signal voltages which are vectors, where:

$$b_1 = a_1 S_{11} + a_2 S_{12} \qquad (3)$$

$$b_2 = a_1 S_{21} + a_2 S_{22} \qquad (4)$$

When the end of test sample is terminated on a precision load, a_2 = 0 and the input reflection coefficient can be calculated as Formula (5):

$$S_{11} = \frac{b_1}{a_1} \qquad (5)$$

5 Test equipment

A vector network analyser (VNA) capable of performing S_{11}/S_{22} measurements and a calibration kit with calibration standards (open, short, load).

6 Preparation of test sample (TS)

Test sample to allow direct connection to either the VNA or terminating load, or both. A cable is connected to a pair of precision test connectors with small inherent reflections to form a cable assembly as a test sample (TS) as shown in Figure 2.

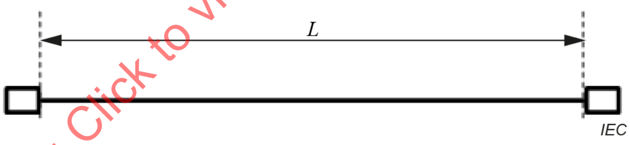

Figure 2 – preparation of the test sample

The change in return loss for small frequency deviations from the resonance frequency of reflection peaks does not depend on the cable length. However, the maximum value of the peak is length-dependent. With decreasing test length, the return loss increases. The change is described by $\Delta a_{\mathrm{r,L}}$ as shown in Formula (6). Therefore, the length of the TS shall be stated in the test report.

$$\Delta a_{\mathrm{r},L} = a_{\mathrm{r}}\left(L_2\right) - a_{\mathrm{r}}\left(L_1\right) = 20\log_{10}\left[\frac{1-e^{-2\alpha L_1}}{1-e^{-2\alpha L_2}}\right] \qquad (6)$$

where

L is the length of the test sample, in m;

$\Delta a_{\mathrm{r,L}}$ is the return loss for the test sample with length L;

α is the cable attenuation at the measured frequency, in Np/m.

NOTE 1 Np ≈ 8,686 dB, and 1 dB ≈ 0,1151 Np.

7 Number of measuring points

VNAs measure at discrete frequency points. In order to get the correct measurement for narrowband peaks in the return loss, the frequency spacing between two neighbouring measurement frequencies shall not be too large.

The bandwidth of reflection peaks is dependent on the cable attenuation. The higher the attenuation, the larger the bandwidth, and consequently the larger could be the frequency spacing between two measurement points. The cable attenuation for RF cables is frequency-dependent and increases with frequency. Thus, finally, the maximum permitted frequency spacing between two measuring points increases with the measurement frequency [1] [2].

The frequency spacing Δf between any two measuring points shall be:

$$\Delta f \leq 1{,}4 \times \frac{300 \times v_r}{868{,}6 \times \pi} \times \alpha(f) \times \sqrt{10^{\frac{\Delta a_{r,f}}{10}} - 1} \tag{7}$$

where

Δf is the maximum permitted frequency spacing between two measurement points, in MHz;

$\alpha(f)$ is the cable attenuation at the measured frequency, in dB/100 m;

v_r is the relative velocity of the cable;

$\Delta a_{r,f}$ is the maximum permitted error which can be caused by the frequency spacing, in dB;

1,4 is the factor which takes into account the difference between theoretical and practical investigations [3].

If not specified otherwise, the maximum permitted error caused by the frequency spacing shall be $\Delta a_{r,f} \leq 1$ dB.

NOTE For the requirement on the frequency spacing for the measurement of return loss (RL) of RF cables, see Annex A.

The number of measuring points shall meet the requirements of Formula (8).

$$n \geq \frac{f_{max} - f_{min}}{\Delta f} + 1 \tag{8}$$

where

n is the number of measuring frequency points;

f_{max} is the highest frequency to be measured, in MHz;

f_{min} is the lowest frequency to be measured, in MHz;

Δf is the maximum permitted frequency spacing between two measurement points, in MHz, calculated for f_{min}.

8 Test procedure

8.1 General

The return loss (RL) and voltage standing wave ratio (VSWR) of the TS shall be measured with the VNA over the specified frequency range.

The requirements for frequency spacing and measuring frequency point specified in Clause 7 shall be fulfilled.

a) For some VNA with an infinite number of measuring frequency points, measurement can be made in one sweep over the specified frequency range. In that case, the maximum permitted frequency spacing between two measurement points shall be calculated according to Formula (7) and the minimum number of measuring points shall meet the requirement of Formula (8).

b) For some VNA with a limited number of measuring frequency points, measurement can also be made in one sweep over the specified frequency range if the number of frequency points available by the VNA is not less than the minimum number of measuring points requirement calculated by Formula (8).

c) For some VNA with a limited number of measuring frequency points, if the number of frequency points available by the VNA is less than the minimum number of measuring points requirement calculated by Formula (8), then the specified frequency range to be measured shall be divided into several frequency subintervals. In each subinterval, the maximum permitted frequency spacing between two measurement points shall be calculated according to Formula (9) and the number of measuring points shall be the number of frequency points available by the VNA. The highest frequency of each subinterval to be measured shall be determined according to Formula (10).

$$\Delta f_{\mathrm{sub}x} \leq 1{,}4 \times \frac{300 \times v_{\mathrm{r}}}{868{,}6 \times \pi} \times \alpha_{\mathrm{sub}x}(f) \times \sqrt{10^{\frac{\Delta\alpha_{\mathrm{r,f}}}{10}} - 1} \qquad (9)$$

where

$\Delta f_{\mathrm{sub}x}$ is the maximum permitted frequency spacing between two measurement points in frequency subinterval "x", in MHz;

$\alpha_{\mathrm{sub}x}(f)$ is the cable attenuation at the minimum measured frequency of frequency subinterval "x", in dB/100 m;

v_{r} is the relative velocity of the cable;

$\Delta\alpha_{\mathrm{r,f}}$ is the maximum permitted error which can be caused by the frequency spacing, in dB; if not specified otherwise, the maximum permitted error caused by the frequency spacing shall be $\Delta\alpha_{\mathrm{r,f}} \leq 1$ dB;

1,4 is the factor which takes into account the difference between theoretical and practical investigations.

"x" is the frequency subinterval number of the whole specified frequency range.

$$f_{\text{sub}x,\text{max}} \leq f_{\text{sub}x,\text{min}} + \Delta f_{\text{sub}x} \times (N_{\text{VNA}} - 1) \quad (10)$$

where

$f_{\text{sub}x,\text{max}}$ is the highest frequency of the subinterval "x" to be measured, in MHz, in general, the value should be rounded to the nearest 100 MHz;

$f_{\text{sub}x,\text{min}}$ is the lowest frequency of the subinterval "x" to be measured, in MHz;

For subinterval 1, it is the lowest frequency of specified frequency range;

For subinterval 2, it is the highest frequency of subinterval 1 to be measured;

And so on.

$\Delta f_{\text{sub}x}$ is the maximum permitted frequency spacing between two measurement points, in MHz, calculated according to Formula (9).

Δf_{sub} is a constant in each subinterval but is different in subinterval.

N_{VNA} is the number of frequency points available by the VNA.

NOTE Annex B provides an example of dividing a specified frequency range to be measured into several frequency subintervals to measure.

8.2 Two-port measurement

The two-port measurement procedure is as follows.

a) According to 8.1 to determine the measurement frequency range or subinterval and the number of measuring points.

b) After the VNA is warmed up, set the measurement frequency range and other related parameters, and then set its test mode to measure the return loss or voltage standing wave ratio.

c) System calibration.

d) Connect two ends of TS to the test equipment, measure and record the S_{11} and S_{22} graphs.

8.3 One-port measurement

The one-port measurement procedure is as follows.

a) According to 8.1 to determine the measurement frequency range or subinterval and the number of measuring points.

b) After the VNA is warmed up, set the measurement frequency range and other related parameters, and then set its test mode to measure the voltage standing wave ratio or return loss.

c) System calibration.

d) Connect A end of TS to the test equipment, the B end to the load, measure and record the record the S_{11} graph.

e) Remove the TS from the equipment, connect the B end to the equipment, the A end to the load, measure and record the S_{11} graph.

9 Failure criterion

The return loss (RL) or voltage standing wave ratio (VSWR) shall be in accordance with the relevant standards.

10 Information to be given in the relevant specification

The following information shall be given in the relevant standards:

a) frequency range to be measured;
b) frequency subintervals, if applicable;
c) method to be used;
d) length of the cable to be measured;
e) test results;
f) difference from this test method.

11 Test report

Test report should include the following information:

a) test name;
b) environmental conditions;
c) name of the test equipment used, number, and validity of the measurement;
d) test sample and test frequency;
e) test results;
f) name of the operator and test date.

Annex A
(informative)

Requirement on the frequency spacing for the measurement of return loss (RL) of RF cables

A.1 General

Nowadays, the frequency-dependent characteristics of coaxial cables are measured by the means of VNA, which measures discrete frequencies. In order to get the correct measure for narrowband peaks in return loss, the frequency spacing between two neighbouring measurement frequencies shall not be too large.

IEC 61196-1:1995[1] required a number of measurement points depending on the frequency span and the sample length:

$$n \geq \frac{5 \times (f_2 - f_1) \times l}{150 \times v_r} \qquad \text{(A.1)}$$

where

n is number of measurement points;

f_2 is the highest frequency of the interval to be measured, in MHz;

f_1 is the lowest frequency of the interval to be measured, in MHz;

l is sample length, in meter;

v_r is the relative velocity.

This Formula (A.1) results in high numbers. For example, the following CATV cable results in about 12 000 measurement points:

- frequency range of 5 MHz to 3 GHz;
- foamed PE dielectric;
- cable length of 100 m.

Usually, the return loss or VSWR for CATV cables is measured on production lengths of 1 000 m which then results in numbers which are 10 times higher.

Considering coaxial cables, which are used up to 12 GHz or 20 GHz (for example, PE insulation semi-rigid cables or RG flexible cables), Formula (A.1) will result in at least 48 000 measurement points for a length of 100 m.

However, standard VNA in general only provide 1 601 points per frequency sweep. Although there exist software solutions which in principle provide infinite measurement points, it is of interest to know how many measurement points are needed to get a correct result.

[1] This publication has been withdrawn.

Annex A investigates the bandwidth of resonances in return-loss measurements. The bandwidth increases with the cable attenuation, i.e. with the frequency. With an increasing resonance bandwidth, the frequency spacing could be increased, and, thus, the number of measurement points could be decreased. It is also demonstrated that the bandwidth of the resonance peak is independent on the cable length.

An investigation has been carried out by K. Erdel. He modelled the reflections by discontinuously distributed parallel capacitances which are only applicable for certain causes of the reflection, but, in reality, continuously distributed reflections also exist.

A.2 Physical basics

A.2.1 General

The critical points in return-loss curves are those with peaks. Those resonant peaks are caused by periodic variations of the characteristic impedance and could be of very small bandwidth.

Also, for homogenous cables with concentrated deviations of the characteristic impedance (for example, at the cable ends), one needs to be careful. In this case, the frequency response of the return loss is changing periodically with a high repetition rate, especially for long distances and cables with low attenuation. But, in general, the reflections caused by the mismatch of the cable are fewer compared to the reflections caused by structural variations along the cable length.

A.2.2 Return-loss model

A.2.2.1 General

The model illustrated in Figure A.1 describes the inhomogeneities of the characteristic impedance by reflections. Summing up the reflected waves of each single reflection propagating to the beginning of the cable results in the reflection coefficient at the cable input.

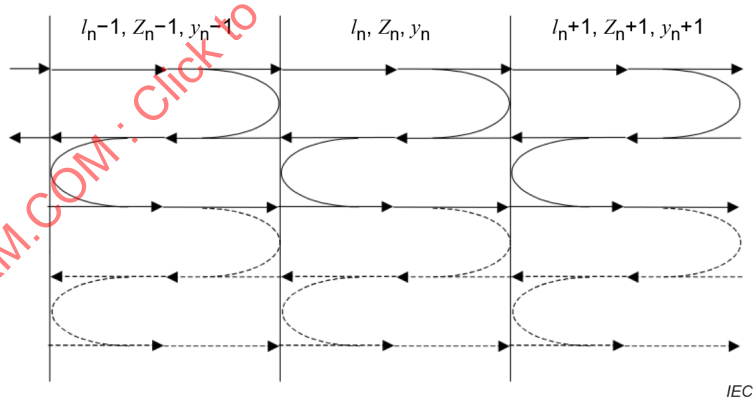

Figure A.1 – Reflection model

A.2.2.2 Solution taking into account all multiple reflections

A wave propagating from a transmission line n with the impedance Z_n to a transmission line n + 1 with the impedance Z_n + 1 is reflected with the reflection factor r_n, n + 1. Due to the reflection, the wave behind the point of the reflection is changed by the factor (1 + r_n, n + 1). Taking into account all multiple reflections and the wave propagation effect results in a geometric series. For the resulting wave in the backward direction (the sum of the reflected waves), the following is obtained:

$$B_n = \frac{\sum u_r}{u_i} = \frac{\left(1 - r_{n,n-1}{}^2\right) r_{n,n+1} e^{-2\gamma_n l_n}}{1 - r_{n,n-1} r_{n,n+1} e^{-2\gamma_n l_n}} - r_{n,n-1} \tag{A.2}$$

$$r_{n,n-1} = \frac{z_{n-1} - z_n}{z_{n-1} + z_n} \tag{A.3}$$

$$r_{n,n+1} = \frac{z_{n+1} - z_n}{z_{n+1} + z_n} \tag{A.4}$$

and for the resulting wave in the forward direction, the following is obtained:

$$F_n = \frac{\sum u_f}{u_i} = \frac{\left(1 - r_{n,n-1}\right)\left(1 + r_{n,n+1}\right) e^{-2\gamma_n l_n}}{1 - r_{n,n-1} r_{n,n+1} e^{-2\gamma_n l_n}} \tag{A.5}$$

Formula (A.2) to Formula (A.5) can be directly applied for the calculation of the resulting backward and forward propagating waves of homogenous cables with concentrated deviations of the characteristic impedance (for example, at the cable ends).

A.2.2.3 Approximate solution

Formula (A.2) to Formula (A.5) are not useful for reflections (continuously) distributed along the cable length. However, on condition of small local reflections, multiple reflections can be neglected. In this case, the distributed reflections can be integrated along the cable length to get the resulting reflection coefficient at the input of the cable.

$$\underline{r}(x) = \lim_{\Delta x \to 0} \frac{Z(x + \Delta x) - Z(x)}{Z(x + \Delta x) + Z(x)} = \frac{Z'(x)}{2Z(x)} \tag{A.6}$$

For the wave related to the cable input, the wave propagation effect should be taken into account. The reflection coefficient at the cable input is then described by:

$$\underline{r}_0(x) = \underline{r}(x) e^{-2\gamma x} \tag{A.7}$$

For the resulting reflection coefficient (with neglect of multiple reflections), the following is obtained:

$$\underline{r}_{\text{res}} \approx \int_{X=0}^{L} \frac{Z'(x)}{2Z(x)} e^{-2\gamma x} dx \quad \text{(A.8)}$$

A sinusoidal variation of the local characteristic impedance along the cable length is assumed. Any other periodic variation could be described by a sum of sinusoidal functions (Fourier):

$$Z(x) = Z_{\text{m}} \left(1 + \frac{\Delta Z}{Z_{\text{m}}} \sin\left(\frac{2\pi}{\lambda_{\text{Z}}} x \right) \right) = Z_{\text{m}} \left(1 + \delta_{\text{Z}} \sin\left(\frac{2\pi}{\lambda_{\text{Z}}} x \right) \right) \quad \text{(A.9)}$$

where

Z_{m} is the mean characteristic impedance;

λ_{Z} is the geometric wavelength of the impedance variation.

$$\underline{r}(x) = \frac{Z'(x)}{2Z(x)} \approx \frac{Z'(x)}{2Z_{\text{m}}} \quad \text{(A.10)}$$

$$\underline{r}(x) = \frac{\delta_{\text{Z}}}{2} \frac{2\pi}{\lambda_{\text{Z}}} \cos\left(\frac{2\pi}{\lambda_{\text{Z}}} x \right) \quad \text{(A.11)}$$

For the resulting reflection coefficient at the input of the cable, the following is obtained:

$$\underline{r} = \frac{\delta_{\text{Z}}}{2} \frac{2\pi}{\lambda_{\text{Z}}} \int_{x=0}^{L} \cos\left(\frac{2\pi}{\lambda_{\text{Z}}} x \right) \Delta e^{-2\gamma x} dx \quad \text{(A.12)}$$

The cable length is always longer than the geometric wavelength of the impedance variation $L >> \lambda_{\text{Z}}$. Thus, L/λ_{Z} can be considered as an integer number. Taking this into account results in:

$$\underline{r} = \frac{\delta_{\text{Z}}}{2} \cdot \frac{1}{\frac{\gamma}{\frac{\pi}{\lambda_z}} + \frac{\frac{\pi}{\lambda_z}}{\gamma}} \cdot \left(1 - e^{-2\gamma L} \right) \quad \text{(A.13)}$$

The factor in brackets describes the length dependency of the reflection coefficient. The reflection coefficient is maximum for an infinite length.

Resonance is given if:

$$\left|\frac{\gamma}{\frac{\pi}{\lambda_Z}}\right| = 1$$

i.e (A.14)

$$\alpha^2 + \beta^2 = \left(\frac{\pi}{\lambda_Z}\right)^2$$

with $\alpha\,\lambda_Z << \beta\,\lambda_Z$ one gets $\beta\,\lambda_Z = \pi$.

In this case, the reflection coefficient has its only absolute maximum. In practice, harmonic reflection peaks are often observed. In this case, the impedance variation is not sinusoidal, but any other periodic function which could be (according to Fourier) split in several sinusoidal components, where each of them creates a resonance peak.

$$r_{max} = \frac{\delta_Z}{2} \cdot \frac{\pi}{2\alpha\lambda_Z}\left(1 - e^{-2\alpha L}\right) \qquad \text{(A.15)}$$

Instead of using the phase constant, β, it is more convenient to use the electrical wavelength $\lambda_e = 2\pi / \beta$. Then, we get at resonance:

$$\lambda_{e,res} \frac{2\lambda_Z}{\sqrt{1+\left(\frac{\alpha\lambda_Z}{\pi}\right)^2}} \approx 2\lambda_Z \qquad \text{(A.16)}$$

$$f_{res} = \frac{c_0}{\lambda_{e,res}\sqrt{\varepsilon_r}} = \frac{c_0}{2\lambda_Z\sqrt{\varepsilon_r}}\sqrt{1+\left(\frac{\alpha\lambda_Z}{\pi}\right)^2} \approx \frac{c_0}{2\lambda_Z\sqrt{\varepsilon_r}} \qquad \text{(A.17)}$$

The relation between the reflection coefficient and the return loss is given by:

$$a_r = -20\lg\left|\underline{r}\right| = 20\lg\left|\frac{1}{\underline{r}}\right| \qquad \text{(A.18)}$$

$$a_{\mathrm{r}} = 20\lg\left\{\frac{\delta_{\mathrm{Z}}}{2}\cdot\left|\frac{\gamma}{\pi/\lambda_{\mathrm{Z}}}+\frac{\pi/\lambda_{\mathrm{Z}}}{\gamma}\right|\right\} - 20\lg\left|\left(1-e^{-2\gamma L}\right)\right| \qquad \text{(A.19)}$$

and at the resonance, the following minimum return loss is obtained:

$$a_{\mathrm{r,min}} = 20\lg\left\{\frac{2}{\delta_{\mathrm{Z}}}\cdot\frac{2\alpha\lambda_{\mathrm{Z}}}{\pi}\right\} - 20\lg\left(1-e^{-2\alpha \mathrm{L}}\right) \qquad \text{(A.20)}$$

If the frequency deviates from the resonance frequency, then the return loss changes by $\Delta a_{\mathrm{r,f}}$. Assuming that α and β do not change significantly for small frequency deviations and $\alpha\lambda_{\mathrm{Z}} << 1$ results in

$$f = f_{\mathrm{res}}\left(1 \pm \delta_{\mathrm{f}}\right)$$

and (A.21)

$$\delta_{\mathrm{f}} \ll 1$$

$$\Delta a_{\mathrm{r,f}} = a_{\mathrm{r}} - a_{\mathrm{r,min}} = 20\lg\frac{\pi}{2\alpha\lambda_{\mathrm{Z}}}\left|\frac{\alpha\lambda_{\mathrm{Z}}}{\pi} + j\left(1+\delta_{\mathrm{f}}\right) + \frac{1}{\frac{\alpha\lambda_{\mathrm{Z}}}{\pi} + j\left(1+\delta_{\mathrm{f}}\right)}\right| \qquad \text{(A.22)}$$

$$\Delta a_{\mathrm{r,f}} \approx 20\lg\frac{\pi}{2\alpha\lambda_{\mathrm{Z}}}\left|\frac{\alpha\lambda_{\mathrm{Z}}}{\pi}\left(1+\frac{1}{\left(1+\delta_{\mathrm{f}}\right)^2}\right) + j\left(\left(1+\delta_{\mathrm{f}}\right) - \frac{1}{1+\delta_{\mathrm{f}}}\right)\right| \qquad \text{(A.23)}$$

$$\Delta a_{\mathrm{r,f}} \approx 20\lg\left\{\frac{\pi}{2\alpha\lambda_{\mathrm{Z}}}\left|\frac{\alpha\lambda_{\mathrm{Z}}}{\pi}\left(1-\delta_{\mathrm{f}}\right) + j2\delta_{\mathrm{f}}\right|\right\} \qquad \text{(A.24)}$$

$$\Delta a_{\mathrm{r,f}} \approx 20\lg\left\{\frac{\pi}{2\alpha\lambda_{\mathrm{Z}}}\sqrt{\left(2\frac{\alpha\lambda_{\mathrm{Z}}}{\pi}\right)^2 + 4\delta_{\mathrm{f}}^2}\right\} = 10\lg\left\{1+\left(\frac{\pi}{\alpha\lambda_{\mathrm{Z}}}\delta_{\mathrm{f}}\right)^2\right\} \qquad \text{(A.25)}$$

and finally:

$$\delta_f = \left| \frac{f - f_{res}}{f_{res}} \right| \approx \frac{\alpha \lambda_Z}{\pi} \sqrt{10^{\frac{\Delta a_{r,f}}{10}} - 1} \tag{A.26}$$

where, in Formulae (A.20) to (A.25),

α is the attenuation of the cable, in Np/m, at the measured frequency;

$\Delta a_{r,f}$ is the deviation of the return loss from the maximum value at the resonant frequency;

δ_f is the relative deviation from the resonant frequency;

λ_Z is the geometric wavelength of the periodic impedance variation (see Formula (A.17));

f is the measured frequency, in Hz;

f_{res} is the resonant frequency caused by periodic impedance variations (see Formula (A.17)).

Note that $2\delta_f$ is the $\Delta a_{r,f}$ bandwidth of the resonant peak (see Figure A.2).

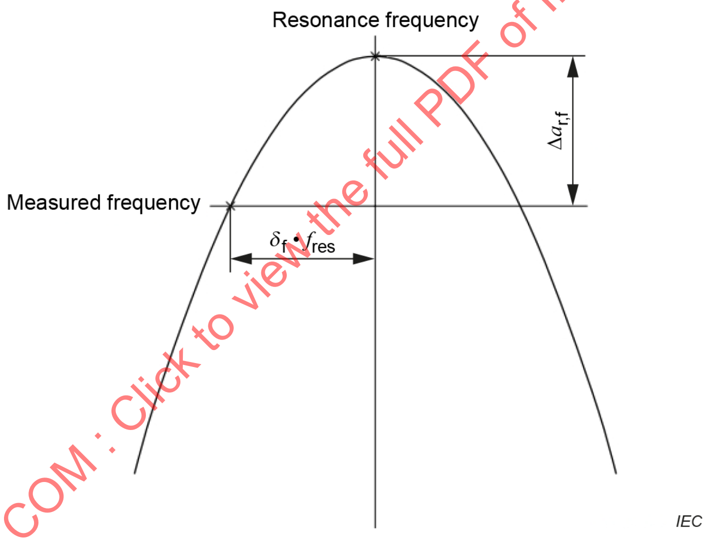

Figure A.2 – Resonance peak

We have seen that the change in return loss for small frequency deviations from the resonance frequency does not depend on the cable length. However, the maximum value of the peak is length dependent. From Formula (A.20), with decreasing test length, the return loss increases. The change is described by $\Delta a_{r,L}$:

$$\Delta a_{r,L} = a_r(L_2) - a_r(L_1) = 20 \lg \left(\frac{1 - e^{-2\alpha L_1}}{1 - e^{-2\alpha L_2}} \right) \tag{A.27}$$

with α (Np/m).

NOTE 1 Np ≈ 8,686 dB, and 1 dB ≈ 0,1151 Np.