

Measurement of quartz crystal unit parameters

Part 5. Methods for the determination of equivalent electrical parameters using automatic network analyzer techniques and error correction

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Change of identifier

Wherever BS 7681 : Part 5 : 1995 appears in this standard, it should be read as BS EN 60444-5 : 1997.

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National foreword

This Part of BS EN 60444 has been prepared by Technical Committee EPL/49 (formerly ECL/11), and is the English language version of EN 60444-5 : 1997, published by the European Committee for Electrotechnical Standardization (CENELEC). It is identical with IEC 444-5 : 1995, *Measurement of quartz crystal unit parameters Part 5. Methods for the determination of equivalent electrical parameters using automatic network analyzer techniques and error correction*, published by the International Electrotechnical Commission (IEC).

Cross references

Attention is drawn to the fact that CEN and CENELEC Standards normally include an annex which lists normative references to international publications with their corresponding European publications. The British Standards which implement these international or European publications may be found in the BSI Standards Catalogue under the section entitled 'International Standards Correspondence Index', or using the 'Find' facility of the BSI Standards Electronic Catalogue.

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Measurement of quartz crystal unit parameters
Part 5: Methods for the determination of equivalent electrical
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(IEC 444-5 : 1995)

Mesure des paramètres des résonateurs à quartz
Partie 5: Méthodes pour la détermination des
paramètres électriques équivalents utilisant des
analyseurs automatiques de réseaux et
correction des erreurs
(CEI 444-5 : 1995)

Messung von Schwingquarz-Kennwerten
Teil 5: Meßverfahren zur Bestimmung der
elektrischen Ersatzschaltungsparameter von
Schwingquarzen mit automatischer
Netzwerkanalysatortechnik und Fehlerkorrektur
(IEC 444-5 : 1995)

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

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Foreword

The text of the International Standard IEC 444-5 : 1995, prepared by IEC TC 49, Piezoelectric and dielectric devices for frequency control and selection, was submitted to the formal vote and was approved by CENELEC as EN 60444-5 on 1997-03-11 without any modification.

The following dates were fixed:

- latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement (dop) 1997-12-01
- latest date by which the national standards conflicting with the EN have to be withdrawn (dow) 1997-12-01

Annexes designated 'normative' are part of the body of the standard. Annexes designated 'informative' are given for information only. In this standard, annexes A and ZA are normative and annexes B and C are informative. Annex ZA has been added by CENELEC.

MEASUREMENT OF QUARTZ CRYSTAL UNIT PARAMETERS –

Part 5: Methods for the determination of equivalent electrical parameters using automatic network analyzer techniques and error correction

1 Scope

The objective of this International Standard is to give methods for determining the best representations of modes in quartz crystal resonators by linear equivalent circuits. Circuit representations are based on electrical parameters measured with vector network analyzer equipment using automatic error correction. Determination of the equivalent parameters by the method of this standard is based on the measurement of device immittance in the vicinity of series resonance. The further problem of characterizing the device for operation with a series load capacitance has not been directly addressed, although it is recognized that some applications require such characterization. The same measuring equipment, and fundamentally the same sort of measurement, provides the means to characterize completely the test load capacity fixture as well as the series combination of load capacity fixture and crystal unit.

2 Introduction

2.1 General

2.1.1 This standard describes methods for determining the values of the electrical parameters of piezoelectric quartz crystal units using automated vector network analyzer equipment. The recommended procedures for S -parameter systems use shielded open-circuit, short-circuit, and resistive terminations, and (in the case of transmission methods) thru-line connections. Coaxial open-circuit, short-circuit and resistive terminations designed for 50 Ω systems are readily available, and can be calibrated in terms of national standards of impedance over very wide frequency ranges. At the present time thru-line connections suitable for calibrating the test fixtures must be calibrated by the user or supplier; however, the techniques for doing this are quite well known. Non-coaxial standard resistors for use in the direct transmission (π -network) method are commercially available as well, but are not as easily traceable to National Standards. Further guidance on the application of this standard may be found in IEC 1080.

2.1.2 The procedure involves the measurement of crystal resonator admittance at prescribed frequency points by one of a number of methods followed by data interpretation and evaluation of the equivalent circuit parameters (figure 1).

2.1.3 The measurement methods described are intended to provide reference values for the electrical equivalent circuit parameters. Manufacturers and users may employ other methods of measurement, but the values thus obtained shall be correlated with those obtained by the reference method.

2.1.4 This standard is only concerned with the representation of quartz crystal resonators by linear equivalent circuits which are valid over a narrow frequency band covering at most a small percentage of the resonance frequency.

2.1.5 In general, some degree of non-linearity will be present and the circuit parameters may have a noticeable dependence on drive level. If non-linear effects are very large then the accepted circuit representations may be unusable.

2.1.6 Normally, the equivalent circuit will be used to represent an isolated mode of vibration, but occasionally additional modes may occur extremely close to the main response; a more complex circuit representation may then be used, and consideration of this problem is included in this standard. See reference [1]*.

2.2 Methods of admittance measurement

2.2.1 The following terminology will be used to describe the circuit elements. See figures 3 and 4:

- C_0 is the static capacitance (for the one-port model)
- C_{01} is the electrode to can capacitance
- C_{02} is the static capacitance (for the simplified two-port model)
- C_{03} is the electrode to can capacitance
- G_0 is the conductance associated with C_0
- G_{01} is the conductance associated with C_{01}
- G_{02} is the conductance associated with C_{02}
- G_{03} is the conductance associated with C_{03}
- R_1 is the motional resistance
- L_1 is the motional inductance
- C_1 is the motional capacitance

$$\omega_s = \frac{1}{(L_1 C_1)^{1/2}} \text{ series resonance frequency (rads/s)}$$

The transfer admittance function, Y_{12} , for the equivalent circuits shown in figures 3 and 4, describes a circular locus in the complex admittance plane, as depicted in figure 5a. The transform of this locus to the impedance ($Z = 1/Y$) plane is also a circle as in figure 5b. There are six characteristic frequencies associated with such a circuit:

- f_s is the series resonance frequency
- f_m is the frequency of maximum admittance (minimum impedance)
- f_r is the resonance frequency (zero phase)
- f_a is the anti-resonance frequency (zero phase)
- f_p is the parallel resonance frequency (lossless)
- f_n is the frequency of minimum admittance (maximum impedance)

Of these, the series resonance frequency alone is essentially independent of the value of static capacitance, and is therefore the parameter of choice for purposes of specification as it will be little influenced by strays. The relationships of the characteristic frequencies to f_s may be found in IEC 302, or in EIA Standard 512 (1985).

2.2.2 Three basic methods of measurement are described (see figure 2a):

- a) Single-port reflection method; the crystal resonator is characterized as a one-port device with one electrode driven and all other electrodes and the crystal enclosure earthed.

In a reflection measurement the admittance Y can be calculated from the measured value of S_{11} .

$$R_0 Y = \frac{1 - S_{11}}{1 + S_{11}} \quad (2.1)$$

NOTE - R_0 is the value of the standard termination used in calibration of the system.

* The figures in square brackets refer to the bibliography in annex C.

b) Two-port transmission method; the crystal resonator is treated as a two-port device with two driven electrodes, all other electrodes and the crystal enclosure being earthed.

In transmission the transfer admittance of the two-port circuit in figure 4 is:

$$Y_{12} = - \left[G_{02} + j\omega C_{02} + \frac{1}{R_1 + j\omega L_1 + 1 / j\omega C_1} \right] \quad (2.2)$$

Using the relationships between admittance and scattering parameters we may define, as above, a quantity Y

$$\begin{aligned} R_0 Y &= R_0 \left[G_{02} + j\omega C_{02} + \frac{1}{R_1 + j\omega L_1 + 1 / j\omega C_1} \right] \\ * \quad \left[\right. &= \frac{2S_{12}}{(1 + S_{11})(1 + S_{22}) - S_{21}S_{12}} \left. \right] \end{aligned} \quad (2.3)$$

which is easily calculated from the measured S -parameters.

c) Direct amplitude/phase transmission method. The crystal resonator is treated as a two-terminal device according to figure 3 in a transmission fixture using nominally resistive elements, as in IEC 444. The impedance of the device is determined from the amplitude and phase of the signal across the fixture. Using standard equations, this impedance is converted to an admittance.

$$Y = G_0 + j\omega C_0 + \frac{1}{R_1 + j\omega L_1 + 1 / j\omega C_1} \quad (2.4)$$

2.2.3 The S -parameter reflection measurement is potentially the most accurate, as only coaxial traceable standard impedances are used for calibration. The S -parameter two-port measurement provides most information about the device, while the direct transmission determines the transimpedance of the device.

2.2.4 Restrictions to the validity of the models

The following approximations are implicit in these equivalent circuits.

- a) It is assumed that a lumped circuit representation is valid.
- b) It is assumed that the device closely approximates an ideal lossless component, and hence that all significant resonances have high Q factors.

However, over narrow bandwidths, spanning at most a small percentage of the resonance frequency, the circuits of figures 6 and 7 provide a very good representation of the resonances in the majority of cases.

2.2.5 Accuracy and traceability

The accuracy and traceability of the measurements are directly related to the calibration components, and are largely independent of the particular network analyzer system. However, the system shall conform to the theoretical models described in annex A, and shall therefore be a linear vector detector system capable of high accuracy in the ratio mode (A/R etc.); beyond this, no detailed specification need be given. A frequency source traceable to a national standard of frequency is also required.

* See national foreword for details of textual error.

2.2.6 Equipment

The use of computer controlled instruments is essential for data collection, error correction, admittance calculations and for the estimation of the crystal parameters. Error correction arises from the need to characterize the measurement circuit. This is achieved by means of a calibration using known standards of impedance. Data collection of large numbers of measurement points is required for subsequent admittance calculations.

2.2.7 Application to other devices

This standard is specifically concerned with single resonator measurements. However, many of the techniques are directly applicable to more complex devices such as bipoles and monolithic filters; these generalizations are indicated where appropriate.

2.3 Admittance analysis and estimation of equivalent circuit parameters

There are four methods (see figure 2b) of admittance analysis leading to the crystal equivalent circuit. If the crystal being measured is described by the normal equivalent circuit and, for instance, the device behaves linearly, then all these methods are equivalent.

a) General least-squares method

This is the more general non-linear technique which can be applied in all situations. The method is capable of measuring multiple resonances, such as inharmonics.

b) Linear least-squares method

This method minimizes the sum of the squares of weighted differences between the measured and theoretical admittances and is applicable to models with a single resonance.

c) Circle-fitting method

This method fits a circle to an odd number of equally spaced points on the right-hand side of the admittance circle of the crystal resonator ($\pm 45^\circ$).

d) Two-point iterative method

This is potentially the fastest method and could be used for production. It involves obtaining two frequencies which lie approximately $\pm 45^\circ$ on the admittance circle of the resonator. The calculated crystal parameters are used to re-estimate better values of these two frequencies. Iterations continue until the estimate is within a given tolerance.

2.4 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of IEC 444. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this part of IEC 444 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 302: 1969, *Standard definitions and methods of measurement for piezoelectric vibrators operating over the frequency range up to 30 MHz*

IEC 1080: 1991, *Guide to the measurement of equivalent electrical parameters of quartz crystal units*

EIA 512: 1985, *Standard methods for measurement of equivalent electrical parameters of quartz crystal units, 1 kHz to 1 GHz*

3 Measurement procedures

3.1 General

The procedure for determination of the equivalent circuit parameters of a quartz crystal unit is shown in figure 8. It is recommended that the crystal enclosure is grounded. In the case of a glass enclosure, the unit is fitted with a grounded shield cover.

3.2 Environmental control

All crystal devices are influenced to at least some degree by temperature, the rate of change of temperature, and by the level of drive. It is therefore necessary to protect the device from temperature change during the period of measurement, and to determine as closely as possible its actual temperature at the time of measurement, so that measured values can be corrected for differences in temperature between two measurements. Care shall also be taken to ensure that the drive level applied during measurement is that specified for the device. Another possible source of error, when measuring low-frequency, high- Q devices especially, is unavoidable small temperature drift during the course of the measurement, as relatively long wait times are required. Such slow drifts between the time the first and last data are recorded will cause distortion of the admittance locus. By a first approximation, this can be avoided if alternate points are recorded with increasing frequency and then the remaining values obtained with decreasing frequency. The least squares estimation methods will effectively average the data so obtained, and thus compensate to a degree for the differences due to temperature drift.

3.3 Calibration

This is described for each method in clause 5.

3.4 Level of drive

The drive level at f_s for the ensuing measurement must be specified either in power or current for that crystal type. This requires that the output level of the generator be set. If a reasonable estimate of the R_1 of the crystal is known, then this can be used to calculate this level. Alternatively, a quick estimate of the R_1 can be determined from an initial sweep through the resonance.

3.5 C_0 measurements

3.5.1 For a one-port measurement at low frequencies the impedance of C_0 may be much greater than $50\ \Omega$. This results in low sensitivity, and hence poor estimation of the static capacitance. Sensitivity may be improved by making a separate measurement at some higher frequency well away from resonance; however, it is possible that the effective static capacitance at this frequency will differ from that at resonance. For most crystal unit types in common use, C_0 will remain essentially constant over the frequency range below about 100 MHz. At higher frequencies, it is advisable to measure C_0 and the other static parameters at frequencies within a small percentage of the resonance frequency. If the unit will influence the behaviour of wide-band circuits, it may be necessary to determine the static parameters over a wide frequency range.

3.5.2 The measurement of the direct pin-to-pin capacitance C_0 may be made using one of two methods:

- a) For crystals up to 30 MHz, the measurement is to be made at five frequencies slightly above 30 MHz (i.e. 30,1, 30,2, 30,3, 30,4 and 30,5 MHz) and the average of the three values nearest the mean of the five should be used as the best estimate.
- b) For crystals above 30 MHz, it is recommended that three pairs of measurements be made, each pair being equidistant from the series resonance frequency, f_s , i.e. $f_s (1 \pm 0,05)$, $f_s (1 \pm 0,06)$ and $f_s (1 \pm 0,07)$. For each pair, the mean of the C_0 values determined from the lower and higher frequency is to be calculated, and then the best estimate taken as the mean of the two such values which are closest together.

Prior to either measurement a) or b) above, it should be confirmed that no spurious responses of the crystal unit exist at the measurement frequency.

3.5.3 The measurement of the two pin-to-case capacitances (usually designated C_{13} and C_{23}) when required by the specification, or to aid in modelling of the transmission fixture, should be made by a separate measurement with a guarded capacitance bridge.

3.6 Choice of measurement frequencies

Two alternative methods for obtaining admittance data on a crystal resonance can be used. The first is a multifrequency method used both by the least squares fitting procedure described in 7.1 and 7.2 and the admittance circle fit described in 7.3.

Here, it is recommended that a total of nine frequency points be used, chosen so that the transadmittance points determined lie within the right-hand half circle of the Y-plane locus (see figure 5a), which implies that several frequencies should lie within the " Q -bandwidth" centred on the series resonance frequency. The measurement program must therefore perform a preliminary search for the frequency of series resonance, and then establish the array of frequencies at which measurements are to be made, based either on an estimate of the Q furnished by the operator, or from examination of the data. The measurement frequencies may be equispaced for convenience, and all points should be within a range of $(\pm f_s/2Q)$ of f_s . Additional points outside this range may also be used, but add little information about the motional parameters of the unit. Closer spacing of the measurement frequencies and coverage of a broader range can be useful if the detection of weak unwanted modes is desired. For general purpose use, 9 to 15 data points are adequate, and result in rapid measurements. For highest accuracy, however, 20 to 30 measurement points are preferred, together with a stable environment.

The second method is the two-point iterative method described in 7.4.

3.7 Data collection

A c.w. mode of measurement is recommended (rather than swept), with adequate settling time calculated from the estimated Q . There are two reasons for this – first, with most signal sources available, frequency accuracy in a slow sweep is degraded and, second, the response of the high- Q crystal devices requires a finite time to reach equilibrium after the excitation frequency is applied. There are three distinct delay times involved in such a stepped-frequency mode: a finite time is required for the frequency source to stabilize after being

programmed to a specific value T_{ins} , a finite time for the receiver to stabilize to that new frequency (T_{rec}). There is also a finite delay while the previously applied frequency response of the crystal decays and the new response builds to equilibrium value (T_r). At low frequencies with high- Q crystals, T_r may be several hundred milliseconds, or even seconds.

Analysis of the equivalent circuit of the crystal installed in a two-port transmission fixture shows that the new response will have settled within 0,1% of its final value in a time of about $2,5 (Q_{\text{eff}}/f_s)$ after application of the drive signal, where Q_{eff} is the loaded Q -factor of the crystal test fixture. The phase transient will decay to within about 0,1 degree of its final value in the same period. For most purposes, this degree of precision is adequate; however, for highest precision, it is recommended that this interval be extended to at least $3,5 (Q_{\text{eff}}/f_s)$, so that no significant distortion of the data will be caused by transient phenomena. Thus, the program should set the frequency source to a specific frequency, then wait for a period $T_d = T_{\text{ins}} + T_r$ before measuring the system response. At this time, several measurements should be made and the average value recorded, so that random deviations caused by electrical noise and digitizer errors will be minimized – the actual number of readings to be averaged can be made a function of the magnitude of the response, as relative noise level increases as the signal decreases.

Alternatively, the rate of frequency stepping can be determined from repetitive measurements at each frequency until the phase response has settled down. Averaging of several readings is also recommended as this minimizes the effects of random and quantization noise.

3.8 Data correction

In the case of the S -parameter methods, the data needs to be corrected by means of error matrices. This is discussed in annex A. This procedure is not required for direct transmission methods.

3.9 Admittance calculation

For S -parameter methods, this is given by the standard S -parameter to Y -parameter conversion equations. For direct transmission methods this procedure is outlined in annex A.

3.10 Admittance analysis and estimation of the equivalent circuit parameters

For the various methods, refer to clause 7.

4 Choice of admittance measurement method

4.1 General

For the vast majority of resonators either one-port or two-port characterization is quite satisfactory. As it provides a more complete description, the two-port transmission method is to be considered as the prime reference standard. However, in certain situations, the one-port technique may provide information under conditions more nearly approximating end-use conditions.

4.2 Advantages and disadvantages of the one-port S -parameter reflection method

- a) This method gives better accuracy and traceability because only coaxial reference impedances are needed for calibration.

- b) This method is more sensitive than transmission for low R_1 crystals, and will give greater measurement speed than two-port S -parameter transmission measurements as the error correction routines are simpler and fewer responses are measured.
- c) It is not very satisfactory for crystals with very high R_1 , although values up to 1 k Ω can be accommodated.
- d) It characterizes the device as a two-terminal component, and this may not be adequate in some applications.
- e) Less accurate at frequencies below 100 kHz.

4.3 *Advantages and disadvantages of the two-port S -parameter transmission method*

- a) The crystal is evaluated as a three-terminal device, and more information is available.
- b) High R_1 crystals are easily measured.
- c) Measurement and calibration are more complex, and some additional uncertainties in the calibration may exist.
- d) The method is less sensitive for low R_1 .
- e) If the measurement frequency range includes the anti-resonance frequency then very accurate values of the static capacitance may be obtained.
- f) Less accurate at frequencies below 100 kHz.

4.4 *Advantages and disadvantages of the direct transmission method*

- a) This method is an extension of the original IEC 444-1 method, but includes full calibration and automation. The basic equipment should already be available.
- b) Large R_1 crystals are easily measured.
- c) The method is less sensitive for small R_1 .
- d) Calibration uses special non-coaxial reference impedances.
- e) Electrode-to-can capacitance C_{01} and C_{03} have to be measured independently if the can is to be earthed, or if the can is floating these are included in C_0 .
- f) The method is fast and is suitable for production.
- g) Accurate at low frequencies.

5 Calibration techniques

5.1 *S-parameter method*

5.1.1 The underlying principle of the calibration procedure lies in a hypothetical error model of the RF measurement system, whose parameters may be determined by measurements on known standards [3]. When the calibration is complete, and the error parameters are known, system errors in actual device measurements may be removed by computation.

5.1.2 The accuracy and traceability of the proposed crystal measurement techniques ultimately rely on the validity of the automatic error correction procedure; annex A gives the equations of the error model and describes suitable calibration procedures.

5.1.3 Any network analyzer capable of performing two-port measurements, as described in this section, is also suitable for one-port measurements; although the converse of this statement is not necessarily true.

5.1.4 The calibration frequency range will depend upon the equipment being used and the application. It should include at least the range of frequencies within which measurements are anticipated. The error terms are generally smooth, slowly varying functions of frequency, and it is only necessary to obtain data at sufficiently closely spaced frequency points to permit accurate interpolation of the functions at any frequency within the range. Given the desired frequency limits, the program should be structured to select automatically the frequencies needed for adequate calibration. In addition to establishing the frequency list, the program shall set up the appropriate instrument settings, including source level, sweep rate, detector bandwidth, number of readings to be averaged (if c.w. mode is selected).

5.2 *Direct transmission method*

The underlying principle of calibration lies in calculating the impedance values of the crystal measurement fixture. This is accomplished using known impedances such as a nominal short, open and standard resistor (25 Ω or 50 Ω). Details are described in annex A.

5.3 *Verification of calibration*

5.3.1 The third important function which should be part of the software system is the capability of making measurements of known components over the entire frequency range of calibration, to verify that the performance of the instrumentation and accuracy of the calibration terms are within required tolerances. Figure 9 is the flowchart of such a program for the *S*-parameter methods. A similar algorithm can be applied to the direct transmission method. Input information to this program should include the frequency range and the number of points for measurement, the drive level at which the measurements are to be made, and the parameters to be output, i.e. transimpedance, transadmittance, input impedance, etc. This program would use the system error terms previously stored by the "calibration" program, and the error correction and parameter conversion routine used by the "measurement" program. The components to be used must be connected to the system at the measurement reference plane.

5.3.2 The verification can be done by measuring the terminations used in the calibration procedure, the short circuits used in calibration or by use of specially prepared components such as R-C networks housed in the same type of enclosures as used for the crystals being measured. With the calibration devices, the measured parameters would be converted to input and output impedances, Z_{11} and Z_{22} , as the transmission with these devices is essentially zero. A device having a series connected R-C between the active pins of a crystal enclosure would provide the Y_{12} (or $Z = 1/Y_{12}$) output. Such components provide a very convenient

verification, but are generally best suited for internal use, as they must be initially calibrated by several measurements made with a well-verified system.

5.3.3 For example, if the verification program is used to measure the standard termination devices used to calibrate the instrument, which would have an impedance of very nearly $50\ \Omega$, and be accurately known, it would be expected that the Z_{11} and Z_{22} values obtained would be within 0,2 % of the correct value, and would have a reactive component less than 0,2 % of the resistive term. If the standard short circuits are measured, Z_{11} and Z_{22} would be expected to give both real and reactive impedance components less than 0,1 Ω .

5.3.4 It is desirable that verification measurements shall not be made at exactly the same frequencies at which calibration measurements were made, so that the accuracy of the interpolation algorithms will also be checked.

5.3.5 Implementations of software systems which provide these functions are commercially available for some of the network analyzer systems offered by instrument manufacturers.

6 Low-frequency measurements

6.1 Measurements at frequencies below 100 kHz present two particular difficulties; first, the impedance level of the resonator may be very high, producing an excessive insertion loss in a $50\ \Omega$ system, and second, the reflectometers in the network analyzer test set may have inadequate directivity at low frequencies.

6.2 It is recommended therefore that the amplitude/phase transmission method be used. For high R_1 devices, it is also recommended that a fixture which presents a high impedance to the crystal terminations be used. To avoid low instrumentation levels, an impedance matching transformer may be required. Should the use of S -parameter methods be desired, annex B outlines some basic details.

7 Admittance analysis and estimation of the equivalent circuit parameters

7.1 General least-squares fitting method

7.1.1 As a general criterion, the values of the equivalent circuit parameters will be defined as those which minimize the function

$$E = \sum_i W_i |Y_i - Y_i^A|^2 = \sum_i W_i ((G_i - G_i^A)^2 + (B_i - B_i^A)^2) \quad (7.1)$$

where $Y_i = G_i + jB_i$ and W_i is a weighting factor.

Y_i denotes the theoretical value of the admittance, Y , computed at the measurement frequency ω_i , and expressed in terms of the parameters G_0 , G_{02} , R_1 , L_1 and C_1 ; Y_i^A represents the measured value of Y at ω_i inferred from the error-corrected S -parameters. Y is essentially the same function for both reflection and transmission measurements, and from now on its parameters will be referred to as G_0 , C_0 , R_1 , L_1 , C_1 . Various possible choices of W_i may be used; if C_0 and G_0 are determined by separate off-resonance measurements then the choice $W_i = 1$ is usually most appropriate; if C_0 is to be estimated from measurements in the vicinity of resonance and it is necessary to ensure that the anti-resonance point is accurately described, then the choice $W_i = |Y_i^A|^{-1}$ should be used.