SLOVENSKI STANDARD
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Measurement of quartz crystal unit parameters - Part 5: Methods for the determination of equivalent analyser techniques and error correction (IEC 60444-5:1995)

Measurement of quartz crystal unit parameters -- Part 5: Methods for the determination of equivalent electrical parameters using automatic network analyzer techniques and error correction

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

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

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Measurement of quartz crystal unit parameters
Part 5: Methods for the determination of equivalent electrical parameters using automatic network analyzer techniques and error correction
(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)

This European Standard was approved by CENELEC on 1997-03-11. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the Central Secretariat has the same status as the official versions.

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

Central Secretariat: rue de Stassart 35, B - 1050 Brussels

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.

Endorsement notice

The text of the International Standard IEC 444-5:1995 was approved by CENELEC as a European Standard without any modification.

Annex ZA (normative)

Normative references to international publications with their corresponding European publications

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies (including amendments).

NOTE: When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
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	-	-

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Partie 5:
Méthodes pour la détermination des paramètres électriques équivalents utilisant des analyseurs automatiques de réseaux et correction des erreurs

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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INTERNATIONAL ELECTROTECHNICAL COMMISSION

MEASUREMENT OF QUARTZ CRYSTAL UNIT PARAMETERS –

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

FOREWORD

1) The IEC (International Electrotechnical Commission) is a world-wide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international cooperation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.

2) The formal decisions or agreements of the IEC on technical matters, prepared by technical committees on which all the National Committees having a special interest therein are represented, express, as nearly as possible, an international consensus of opinion on the subjects dealt with.

3) They have the form of recommendations for international use published in the form of standards, technical reports or guides and they are accepted by the National Committees in that sense.

4) In order to promote international unification, IEC National Committees undertake to apply IEC International Standards transparently to the maximum extent possible in their national and regional standards. Any divergence between the IEC Standard and the corresponding national or regional standard shall be clearly indicated in the latter.

International Standard IEC 444-5 has been prepared by IEC technical committee 49: Piezoelectric and dielectric devices for frequency control and selection.

It forms Part 5 of a series of publications dealing with the measurements of piezoelectric quartz crystal unit parameters.

Part 1: Basic method for the measurement of resonance frequency and resonance resistance of quartz crystal units by zero phase technique in a π-network, is issued as IEC 444-1.

Part 2: Phase offset method for measurement of motional capacitance of quartz crystal units, is issued as IEC 444-2.

Part 3: Basic method for the measurement of two-terminal parameters of quartz crystal units up to 200 MHz by phase technique in a π-network with compensation of parallel capacitance C_0, is issued as IEC 444-3.

Part 4: Method for the measurement of the load resonance frequency f_L, load resonance resistance, R_L and the calculation of other derived values of quartz crystal units, up to 30 MHz, is issued as IEC 444-4.

Part 6: Measurement of drive level dependence (DLD), is issued as IEC 444-6.

The text of this standard is based on the following documents:

DIS	Report on voting
49(CO)248	49(CO)268

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

Annex A forms an integral part of this standard.

Annexes B and C are for information only.

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

$\omega_s = \dfrac{1}{(L_1 C_1)^{1/2}}$ 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}.

$$R_0 Y = \frac{1 - S_{11}}{1 + S_{11}} \tag{2.1}$$

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

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* 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:

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

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

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

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.

$$Y = G_0 + j\omega C_0 + \frac{1}{R_1 + j\omega L_1 + 1/\,j\omega C_1} \tag{2.4}$$

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.

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 (±45°).

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 ±45° 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 Ω. 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 ± 0,05), f_s (1 ± 0,06) and f_s (1 ± 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