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Measurement of quartz crystal unit parameters -
Part 11: Standard method for the determination of the load resonance frequency f_L and the effective load capacitance C_{Leff} using automatic network analyzer techniques and error correction

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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition IEC 60444-11:2010. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

IEC 60444-11 has been prepared by IEC technical committee 49: Piezoelectric, dielectric and electrostatic devices and associated materials for frequency control, selection and detection. It is an International Standard.

This second edition cancels and replaces the first edition published in 2010. This edition constitutes a technical revision.

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

a) key content of withdrawn IEC TR 60444-4 is reproduced as Annex A;

b) some formulae in the first edition have been corrected.

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

Draft	Report on voting
49/1489/CDV	49/1515/RVC

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.

A list of all parts in the IEC 60444 series, published under the general title *Measurement of quartz crystal unit parameters*, 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– withdrawn, or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.

INTRODUCTION

This part of IEC 60444 defines the measuring method of load resonance frequency f_L using automatic network analyzer techniques.

At the same time, even though IEC TR 60444-4 [8][1] specifying the manual measuring method has been withdrawn, the main contents of the manual measuring method remain as Annex A for the user's convenience. However, in case of dispute, the standard method as described below should be used as reference.

The figure of merit M, according to IEC 60122-1:2002, Table 1, is expressed in the following formula:

$$M = \frac{Q}{r} = \frac{1}{\omega C_0 R_1} \tag{1}$$

This gives good results in a frequency range up to 200 MHz. This method allows the calculation of load resonance frequency offset Δf_L, frequency pulling range Δf_{L1}, Δf_{L2} and pulling sensitivity S as described in IEC 60122-1:2002, 2.2.31. In contrary to the simple method of IEC 60444-4, This measurement technique avoids the use of physical load capacitors, and allows higher accuracy, better reproducibility and correlation to the application. It extends the upper frequency limit from 30 MHz by the manual method of IEC 60444-4 to 200 MHz approximately. This method is based on the error-corrected measurement technique of IEC 60444-5:1995 [9] and therefore allows the measurement of f_L and C_{Leff} together with the determination of the equivalent crystal parameters in one sequence without changing the test fixture.

With this method the frequency f_L is searched where the reactance X_C of the crystal has the opposite value of the reactance of the load capacitance.

$$X_C = -X_{CL} = \frac{1}{\omega_L C_L} \tag{2}$$

Furthermore, this method allows to determine the effective load capacitance C_{Leff} at the nominal frequency f_{nom}.

[1] Numbers in square brackets refer to the Bibliography.

1 Scope

This part of IEC 60444 defines the standard method of measuring load resonance frequency f_L at the nominal value of C_L, and the determination of the effective load capacitance C_{Leff} at the nominal frequency for crystals with the figure of merit $M > 4$.

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 60122-1:2002, *Quartz crystal units of assessed quality - Part 1: Generic specification*
IEC 60122-1:2002/AMD1:2017

IEC 60444-1:1986, *Measurement of quartz crystal unit parameters by zero phase technique in a pi-network - Part 1: Basic method for the measurement of resonance frequency and resonance resistance of quartz crystal units by zero phase technique in a pi*-network
IEC 60444-1:1986/AMD1:*1999*

~~IEC/TR 60444-4, *Measurement of quartz crystal unit parameters by zero phase technique in a π-network – 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*~~

~~IEC 60444-5:1995, *Measurement of quartz crystal units parameters – Part 5: Methods for the determination of equivalent electrical parameters using automatic* network *analyzer techniques and error correction*~~

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60122-1 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

4 General concepts

4.1 Load resonance frequencies f_{Lr} and f_{La}

As can be seen in Figure 1, there are two intersection frequencies where $X_C = -X_{CL}$, f_{Lr} with high admittance (low impedance) and f_{La} with low admittance (high impedance).

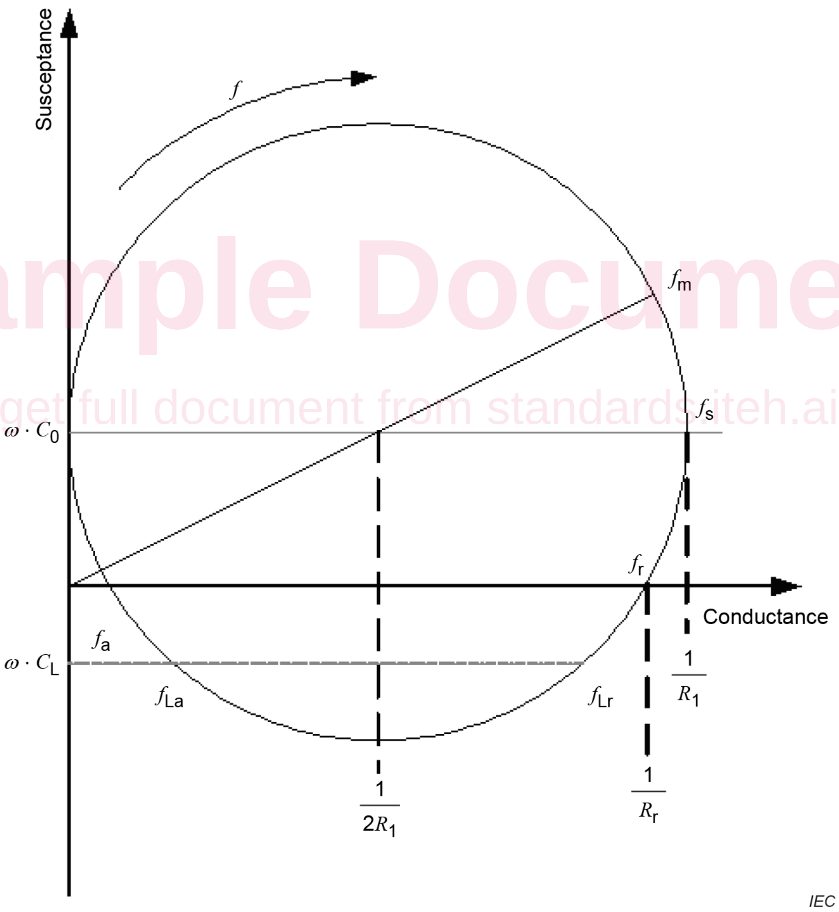
The load resonant frequency f_L is one of the two frequencies of a crystal unit in association with a series or with a parallel load capacitance, at which the electrical admittance (respectively impedance) of the combination is resistive. The load resonance frequency f_L is the lower of the two frequencies.

In a first approximation f_L can be calculated by:

$$\frac{1}{f_L} \approx 2\pi \sqrt{\frac{L_1 C_1 (C_0 + C_L)}{C_1 + C_0 + C_L}} \quad (3)$$

$$f_S = \frac{1}{2\pi\sqrt{L_1 C_1}} \quad (3)$$

$$f_L \approx f_S \cdot \left(1 + \frac{C_1}{2 \cdot (C_0 + C_L)}\right) \quad (4)$$



NOTE f_{Lr} is the load resonance frequency that is commonly expressed as f_L.

Figure 1 – Admittance of a quartz crystal unit

4.2 Effective load capacitance C_{Leff}

C_{Leff} is defined by the reactance of the crystal at the nominal frequency:

$$C_{Leff} = \frac{1}{\omega_{nom} X_C(\omega_{nom})} \tag{5}$$

5 Reference plane and test conditions

5.1 General

Reference plane: as in IEC 60444-5:1995 [9], 8.4.

Test conditions: crystal case not grounded.

Level of drive: the output level of the generator is set, such that at its (series) resonance frequency, the crystal under test is measured at the nominal drive level.

The measurement at the load resonance frequency using the method described below leads to a level of drive, which is remarkably lower than at the (series) resonance frequency due to the relative high reactance value. Therefore, a correction measurement is performed; for details see 5.2.

5.2 Principle of measurement

The principles of measurement are the following.

a) Calibration

Due to the high impedance measurements with this method special care has to be taken in the calibration of the test set-up.

As specified in IEC 60444-5~~:1995~~ [9], use the following three known calibration elements:

1) short-circuit (0 Ω) or resistor with low resistance;
2) resistor of 25 Ω or 50 Ω nominal;
3) open circuit (infinite resistance) or capacitor of 10 pF nominal.

b) Calibration with three known calibration elements:

1) short-circuit calibration;
2) calibration load (25 Ω or 50 Ω);
3) open circuit calibration (or calibration capacitor of 10 pF)

$$R_T = \frac{Z_1 Z_2 (V_1 - V_2) + Z_2 Z_3 (V_2 - V_3) + Z_3 Z_1 (V_3 - V_1)}{Z_1 (V_2 - V_3) + Z_2 (V_3 - V_1) + Z_3 (V_1 - V_2)} \tag{6}$$

$$V_s = \frac{V_3 Z_1 Z_2 (V_1 - V_2) + V_1 Z_2 Z_3 (V_2 - V_3) + V_2 Z_3 Z_1 (V_3 - V_1)}{Z_1 Z_2 (V_1 - V_2) + Z_2 Z_3 (V_2 - V_3) + Z_3 Z_1 (V_3 - V_1)} \tag{7}$$

$$V_o = \frac{Z_1V_1(V_2 - V_3) + Z_2V_2(V_3 - V_1) + Z_3V_3(V_1 - V_2)}{Z_1(V_2 - V_3) + Z_2(V_3 - V_1) + Z_3(V_1 - V_2)} \quad (8)$$

where

Z_1 is the impedance of calibration element 1;

Z_2 is the impedance of calibration element 2;

Z_3 is the impedance of calibration element 3;

V_1 is the measured voltage with calibration element 1;

V_2 is the measured voltage with calibration element 2;

V_3 is the measured voltage with calibration element 3.

The following parameters are then used for the measurement of quartz crystal units:

R_T is the termination impedance of the π-network;

V_s is the error-corrected "short" voltage;

V_o is the error-corrected "open" voltage.

NOTE 1 If Z_3 is taken as infinite number (ideal open circuit), the result of Formulae (6), (7) and (8) is not ~~allowed divisions of infinite by infinite~~ applied.

c) Measurement of a quartz crystal unit impedance Z_c

From the measured voltage with a quartz crystal unit V_c, the impedance Z_c of the quartz crystal unit is calculated with:

$$Z_c = R_T \frac{(V_S - V_C)}{(V_C - V_0)} \quad (9)$$

d) Measurement procedure for f_L

At load resonance frequency, the impedance of a quartz crystal unit is

$$Z_{CL} = R_L + jX_C \quad (10)$$

For the determination of the load resonance frequency, the frequency f_L the lower frequency is searched for which Formula (2) is fulfilled, i.e.

$$X_C + X_{CL} = 0 \quad (11)$$

With network analyzers, the frequency f_L is easily determined ~~by using «marker search». functions~~.

e) Evaluation of R_L

The computation of the load resonance resistance R_L from the real part of Z_c at the load resonance frequency f_L by the formula:

$$R_L = R_C(\omega_L) = R_e(Z_c(\omega_L)) \quad (12)$$

~~may~~ can result in excessive inaccuracy, because – especially for low frequency crystals – the angle of the voltage V_c is close to 90°.

Only for $\frac{X_{CL}}{R_L} < 10$ this method yields reasonable results.

In all other cases, the R_L should be computed from the formula given in IEC 60122-1:

$$R_L = R_1\left(1+\frac{C_0}{C_L}\right)^2 \quad (13)$$

f) Measurement procedure for C_{Leff}

The reactance $X_C(\omega_{nom})$ is measured at the nominal frequency and the effective load capacity C_{Leff} is then calculated with the following formula:

$$C_{Leff} = \frac{1}{\omega_{nom} X_C(\omega_{nom})} \quad (14)$$

Figure 2 shows X_C as a function of frequency (solid line) in the vicinity of f_L.

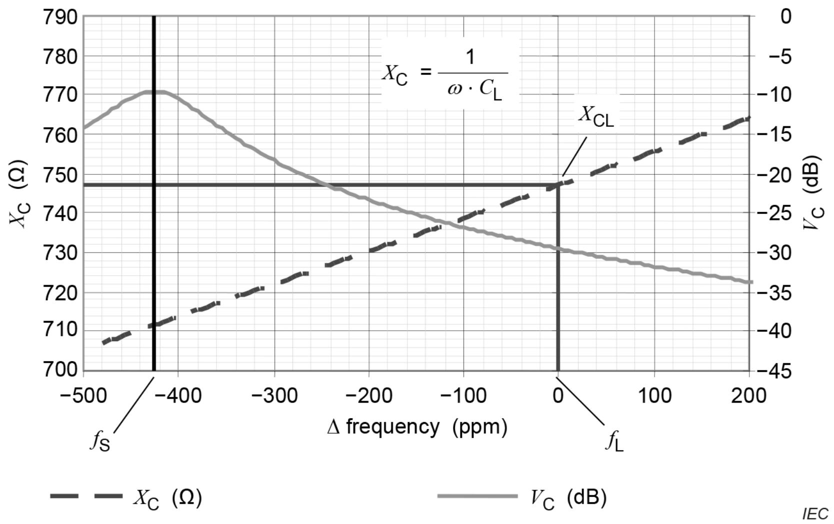


Figure 2 – X_C as a function of frequency (solid line) in the vicinity of f_L

g) Level of drive

At the resonance frequency f_r, the level of drive P of a quartz crystal unit in a π-network is given by the voltage V_{xr} across the crystal

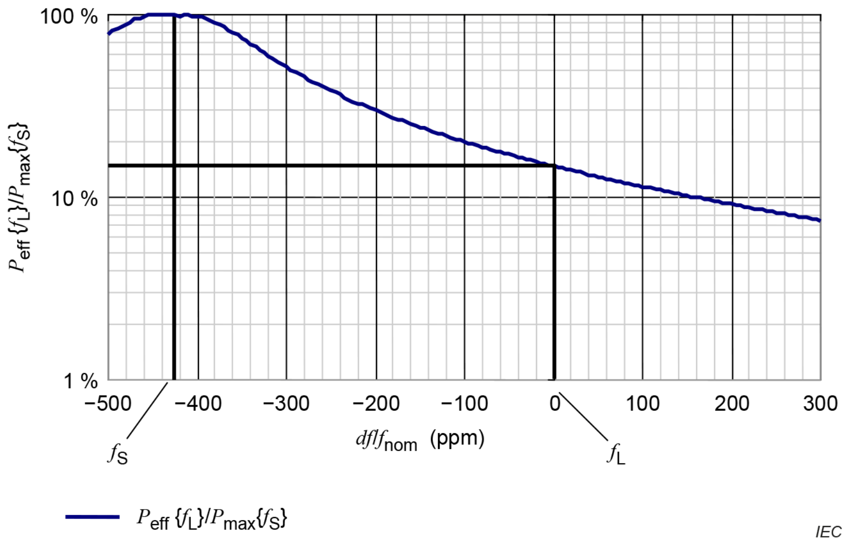


Figure 3 – P_{eff} as level of drive of a crystal in a π-network versus df/f_{nom} as frequency

with

$$P = \frac{V_{xr}^{2}}{R_r} \tag{15}$$

and

$$V_{xr} = \frac{V_g R_r}{R_r + R_T} \tag{16}$$

where

V_g is the voltage with measured element.

$$V_g = \sqrt{P R_r}\,\frac{R_r + R_T}{R_r} \tag{17}$$

At load resonance frequency f_L, the impedance Z_L of a quartz crystal unit is given by the load resonance resistance R_L and the modulus of the reactance of the load capacitor X_L:

$$|Z_L| = \sqrt{R_L^{2} + X_L^{2}} \tag{18}$$

and, therefore, the drive level is

$$P = \frac{{V_{Xr}}^2}{Z_L} \tag{19}$$

~~$$V_{gL} = \sqrt{P \cdot R_1} \cdot \sqrt{\frac{{X_{CL}}^2\left(1 + {X_{CL}}^2 + (R_L + R_T)^2\right)^2 + {R_L}^2\left((R_L + R_T)^2 - 1\right)}{{R_L}^2 + {X_{CL}}^2}} \tag{18}$$~~

$$V_{gL} = \sqrt{\frac{P\left((R_L + R_T)^2 + {X_{CL}}^2\right)}{R_L}} \tag{20}$$

In order to get the same level of drive at the load frequency f_L as at the series resonance frequency f_S, it is necessary to increase the output power of the generator by the ratio:

$$ABS\left[\frac{V_{gL}}{V_{gr}}\right] = \sqrt{\frac{R_r}{R_L}} \frac{\sqrt{(R_L + R_T)^2 + {X_{CL}}^2}}{R_r + R_T} \tag{21}$$

NOTE 2 If the required power cannot be reached by the generator, a second measurement at resonance frequency f_r is performed ~~with a by factor~~ by the ratio $ABS\left(\frac{V_{gL}}{V_{gr}}\right)$ lower level and the difference of both series resonance measurements is added to the load resonance frequency f_L.

5.3 Evaluation of errors

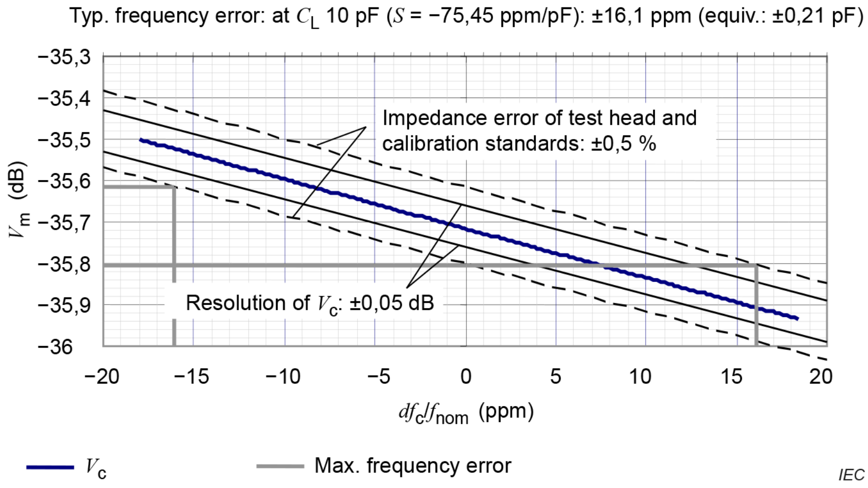
5.3.1 General comments

According to the application of quartz crystal units in oscillators, the measurement accuracy of the load resonance frequency f_L is presented here. The accuracy of the load capacitance C_{Leff} can be calculated then from the frequency accuracy and the equivalent parameters of the crystal C_0 and C_1 from the relation

$$\frac{f_L - f_S}{f_S} = \frac{C_1}{2(C_0 + C_L)} \tag{22}$$

5.3.2 Accuracy of measurement

The accuracy of the measurement is given by the calibration resistors and the measured voltages. In order to achieve an accuracy of the voltages of 1 %, it ~~may~~ can be necessary to calibrate the test equipment in the whole power range.



NOTE Example for a quartz crystal 11 MHz in HC-49/U package.

Figure 4 – Error of the load resonance frequency due to the inaccuracy of the measured voltages (dashed line) and the calibration resistances (soft line)

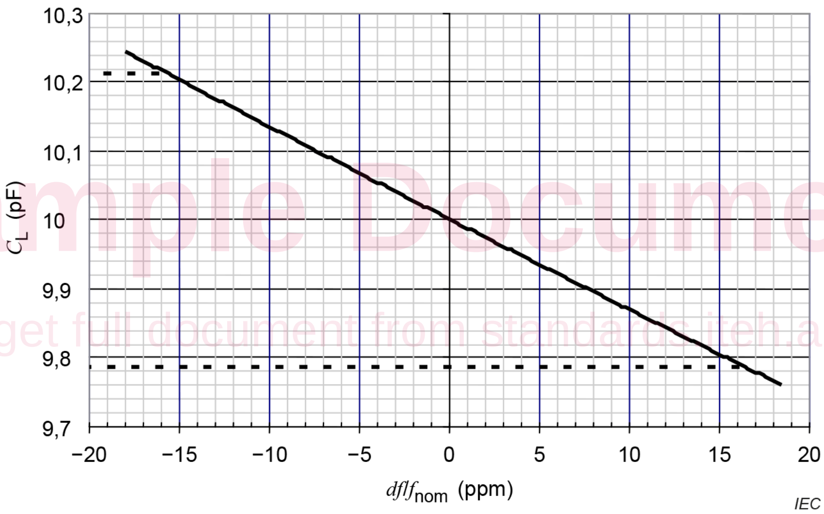


Figure 5 – ~~C_L-error resulting from f_L error (due to inaccuracy of the measured voltages and the calibration resistances)~~ Error of the load resonance frequency due to the change of the setting C_L for the same crystal as in Figure 4

5.3.3 Reproducibility

Since the determination of the load frequency is based on a voltage measurement, the reproducibility of the f_L measurement is influenced by noise. Figure 6 shows the error of the load resonance frequency due to noise of V_C as the measured voltages. And Figure 7 shows the error of load resonance frequency F_L at different C_L for typical equivalent parameters of quartz crystal units for better reproducibility.

Depending on the level of the expected voltage the measured noise is directly proportional to the evaluated frequency.

To increase the accuracy it is recommended to use smaller bandwidths of intermediate frequency (IF) filters of the used measurement equipment and to use an averaged signal.