Sensors & Transducers, Vol. 237, Issue 9-10, September-October 2019, pp. 171-177

Sensors & Transducers

Published by IFSA Publishing, S. L., 2019
http://www.sensorsportal.com

Features of Calibration of Precision LCR Meters

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Received: 30 August 2019 /Accepted: 27 September 2019 /Published: 30 November 2019

Abstract: The features of estimation of the measurement uncertainty at calibration of LCR-meters of precision on the State primary standard of units of inductance and tangent of loss angle, as well as on the State primary standard of units of electric capacitance and factor of loss are presented. The general approaches to calibration of LCR meters and equations (models) of measurements during calibration are presented, as well as details of the calculations of uncertainty of measurements of active resistance, inductance and electrical capacitance for calibration of LCR meters using standard measures. The factors that influence the result of measurements of electrical quantities are considered. The approaches to uncertainty estimation allow calibration of a wide range of LCR meters across a wide frequency range and range of values, and will help create a unified approach to identifying the main components of the measurement model, the uncertainty budget, and the design of calibration results. The materials can be used by laboratories that perform the calibration, testing and conformity assessment of the electromagnetic measuring equipment. The research materials can also be used in conducting international comparisons of reference standards of national metrological institutes and interlaboratory comparisons of measurement results. The research results will help to organize the metrological provision of impedance parameter measurements in many fields of science and technology.

Keywords: Uncertainty budget, Measurement, Standard, Calibration, LCR meter, Uncertainty estimation.

1. Introduction

One of the most important tasks for all fields of science and technology involved in the use of electrical measurements is the measurement of inductance, capacitance and active resistance across a wide range of frequencies and values.

The high accuracy and traceability of impedance parameter measurements is essential in such fields as electrical engineering, electronics, machine tools, instrumentation, construction, transportation, telecommunications, metallurgy, mechanical and aeronautical industries, security, and research and defense [1-4].

Currently, a large number of high-precision reference and impedance measuring instruments are widely used, namely: precision Keysight (Agilent) E4980 AL LCR meters of various modifications, IET/QuadTech 7600 Plus, GW INSTEK LCR-6300, Applent Instruments AT810A, MHC-1100 and MOE-1200, etc. Combined devices and multimeters have become the most widely used in the creation, commissioning and operation of various electronic equipment. They require calibration over a wide frequency range and range of values of inductance, electrical capacitance, active resistance.

The purpose of the research is to develop methods of calibration of LCR-meters of precision and other impedance parameter meters, as well as to create a unified approach to determining the main components of the measurement model, uncertainty budget and design of calibration results [5].

2. The Main Content of the Research

The vast majority of calibrated precision LCR meters have the following metrological characteristic:

- Measurement ranges at the fundamental frequency of 1 kHz;
- Active resistance R from 1·10E-5 to 1·10E11 Ohms;
- Electrical capacitance C from 1·10E-17 to 10 F;
- Inductance L from 1·10E-10 to 1·10E8 H;
- Loss tangent tgδ from ± 1·10E-6 to ± 1;
- Operating frequency range from 0.5 to 1000000 Hz;
- The extended relative uncertainty of measurement of specified parameters at the fundamental frequency and at direct current depending on the range is from 1·10E-3 to 1·10E-5.

Calibration of precision LCR meters in Ukraine is performed with the help of highly stable measures of inductance, electrical capacity and active resistance, which are part of the State primary standard of units of inductance and loss tangent, as well as of State primary standard of units of electric capacity and factor of losses.

These measures have metrological traceability to international standards on fundamental physical constants by calibration or participation in international intelligence [6-13].

Before calibrating the LCR meter, the operating frequency, the measuring voltage, and its automatic self-calibration are set. The LCR meter controls must specify a substitution (capacitance/inductance, parallel/consequent) circuit for the measurement object. If the circuit is incorrectly selected, the overriding value of the main parameter being measured may be very different from the true values.

Before connecting to a LCR meter for a reactive measurements object must be discharged – shorten the contacts for a few seconds. As a rule, the calibration of LCR meters is carried out in terms of: active resistance, electric capacitance and inductance. Sometimes customers who need to use the LCR meter in the most accurate measurements require calibration at operating frequency and loss angle tangent.

2.1. Calibration of LCR Meter for Active Resistance Measurements

For calibration of the LCR-meter for active resistance measurements, use standard measures from the set of MAC-2 with nominal values of 0.1 Ohm, 1 Ohm, 10 Ohm, 100 Ohm, 1 kOhm, 10 kOhm, P4015 with nominal value 100 kOhm, P4016 with nominal value 1 MOhm, P4022M1 with nominal value 10 MOhm. The measurement scheme is shown in Fig. 1.

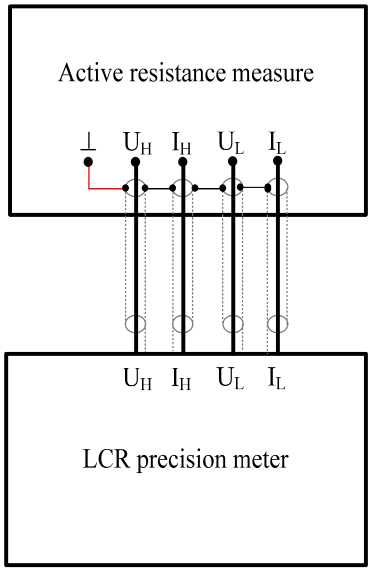

Fig. 1. Scheme for active resistance measurements for calibration of LCR-meter.

For active resistance measurements, the choice of an equivalent substitution scheme is carried out by investigating the dependence of the phase angle tangent $tg\varphi$ on the frequency of the working signal f.

If $tg\varphi < 0$, then the substitution scheme is capacitive. If, with increasing frequency f, the modulus of the phase angle tangent tgφ increases, then the substitution scheme is parallel, if it decreases, it is consistent.

If $tg\varphi > 0$, then the substitution scheme is inductive. If, with increasing frequency f, the tangent modulus of the phase angle $tg\varphi$ increases, the substitution scheme is sequential, if it decreases, it is parallel.

For calibration, n independent measurements of the resistance R_S are reproduced; this is reproduced by a reference measure. The LCR meter reads the average $\overline{R}_{LCR}$.

The equation (model) of measurements has the following form:

$$\begin{aligned}\Delta R_{LCR} = \overline{R}_{LCR} - R_S + \Delta R_{Sf} + \Delta R_{S\gamma} + \\ + \Delta R_{QLCR} + \Delta R_{ST} + \Delta R_{TLCR} + \Delta R_l\end{aligned}, \quad (1)$$

where ΔR_{LCR} is the deviation of readings of LCR meter being calibrated from the true value of the active resistance reproduced by the reference measure; $\overline{R}_{LCR}$ is the mean of the active resistance displayed on the screen of the LCR meter with n measurements of active resistance of the reference measure; R_S is the value of the active resistance of the reference measure from the calibration certificate; ΔR_{Sf} is correction for frequency dependence of the reference measure of active resistance; $\Delta R_{S\gamma}$ is correction to drift of the reference measure of active resistance since the last calibration; ΔR_{QLCR} is correction for the quantization error (sampling) of LCR meter being calibrated; ΔR_{ST} is correction for the temperature dependence of the reference measure; ΔR_{TLCR} is correction for the temperature dependence of calibrated LCR meter for the active resistance measurements; ΔR_l is correction for spurious active resistance of connecting cables and contacts.

Based on this measurements model, an example of calculating the uncertainty budget for calibration of LCR meter for active resistance measurements with using a reference measure of 100 Ohms at a frequency of 1 kHz may have the form shown in Table 1.

Table 1. The uncertainty budget for the active resistance measurements of a reference measure of 100 Ohms at 1 kHz for calibration of LCR meter.

Quantity X_i, *Ohm*	Estimate x_i, *Ohm*	Standard uncertainty $u(x_i)$, *Ohm*	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$, *Ohm*
$\overline{R}_{LCR}$	99.9989	1.45E-04	Normal	A	1	1.45E-04
R_S	99.9977	1.75E-05	Normal	B	-1	-1.75E-05
ΔR_{Sf}	-0.0461	1.10E-05	Normal	B	1	1.10E-05
$\Delta R_{S\gamma}$	0.00001	1.00E-05	Normal	B	1	1.00E-05
ΔR_{QLCR}	0	5.77E-05	Rectang.	B	1	5.77E-05
ΔR_{ST}	0	5.00E-05	Rectang.	B	1	5.00E-05
ΔR_{TLCR}	0	1.00E-04	Rectang.	B	1	1.00E-04
ΔR_l	0	1.00E-04	Normal	B	1	1.00E-04
ΔR_{LCR}	0.0012					
		Combined standard uncertainty				2.17E-04
		Effective degrees of freedom			n_{eff}	>200, k = 2
		Expanded uncertainty (p ≈ 95 %)				4.34E-04

Type A standard uncertainty associated with a random component of the estimate is determined by the formula:

$$u_A\left(R_{LCR}\right) = \sqrt{\left(\frac{1}{n(n-1)}\right)\sum_{j=1}^{n}(R_{LCRi}-\overline{R}_{LCR})^2} \quad (2)$$

The total standard uncertainty of the of active resistance measurements for calibrating of LCR meter is calculated by the formula:

$$u_\Sigma\left(\Delta R_{LCR}\right) = \sqrt{u_A^2\left(R_{LCR}\right)+\sum_{i=1}^{N}u_{Bi}^2\left(\Delta R_{LCR}\right)} \quad (3)$$

Extended uncertainty with coverage factor $k = 2$ and confidence probability $p \approx 95$ %:

$$U = k\cdot u_\Sigma\left(\Delta R_{LCR}\right) = 2\cdot u_\Sigma\left(\Delta R_{LCR}\right) \quad (4)$$

It will be noted that the above calibration results correspond to only one measurement point – 100 Ohms at a frequency of 1 kHz. At the same time, the calibration of the meter, which is also LCR meter, must be carried out in the full range of frequencies and values. The only exception is when the calibration range is narrowed at the request of the customer.

Therefore, calibration will be performed at several points (at least three) of each sub-band. It is advisable to give the result of the calibration as a graph depicting the deviation of the LCR meter's readings from the true value of the measured value with its associated measurement uncertainty.

The graph is obtained by approximating the calibration results at the corresponding calibration points. In areas where there may be extremes of the graph, or significant nonlinearity, the number of calibration points should be increased.

2.2. Calibration of LCR Meter for Electrical Capacitance Measurements

For calibration of the LCR-meter for electrical capacitance measurements, the standard thermostatic measures of the Andeen-Hagerling type AH11A of 10 pF and 100 pF from the State primary standard of units of capacitance and loss factor, thermostated capacitance store and resistances, and capacities are used as standard. P597 rated at 1 pF, 10 pF, 100 pF and others. The measurement scheme is shown in Fig. 2.

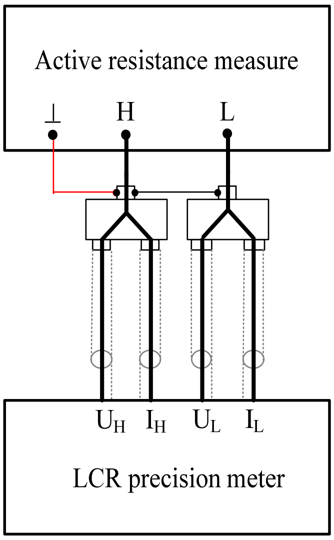

Fig. 2. Scheme for electrical capacitance measurements for calibration of LCR meter.

For capacitance measurements by LCR meter, the choice of an equivalent substitution scheme is carried out by research the dependence of the loss angle *tgδ* on the frequency *f*. If, with increasing frequency *f*, the loss tangent modulus *tgδ* increases, then the replacement scheme is sequential, if it decreases, it is parallel.

For example, consider the calibration of an LCR meter for electric capacitance measurements using a 100 pF Andeen-Hagerling type AH11A-type thermostatized reference electrical capacitance standard.

The equation (model) of measurements has the following form:

$$\Delta C_{LCR} = \bar{C}_{LCR} - C_S + \Delta C_{Sf} + \Delta C_{S\gamma} + \\ + \Delta C_{QLCR} + \Delta C_{ST} + \Delta C_{TLCR} + \Delta C_l \quad , \tag{5}$$

where ΔC_{LCR} is the deviation of the readings of LCR meter being calibrated from the true value of the inductance reproduced by the reference measure; $\bar{C}_{LCR}$ is the average value of capacitance displayed on the screen of LCR-meter for the capacitance measurements of the reference measure; C_S is the value of the reference measure capacitance from the calibration certificate; ΔC_{Sf} is correction of frequency dependence of the reference measure of capacitance; $\Delta C_{S\gamma}$ is correction to drift of the reference capacity measure since the last calibration; ΔC_{QLCR} is correction for the quantization error of LCR meter being calibrated; ΔC_{ST} is correction for the temperature dependence of the reference measure; ΔC_{TLCR} is correction for the temperature dependence of the calibrated LCR meter; ΔC_l is correction for spurious capacitance of connecting cables and contacts.

Based on this measurement model, an example of calculating the uncertainty budget for calibration of LCR meter for capacitance measurements with using a reference measure of 100 pF at a frequency of 1 kHz may have the form shown in Table 2.

Type A standard uncertainty associated with a random component of the estimate C_{LCR} is determined by the formula:

$$u_A\left(C_{LCR}\right) = \\ = \sqrt{\left(\frac{1}{n(n-1)}\right)\sum_{j=1}^{n}(C_{LCRi} - \bar{C}_{LCR})^2} \tag{6}$$

The total standard uncertainty of the capacitance measurements for calibration of LCR meter is calculated by the formula:

$$u_\Sigma\left(\Delta C_{LCR}\right) = \\ = \sqrt{u_A^2\left(C_{LCR}\right) + \sum_{i=1}^{N} u_{Bi}^2\left(\Delta C_{LCR}\right)} \tag{7}$$

Extended uncertainty with coverage factor $k = 2$ and confidence probability $p \approx 95$ %:

$$U = k \cdot u_\Sigma\left(\Delta C_{LCR}\right) = 2 \cdot u_\Sigma\left(\Delta C_{LCR}\right) \tag{8}$$

2.3. Calibration of LCR Meter for Electrical Inductance Measurements

For calibration of the LCR-meter for electrical inductance measurements, the standard thermostatized measures of inductance P5113 of the State primary standard of units of inductance and loss tangent of nominal 1 mH, 10 mH, 100 mH, and reference measures P593, P596, P5101 with a value from 0.01 μH to 100 mH and others. Diagrams of measurements at 2-pin and 3-pin connection are shown in Fig. 3 and Fig. 4.

Table 2. The uncertainty budget for the electrical capacitance measurements of a reference measure of 100 pF at 1 kHz for calibration of LCR meter.

Quantity X_i	Estimate x_i, pF	Standard uncertainty $u(x_i)$, pF	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$, pF
$\overline{C}_{LCR}$	100.00008	1.47E-05	Normal	A	1	1.47E-05
C_S	100.00014	4.00E-05	Normal	B	-1	-4.00E-05
ΔC_{Sf}	0.00008	1.00E-05	Normal	B	1	1.00E-05
$\Delta C_{S\gamma}$	-0.00001	4.00E-05	Normal	B	1	4.00E-05
ΔC_{QLCR}	0	5.77E-05	Rectang.	B	1	5.77E-05
ΔC_{ST}	0	1.90E-04	Rectang.	B	1	1.90E-04
ΔC_{TLCR}	0	1.00E-04	Rectang.	B	1	1.00E-04
ΔC_l	0	1.00E-04	Normal	B	1	1.00E-04
ΔC_{LCR}	-0.00007					
		Combined standard uncertainty				2.51E-04
		Effective degrees of freedom			n_{eff}	>200, k = 2
		Expanded uncertainty (p ≈ 95 %)				5.01E-04

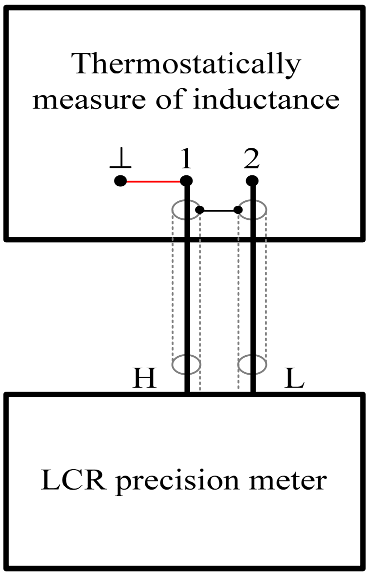

Fig. 3. Scheme for inductance measurements for calibration of LCR-meter (2-pin connection).

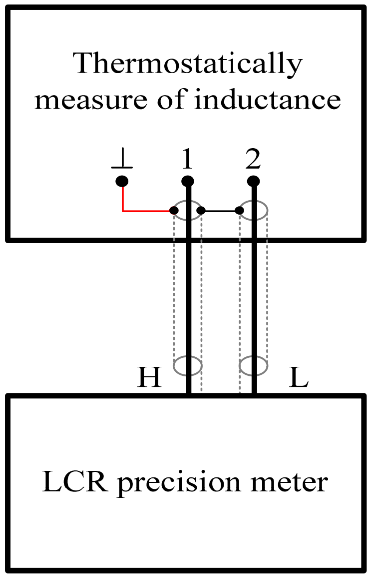

Fig. 4. Scheme for inductance measurements for calibration of LCR-meter (3-pin connection).

For inductance measurement by LCR meter, the choice of an equivalent substitution scheme is made by investigating the dependence of the loss tangent *tgδ* on the frequency *f*. If, with increasing frequency *f*, the loss tangent modulus *tgδ* increases, then the substitution scheme is parallel, if it decreases, it is consistent.

For example, consider the calibration of LCR meter for inductance measurements with using the thermostated precision standard 100 mH of P5113 [14].

The equation (model) of measurements has the following form:

$$\Delta L_{LCR} = \overline{L}_{LCR} - L_S + \Delta L_{Sf} + \Delta L_{S\gamma} + \\ + \Delta L_{QLCR} + \Delta L_{ST} + \Delta L_{TLCR} + \Delta L_l , \quad (9)$$

where ΔL_{LCR} is the deviation of the readings of LCR meter being calibrated from the true value of the inductance reproduced by reference measure; $\overline{L}_{LCR}$ is the average value of the inductance displayed on the screen of LCR meter for inductance measurements of reference measure; L_S is the value of inductance of the reference measure from the calibration certificate; ΔL_{Sf} is correction for frequency dependence of the standard measure of inductance; $\Delta L_{S\gamma}$ is correction to drift of the reference measure of inductance since the last calibration; ΔL_{QLCR} is correction for the quantization error of the LCR meter being calibrated; ΔL_{ST} is correction for the temperature dependence of reference measure; ΔL_{TLCR} is correction for the temperature dependence of the calibrated LCR meter; ΔL_l is correction for spurious inductance of connecting cables and contacts.

Based on this measurements model, an example of calculating the uncertainty budget for calibration an LCR meter for inductance measurements with using a reference measure of 100 mH at 1 kHz may be as shown in Table 3.

Table 3. The uncertainty budget for the electrical capacitance measurements of a reference measure of 100 mH at 1 kHz for calibration of LCR meter.

Quantity X_i	Estimate x_i, mH	Standard uncertainty $u(x_i)$, mH	Probability distribution	Method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$, mH
$\overline{L}_{LCR}$	100.1100	3.52E-04	Normal	A	1	3.52E-04
L_S	100.0082	4.00E-04	Normal	B	-1	-4.00E-04
ΔL_{Sf}	0.0001	1.00E-05	Normal	B	1	1.00E-05
$\Delta L_{S\gamma}$	0	1.10E-05	Normal	B	1	1.10E-05
ΔL_{QLCR}	0	5.77E-05	Rectang.	B	1	5.77E-05
ΔL_{ST}	0	3.60E-05	Rectang.	B	1	3.60E-05
ΔL_{TLCR}	0	1.00E-04	Rectang.	B	1	1.00E-04
ΔL_l	0	1.00E-04	Normal	B	1	1.00E-04
ΔL_{LCR}	0.1018					
		Combined standard uncertainty				5.56E-04
		Effective degrees of freedom			n_{eff}	>200, k = 2
		Expanded uncertainty (p ≈ 95 %)				1.11E-03

Type A standard uncertainty associated with a random component of the estimate L_{LCR} is determined by the formula:

$$u_A(L_{LCR}) = \sqrt{\left(\frac{1}{n(n-1)}\right)\sum_{j=1}^{n}(L_{LCRi}-\overline{L}_{LCR})^2} \quad (10)$$

The total standard uncertainty of inductance measurements for calibration of LCR meter is calculated by the formula:

$$u_\Sigma(\Delta L_{LCR}) = \sqrt{u_A^2(L_{LCR}) + \sum_{i=1}^{N} u_{Bi}^2(\Delta L_{LCR})} \quad (11)$$

Extended uncertainty with coverage factor $k = 2$ and confidence probability $p \approx 95$ %:

$$U = k \cdot u_\Sigma(\Delta L_{LCR}) = 2 \cdot u_\Sigma(\Delta L_{LCR}) \quad (12)$$

For calibration of LCR meter, the results of measurements and the uncertainty budget are calculated in the same order by such values as operating frequency *f*, phase angle *tgφ*, loss angle *tgδ*, and other impedance parameters.

3. Conclusions

As a result of the conducted researches the method of calibration of LCR-meters on the State primary standard of units of inductance and tangent of loss angle and the State primary standard of units of electric capacitance and factor of loss was developed. The technique fully enables the calculation of calibration results and the uncertainty budget for the calibration of LCR meters, multimeters, and combined devices by such values as inductance, electrical capacitance, and active resistance over the full frequency range and values.

In order to achieve high accuracy of impedance parameter measurements, it is of great importance to choose an equivalent circuit (capacitance/ inductance, parallel/consequent) for the measurement object.

For active resistance measurements by LCR meter, the choice of an equivalent substitution scheme is carried out by studying the dependence of the phase angle tangent tgφ on the frequency of the working signal f, and for electrical capacitance or inductance measurements are depending on the frequency f the tangents of the loss angle tgδ.

Uncertainty estimation approaches can be used in conducting international reconciliation of reference standards of national metrology institutes and interlaboratory comparisons of measurement results. The research results will help to organize the metrological provision of impedance parameter measurements in all fields of science and technology.

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