METROLOGICAL TRACEABILITY OF IMPEDANCE PARAMETER MEASUREMENTS IN UKRAINE

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Встановлено ступені еквівалентності національного еталону одиниці електричної ємності для номіналів 10 пФ і 100 пФ на частотах 1 кГц і 1,592 кГц і розширені невизначеності, отримані за результатами міжнародних звірень національних еталонів одиниць електричної ємності, та проведено їх порівняльний аналіз. Встановлено ступені еквівалентності національного еталону одиниці індуктивності для номіналів 10 мГн і 100 мГн на частоті 1 кГц і розширені невизначеності, отримані за результатами міжнародних додаткових звірень національних еталонів одиниць індуктивності, та проведено їх порівняльний аналіз. Звірення проведені регіональними метрологічними організаціями за участі національного метрологічного інституту України.

Проведено аналіз застосованих у звітах про звірення методів оброблення даних з метою адекватного оцінювання результатів, отриманих кожним з учасників звірень. Результати національного метрологічного інституту України стали основою для встановлення метрологічної простежуваності вимірювань параметрів імпедансу в країні та визнання результатів цих вимірювань в інших країнах.

Розраховані значення розширеної невизначеності вимірювань електричної ємності у діапазоні значень від 10 пФ до 10 нФ при високоточному калібруванні мір електричної ємності. Розраховані значення розширеної невизначеності вимірювань індуктивності у діапазоні значень від 1 мкГн до 10 Гн при високоточному калібруванні мір індуктивності.

Встановлені найкращі значення розширеної невизначеності вимірювань параметрів імпедансу (електричної ємності та індуктивності) в широкому діапазоні значень в Україні. Проведений порівняльний аналіз показав, що опубліковані дані щодо калібрувальних та вимірювальних можливостей національних метрологічних інститутів України для вимірювання електричної ємності та індуктивності потенційно можуть бути значно покращені у широких діапазонах значень

Ключові слова: звірення еталонів, метрологічна простежуваність, імпеданс, національний метрологічний інститут, регіональна метрологічна організація

1. Introduction

International and regional coordination, close cooperation of all countries on a global scale and ensuring the equivalence of national standards of different countries are an important element for modern metrology activities. To implement, transfer the size of legal units of measurement of various physical quantities and meet the needs of the national economy, a system of national standards is created.

In the case of independent implementation of units of measurement by national standards, regular verification with national standards of other countries is necessary to confirm equivalence.

International comparisons are carried out by the Consultative Committees (CC) of the International Committee of Weights and Measures (CIPM) or regional metrology organizations (RMO) [1, 2]. Confirmation of the equivalence of national standards with the standards of other countries is

carried out in accordance with the procedures established at the international level in the framework of the multilateral "Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes" (MRA CIPM Agreement) [3].

According to the International Vocabulary of Metrology (VIM), metrological traceability is a property of the result of measurements, by which the result can be compared with the value of the standard through a documented continuous chain of calibrations, which determine the uncertainty of measurements [4]. According to VIM, metrological traceability is defined as an inalienable parameter characterizing a dispersion of a quantitative value that can be attributed to a measurable value based on the information used.

The practical application of the concept of metrological traceability allows us to compare the accuracy of the measurements carried out using a standardized procedure of measurement uncertainty assessment [5, 6]. The basis for measuring measurement uncertainty at the international level is the "Guide to the expression of uncertainty in measurement" (GUM) [7]. The requirements of regional organizations for measuring the uncertainty of measurements are based on the provisions of the GUM.

Calibration and Measurement Capabilities (CMC) are the highest level of calibration and measurement, which is guaranteed by National Metrology Institutes (NMI) [8]. CMC is published in the form of tables in the Key Comparison Database (KCDB) of the International Bureau of Measures and Weights (BIPM). CMC contain the significance of the increased uncertainty of the results of the NMI measurements performed for the confidence level of 0.95 and characterize the quality of the metrological services provided on a constant basis to consumers [9].

Carrying out of relevant comparison in the framework of the RMO is necessary to ensure the metrological traceability of measurements of the impedance parameters (electric capacitance and inductance) in Ukraine to the international level:

– Euro-Asian Cooperation of National Metrological Institutions (COOMET), of which Ukraine is a member;

– European Association of National Metrology Institutes (EURAMET).

The role of the NMI in ensuring the mutual recognition of the results of measurements received by the NMI itself and the effective functioning of national metrology services has significantly increased in the context of the globalization of the world economy and the international division of labor.

2. Literature review and problem statement

In [10], an analysis of common international guidelines and standards that are used to provide and evaluate elements of metrological traceability is shown. The procedures used to evaluate CIPM international key comparisons (KC) data are designed to provide linkage with CIPM KC data with low uncertainty. These procedures must be in accordance with the procedures used to assess the data of the RMO KC.

During the conduct of the KC, both the CC CIPM and the RMO use the agreed method (general rules) for measuring the results of measurements, which is reflected, in particular, in the following works:

– a general approach for evaluating the results of the KC is presented in [11];

– clarification of the general approach for determining the largest consecutive subset is given in [12];

– a general approach for evaluating the results of all KC and an example of a model of choice in the average size of inconsistent data is presented in [13].

However, in the majority of cases, when processing the results of comparisons, applying these generalized approaches is rather difficult in practice, and sometimes impossible. Therefore, the clarification of these approaches to determine the largest consecutive subset [14] and special examples, such as the model of choice in the average value of inconsistent data are developed [15]. Nevertheless, the task of processing the results of comparisons is still completely not solved. This is due to the fact that the general rules for processing the measurement results when comparing national standards and modifying these rules can not provide satisfactory results for an extremely wide range of measured values. Therefore, there is an urgent need for a detailed analysis of the approaches to assessing the results of comparisons presented in the final reports on the comparison of the standards for specific units of measurement.

The real state of the metrological traceability of measurements of any value can not be estimated without carrying out a detailed analysis of the results of the comparison of the standard units of this magnitude and the calibration of the corresponding measuring instruments (MI). It is impossible to carry out such an analysis without conducting a practical assessment of the corresponding uncertainties of measurements.

In 1996-1998 in the framework of the CIPM CC of the Electricity and Magnetism (CCEM), international KC of the national standards of units of electric capacitance of 10 pF of CCEM-K4 [14] was conducted. The aforementioned comparison became the basis for conducting similar assessments within the framework of various RMO in 2003–2013. In the framework of the RMO of the European countries, there were checks for the capacitance of 10 pF [15], the RMO of the Americas – for a capacity of 10 pF [16] and a capacitance of 100 pF [17]. In the framework of COOMET, the NMI of Ukraine participated in the surveys: for a capacitance of 10 pF at frequencies of 1 kHz and 1.592 kHz [18], for a capacitance of 100 pF at frequencies of 1 kHz and 1.592 kHz [19] and for capacitances of 10 pF and 100 pF at a frequency of 1 kHz [20].

The analysis of the processing methods of the results used in the above-mentioned comparisons showed that the reports on the comparisons of all RMO used the same procedure as described in [15]. This allows an adequate assessment of the results obtained by each of the NMI participants of the surveys. The result of the NMI of Ukraine is the basis for establishing the metrological traceability of measurement of electrical capacitance in the country and recognition of the results of these measurements in other countries.

In 1989–1999 within the framework of the CIPM CCEM, international KC of the national standards for the inductance unit of 10 mH CCEM-K3 [21] was conducted. These comparisons became the basis for similar comparisons between different RMO in 2002-2014. Within the framework of the RMO of European countries, comparisons were made for inductances of 10 mH in 2006 [22] and 100 mH at a frequency of 1 kHz in 2002-2003 [23] and 2006–2008 [24], RMO of the Americas – inductance of 10 mH at a frequency of 1 kHz [25] in 2013-2014. The NMI of Ukraine in 2013–2014 within the framework of COOMET participated

in comparisons for inductances with the nominal values of 10 mH and 100 mH at a frequency of 1 kHz [26].

The analysis of the processing methods of the results used in the above-mentioned comparisons has shown that in the reports of comparisons of all RMO, although several different procedures were used, consistency results were obtained. This allows an adequate assessment of the results obtained by each of the NMI participants of the comparisons. The result of the NMI of Ukraine is the basis for establishing the metrological traceability of the measurement of impedance in the country and recognition of the results of these measurements in other countries.

3. The aim and objectives of the study

The research was aimed to evaluate all the main components of the metrological traceability of impedance measurement in Ukraine.

To achieve this aim, the following objectives were set:

– to establish the degrees of equivalence of the national standard of the unit of electrical capacitance for the values of 10 pF and 100 pF at frequencies of 1 kHz and 1.592 kHz and the expanded uncertainties received by the results of international comparisons of national standards of units of electrical capacitance and to carry out the corresponding analysis;

– to establish the degrees of equivalence of the national standard of the unit of inductance for the values of 10 mH and 100 mH at a frequency of 1 kHz and the expanded uncertainties received by the results of international comparisons of the national standards of units of inductance, and to conduct an appropriate analysis;

– to calculate the value of the expanded uncertainty of measurements of the electrical capacitance in the range of values from 10 pF to 10 nF, obtained by a precision calibration of the measures of electrical capacitance;

– to calculate the value of the expanded uncertainty of inductance measurements in the range of values from 1 mH to 10 H, obtained by a precision calibration of the measures of inductance;

– to establish the best values of the expanded uncertainty of measurements of impedance parameters (electrical capacitance and inductance) in a wide range of values in Ukraine and to carry out the corresponding comparative analysis.

4. Materials and methods of research in the framework of international comparisons of national standards

International key and additional comparisons of the national standards of the unit of electrical capacitance of 10 pF and 100 pF at 1 kHz and 1.592 kHz were carried out during 2006–2009 under the project COOMET 345/UA/05 (COOMET.EM-K4, COOMET.EM-S4) [18, 19]. Seven NMI participated in the surveys: Ukrmetrteststandard (UMTS, Ukraine – pilot laboratory); PTB (Germany); NMIJ/AIST (Japan); BIM (Bulgaria); VNIIM (Russia); KazInMetr (Kazakhstan); BelGIM (Belarus).

International supplementary comparisons of the national standards of the unit of electrical capacitance of 10 pF and 100 pF at a frequency of 1 kHz under the COOMET 554/UA/12 project (COOMET.EM-S13) [20] were conducted with the participation of three NMIs during 2012-2013. Participants of these comparisons are NMI: Ukrmetrteststan-

dard (UMTS, Ukraine – pilot laboratory); GUM (Poland); BelGIM (Belarus).

In all of these comparisons, Ukraine presented the State primary standard of Ukraine units of electrical capacitance and loss factor (DETU 08-06-01), which is stored in the State Enterprise (SE) "Ukrmetrteststandard" since 2001. The analysis of comparison results showed that the degrees of equivalence D at frequencies of 1 kHz and 1.592 kHz of this standard with the expanded uncertainties U(D) (k=2) in the sense of the reference value of the comparisons are shown in Table 1 [18–20] and Fig. 1, 2.

Table 1

Degrees of equivalence of the DETU standard 08-06-01 for both surveys with expanded uncertainty, µF/F

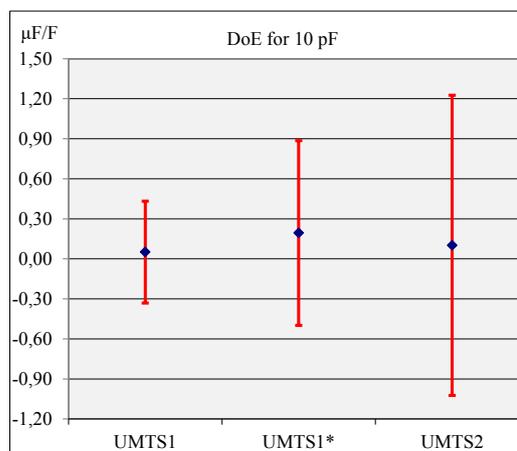| 10 pF				100 pF			
1 kHz		1.592 kHz		1 kHz		1.592 kHz	
D	U(D)	D	U(D)	D	U(D)	D	U(D)
COOMET.EM-K4[1]				COOMET.EM-S4[3]			
0.051	0.382	0.194	0.692	0.278	0.398	0.069	0.693
COOMET.EM-S132							
0.101	1.125	–	–	0.122	1.427	–	–

Fig. 1. Degrees of equivalence of the DETU standard 08-06 01 for 10 pF at frequencies of 1 kHz and 1.592 kHz (*)

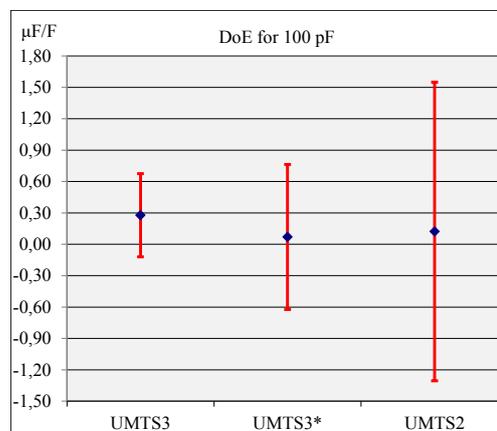

Fig. 2. Degrees of equivalence of the DETU standard 08-06-01 for 100 pF at frequencies of 1 kHz and 1.592 kHz (*)

The degree of equivalence of the standard of the i-th NMI Di and the expanded uncertainties in the sense of the reference value $U(D_i)$ are determined by the expressions [27–29]:

$$D_i = x_i - x_{ref}, \qquad (1)$$

$$u^2(D_i) = u^2(x_i) - u^2(x_{ref}), \quad U(D_i) = 2u(D_i), \qquad (2)$$

where x_i is the i-th result of the NMI participant of comparisons; x_{ref} is the reference value of comparisons; $u(x_i)$ is the standard uncertainty of the result of the i-th NMI participant of the comparisons; $u(x_{ref})$ is the standard uncertainty of the reference value of comparisons; $u(D_i)$ is the standard uncertainty of the degree of equivalence of the i-th NMI participant of comparisons.

International supplementary comparisons of national standards of the unit of inductance with the nominal values of 100 mH at a frequency of 1 kHz under the EURAMET 816 project (EURAMET.EM-S26) were carried out with the participation of 16 NMIs during 2006–2008 [24]. In these comparisons, SE "Ukrmetrteststandard" participated (UMTS, Ukraine). In comparisons, 2 transported standards were applied.

International additional comparisons of national standards of units of inductance with the nominal values of 10 mH and 100 mH at a frequency of 1 kHz for 2 and 3-terminal connections of measures within the framework of the COOMET 584/UA/12 project (COOMET.EM-S14) were conducted with the participation of 4 NMIs during 2013–2014 [26]. NMI participants of these comparisons: Ukrmetrteststandard (UMTS, Ukraine – pilot laboratory); GUM (Poland); KazInMetr (Kazakhstan); BelGIM (Belarus).

The State primary standard of Ukraine for inductance and tangent angles of losses (DETU 08-09-09) was presented for comparisons from Ukraine, which is stored in the SE "Ukrmetrteststandard". The analysis of comparison results has shown that the degrees of equivalence D for the frequency of 1 kHz of this standard with the expanded uncertainties $U(D)$ ($k=2$) in the sense of the reference value of the comparisons are shown in Table 2 [24, 26] and Fig. 3, 4.

Table 2

Degrees of equivalence of the DETU standard 08-09-09 for both comparisons with expanded uncertainty, mH/H

10 mH		100 mH		10 mH		100 mH	
2-terminal connection				3-terminal connection *			
D	U(D)	D	U(D)	D	U(D)	D	U(D)
EURAMET.EM-S261							
–	–	−0.045	0.049	–	–	–	–
COOMET.EM-S142							
0.012	0.013	0.007	0.010	0.013	0.013	0.004	0.010

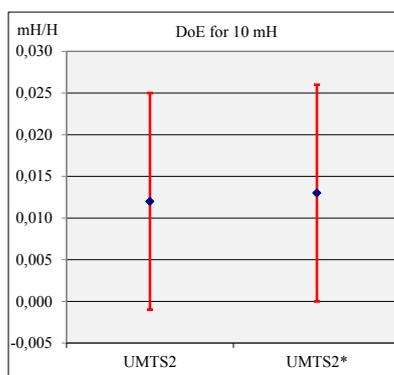Fig. 3. Degrees of equivalence of the DETU standard 08-09-09 for 10 mH at a frequency of 1 kHz for 2- and 3-terminal connections (*)
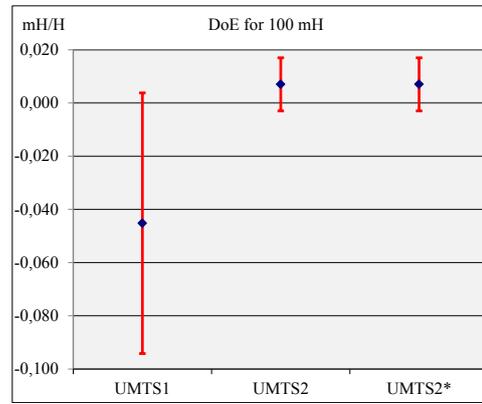

Fig. 4. Degrees of equivalence of the DETU standard 08-09-09 for 100 mH at a frequency of 1 kHz for 2- and 3-terminal connections (*)

5. Assessment of uncertainty of calibration of measures of electrical capacitance and measures of inductance

The DETU 08-06-01 standard includes the Andeen-Hagerling (USA) model AH11A with a nominal value of electrical capacitances of 10 pF and 100 pF calibrated in such NMIs: NIST (USA), PTB (Germany) and NPL (UK). The values of these measures contain the expanded uncertainty $U_{AH}=7.4 \cdot 10^{-6}$ pF with probability $P=0.95$ with the coverage factor $k=2$.

The procedure for transmitting the size of a unit of electrical capacitance in a wide range of values (from 10 pF to 10 nF) using the universal automated precision comparator, which is part of the DETU 08-06-01 standard, in detail was described in [30]. Also, in [30] uncertainty in the calibration of measures of electrical capacitance is estimated and an example of a budget of uncertainty of measurements of the value of electrical capacitance during calibration of these measures is given [31]. Relative expanded uncertainty in the calibration of measures of electrical capacitance was $U=7.52$ µF/F with probability $P=0.95$ with a coverage factor $k=2$. The calibration of the measures of the electrical capacitance was carried out at an ambient temperature of $(22 \div 24)$ °C, relative humidity of $(30 \div 45)$ % at the frequency of the test signal of 1 kHz.

According to the results of the analysis and calculations under to the requirements [7], the best expanded uncertainties in the measurement of electrical capacitance at frequencies of 1 kHz and 1.592 kHz with a probability $P=0.95$ with a coverage factor $k=2$ are shown in Table 3.

Table 3

Expanded uncertainties in the measurement of electrical capacitance, obtained by comparison of standards and calibration of measures of electrical capacitance, µF/F

10 pF				100 pF				1 nF	10 nF
1 kHz		1.592 kHz		1 kHz		1.592 kHz		1 kHz	
1	2	1	2	1	2	1	2	2	2
0.382	0.768	0.692	0.768	0.398	0.792	0.693	0.792	2.531	3.487

Notes: 1 – according to the comparison of the standards; 2 – according to the results of calibration of the measures of electrical capacitance

The data of Ukraine for measuring electrical capacitance published in KCDB BIPM [2] contain the expanded uncertainty of measurements with probability P=0.95 with the coverage factor k=2 at frequencies of 1 kHz and 1.592 kHz in the range of values:

– from 10 pF to 100 pF – 1 µF/F;

– from 1 pF to 1000 pF – 12 µF/F;

– from 1 nF to 10 nF – 14 µF/F.

To calibrate high-precision inductance measures, it is necessary to provide traceability from a calibrated high-precision measure of electrical capacitance of 100 pF or 10 pF with a corresponding uncertainty. Such measures are part of the DETU standard 08-06-01 as a group of four high-precision measures of electrical capacitance [30].

The procedure for transmitting the size of the inductance unit in the range of values from the measures of electrical capacitance using the universal automated precision comparators included in the standards of both DETU 08-06-01 and DETU 08-09-09 was described in detail in [32].

In [31, 32], the uncertainty for the calibration of measures of inductance is estimated and examples of uncertainty budgets are given:

– capacities for calibration of a measure of electrical capacitance of 100 pF;

– inductance for calibrating the measure of inductance with a support on the basis of a capacitance of a nominal value of 100 pF.

Relative expanded uncertainty in the calibration of measures of inductance is 0.035 µH/H with probability P=0.95 with the coverage factor k=2. The calibration of the measures of inductance was carried out at an ambient temperature of (22÷24) °C, relative humidity of (30÷45) % at the frequency of the investigated signal of 1 kHz.

The data of Ukraine for inductance measurement published in KCDB BIPM [2] contain the expanded uncertainty of measurements with probability P=0.95 with the coverage factor k=2 at a frequency of 1 kHz in the range of values:

– from 1 µH to 1,000 µH – 10 µH/H;

– from 1 mH to 1,000 mH – 10 µH/H;

– from 1 H to 10 H – 10 µH/H.

According to the results of the analysis and calculations under to the requirements [7], the best expanded uncertainties of the inductance measurement at a frequency of 1 kHz with a probability P=0.95 with a coverage factor k=2, obtained by comparing the standards (1) and calibration of the measures of inductance (2) are shown in Table 4.

6. Discussion of the results of the metrological traceability measurement of impedance parameters

The analysis of the results of international key and supplementary comparisons of the national standards of units of electrical capacitance of 10 pF and 100 pF allowed to establish the degrees of equivalence of the standard of the unit of electrical capacitance DETU 08-06-01 at frequencies of 1 kHz and 1.592 kHz. These degrees of equivalence for the specified electrical capacitance ratings contain expanded uncertainties of 0.382 µF/F and 0.693 µF/F, respectively, at frequencies of 1 kHz and 1.592 kHz with a probability P=0.95 with a coverage factor k=2.

Calculations of the values of the expanded uncertainty of measurements of electrical capacitance in the range of values from 10 pF to 10 nF in the calibration of the corresponding measures were carried out. These calculations showed that the expanded uncertainties of measurements ranged from 0.015 µF/F to 0.024 µF/F with probability P=0.95 and the coverage factor k=2.

The comparative analysis of the best values of the expanded uncertainty of electrical capacitance measurements in the range of values from 10 pF to 10 nF obtained in Ukraine both in the comparisons of the standards, and with a precision calibration of the measures of electrical capacitance, showed the following. It has been established that the data for Ukraine on CMC for an electrical capacitance unit published in KCDB BIPM [2] in the range of values of electrical capacitance from 10 pF to 10 nF at frequencies of 1 kHz and 1.592 kHz can be improved from 1.9 to 2.6 times (Fig. 5).
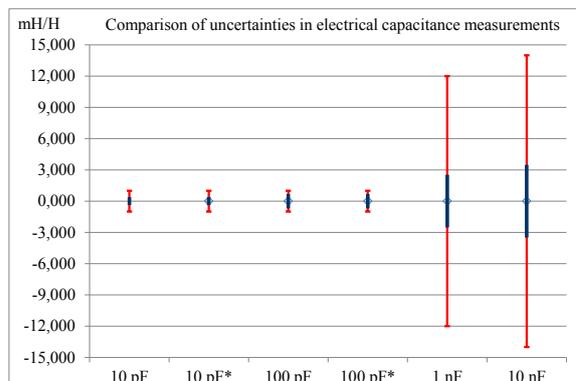

Fig. 5. Comparison of uncertainties of measurements of electrical capacitance in the range from 10 pF to 10 nF at frequencies of 1 kHz and 1.592 kHz (*)

Table 4

Expanded uncertainties in the measurement of inductance, obtained by comparison of the standards and calibrating the measures of inductance, mH/H

1 µH	10 µH	100 µH	1 µH	10 mH		100 mH		1 H	10 H	100 H
2	2	2	2	1	2	1	2	2	2	2
0.024	0.023	0.022	0.021	0.013	0.02	0.010	0.015	0.015	0.024	0.023

The expanded uncertainty of measuring the impedance parameters (electrical capacitance and inductance) obtained in Tables 3, 4 can be used for the comparative analysis of metrological traceability of measurements of impedance parameters in Ukraine.

In Fig. 5, thin red strip lines with planks marked the expanded uncertainty, which was published in KCDB BIPM in the tables of CMC for Ukraine in the field of electricity and magnetism for measuring electrical capacitance. The blue thick lines marked the expanded uncertainty of measurement of electrical capacitance, obtained by comparing the standards and with a precision calibration of the measures of electrical capacitance.

The analysis of the results of international supplementary comparisons of national standards of inductance units of 10 mH and 100 mH at a frequency of 1 kHz allowed to establish the degrees of equivalence of the standard of the inductance unit DETU 08-09-09 with the corresponding expanded uncertainties from 0.010 mH/H to 0.013 mH/H for the indicated inductance values.

The results of the calculations of the values of the expanded uncertainty of inductance measurements in the range of values from 1 μH to 10 H showed that the increased uncertainty of measurements during the calibration of the measures of inductance is 0.035 mH/H with probability $P=0.95$ with the coverage factor $k=2$.

The comparative analysis of the best values of the expanded uncertainty of inductance measurements in the range of values from 1 μH to 10 H, obtained in Ukraine both in the comparison of standards, and with high-precision calibration of the measures of inductance, showed the following. On the basis of the analysis, it was established that the data on the CMC for the inductance unit in KCDB BIPM [2] published for Ukraine in the range of inductance values from 1 μH to 10 H at a frequency of 1 kHz can be improved from 285 to 1,000 times (Fig. 6).
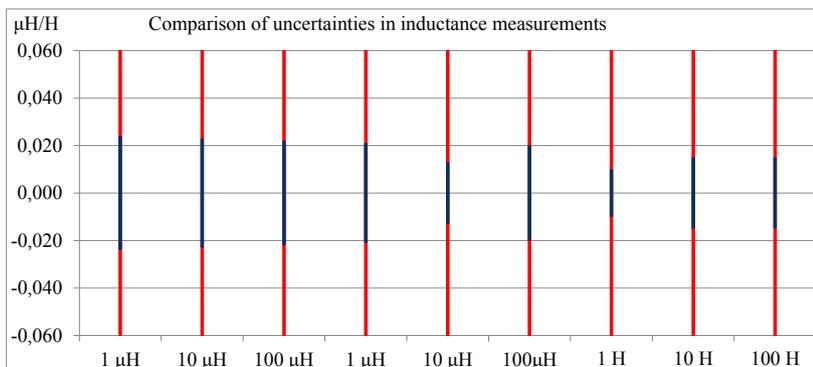

Fig. 6. Comparison of uncertainties of measurements of inductance in the range from 1 μH to 100 H at a frequency of 1 kHz

In Fig. 6, thin red lines marked the expanded uncertainty, which is published in KCDB BIPM in the tables of CMC for Ukraine in the field of electricity and magnetism for measuring inductance. The blue thick lines indicate an expanded uncertainty in the measurement of the inductance obtained by comparison of the standards and in the high-precision calibration of the measures of inductance.

The results of the comparative analysis show that Ukraine's NMIs can significantly improve their CMC. A significant decrease in the uncertainty of measurements of impedance parameters for CMC of Ukraine will allow customers of calibration of the appropriate measures to order calibration with improved characteristics in NMI. This will indirectly contribute to improving the metrological traceability of the relevant measurements.

The considered approach has no limitations and can be used to evaluate all the main components of the metrological traceability of any measurements. It is known that according to the requirements [33], the owner of the MI voluntarily orders calibration. Usually, for the purpose of choosing a calibration agent, MI owners use well-known databases, in particular [2]. Such bases should contain the best calibration capabilities and be constantly updated. The NMIs should ensure this relevance in accordance with the procedures and the requirements [8]. In view of this, it is advisable to use such studies for other types of measurements. This will determine the best values of the expanded uncertainty of the corresponding measurements in a wide range of values.

7. Conclusions

1. The degree of equivalence of the national standard of the unit of electrical capacitance for the values of 10 pF and 100 pF at frequencies of 1 kHz and 1.592 kHz and the expanded uncertainties obtained on the basis of international comparisons of the national standards of units of electrical capacitance was established; and their comparative analysis was carried out. The degree of equivalence of the national standard of the unit of inductance for the nominals of 10 mH and 100 mH at the frequency of 1 kHz and the expanded uncertainties obtained on the basis of the results of international supplementary comparisons of the national standards of the units of inductance was established, and their comparative analysis was carried out.

2. Values of the expanded uncertainty of measurements of electrical capacitance in the range of values from 10 pF to 10 nF with high accuracy calibration of measures of electrical capacitance were calculated. Values of the expanded uncertainty of inductance measurements in the range of values from 1 μH to 10 H in the high-precision calibration of the measures of inductance were calculated.

3. The best values of the expanded uncertainty of measurements of impedance parameters (electrical capacitance and inductance) in the wide range of values in Ukraine were established. The comparative analysis has shown that the data on CMC published in KCDB can be greatly improved:

– for electrical capacitance in the range of values of electrical capacitance from 10 pF to 10 nF at frequencies of 1 kHz and 1.592 kHz from 1.9 to 2.6 times;

– for inductance in the range of values of inductance from 1 μH to 10 H at a frequency of 1 kHz from 285 to 1,000 times.

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