METROLOGY, QUALITY, STANDARDIZATION AND CERTIFICATION

RESEARCH OF LONG-TERM DRIFT OF THE NATIONAL INDUCTANCE STANDARD

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Abstract. Inductance measurements is important for all branches of technology related to the application of electricity: energy and electronics, radio and television, transport and communication, and scientific research. Electromechanical devices and electronic components can be characterized using impedance measurements to identify the parameters of their equivalent electrical model. New inductance measurement methods are being developed in specific fields of activity. Manufacturers of standards and measuring instruments of inductance develop special handbooks outlining various methods of inductance measurement. The State Primary Standard of Ukraine for inductance and loss angle tangent reproduces and transmits a unit of inductance in the range from $1{\cdot}10^{-6}$ H to 10 H at a frequency of 1 kHz. It is keeping in the SE "Ukrmetrteststandard" and participated in several comparisons of national standards within the framework of the activities of regional metrological organizations. The calibration and measurement capabilities of inductance measurement of national laboratories of different countries were studied to analyze and compare the capabilities of the national standard with the standards of other countries. Long-term instability studies of inductance measures of 1 mH, 10 mH and 100 mH, which are part of the national standard unit of inductance, have been conducted. The research period covered from 2009 to 2022. It was established that the drift lines of the specified inductance measures can be described using linear approximations. The rationale for choosing inductance measures of 10 mH and 100 mH for their use as transmission standards in the calibration of standards, which were organized and conducted by SE "Ukrmetrteststandard" as their pilot laboratory, is given.

Key words: Inductance, long-term instability, linear approximation, standard, measurement uncertainty.

1. Introduction

Inductance is a physical quantity that characterizes the ability of a conductor to accumulate magnetic field energy when an electric current flow. It is characterized by the property of the conductor to counteract the appearance, termination, and any change of the electric current in it, i.e., electric inertia. Inductance measurement is important for all branches of technology related to the application of electricity: energy and electronics, radio and television, transport and communication, and scientific research.

Electromechanical devices and electronic components can be characterized using impedance measurements to identify the parameters of their equivalent electrical model. Properties such as resistivity, permittivity, and permeability of material samples can be obtained by impedance measurements made using appropriate electrical instruments [1].

New measurement methods are being developed in specific fields of activity. A new method of measuring the dynamic inductance of a coil with a saturable core is described in [2]. The method of precision measurement of the magnetic pulse field inductance based on the digital synchronization method is given in [3]. Many studies on inductance measurement are applied to different types of electric motors. Evaluation of different inductance measurement methods on the same motors to determine whether they lead to the same result is the subject of research [4].

Manufacturers of standards and measuring instruments for inductance develop special handbooks outlining various methods of measuring inductance [5, 6]. Such manuals are very useful for professionals who carry out such measurements. They present the features of conducting inductance measurements and show the influence on the measurement result of various components of measuring circuits.

2. Drawbacks

Various methods of inductance measurement are given in detail in [1–6]. Precision inductance measurements are devoted in [7–10]. The study of the influence of component measuring schemes when using inductance standards is devoted in [1, 5, 6, 11, 12]. Evaluation of the uncertainty of inductance measurements was carried out in [13, 14] taking into account international and regional guidelines on these issues [15–17]. At the same time, only one work was found [18] dedicated to the evaluation of the long-term drift of the inductance standard, which shows the relevance of conducting such studies and highlighting their results.

3. Goal

The purpose of the research on the long-term instability of inductance measures included in the National Standard of inductance unit is to analyze and confirm the measurement capabilities of the standard.

4. Methods of precision inductance measurements

The main method of inductance measurement is measurement using balancing alternating current bridges that contain reactive elements. Wien and Maxwell's bridges are used to measure inductance. Bridge circuits have high sensitivity, are characterized by high accuracy, a wide range of value measurements. High-accuracy RLC meters are also used to measure inductance [1, 5, 6].

Inductance measurement based on the Maxwell bridge is carried out using reference measurements of resistance and capacitance. The difficulty in using the Maxwell bridge arises when there is a mutual inductance (electromagnetic guidance) between the measured load and the known values of the bridge components, which is one of the components of the total measurement uncertainty. The reactive resistance of the bridge capacitance is directly opposite to the reactive resistance of the measured inductance, which allows you to reliably determine the value of inductance and active resistance.

Quite a limited range of measurement tools is available for high-precision impedance measurement, of which capacitive bridges are common. New calibration methods for inductance measures from 1 μH to 10 kH using a precise capacitive bridge with an error of 1 kHz better than 50 ppm for 100 μH to 10 kH and better than 500 ppm for 1 μH and 10 μH are described in [7]. The main focus is on the measurement method using active or passive T-chain for inductance from 1 μH to 1 H.

The practical aspects of using the series resonance method for the realization of an inductance of 100 mH at 1 kHz and a comparison with the results of implementation by the Maxwell-Wein method were studied in [8]. The results showed that the uncertainty of 1 σ of the implementation of 100 mH by this method can be at the level of parts of 10^{-6} mH/H.

A simple measurement method that determines the inductance by capacitance standards is presented in [9]. The principle of measurement is the compensation method using the LC series circuit. The relative combined standard uncertainty of the measurement of 10 mH and 100 mH inductances at the frequency of 1592 Hz was estimated to be 9.2 ppm and 12.0 ppm, respectively.

The results of the research project, including designs of digital impedance bridges and details of a multiphase digital synthesized multichannel source, are presented in [10]. The project aims to implement an impedance scale in the range from 1 nF to 10 μF and from 1 mH to 10 H with a relative uncertainty in the range from 10 ppm to 1 ppm.

It is important to take into account the effect of special adapters and cables for connecting inductance measurements on the measurement results [1]. The influence of adapters on the calibration of 100 μH inductance measures was studied in [11, 12]. The calculated inductance of 99.956 μH, corrected by subtracting adapter inductance and contact resistance contributions from the measured value, is in good agreement with the existing calibration certificate (99.948 μH) within a measurement uncertainty of 140 ppm.

5. National primary standard of inductance unit

In the International System of Units, inductance is expressed in Henry (H). The circuit has an inductance of 1 H, if when the current changes by 1 A in 1 s, a voltage of 1 V occurs at the contacts of the electrical circuit. The National Primary Standard of Inductance and Loss Angle Tangent (DETU 08 -09-09) was created in 2009. It is designed to provide reproduction and transfer of the size of the inductance unit to working standards (mainly inductance meters) and measuring instruments (mainly RLC meters). The standard DETU 08-09-09 is periodically researched and participates in international comparisons of national standards. The general view of the standard is shown in Fig. 1.

Metrological characteristics of the standard:

– the nominal value of the inductance, on which the unit of measurement is reproduced, is 100 mH;

– the range of inductance values, in which the unit of measurement is transmitted, is from $1\cdot10^{-6}$ H to 10 H;

– operating frequency – 1000 Hz;

– the root means square deviation of the measurement results when transferring the size of the inductance unit is from $1.05\cdot10^{-4}$ to $3.15\cdot10^{-3}$;

– the expanded uncertainty of the reproduction of the inductance unit with a coverage factor equal to 2 and a confidence probability of 0.95 is $4\cdot10^{-5}$;

– the long-term instability of the standard is $1\cdot10^{-5}$ per year.

The results of a detailed evaluation of measurement uncertainty using the DETU 08-09-09 standard are given in [13, 14]. The obtained expanded measurement uncertainty for inductance of 100 mH is 0.035 ppm.

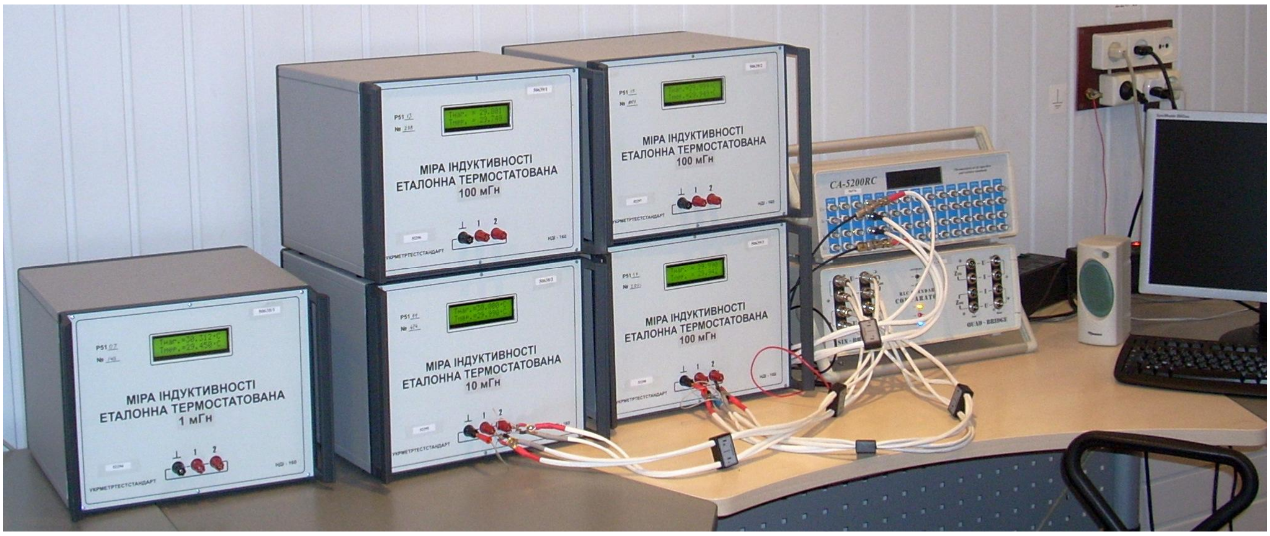


Fig. 1. General view of the DETU 08-09-09 standard

Fig. 2 shows the structural diagram of the DETU 08-09-09 standard, which consists of inductance measures with nominal values of 1 mH, 10 mH, and 100 mH (three samples), a CA2100 autotransformer-comparator bridge, which is controlled by a personal computer (PC), as well as a magazine transient measures of electric capacity and resistance.

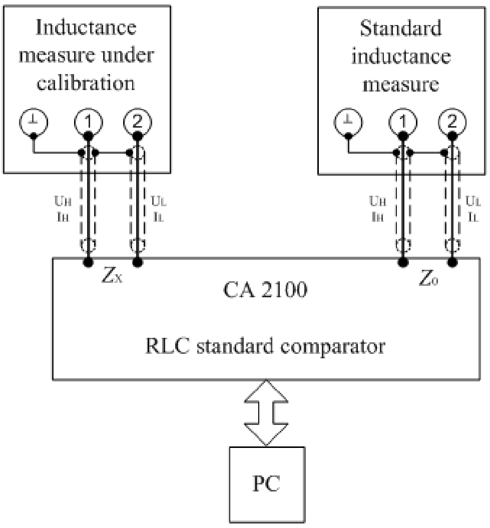
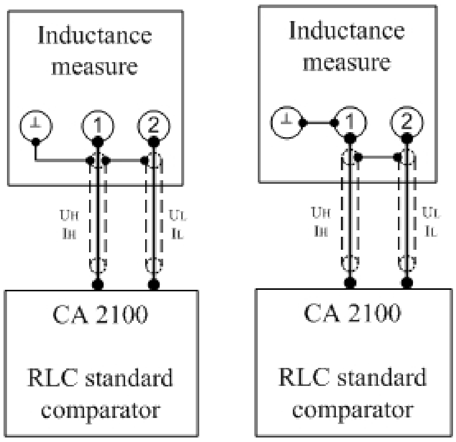


Fig. 2. Structural diagram of the DETU 08-09-09 standard

The measure under calibration and the standard measure used for calibration are connected by measuring cables to the corresponding connectors (U_H, I_H, U_L, I_L) of the reference RLC comparator CA 2100 for inductance measurements (Fig. 2). At the same time, it is taken into account that the measure with a higher impedance should be connected as "Z_x", and the measure with a lower impedance as "Z_0". All settings and measurement processing are carried out automatically using a special comparator control program installed on the PC of the DETU 08-09-09 standard.

A two– (Fig. 3, a) and three-pin (Fig. 3, b) connection of the inductance measure to the CA 2100 comparator is implemented for measurements using the DETU 08-09-09 standard.

The calibration and measurement capabilities (CMC) of national laboratories of different countries were studied to analyze the competitive capabilities of inductance measurement calibration in the Key Data Base (KCDB) of the International Bureau of Weights and Measures (BIPM) [19].



a *b*

Fig. 3. Types of connection of the inductance measure to the comparator a is two-contact; b is three-pin

Among the 10 countries represented, 4 national metrological institutes (Germany, the Czech Republic, Switzerland, and Italy) have inductance standards that allow calibration at measurement points of 1 mH, 10 mH, and 100 mH with a lower expanded measurement uncertainty (0.01 to 0.1 ppm) than the state standard of Ukraine, at the same time, 4 national metrological institutes (Great Britain, the Netherlands, the USA, Poland and Romania) have slightly worse CMC, but their measurement uncertainty is at a rather high level (from 0.07 to 6.0 ppm).

6. The results of the research on the long-term instability of the standard

Regular studies of inductance measures of 1 mH, 10 mH, and 100 mH (three copies) at a frequency of 1000 Hz have been conducted since the creation of the DETU 08-09-09 standard in 2009. This makes it possible to assess the long-term instability of the standard. The obtained results are presented in figures (Figs. 3–5). For measures of the inductance of 100 mH in Fig. 5, uncertainties are not given, as this can significantly clutter it. The expanded measurement uncertainty for all inductance measures of 100 mH at all points in Fig. 5 is 0.015 mH. Each of the plotted values is the average of quarterly measurements. The average value of each measure is indicated in the figures by a green line. Linear approximations of long-term instability of measures are plotted in the figures with red dashed lines. The figures show expressions for the obtained linear approximation [20]. These approximations are calculated by the method of least squares. All of them satisfy the coefficient of determination R^2, which is used to assess the accuracy of such a model of long-term instability ($R^2 \leq 1.0$) [21]. All measures have a positive instability tendency.

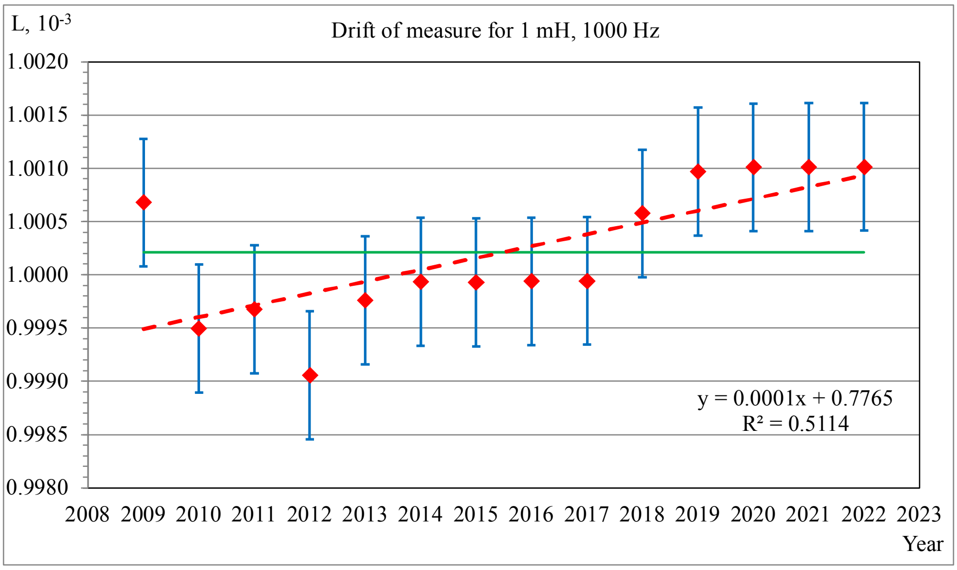


Fig. 3 Long-term instability measure of 1 mH at a frequency of 1000 Hz

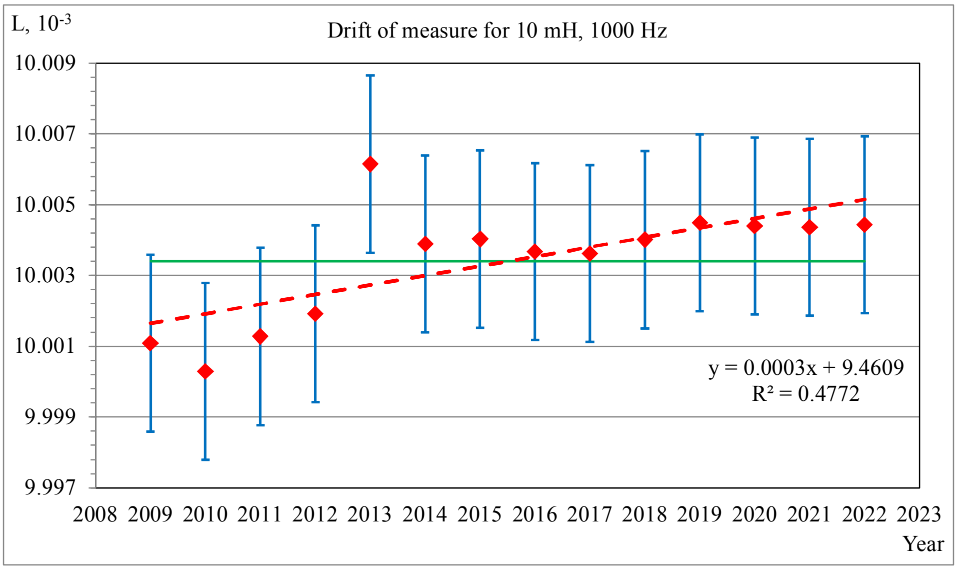


Fig. 4 Long-term instability measure of 10 mH at a frequency of 1000 Hz

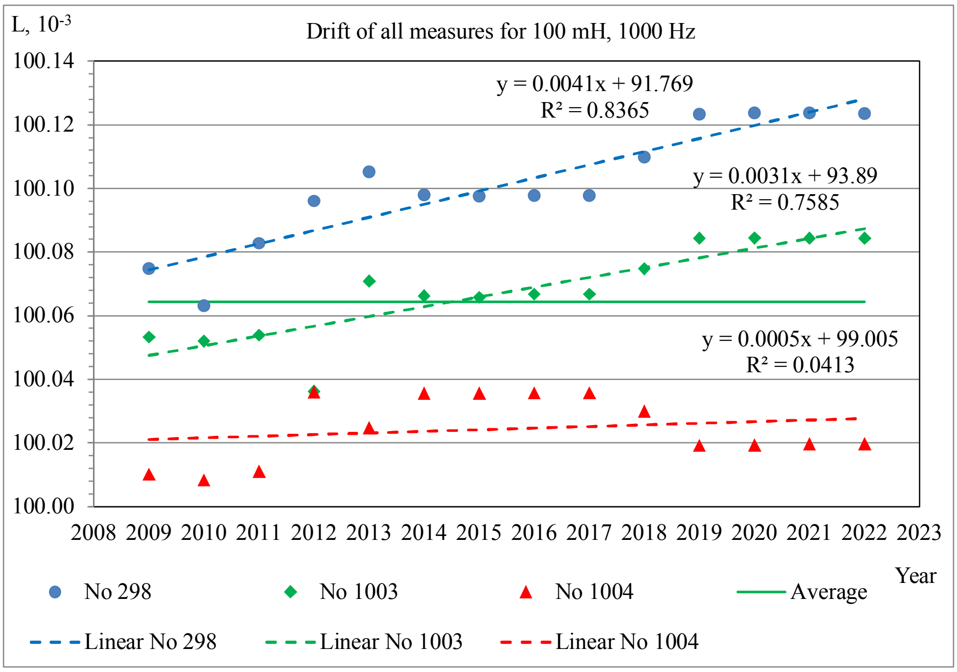


Fig. 5 Long-term instability of measures of 100 mH at a frequency of 1000 Hz

The average value measure of 1 mH from 2009 to 2022 is 1.0002 mH, the measure of 10 mH is 10.0034 mH, and the measure of 100 mH (three samples) is 100.0067 mH (average value). The difference between the maximum and minimum measurement values of 1 mH for the same period is 0.002 mH, 10 mH is 0.0058 mH, and 100 mH (No. 1003) is 0.048 mH. The difference between the last and first measurement values of 1 mH for the same period is 0.0003 mH, 10 mH is 0.031 mH, and 100 mH (No. 1003) is 0.03 mH. The standard deviation measurements of 1 mH from 2009 to 2022 are 0.0006, 10 mH is 0.016, and 100 mH (No. 1003) is 0.015. The manufacturer's specification of inductance measures indicates the instability of measures of 10 mH/H per year. The obtained results show that the measures satisfy these requirements.

The results of the research on the national standard of inductance for the period from 1980 to 2005 are presented in [18]. During this time, the standard participated in some international comparisons of similar standards from other countries. The measure of 100 mH at the frequency of 1000 Hz had a negative long-term instability to which a linear approximation of the instability line could be applied.

The methodologies for the study of long-term instability of resistance measures, outlined in [22], can also be applied to inductance measures. The study also uses a linear approximation of the instability line. This makes it possible to improve the estimation of the instability of measurements in comparison with the manufacturer's specification and, accordingly, to reduce the measurement uncertainties of their application.

An important issue is the choice of a traveling standard by the pilot laboratory for conducting international standards comparisons. To do this, such a laboratory examines all the standards available to it, which would be best suited as traveling standards. At the same time, the long-term instability of standards is primarily taken into account.

The pilot laboratory of EUROAMET.EM-S26 comparison of national inductance standards of 100 mH traveling standard was researched for a much longer period than only during comparison. A linear approximation was applied to the instability line during the actual comparison. A personal correction was applied to the result obtained by each of the participants of the reconciliations following the characteristics of the approximated instability line [23].

In the COMET.EM-S13 [24] and GULFMET.EM-S4 [25] regional comparisons of national inductance standards of 10 and 100 mH, the pilot laboratory was the SE "Ukrmetrteststandard". The pilot laboratory selected traveling standards. Given the availability of three samples of 100 mH inductance measures in the laboratory, the nominal values of the measures and their long-term instability were analyzed (Fig. 5). Since only the inductance measure of 100 mH for No. 1003 had an intersection with the average value of the group of measures and the same uncertainty as them, it was chosen as the traveling standard for both comparisons. Inductance measurements of the traveling standards in the specified comparisons were carried out with two and three-contact connections (Fig. 3).

The assessment of the long-term instability of the inductance measure for No. 1003 using linear approximation is shown in Fig. 6. The COMET EM-S13 sampling period was from May 2013 to October 2014, and the GULFMET.EM-S4 was from June to October 2018. The instability of the traveling standards during both comparisons was insignificant considering the short duration of their implementation, so there was no need to take it into account in the results of their participants.

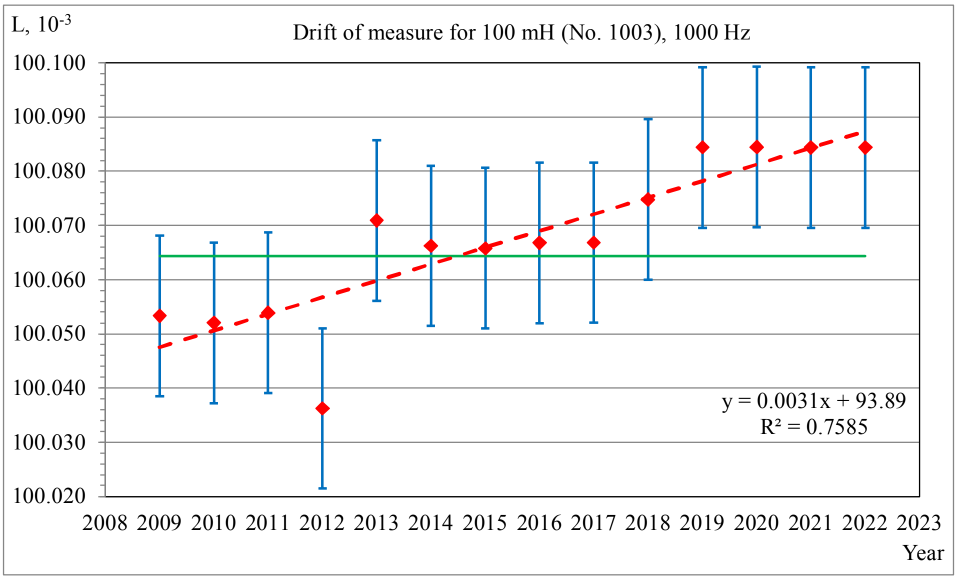


Fig. 6 Evaluation of the instability of the measure 100 mH (No. 1003)

7. Conclusions

Inductance measurement is important for many branches of technology, and precise measurement methods are based on the use of alternating current bridges, which are characterized by high accuracy and a wide range of measurements of quantity. It is important to consider the influence of special adapters and cables for connecting inductance measurements on the measurement results.

National metrological laboratories carry out constant research on inductance standards keeping in them. One of the important characteristics of such studies is the long-term instability of the measures that are part of the standards. Laboratories that are selected as pilots for conducting international comparisons of national standards of different countries select a traveling standard based on an analysis of the long-term instability of the available ones from among those available to them. The results of the drift of the traveling standards are taken into account by the pilot laboratory for evaluating the results of the conducted comparisons.

8. Gratitude

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9. Mutual claims of authors

The authors have no claims against each other.

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