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The estimation of the long-term drift of the inductance measurement standards

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Abstract

Inductance measurements are important in many fields, especially in electronics, electrical engineering, radio engineering, and other areas. The inductance is often an important parameter in a wide range of applications such as radio transmitters, power circuits, magnetic resonance pulsed sources, etc. The accuracy of the inductance affects the quality of products, especially in devices where inductors are used, such as filters, transformers, inverters, etc. High-precision inductance measurements are used for the product quality control to ensure that manufactured devices meet established specifications and standards.

Drift is an undesirable property of all measuring instruments and measurement standards during their life cycle. The analysis of the instrumental drift of measurement standards is of great importance in metrology. Reliable drift accounting plays an important role in maintaining measurement accuracy. For electrical measurement standards, the long-term drift is predictable. The drift types and main methods of its estimation for measurement standards between their calibrations were analysed. The drift uncertainty can be evaluated from the history of successive calibrations, and in the absence of such history, the order of magnitude of the calibration uncertainty can be estimated.

The results of the estimation of the long-term drift of the inductance measurement standards for high-precision calibration of measuring instruments and measurement standards by two methods, polynomial regression curves and Exponentially Weighted Moving Average (EWMA) schemes, are given. The EWMA schemes reduce the lag inherent in traditional moving averages by giving more weight to recent observations. It is shown that the use of the EWMA schemes compared to the regression analysis shows greater sensitivity to the drift changes in the last years of observations. This allows the laboratory to take this factor into account when calibrating measuring instruments and measurement standards.

Keywords: long-term drift; inductance measurement standard; measurement uncertainty; polynomial regression; Exponential Weighted Moving Average.

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Introduction

Inductance measurements are important in many fields, especially in electronics, electrical engineering, radio engineering, and other areas. The inductance is often an important parameter in a wide range of applications such as radio transmitters, power circuits, magnetic resonance pulsed sources, etc. The accuracy of the inductance affects the quality of the products, especially in devices where inductors are used, such as filters, transformers, inverters, etc. High-precision inductance measurements are used for the product quality control to ensure that manufactured devices meet established specifications and standards [1–5].

The drift of a standard indicates a tendency for it to lose accuracy or stability over time and is an undesirable property during its life cycle. This drift can be caused by many factors: changes in temperature and humidity, electric and magnetic fields, mechanical vibrations, wear of electronic elements, etc. There are several types of the drift of measuring instrument and measurement standards, in particular: time drift, temperature drift, electrical drift, etc [6].

Periodic calibrations can help detect and account for the drift of measuring instrument and measurement standards. The drift uncertainty can be evaluated from the history of successive calibrations, and in the absence of such history, the order of magnitude of the calibration uncertainty can be estimated.

Calibrated values of measuring instruments and measurement standards in many cases have a predictable drift over time, so it is advisable to estimate their long-term drift. Temperature and some other types of drift are mainly related to the short-term drift. During the entire intercalibration interval of measuring instruments or measurement standards, it is necessary to take into account the time drift when performing accurate measurements. For many electrical measurements standards, a time drift is predictable.

Methods of estimating the drift of measurement standards

In accordance with the International Vocabulary of Metrology (VIM) [7], instrumental drift of a measuring instrument is a continuous or gradual change in readings over time due to a change in metrological properties of the measuring instrument. Such drift is due neither to a change in the quantity being measured, nor to a change in any recognized influence quantity and applies to both the measuring instrument and the measurement standard.

There are short-term and long-term drifts of a measuring instrument or measurement standard, which depend on the observation time interval used. It is quite difficult to accurately estimate the short-term drift of a measuring instrument or measurement standard by means of calibration. Successive calibrations of a measuring instrument or measurement standard allow a fairly accurate estimate of its long-term drift. The estimation of the long-term drift is mandatory to establish calibration intervals [8].

Calibration drift is associated with changes in the readings of a measuring instrument over a certain period of time during normal continuous operation. This drift is estimated by comparing a known reference value and the current measured value. The main contribution to the combined measurement uncertainty is made by a time drift since the last calibration of the measuring instrument or measurement standard [9].

The drift can be of several main types: zero drift; span drift or sensitivity drift; zonal drift, nonlinear, power, etc [6]. A long-term drift is the main tendency of a certain process to change over time or a time series, which is described by various equations: linear, logarithmic, power, etc. The actual type of drift is established based on the establishment of its functional model using statistical methods. Time series data are used to predict changes in a certain process or phenomenon. A drift line is a line along which the points representing data from a specific data time series are located on a graph.

To determine the nature of the long-term drift, the results of multiple measurements are recorded on a certain timescale (days, months, years). The drift rarely changes in the same direction and at the same speed over a long period of time. As a result of the analysis of the obtained data, the maximum change that occurs over a set period of time is determined, which allows all the necessary corrections to be made to the results of the measurements. The uncorrected drift can be considered a Type A component in the measurement uncertainty analysis.

To clearly demonstrate the drift, smoothing of the data fluctuations using a mean trend line variable is used. The average of a certain number of data points over a certain period is used as the reference point of the trend line. The average of the first two data points is used as the first point to move the average trend line if the value for that period is two. The average of the second and third data points is used as the second point of the trend line, and so on.

The ordinary least squares (OLS) can be used to study the drift. It is one of the main analysis methods for evaluating the unknown parameters of regression models based on sample data. It is based on minimizing the sum of squared deviations of the selected function from the data under consideration. The sum of the squared deviations between empirical and theoretical values of the time series is minimized [10].

A certain mathematical function describes the theoretical values and best reflects the underlying shift of the time series. It is called an adequate function and is calculated by the least squares method. The determination coefficient is used to assess the accuracy of such a drift model with using values of dispersions of theoretical data obtained according to the drift model and empirical data. The most reliable drift line is if its approximation probability value (R^2) is equal to or close to 1. The drift model is adequate for the process under consideration and reflects the tendency of its development over time with R^2 values close to 1.

A cumulative sum (CUSUM) chart is a type of control chart that is used to track small changes in a process average. This chart displays the cumulative sum of deviations from the target value for individual measurements or subgroup averages. To design a CUSUM chart, it is necessary to consider the average run length and a shift to be detected. With this modified chart it is more quickly possible to detect a process that is out-of-control at start-up [6].

The CUSUM charts for the identification of the process disorder caused by the influence of a non-random variable is show in [11]. These charts make it possible to detect the long-term drift of metrological characteristics of measuring instruments or measurement standards. The peculiarity of the CUSUM charts is that the decision regarding the compliance of the metrological characteristics with established requirements is made taking into account information about all the obtained results from the first to the last inclusive. The paper does not consider the measurement uncertainty during the calibration when using the CUSUM charts.

The CUSUM chart is not applicable to the data with a large number of decimal places and is only applicable to relative data. For such data, an Exponential Weighted Moving Average (EWMA) scheme is used. The EWMA scheme displays weighted observations in geometrically descending order. The most recent observations make a large contribution, and the latest observations make a very small contribution. Such a scheme applies to absolute data, not just relative data. The EWMA scheme can preferably be used to analyse the long-term drift of measurement standards of electrical quantities instead of the CUSUM chart [6, 12].

The EWMA scheme refers to the average value of data obtained over some time. The weight of the EWMA value decreases exponentially for each period further into the past. The EWMA value contains a previously calculated average, and the calculated result will be cumulative. Therefore, all received data contribute to the result, but the contribution factor is reduced when calculating the next period of the EWMA scheme. The distribution of the EWMA scheme over run lengths with the evaluated parameters is obtained in [13].

Estimation of the drift of the inductance measurement standards for calibrations using two methods

Analysis and consideration of the long-term drift of measurement standards during calibrations are important step to increase the measurement accuracy. The traditional method of the long-term drift analysis includes the use of regression models followed by their analysis. The coefficient of determination R^2 is used to assess the accuracy of such a drift model. In known key and supplementary comparisons of electrical measurement standards, linear regression has been used to describe the line drift of travelling measurement standards [14–19].

A portable inductance standard with nominal values of 10 mH and 100 mH at frequencies of 1 kHz and 1.6 kHz is considered in [20]. The established inductance measurement standard had measurement uncertainty of (1–3) μH/H. The time drift of the standard was no more than 30 (μH/H)/year.

Ukrainian national measurement standards of the inductance unit were established at the SE “Ukrmetrteststandard” (Kyiv, Ukraine) in 2009 and used for precision calibrations of working inductance measurement standards. Those standards took part in comparisons of national measurement standards within the framework of regional metrology organizations from 2012 to 2019 [14, 18, 19]. The high stability of these measurement standards over a rather long time period is shown by continuous measurements. Time series of measurement data of the inductance measurement standard is available from 2009 to 2022.

Thermostatically adjustable inductance measures of 10 mH (type P5109, no. 424) and 100 mH (type P5113, no. 1003) of the inductance measurement standard are specially designed at the SE “Ukrmetrteststandard” and contain a built-in precision thermostat with two temperature sensors. The drifts of those measures are 10 ppm/year. The results of the estimation of the long-term drift of measures of 10 mH and 100 mH of the inductance measurement standard at frequency of 1 kHz using the 3rd-order polynomial regression are shown in Figs 1 and 2. In the Figures, the green solid line shows the mean value for the drift, and the red dashed line shows the corresponding polynomial approximation of the drift. The specified approximations of the drift lines of the inductance measures have values of R^2 equal to 0.66 and 0.78, respectively, that is, they confirm their adequacy.

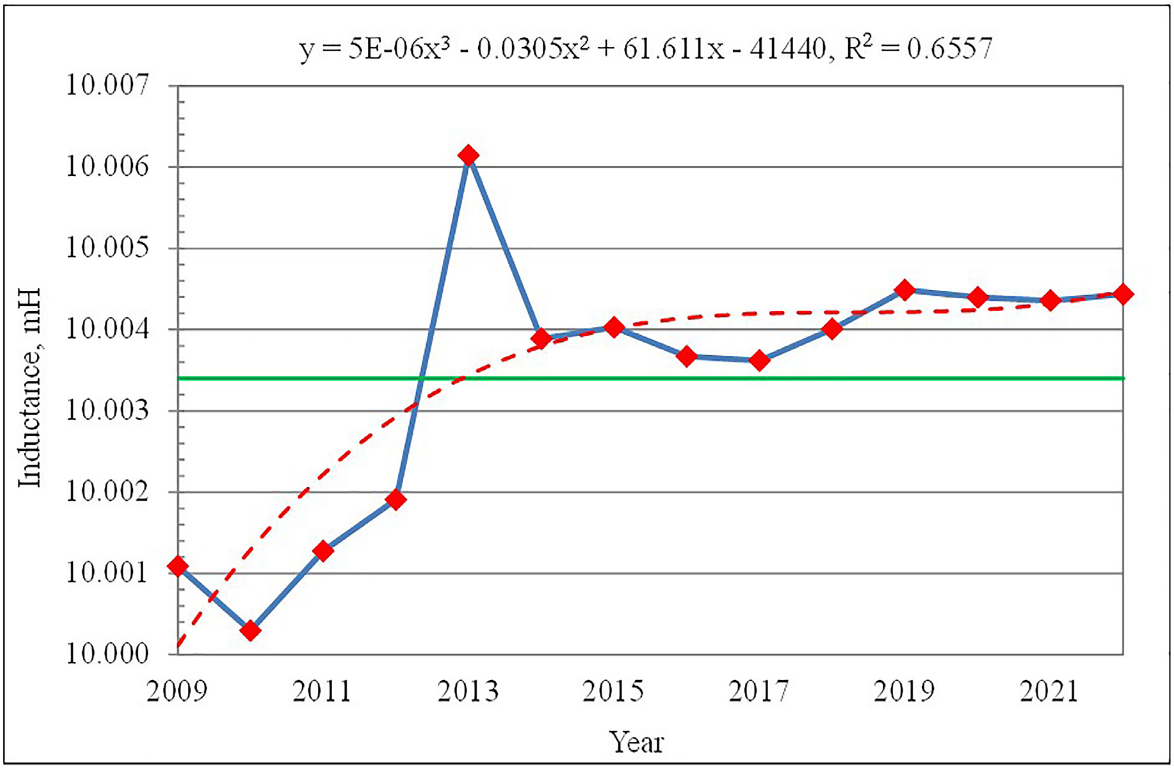

Fig. 1. Drift of 10 mH measure with polynomial regression

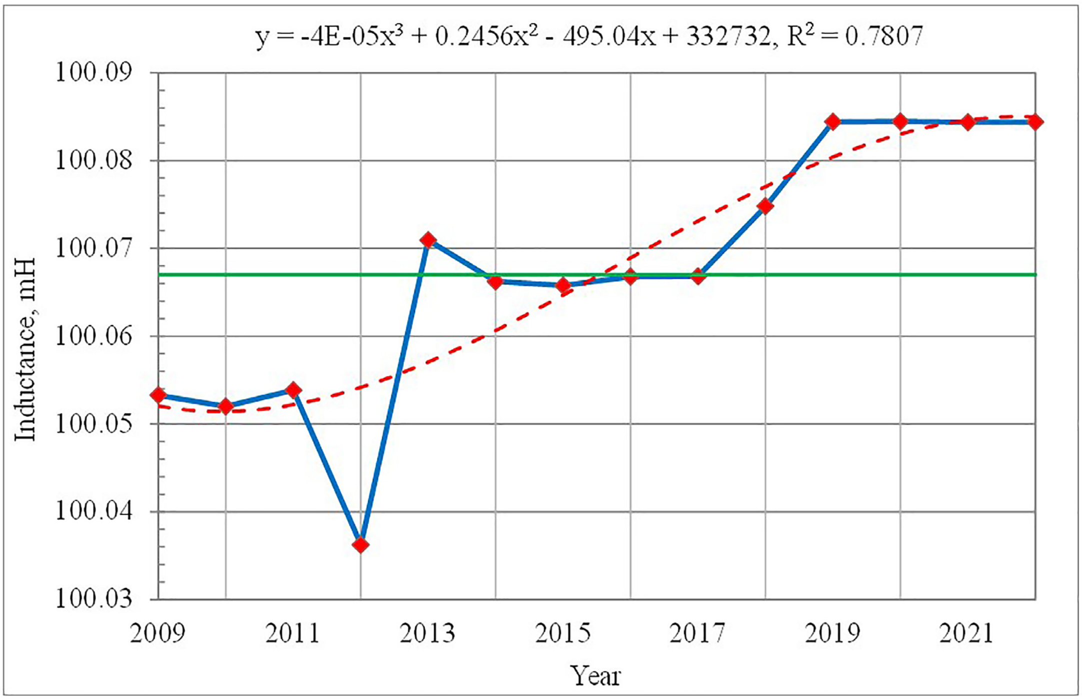

Fig. 2. Drift of 100 mH measure with polynomial regression

The mean value of 10 mH measure from 2009 to 2022 is 10.0034 mH, and of 100 mH measure it is 100.0067 mH. The difference between the maximum and minimum values of 10 mH measure for the same time period is 0.0058 mH, and of 100 mH measure it is 0.048 mH. The difference between the last and first values of 10 mH measure for the same time period is 0.0033 mH, and of 100 mH measure it is 0.031 mH. The standard deviation of 100 mH measure from 2009 to 2022 is 0.0016 mH, and of 100 mH measure it is 0.015 mH. The measurement uncertainty for the inductance measure of 10 mH was 0.21 mH/H, and for the inductance measure of 100 mH capacitance measurement standard it was 0.21 mH/H at a frequency of 1 kHz.

The drift of inductance measures from 2013 to 2022 is stabilized, as can be seen from Fig. 1 and 2, therefore it is appropriate to consider the long-term drift of the measures during this period. The results of the estimation of the long-term drift of measures of 10 mH and 100 mH from 2013 to 2022 are shown in Figs 3 and 4.

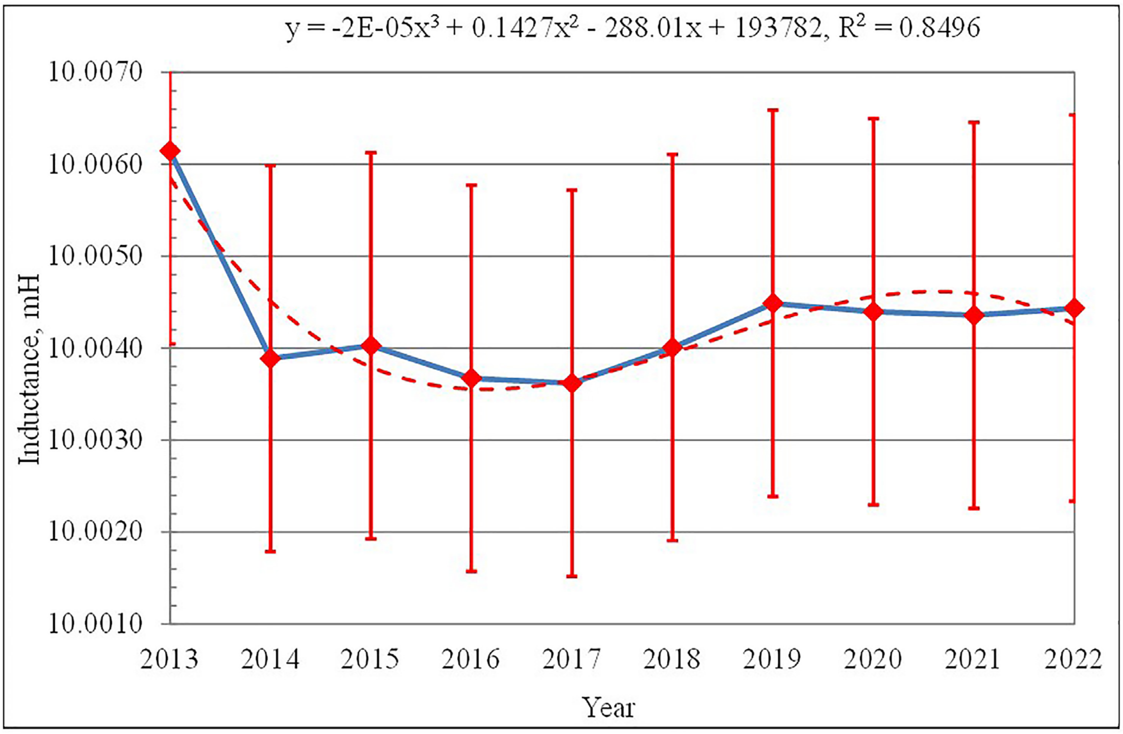

Fig. 3. Drift of 10 mH measure from 2013 to 2023

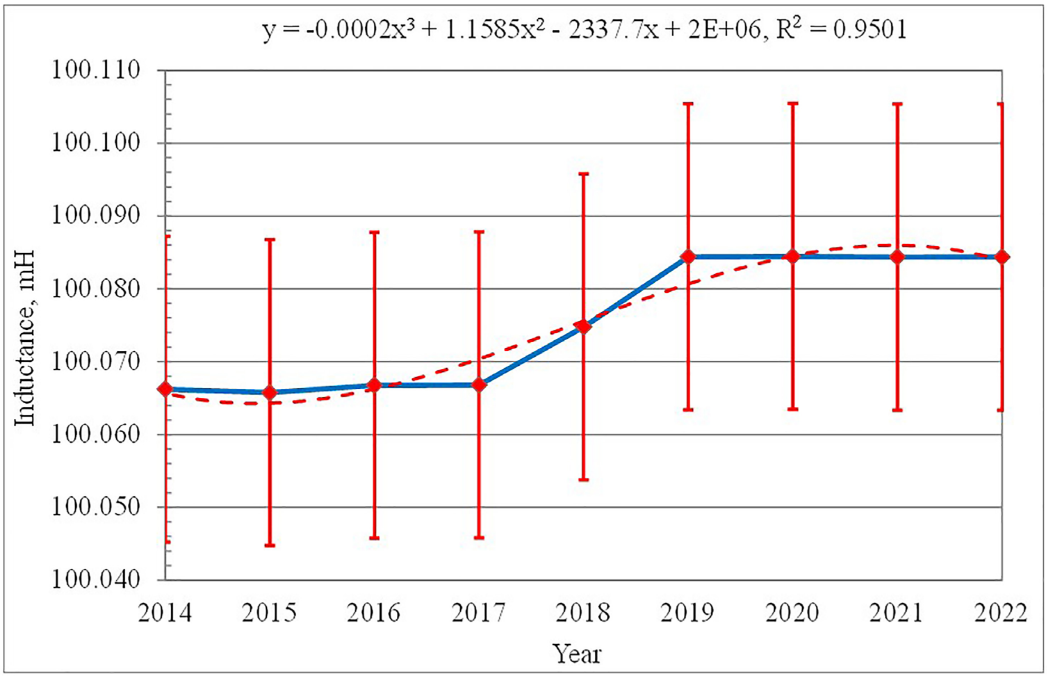

Fig. 4. Drift of 100 mH measure from 2013 to 2023

The average value of 10 mH measure from 2013 to 2022 is 10.0043 mH, and of 100 mH measure it is 100.0075 mH. The difference between the maximum and minimum values of 10 mH measure for the same time period is 0.0025 mH, and of 100 mH it is 0.018 mH. The difference between the last and first values of 10 mH measure for the same time period is –0.0017 mH, and of 100 mH measure it is 0.013 mH. The standard deviation of 100 mH measure from 2009 to 2022 is 0.0007 mH, and of 100 mH measure it is 0.009 mH. Polynomial regressions of the 3rd order are used, which have drift line approximations with values of R^2 equal to 0.85 and 0.95, respectively, that is, they confirm their adequacy.

The results of the estimation of the long-term drift of 10 mH and 100 mH measures at frequency 1 kHz using the EWMA are shown in Fig. 5 and 6. In the Figures, the green solid line shows the mean value of the drift (CL), and the red dashed line shows both the upper (UCL) and the lower (LCL) control limits. The last point of the diagram in Fig. 5 for 10 mH measure is within the calculated control limits. The last point of the diagram in Fig. 6 for 100 mH measure is above the calculated UCL, so this trend needs to be taken into account when reporting calibration results using this measure.

The results of the estimation of the long-term drift of 10 mH and 100 mH measures at frequency

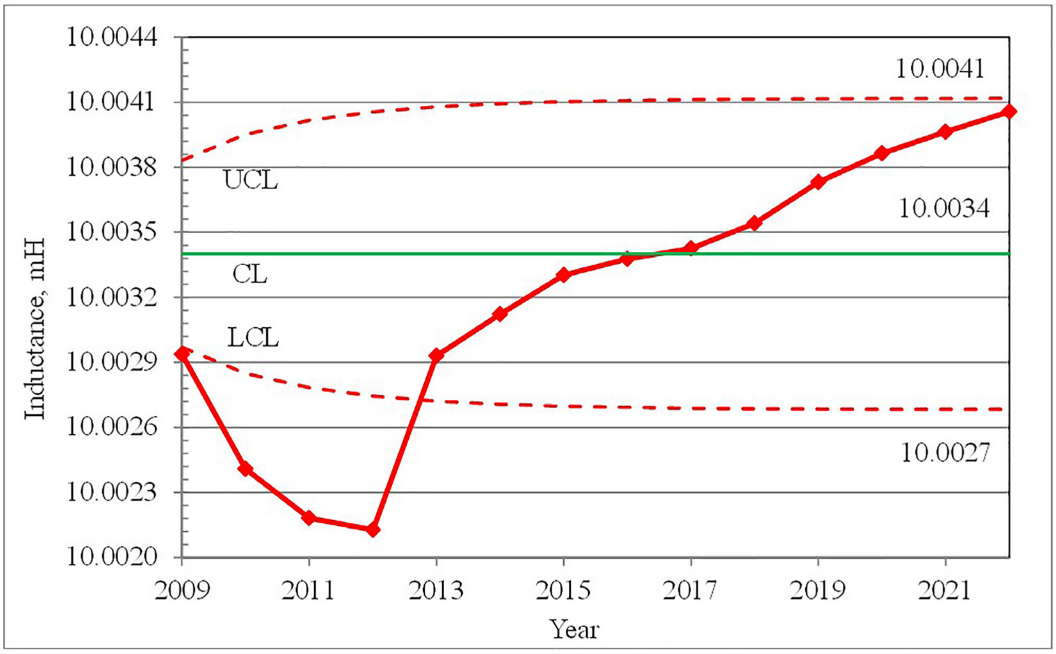

Fig. 5. Drift for 10 mH measure with EWMA

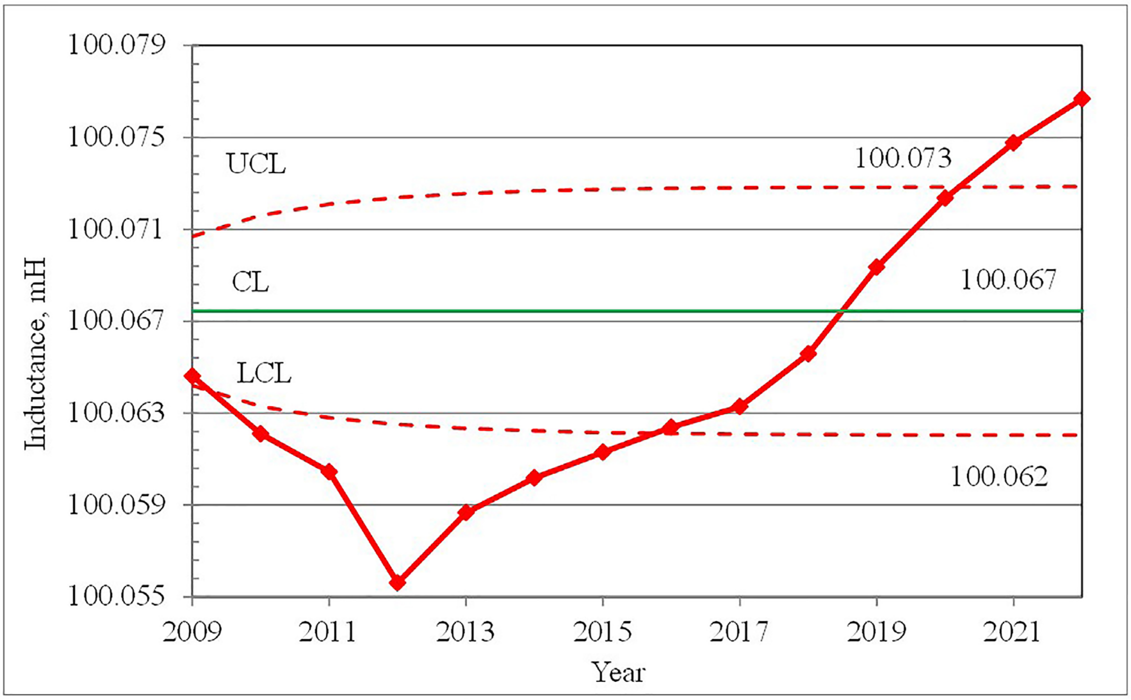

Fig. 6. Drift for 100 mH measure with EWMA

1 kHz using the EWMA schemes from 2013 to 2022 are shown in Fig. 7 and 8. The characteristics of the obtained results have become better than during the entire observation period. The similar results are obtained when using polynomial regression.

Summary

The analysis of the main methods to estimate the drift allows selecting methods for estimating the long-term drift of measurement standards and measuring instruments between their calibrations. To estimate the drift of electrical measurement standards when calibrating measuring instruments, the regression analysis methods are most often used. The EWMA scheme was also chosen to analyse the small long-term drift of high-precision inductance measurement standards.

Estimation of the drift of these measurement standards was applied for high-precision calibration using polynomial regression curves and EWMA schemes. Polynomials of the 3rd order were enough to approximate the drift of the inductance measurement standards. The difference between the maximum and

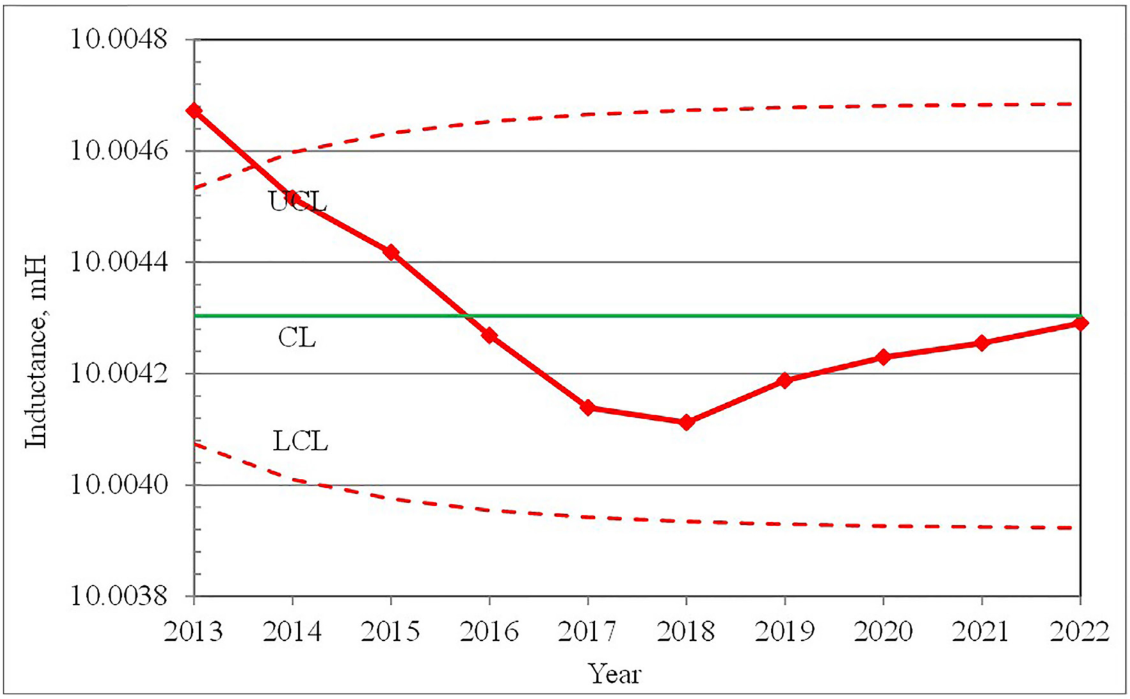

Fig. 7. Drift for 10 mH measure with EWMA from 2013 to 2022

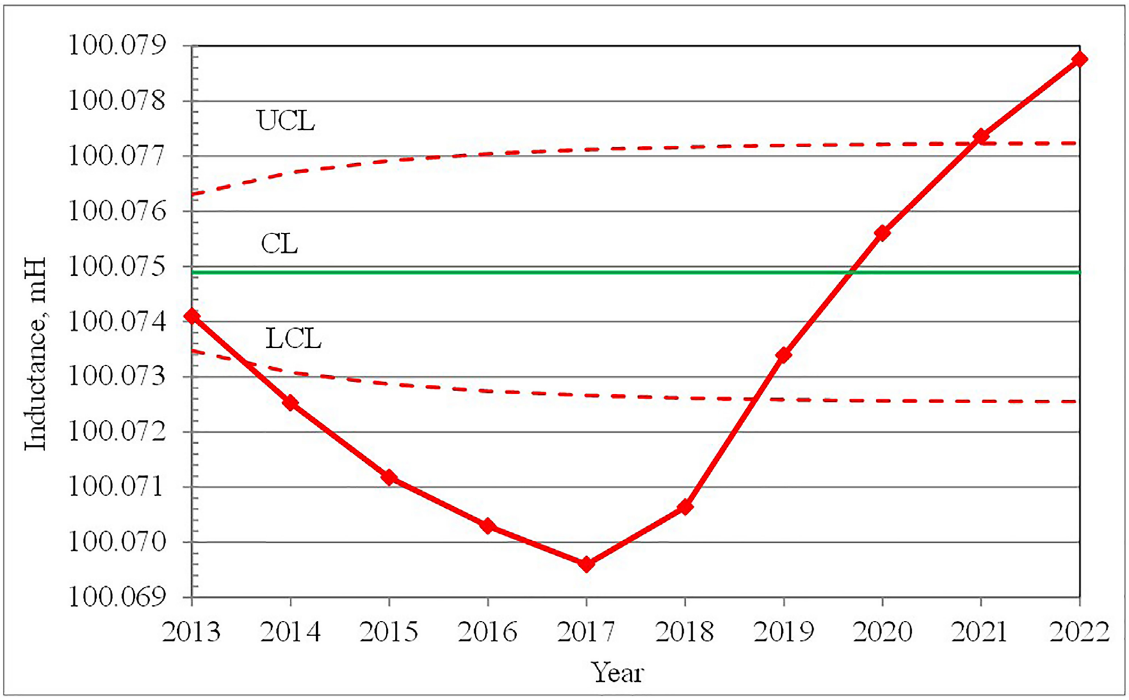

Fig. 8. Drift for 100 mH measure with EWMA from 2013 to 2022

minimum values of 10 mH measure from 2009 to 2022 is 0.0058 mH, and of 100 mH it is 0.048 mH. The same difference of 10 mH measure from 2013 to 2022 is 0.0025 mH, and of 100 mH it is 0.018 mH. This shows a 2.3-fold and 2.7-fold improvement in the drift characteristics of the measures over the last time period, respectively.

The EWMA reduces the lag inherent in traditional moving averages, as it assigns more weight to recent observations. The application of the EWMA schemes of comparison with regression analysis shows a greater sensitivity to the change of the drift in the last years of observations. This allows the laboratory to take this factor into account when calibrating measuring instruments and measurement standards.

Оцінка довготривалого дрейфу еталонів індуктивності

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Анотація

Вимірювання індуктивності є важливим у багатьох галузях, особливо в електроніці, електротехніці, радіотехніці тощо. Індуктивність часто є важливим параметром у широкому діапазоні застосувань, таких як радіопередавачі, схеми живлення, магнітно-резонансні імпульсні джерела. Точність індуктивності впливає на якість продукції, особливо в пристроях, де використовуються котушки індуктивності, наприклад фільтри, трансформатори, інвертори тощо. Високоточні вимірювання індуктивності використовуються для контролю якості продукції, щоб переконатися, що вироблені пристрої відповідають встановленим специфікаціям і стандартам.

Дрейф є небажаною властивістю всіх засобів вимірювання та еталонів протягом їхнього життєвого циклу. Аналіз інструментального дрейфу еталонів має велике значення в метрології. Надійний облік дрейфу відіграє важливу роль у підтримці точності вимірювань. Для електричних еталонів довгостроковий дрейф є передбачуваним. Проведено аналіз видів дрейфу та основних методів його оцінки еталонів між їх калібруваннями. Невизначеність дрейфу можна оцінити на основі історії послідовних калібрувань, а за відсутності такої історії можна зробити оцінку порядку величини невизначеності калібрування.

Наведено результати оцінки довготривалого дрейфу еталонів індуктивності для високоточного калібрування засобів вимірювання та еталонів двома методами: діаграмами поліноміальної регресії та діаграмами експоненційного зваженого ковзного середнього (EWMA). Графіки EWMA зменшують відставання, властиве традиційним ковзним середнім, надаючи більшої ваги останнім спостереженням. Показано, що використання діаграм EWMA порівняно з регресійним аналізом демонструє більшу чутливість до змін дрейфу в останні роки спостережень. Це дозволяє лабораторії враховувати цей фактор при калібруванні засобів вимірювання та еталонів.

Ключові слова: довготривалий дрейф; еталон індуктивності; невизначеність вимірювання; поліноміальна регресія; експоненційне зважене ковзне середнє.

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