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UNCERTAINTY EVALUATION OF THE DISSIPATION FACTOR IN THE CALIBRATION OF PRECISION CAPACITANCE STANDARDS

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This paper presents a methodological and metrological approach to thecalibration of precision capacitance standards with respect to the dissipation factor (loss factor) at the State Primary Standard of Electrical Capacitance and Dissipation Factor. The relevance of the study is driven by the need to ensure high accuracy measurements of capacitance and loss parameters in capacitors widely used in measurement systems and instrumentation, power engineering, telecommunications, and, in particular, electrical insulation testing equipment. The dissipation factor is an important characteristic of dielectric materials and capacitorsdetermining the level of energy losses in the dielectric and significantly affecting the accuracy of complex impedance measurements, as well as the results of electrical insulation diagnostics.
A measurement system used for the calibration of precision capacitance standards with respect to the dissipation factor is presented, and its operating principle is described. A mathematicalmeasurement model has been developed that accounts for the main contributors affecting the determination of the dissipation factor, including measuring bridge parameters, quadrature signal errors, frequency and supply voltage instability, and parasitic losses in the measurement circuit. The measurement model equation is presented, and the physical meaning of its individual components is discussed in detail.
Particular attention is devoted to the analysis of measurement uncertainty sources and the development of an uncertainty budget for the calibration procedure. An example is provided for calculating the combined standard uncertainty and expanded uncertainty of the calibration result for a precision capacitance standard with respect to the dissipation factor. The obtained results may be used in the development of calibration procedures for capacitance standards based on the dissipation factor and in ensuring the metrological traceability of capacitor parameter measurements to the State Primary Standard. References 20, figures 5, table 1.
Keywords: uncertainty budget, capacitance standard, measurement model, State Primary Standard, precision capacitor, measurement traceability, dissipation factor, loss factor.

Introduction. Measurement of capacitance and dielectric loss parameters is an important area of modern electromagnetic metrology. One of the key characteristics of capacitors and dielectric materials is the dissipation factor, which represents the ratio of the active current component associated with energy losses in the dielectric to the reactive current component associated with energy storage in the electric field. This parameter characterizes the quality of the dielectric and serves as an important indicator of the performance of insulating materials and capacitors [1].

The physical meaning of the dissipation factor can be explained as follows. In a real capacitor, the dielectric is not ideal and therefore exhibits energy losses. As a result, an active current component appears in

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addition to the reactive component. The dissipation factor is independent of the geometric dimensions of the capacitor and is determined primarily by the properties and structure of the dielectric material itself.

An ideal capacitor does not conduct direct current, and under alternating current conditions the current leads the voltage by 90°. In a real capacitor, this phase shift is slightly smaller due to dielectric losses. The difference between the ideal phase shift of 90° and the actual phase shift is referred to as the dielectric loss angle.

The dielectric loss angle δ is shown in Fig. 1.

A real capacitor is commonly represented by an equivqlent circuit consisting of an ideal capacitance C connected in parallel with an ideal resistance, which causes losses R_{loss}. The equivalent circuit of such a capacitor is shown in Fig. 2.

In this model, the dissipation factor is defined as the ratio of the active current component to the reactive current component:

$$\tan\delta = I_R / I_C .$$

A capacitor may also be represented by an equivalent circuit consisting of a series connection of an equivqlent loss resistance R_{loss} and an ideal capacitance C. The corresponding series equivalent circuit is shown in Fig. 3.

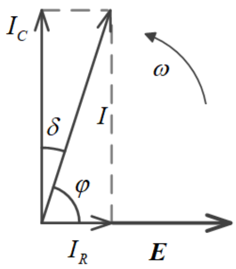

Fig. 1

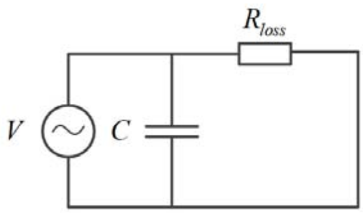

Fig. 2

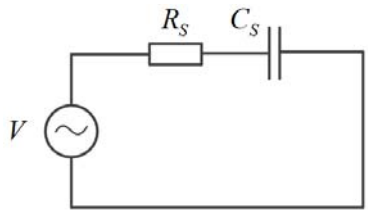

Fig. 3

The dissipation factor is determined by the formula:

$$\tan\delta = \omega C R_S ,$$

where $\omega = 2\pi f$ is the angular frequency; C is the capacitance; and R_S is the equivalent series resistance.

For standard air, gas-filled, or silicon capacitors, the dissipation factor typically ranges from 1×10^{-8} to 1×10^{-5}. Therefore, measurement of $\tan\delta$ is considerably more challenging than measurement of capacitance itself.

Dissipation factor measurements are widely used in measurement technology, power engineering, telecommunications and other fields where capacitors with stringent requirements for parameter stability are employed [2, 3]. In particular, the dissipation factor is used to assess the condition of the electrical insulation of high-voltage equipment and for the diagnostics of transformers, cable systems, and capacitor banks. An increase in the dissipation factor value may indicate dielectric aging or degradation, the presence of moisture, partial discharges, or other insulation defects. Therefore, accurate determination of this parameter is essential for ensuring the reliable operation of electrical equipment, including critical infrastructure facilities.

To ensure the reliability and international recognition of measurement results, their metrological traceability to international and national measurement standards must be established [4].

However, the calibration of precision capacitance standards with respect to the dissipation factor is associated with a number of challenging metrological problems [5, 6]. These include the influence of parasitic losses in the measurement circuit, errors in the generation of the quadrature signal component, instability of the excitation frequency and voltage, as well as the effects of temperature and other environmental factors on the measurement results. Additional difficulties arise in developing an adequate measurement model and in the proper evaluation of calibration uncertainty, since the dissipation factor of precision capacitors is typically extremely small.

Therefore, the development and improvement of a methodological approach to the calibration of precision capacitance standards with respect to the dissipation factor, the establishment of an appropriate measurement model, and the development of a reliable uncertainty budget remain relevant tasks. This paper is devoted to addressing these issues.

The scientific novelty of the work is as follows:

– A methodological approach to the calibration of precision capacitance standards for the determination of the dissipation factor (loss tangent) using the State Primary Standard of Electrical Capacitance and Dissipation Factor has been developed. In contrast to existing approaches, it is based on the application of the modern framework for measurement uncertainty evaluation in accordance with the requirements of the international guidance documents JCGM [7] and EA [8], thereby ensuring international recognition of calibration results and improving the reliability of uncertainty evaluation;

– An extended measurement model has been developed which, unlike existing models, enables comprehensive consideration of all significant sources of measurement uncertainty and provides a sound basis for the establishment of a well-justified uncertainty budget.

1. Justification for developing a methodical approach to the calibration of capacitance standards for the dissipation factor measurements using the State Primary Standard. The modern development of the national metrology system of Ukraine is taking place in the context of European integration and the harmonization of technical regulations with European Union legislation. One of the key elements of this system is ensuring the metrological traceability of measurement results to the units of the International System of Units (SI) [9] through the national standards infrastructure. According to the requirements of the international standard DSTU EN ISO/IEC 17025 [10], laboratories are required to ensure the metrological traceability of measurement results through a documented and unbroken chain of calibrations, each contributing to the overall measurement uncertainty.

In this context, the development and improvement of methodical approach to the calibration of precision capacitance standards for dissipation factor ($\tan\delta$) measurements is of particular importance. This parameter characterizes energy losses in the capacitor dielectric and represents an important characteristic when capacitors are used as standards in precision impedance measurements. The availability of reliable information on the dissipation factor is essential for ensuring high-accuracy measurements in electrical metrology, particularly in the calibration of impedance bridges, capacitance meters, and other high-precision measuring instruments.

The importance of implementing such a methodological approach is driven by the need for international recognition of measurement results obtained by national metrological institutes. Ukraine participates in the international metrological infrastructure and is a signatory to the Mutual Recognition Agreement of the International Committee for Weights and Measures (CIPM MRA) [11], which provides the basis for the international recognition of national measurement standards, calibration certificates, and measurement results. Within the framework of the CIPM MRA, the measurement capabilities of national metrology institutes are confirmed through international comparisons that demonstrate the equivalence of national standards maintained by different countries and thereby establish confidence in calibration and measurement results.

The development and implementation of national calibration procedures based on the proposed approach will also contribute to the removal of technical barriers to international trade, since international recognition of measurement results enables the mutual acceptance of testing and calibration results among countries. This, in turn, facilitates Ukraine's integration into the European economic area and enhances the competitiveness of Ukrainian products in international markets.

Despite significant advances in electrical metrology, the calibration of capacitance standards for dissipation factor measurements and the evaluation of the associated measurement uncertainty remain challenging scientific and technical tasks. This is due to the extremely small values of the dissipation factor in precision capacitors, the significant influence of parasitic elements in measurement circuits, the instability of connecting cable parameters, and the effects of frequency, temperature, and other environmental factors on the measurement result. In addition, the development of an appropriate measurement model is of particular importance, since it enables comprehensive consideration of all significant contributors to measurement uncertainty and provides a sound basis for establishing an uncertainty budget in accordance with recommendations of international documents on measurement uncertainty evaluation [7, 8, 10].

Therefore, there is a need to develop a scientifically substantiated approach to the calibration of precision capacitance standards for dissipation factor measurement using the State Primary Standard of Electrical Capacitance and Dissipation Factor. Such an approach should comply with the requirements of ISO/IEC 17025 [10], ensure metrological traceability of measurement results, and provide calibration results with properly evaluated and documented uncertainty.

The results of this work are important for the further development of the national metrology infrastructure, the expansion of Ukraine's calibration and measurement capabilities, and the international recognition of measurement results in the field of electrical metrology.

2. Technical facilities used for calibration. In 2001, the State Enterprise "UKRMETRTESTSTANDART" developed and commissioned the State Primary Standard of Electrical Capacitance and Dissipation Factor DETU 08-06-01. appearance phtograph of the standard is shown in Fig. 4.

The State Primary Standard of Electrical Capacitance and Dissipation Factor comprises of the following measurement facilities:

– a set of Andeen-Hagerling type AH11A 10 pF reference capacitance standards (4 units);
– a set of Andeen-Hagerling type AH11A 100 pF reference capacitance standards (4 units);
– a set of transfer capacitance standards covering the range from 1 pF to 1.0 μF;
– a set of reference resistance standards covering the range from 0.1 Ohm to 1.0 MOhm;
– a Model 5100 Universal Impedance Comparator;
– auxiliary equipment.

Fig. 4

The standard reproduces electrical capacitance values in the range from $1 \cdot 10^{-3}$ pF to 100 μF and dissipation factor values in the range from $1 \cdot 10^{-7}$ to 1.0.

Temperature-controlled Andeen-Hagerling type AH11A reference capacitance standards are used to form two group capacitance standards with nominal values of 10 pF and 100 pF.

The State Primary Standard provides reproduction of the units of electrical capacitance and dissipation factor at a frequency of 1000.0 Hz.

The comparator incorporated in DETU 08-06-01 enables the transfer of the of the units of impedance parameters over the measurement range defined by the available sets of resistance and capacitance standards [11].

The State Primary Standard of Electrical Capacitance and Dissipation Factor provides the reproduction, maintenance, and transfer of the dissipation factor unit to precision capacitance standards used as secondary and working standards in calibration and testing laboratories.

3. Ensuring metrological traceability of capacitance and dissipation factor measurements. The reference capacitance standards forming the group standards have been continuously studied for more than 25 years. Owing to calibrations performed at leading national metrology institutes, including BIPM (France), PTB (Germany), NIST (USA), NPL (Great Britain), GUM (Poland), and CMI (Czech Republic), as well as investigations carried out at the State Enterprise "UKRMETRTESTSTANDART", the capacitance values of the AH11A reference standards are known with an expanded uncertainty of $U\left(\hat{C}_{AH}\right) = 1.0 \cdot 10^{-7}$ pF, while their dissipation factor values are known with expanded uncertainty of $U\left(\widehat{\tan\delta}\right) = 6.0 \cdot 10^{-7}$, corresponding to a coverage factor $k = 2$ and a confidence level p, which is approximately equal to 0.95. Continuous investigations of these standards make it possible to evaluate and account for the drift of their principal metrological characteristics.

The results of international comparisons involving the State Primary Standard [12] confirm the calibration and measurement capabilities (CMC) of the State Enterprise "UKRMETRTESTSTANDART", which are published in Annex C of the CIPM Mutual Recognition Arrangement (CIPM MRA) [13]. In accordance with the CIPM MRA, calibration and measurement results issued by participating national metrology institutes are mutually recognized within the specified ranges, measurement parameters, and uncertainties published in the BIPM Key Comparison Database (KCDB) [14].

4. Calibration of capacitance standards by dissipation factor measurements. Before the measurements are initiated, the Model 5100 Universal Impedance Comparator shall be subjected to the automatic calibration procedure in accordance with the manufacturer's operating manual.

Following completion of the automatic calibration procedure, the comparator is calibrated against an external reference capacitance standard using the measurement configuration shown in Fig. 5.

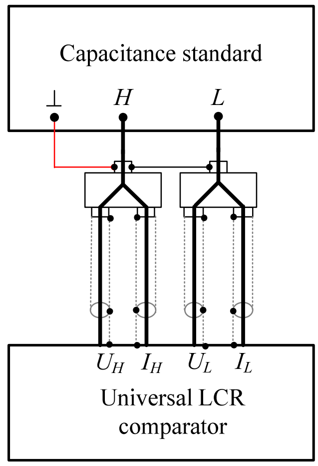

Fig. 5

A reference capacitance standard with known capacitance and dissipation factor values specified in its calibration certificate is connected to the comparator using standard measurement cables. The high-potential (*H*) and low-potential (*L*) terminals of the capacitance standard shall be connected to the corresponding *H* and *L* terminals of the comparator. The comparator housing, the capacitance standard housing, and the cable shields shall be connected to a common ground.

The capacitance and dissipation factor values specified in the calibration certificate of the reference standard, taking into account the drift since the previous calibration, are entered into the corresponding fields of the comparator software. Subsequently, the external standard calibration mode is activated, during which the internal standards of the comparator are calibrated.

To determine the comparator calibration error (comparison error), a series of 10 measurements of the capacitance and dissipation factor of the reference standard is performed.

The capacitance and dissipation factor are measured simultaneously and displayed by the comparator. The numerical value of the comparison error $\Delta\tan\delta_{CE}$ is determined as the difference between the actual and average measured dissipation factor values.

The standard uncertainty associated with the comparison error is evaluated taking into account the standard deviation obtained from the series of 10 measurements in accordance with [7, 8]:

$$u_A(\widehat{\Delta\tan\delta_{CE}}) = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}\left(\widehat{\tan\delta_{Ci}} - \overline{\widehat{\tan\delta_C}}\right)^2}, \ n = 10;$$

as well as the uncertainty associated with the quantization error of the comparator readings:

$$u_B(\widehat{\Delta\tan\delta_{QC}}) = \frac{a}{2\sqrt{3}},$$

where a is the comparator readings discretization step [7-8].

For calibration of capacitance standards for dissipation factor measurements, a measurement configuration similar to that shown in Fig. 5 is used. Capacitance and dissipation factor measurements are performed by the comparator at an applied RMS voltage of 100.0 V and a frequency of 1000.0 Hz. A series of 10 measurements of the capacitance and dissipation factor of the capacitance standard under calibration is then carried out.

5. Development of a measurement model for dissipation factor determination and evaluation of measurement uncertainty. During the calibration of a capacitance standard, the dissipation factor $\tan\delta_X$ of the standard under calibration is determined using the following measurement model:

$$\tan\delta_X = \tan\delta_S + \Delta\tan\delta_C + \Delta\tan\delta_{QC} + \Delta\tan\delta_{TX} + \Delta\tan\delta_{SC} + \Delta\tan\delta_{CE} + \Delta\tan\delta_{S\gamma},$$

where $\tan\delta_S$ is the dissipation factor of the reference standard taken from its calibration certificate; $\Delta\tan\delta_C$ is the correction associated with the difference between the dissipation factor value reproduced by the reference standard and the value measured by the comparator. Its numerical value is determined as the difference between the mean value obtained from a series of ten comparator readings and the certified value of the reference standard, taking into account the drift since its last calibration:

$$\widehat{\Delta\tan\delta_C} = \overline{\widehat{\tan\delta_C}} - \left(\widehat{\tan\delta_S} + \widehat{\Delta\tan\delta_{S\gamma}}\right),$$

its type A standard uncertainty is evaluated, in accordance with [7, 8], as the standard deviation of the comparator readings of a series of 10 measurements:

$$u_A(\widehat{\Delta \tan \delta_C}) = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} \left(\widehat{\tan\delta_{Ci}} - \overline{\widehat{\tan\delta_C}} \right)^2}, \; n = 10;$$

$\Delta \tan \delta_{QC}$ is the correction for the comparator quantization error. Its numerical value is assumed to be zero, while the corresponding standard uncertainty is evaluated from the comparator resolution in the same manner as the one above $u_B(\widehat{\Delta \tan \delta_{QC}})$; $\Delta \tan \delta_{TX}$ is the correction associated with the temperature dependence of the capacitor under calibration. Its numerical value is assumed to be zero when the capacitor is used at the same temperature at which it was calibrated. The corresponding standard uncertainty is determined as:

$$u(\Delta \tan \delta_{TX}) = \frac{\hat{K}_{\tan \delta_{TX}} (t_{\max} - t_{\min})}{2\sqrt{3}},$$

where $K_{\tan \delta_{TX}}$ is the temperature coefficient of the dissipation factor. Its value is obtained either from the manufacturer's specifications for the capacitor under calibration [15] or from additional investigations [5-6]; $t_{\min}$ and $t_{\max}$ are the limits of the temperature range within which the capacitor is calibrated; $\Delta \tan \delta_{SC}$ is the correction associated with the comparator sensitivity , whose numerical value is taken from the manufacturer's specifications; $\Delta \tan \delta_{CE}$ is the correction associated with the comparator comparison error (see above); $\Delta \tan \delta_{S\gamma}$ is the correction accounting for the drift of the dissipation factor of the reference standard since its last calibration. To evaluate the drift and its associated uncertainty, the predicted value of the dissipation factor of the reference standard at the calibration date shall be determined in accordance with [16–20].

The temperature coefficient of the dissipation factor $K_{\tan \delta_{TX}}$ is an important metrological characteristic of precision capacitance standards, describing the variation of $\tan \delta$ under the influence of temperature. The physical basis of this dependence is associated with a combination of processes occurring within the capacitor dielectric, including the temperature dependence of electrical conductivity and dielectric polarization mechanisms. As the temperature increases, the conductivity of the dielectric material generally increases, resulting in a higher active current component and, consequently, an increase in the dissipation factor. Furthermore, temperature variations affect dielectric relaxation processes, which may lead to a nonlinear dependence of $\tan \delta$ on temperature, particularly in capacitors employing complex or composite dielectric materials.

The temperature coefficient $K_{\tan \delta_{TX}}$ is also influenced by the design features of the capacitor and the measurement conditions. These factors include parasitic losses in conductive elements, contact resistances, surface leakage currents, and the properties of insulating materials. Variations in temperature may alter these parameters and thereby affect the measured value of the dissipation factor. The frequency of the measurement signal is another important factor, since the relative contributions of conductive and dielectric losses depend on frequency, which in turn influences the temperature dependence of $\tan \delta$. In high-accuracy measurements, it is also necessary to consider the influence of external factors, particularly humidity and temperature gradients, which may introduce additional instabilities and errors.

For precision capacitors, for which the values of $\tan \delta$ are extremely small (typically in the range of 10 to 10^{-5}), even minor temperature variations may result in significant relative deviations of the measurement results. Therefore, maintaining stable temperature conditions, particularly through temperature control, is an essential requirement for high-accuracy calibrations. The temperature coefficient of the dissipation factor $K_{\tan \delta_{TX}}$ must be taken into account in the measurement model through an appropriate correction term and included in the uncertainty budget as a significant source of measurement uncertainty. This contributes to the reliability of the calibration results and ensures their metrological traceability to national and international measurement standard.

Table 1 presents an example of an uncertainty budget ($\tan \delta_X$)for dissipation factor calibration of precision capacitors.

The standard uncertainty associated with the dissipation factor of the reference standard $u(\tan \delta_S)$ is obtained from its calibration certificate.

The combined standard uncertainty of the dissipation factor is calculated from the uncertainty contributions $u_i\left(\widehat{\tan\delta_X}\right)$ listed in Table 1 according to the following expression:

$$u\left(\widehat{\tan\delta_X}\right)=\sqrt{\sum_{i=1}^{m}u_i^2\left(\widehat{\tan\delta_X}\right)}\ .$$

The expanded uncertainty presented in Table 1 is calculated using the following expression:

$$U=k\cdot u\left(\tan\delta_X\right)=2\cdot 3.92\mathrm{E}-06=7.83\mathrm{E}-06$$

with coverage factor $k=2$ and $p=0.95$.

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Type of standard uncertainty evaluation	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$
$\tan\delta_S$	1.06E-06	1.50E-06	normal	B	1	1.50E-06
$\Delta\tan\delta_C$	-2.48E-07	2.91E-06	normal	A	1	2.91E-06
$\Delta\tan\delta_{QC}$	0	5.78E-07	rectang.	B	1	5.78E-07
$\Delta\tan\delta_{TX}$	0	1.80E-07	normal	B	1	1.80E-07
$\Delta\tan\delta_{SC}$	0	1.05E-07	normal	B	1	1.05E-07
$\Delta\tan\delta_{CE}$	-1.30E-06	1.80E-06	normal	B	1	1.80E-06
$\Delta\tan\delta_{S\gamma}$	1.20E-07	1.00E-06	normal	B	1	1.00E-06
$\tan\delta_X$	9.32E-07	Combined standard uncertainty			u_c	3.92E-06
		Effective degrees of freedom			n_{eff}	>200, $k=2$
		Expanded uncertainty (p » 95 %)			U	7.83E-06

The stability of the 1000 Hz measurement frequency makes it possible to neglect the frequency dependence of both the reference standard and the c capacitance standard under calibration.

Conclusions.

1. A methodological approach to the calibration of precision capacitance standards for dissipation factor at the State Primary Standard of Electrical Capacitance and Dissipation Factor has been developed and scientifically substantiated. The proposed approach is based on the use of a Universal Impedance Comparator, a measurement model, and a well-founded uncertainty budget, enabling the main factors affecting the determination of the dissipation factor to be taken into account.

2. A measurement model has been developed that describes the determination process of the dissipation factor during the calibration of capacitance standards and takes into account contributions associated with the reference standard, comparison errors, temperature effects, comparator quantization, and drift of the reference standard characteristics. Based on this model, an uncertainty budget has been established, enabling quantitative evaluation of the contributions of individual uncertainty sources to the combined standard uncertainty of the measurement result.

3. It has been shown that the measurement of the dissipation factor of precision capacitors is a challenging metrological task owing to the extremely small values of this parameter and the significant influence of parasitic losses in the measurement circuit. The obtained results demonstrate the feasibility of determining the dissipation factor with a properly evaluated uncertainty that satisfies modern requirements for high-accuracy electrical measurements.

4. The proposed approach ensures the metrological traceability of capacitor parameter measurements to the State Primary Standard of Electrical Capacitance and Dissipation Factor and can be applied in the calibration of secondary and working capacitance standards used in calibration and testing laboratories.

5. The results of this study contribute to the further development of Ukraine's national metrology infrastructure by improvingthe methodological basis for the calibration of measuring instruments used in electromagnetic measurements. Implementation of the proposed approach will facilitate international recognition of measurement results and their mutual acceptance within the framework of the CIPM Mutual Recognition Arrangement (CIPM MRA) [13].

6. Practical implementation of the proposed approach will contribute to improving the reliability of capacitor parameter measurements and of measurements involving other components of electrical systems used in measuring equipment, power engineering, telecommunications, and electrical insulation testing. The results of this work support the reliable operation of energy infrastructure, the development of high-technology industries, and the further integration of Ukraine into the international metrological and economic community.

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ОЦІНКА НЕВИЗНАЧЕНОСТІ ТАНГЕНСА КУТА ВТРАТ ПІД ЧАС КАЛІБРУВАННЯ ПРЕЦИЗІЙНИХ МІР ЕЛЕКТРИЧНОЇ ЄМНОСТІ

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Розглянуто методичний та метрологічний підхід до калібрування прецизійних мір електричної ємності за тангенсом кута діелектричних втрат на Державному первинному еталоні одиниць електричної ємності та фактора втрат. Актуальність дослідження зумовлена необхідністю забезпечення високої точності вимірювань параметрів ємності та втрат у конденсаторах, що широко застосовуються у вимірювальній техніці, енергетиці, телекомунікаційних системах тощо, насамперед, у засобах контролю електроізоляції. Тангенс кута втрат є важливою характеристикою діелектричних матеріалів і конденсаторів, яка визначає рівень енергетичних втрат у діелектрику та істотно впливає на точність вимірювання комплексного імпедансу, а також на результати діагностики електроізоляційних систем.
У роботі наведено структурну схему вимірювань, що використовується для калібрування прецизійних мір ємності за тангенсом кута втрат, та описано принцип її функціонування. Розроблено математичну модель вимірювань, яка враховує основні складові, що впливають на результат визначення тангенса кута втрат, зокрема параметри вимірювального моста, похибки квадратурного сигналу, вплив нестабільності частоти та напруги живлення, а також паразитні втрати в елементах вимірювального тракту. Подано модельне рівняння вимірювання та здійснено детальну інтерпретацію фізичного змісту його складових.
Особливу увагу приділено аналізу джерел невизначеності вимірювань та формуванню бюджету невизначеності для процедури калібрування. Наведено приклад розрахунку сумарної стандартної та розширеної невизначеності результату калібрування прецизійної міри ємності за тангенсом кута втрат. Отримані результати можуть бути використані задля розроблення методик калібрування мір ємності за тангенсом кута втрат та забезпечення метрологічної простежуваності вимірювань параметрів електричних конденсаторів до Державного первинного еталона. Бібл. 20, рис. 5, табл. 1.
Ключові слова: бюджет невизначеності, міра ємності, модель вимірювань, державний первинний еталон, прецизійний конденсатор, простежуваність вимірювань, тангенс кута втрат, фактор втрат.

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