METROLOGY, QUALITY, STANDARDIZATION AND CERTIFICATION

RESEARCH OF PHASE STANDARD OF THE STATE PRIMARY STANDARDS OF UNIT PHASE SHIFT ANGLE BETWEEN TWO VOLTAGES

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Abstract. The measurement of the phase shift angle (PSA) between two voltage harmonics is important in many areas of electrical engineering and electronics. They are used in the analysis of alternating currents and electrical systems and are a key tool for evaluating their quality and efficiency. The main purpose of phase meters is to measure the phase shift, which allows analyzing the operation of electrical and electronic systems, increasing their efficiency, and diagnosing malfunctions. Phase meters directly measure the PSA between two signals. Modern phase meters have a high resolution and are able to measure the phase shift with an accuracy of thousandths of a degree. In the electric power industry, phase standards help maintain phase stability and synchronization in large electrical networks in a variety of industries, from industry to scientific research. Phase standards are used to calibrate phase meters, oscilloscopes, and other measuring equipment that measures phase shifts. The basis of the precise PSA standard is the applied phase standard, which determines its general metrological characteristics. This phase standard must be regularly calibrated by leading national metrology institutes. Its obtained metrological characteristics can be the basis for publishing CMC of a certain national metrological institute. The national standard of the PSA of Ukraine has established metrological traceability to the national metrological institute of Germany – PTB. This traceability made it possible to publish CMC of Ukraine both for the phase generator (standard) and for the phase meter included in the standard. These CMC correspond to the established metrological characteristics of the national standard. To assess the long-term stability of standards, the method of regression analysis is most often used. Polynomials of the third degree were sufficient to approximate its drift line of the PSA standard for various PSA in the period from 2011 to 2024. The indicated approximations of the drift lines have confirmed their adequacy.

Key words: Phase shift angle, phase standards, voltage, phase measurements, measurement standard.

1. Introduction

Measuring the phase shift angle (PSA) between two harmonic voltages is important in many areas of electrical engineering and electronics. They are used in the analysis of alternating currents and electrical systems and are a key tool for evaluating their quality and efficiency. Measurement of PSA has several key features that determine its accuracy and reliability. Both harmonic voltages must have the same frequency. If the signal frequencies are different, it will be impossible to measure the phase shift angle correctly, because the phase shift will constantly change over time. In addition, with significant differences in the amplitudes of the two signals, it may be more difficult to accurately record the moments of the transition through zero or other characteristic points [1, 2].

The main purpose of phase meters is to measure the phase shift, which allows you to analyze the operation of electrical and electronic systems, improve their efficiency, and diagnose malfunctions. Phase meters directly measure the PSA between two signals. This is important in alternating current systems for the analysis of electrical processes in resistive, inductive and capacitive loads. For accurate measurement of the PSA, the accuracy of the used devices is important. Modern phase meters have a high resolution and are able to measure the phase shift with an accuracy of thousandths of a degree [3, 4].

The main purpose of phase standards is to ensure the accuracy and uniformity of PSA measurements in electrical and electronic systems. In electricity, phase standards help maintain phase stability and synchronization in large electrical networks in various fields, from industry to scientific research. They apply as standards for the calibration of instruments and equipment used to measure and analyze the phase characteristics of electrical signals. Phase standards are used to calibrate phase meters, oscilloscopes, and other measuring equipment that measures phase shift [5, 6].

2. Drawbacks

The improvement of various methods of measuring PSA between two voltages is considered in [1-3, 7-15]. The main methods of measuring PSA are considered in [1, 5]. The issues of uncertainty assessment in the calibration of measuring instruments of PSA are presented in [16–18]. The automation of high-precision measuring instruments of PSA is considered in [5]. At the same time, there are practically no results of detailed research of phase standards in scientific publications.

3. Goal

The purpose of the article is to present the results of research on a high-precision phase standard. At the same time, the main attention is paid to establishing the metrological characteristics of the phase standard, which affect the total accuracy of the national standard of PSA.

4. Methodology for researching the metrological characteristics of the precision phase standard

The national standard of the PSA unit between two voltages (DETU 09-07-11), which is keeping in the State Enterprise "Ukrmetrteststandard" (Kyiv), is intended to ensure metrological traceability of PSA measurement in Ukraine. To implement this traceability, the main components of the standard, which are Phase Standard Clarke-Hess 5500-2 [19] and precision meter-converter PSA Clarke-Hess 6000A [20], were calibrated at the National Metrological Institute of Germany – PTB in 2023 [5].

Phase Standard Clarke-Hess 5500-2 (Fig. 1) is designed to reproduce the PSA unit in the DETU 09-07-11 standard (Fig. 2). The universal digital oscilloscope Tektronix TDS 2024 is used to control the parameters of the reproduced voltages: U_{REF} is the voltage of the reference harmonic signal and U_{VAR} is the voltage of the variable harmonic signal with a specified PSA. A specially developed program in the LabVIEW environment [5] is installed on a personal computer (PC), which is used to control of meter-transducer of PSA Clarke-Hess 6000A and display the PSA unit reproduced by the standard.

Fig. 1 General view of the phase standard Clarke-Hess 5500-2.

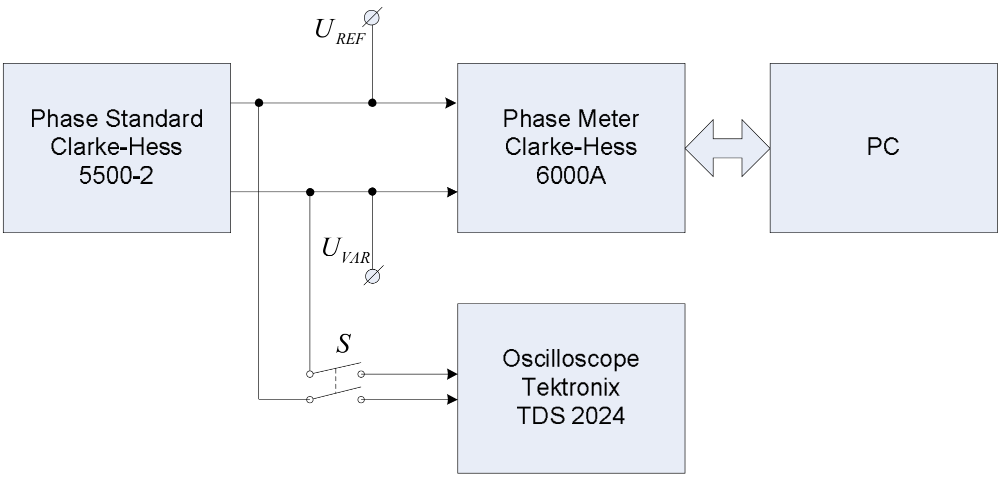

Fig. 2 Scheme for reproducing the PSA unit in the DETU 09-07-11 standard.

Phase Standard Clarke-Hess 5500-2 reproduces two digitally synthesized, low-distortion sine waves with independently selectable amplitudes. The phase angle between the two harmonic signals can be selected from -999.999° to 999.999° with a resolution of 0.001°. The standard can be managed through the IEEE-488.2 interface [19].

The main metrological characteristics of Phase Standard Clarke-Hess 5500-2 are as follows:

– range of PSA: from 0.000° to +999.999°;
– resolution of PSA reproduction: 0.001°;
– reproduction error for voltage from 50 mV to 100 V: ±0.005° at frequencies from 1 Hz to 1 kHz;
±0.010° at frequencies from 1 kHz to 6.25 kHz;
±0.015° at frequencies from 6.25 kHz to 50 kHz;
±0.040° at frequencies from 50 kHz to 200 kHz;
– frequency range: from 1 Hz to 200 kHz;
– output voltage: from 50 mV to 120 V (root mean square, RMS);
– stability: 0.005° for 20 minutes;
10 ppm for 24 hours.

Table 1. Calibration results of Phase Standard Clarke-Hess 5500-2

Given PSA φ_N, °	Difference of PSAs Δφ, °							
	10,4167 Hz	41,666 Hz	55,555 Hz	86,8056 Hz	312,5 Hz	1 kHz*	1 kHz**	10 kHz
0	0.0001	0.0001	0.0000	0.0000	-0.0003	0.0001	-0.0006	0,.001
30	-0.0001	-0.0005	-0.0003	-0.0002	-0.0007	0.0001	-0.0010	0.0001
60	0.0011	0.0008	0.0006	0.0009	0.0002	0.0001	0.0001	0.0001
90	0.0007	0.0001	0.0001	0.0004	-0.0001	0.0001	-0.0006	0.0001
120	0.0001	-0.0006	-0.0006	-0.0004	-0.0008	0.0001	-0.0017	0.0001
180	0.0000	0.0000	0.0000	0.0000	-0.0002	0.0001	-0.0015	0.0001
270	0.0006	0.0000	-0.0001	-0.0006	-0.0003	0.0001	-0.0005	0.0001
Uncertainty	0.0010	0.0010	0.0010	0.0010	0.0020	0.0025	0.0025	0.0030
Calibration results: * 2013, ** 2023.								

The standard has an internal oscillator with a nominal frequency of 2.304 MHz. The internal oscillator can be disabled and the external system clock can be used for calibration.

Phase Standard Clarke-Hess 5500-2 was calibrated over a nominal PSA range of 0.000° to 300.000° at PTB in 2013 and 2023 at frequencies: 10.4167 Hz; 41.666 Hz; 55.555 Hz; 86.8056 Hz; 312.5 Hz; 1 kHz and 10 kHz at an output voltage of 5,000 V (Table 1).

It is indicated in the Table. 1 value of the difference of PSA between the measured value φ_M and nominal values φ_N:

$$\Delta\varphi = \varphi M - \varphi N \quad (1)$$

for various phase angles in the nominal range from 0.000° to 270.000° at the specified measurement frequencies.

During calibration, the system clock of the phase standard was synchronized with the clock of the applied precision digital voltmeter. After setting the values of the amplitude and frequency of the output signal, as well as the nominal phase angle between both voltages, the synthesized voltages were digitized with a voltmeter. The studied signals were analyzed using a discrete Fourier transform, which gave the value of the obtained phase angle.

SE "Ukrmetrteststandard" has published internationally recognized calibration and measurement capabilities (CMC) in the Key Comparison Database (KCDB) of the International Bureau of Weights and Measures (BIPM) [21]. These CMC cover the metrological capabilities of the Phase Standard Clarke-Hess 5500-2 of the DETU 09-07-11 standard. The expanded measurement uncertainty is from 0.014° to 0.018° for reproducible KSF from 0.000° to 360.000° in the frequency range from 42 Hz to 1 kHz at the output voltage from 0.05 V to 120 V. These CMC are provided with a large margin due to the calibration of the Phase Standard in the PTB (see Table 1).

5. Research of the long-term stability of the etalon of the phase shift angle unit

Regular research of the long-term stability of the DETU 09-07-11 standard have been conducted since 2011. The basis for this research is Phase Standard Clarke-Hess 5500-2. The results of research of the reproduction of the PSA unit 0°, 30°, 60°, 90°, 180°, and 270° standard at a frequency of 1 kHz from 2011 to 2024 are shown in the Table. 2. All data are based on the averaging of multiple measurements: from 2011 to 2017 – 20, from 2018 to 2024 – 100. The expanded uncertainty of all measurements was 0.015°.

The results of the evaluation of the long-term stability of the standard can be approximated using a polynomial regression of the 3rd order. In the figures, green solid lines show the average value of the PSA, and red dashed lines show the corresponding polynomial approximations of the drifts. The indicated approximations of the drift lines of the standard have a value of the coefficient of determinacy R^2 from 0.42 to 0.60, that is, they confirm their adequacy.

Table 2. Results of research of the DETU 09-07-11 standard at a frequency of 1 kHz by years.

Given PSA φ_N, °	Measurand PSA φ_M, °							
	2011	2012	2013	2014	2015	2016-1	2016-2	2017
0	0.0004	0.0008	0.0013	0.0024	0.0034	0.0014	0.0015	0.0032
30	29.9993	30.0007	30.0009	30.0022	30.0029	30.0009	30.0019	30.0029
60	59.9997	60.0000	60.0002	60.0015	60.0020	60.0000	60.0001	60.0014
90	89.9999	90.0008	90.0010	90.0024	90.0034	90.0008	90.0016	90.0022
180	179.9997	180.0008	180.0012	180.0028	180.0038	180.0016	180.0021	180.0028
270	269.9997	270.0008	270.0011	270.0011	270.0033	270.0010	270.0019	270.0026
	2018-1	2018-2	2019	2020	2021	2022	2023	2024
0	0.0021	0.0028	0.0020	0.0020	0.0027	0.0006	0.0024	0.0025
30	30.0019	30.0024	30.0012	30.0018	30.0027	30.0007	30.0022	30.0030
60	60.0010	60.0018	60.0010	60.0009	60.0014	59.9995	60.0012	60.0011
90	90.0020	90.0032	90.0019	90.0019	90.0028	90.0007	90.0025	90.0022
180	180.0027	180.0033	180.0021	180.0021	180.0029	180.0008	180.0025	180.0030
270	270.0020	270.0029	270.0019	270.0020	270.0027	270.0004	270.0025	270.0026

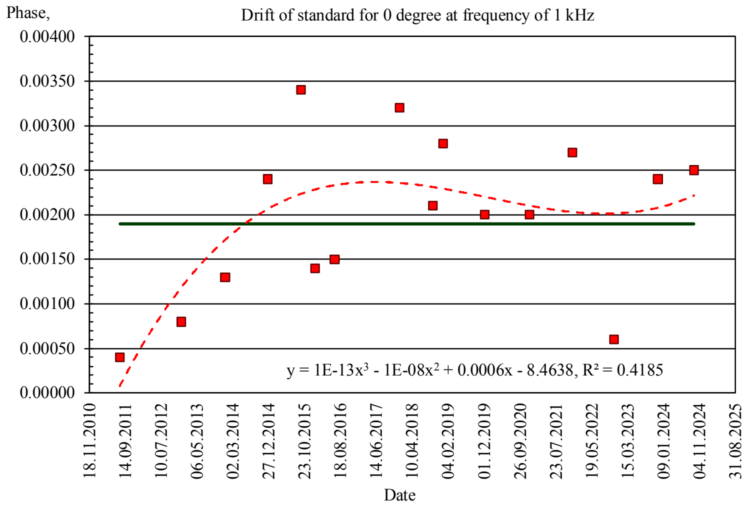

Fig. 3 Drift from the reproduction standard of the PSA unit 0° at a frequency of 1 kHz.

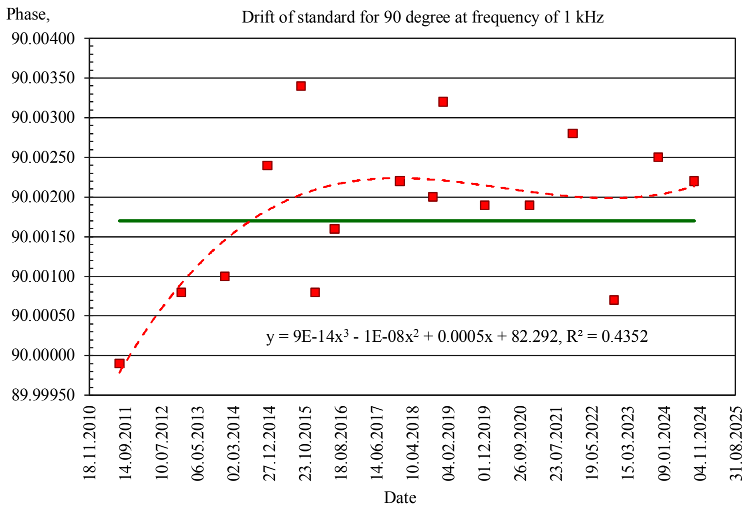

Fig. 4 Drift from the reproduction standard of the PSA unit 90° at a frequency of 1 kHz.

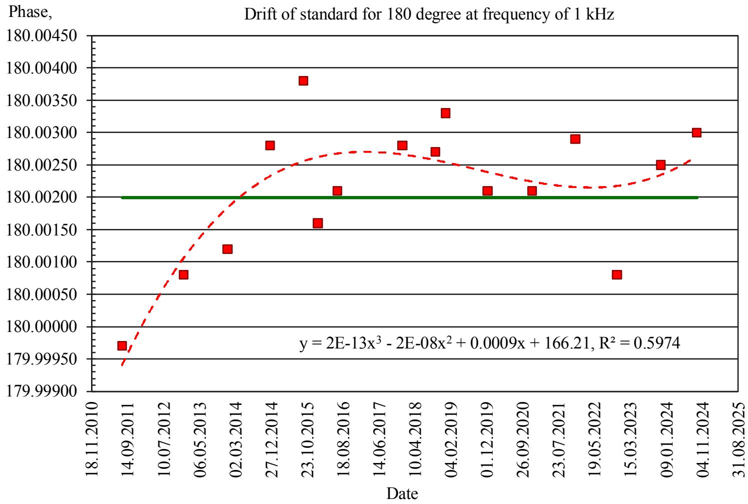

Fig. 5 Drift from the reproduction standard of the PSA unit 180° at a frequency of 1 kHz.

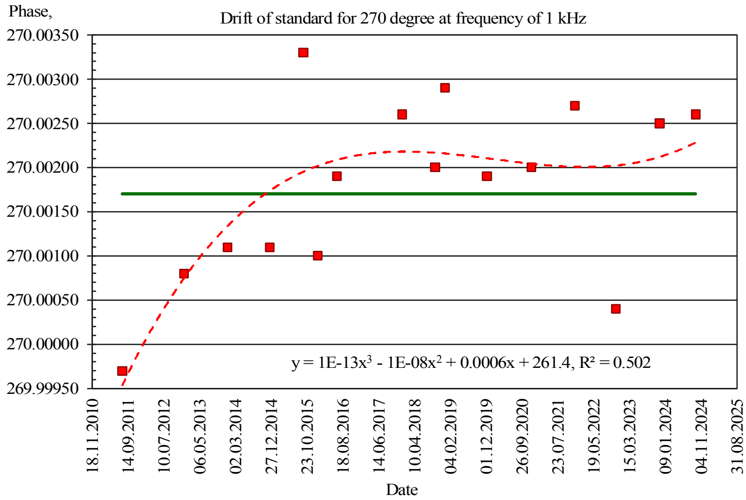

Fig. 6 Drift from the reproduction standard of the PSA unit 270° at a frequency of 1 kHz.

The average PSA value of the calibration results of the standard with a value of 0° is 0.0019°, with a value of 90° – 90.0017°, with a value of 180° – 180.0020°, with a value of 270° – 270.0017°. The difference between the maximum and minimum value of PSA from 2011 to 2024 pp. is for: 0° is 0.0030°, 90° – 0.0037°, 180° – 0.0025°, 270° – 0.0033°. The standard deviation of PSA values during the same period was for: 0° is 0.0009, 90° – 0.0010, 180° – 0.0008, 270° – 0.0010. All the given characteristics of the standard meet the established requirements.

6. Conclusions

The basis of the precise PSA standard is the applied phase standard, which determines its general metrological characteristics. This phase standard must be regularly calibrated by leading national metrology institutes. Its obtained metrological characteristics can be the basis for publishing CMC of a certain national metrological institute.

The national standard of the PSA of Ukraine has established metrological traceability to the national metrological institute of Germany – PTB. This traceability made it possible to publish CMC of Ukraine both for the phase generator (standard) and for the phase meter included in the standard. These CMC correspond to the established metrological characteristics of the national standard.

To assess the long-term stability of standards, the method of regression analysis is most often used. Polynomials of the third degree were sufficient to approximate its drift line of the DETU 09-07-11 standard for various PSA in the period from 2011 to 2024. The indicated approximations of the drift lines have a value of the coefficient of determination from 0.42 to 0.60, that is, they confirm their adequacy.

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