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Study of the State Primary Measurement Standard of the Unit of Phase Shift Angle Between Two Voltages

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Abstract

Phase measurements are necessary for determining main parameters of the oscillatory process in complex electrical networks. Most often, it is precisely the phase shift angle (PSA) between two oscillatory processes of the same frequency that is measured. An essential indicator of the quality of electrical energy is the coefficient of asymmetry in a three-phase electrical network, which depends on the load of consumers in this network. This indicator is affected by a short circuit between two phase voltages.

Phase measurement standards, phase meters, and phase converters are included in the measuring equipment for phase measurements. They are widely used in such fields as radiolocation, radio navigation, non-destructive testing, radio engineering, telecommunications, acoustics, metallurgy, machine and aircraft industry, space industry, as well as in scientific research and defence.

The State Measurement Standard of Ukraine of the PSA unit between two voltages in the frequency range from 0.01 Hz to 10 MHz is maintained at the State Enterprise "UKRMETRTESTSTANDARD", Kyiv. It provides metrological traceability of phases measured in the country. The main components of the standard were calibrated at the PTB, the National Metrology Institute of Germany. In Ukraine, numerous measurement standards and measurement instruments for phase measurements (more than 500.000 units) are used, in particular, phase calibrators, phase meters, phase shifters, synchronoscopes etc.

Regular study of metrological characteristics of the DETU 09-07-11 measurement standard is conducted both in the main (from 5 Hz to 200 kHz) and in the extended (from 0.01 Hz to 10 MHz) frequency range. The PSA values obtained as a result of the research in the main frequency range do not exceed 0.001° (which is maximum according to measurements at all calibration points 0.00015°), and in the extended frequency range – 0.01° (which is maximum according to measurements at all calibration points 0.0053°). To eliminate the systematic measurement uncertainty component of the phase measurement standard, a special calibration is regularly performed using a set of resistive and capacitive phase bridges.

Keywords: phase shift angle; voltage; phase measurements; measurement standard; measurement uncertainty.

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Introduction

Phase measurements are necessary for determining main parameters of the oscillatory process in complex electrical networks. Most often, it is precisely the phase shift angle (PSA) between two oscillatory processes of the same frequency that is measured. An important indicator of the quality of electrical energy is the coefficient of asymmetry in a three-phase electrical network, which depends on the load of consumers in this network. This indicator is also affected by a short circuit between two phase voltages [1].

The angular error of the measuring transformer is determined by the angle between the primary and secondary voltage vectors, so accurate phase measurements are crucial [2]. The PSA for a certain point of the power transmission line compared to the reference point of the phase at the substation shall be within the established limits. Depending on the method of connecting the transformer, the length of the line and the currents in it at a certain moment, this PSA may differ from the established one. Therefore, the exact determining of this PSA is necessary for stable operation of a specific power grid [3].

Phase measurement standards, phase meters, and phase converters are included in the measuring equipment for phase measurements. They are widely used in such fields as radiolocation, radio navigation, non-destructive testing, radio engineering, telecommunications, acoustics, metallurgy, machine and aircraft industry, space industry, as well as in scientific research and defence.

The issue of improvement of various methods of the PSA measurement between two voltages [4–10], provision of metrological traceability of these measurements [11], measurement uncertainty evaluation during the calibration of phase meters and phase measurement standards [12, 13], automation of phase measurements at the highest metrological level [14] is covered in numerous scientific works. However, scientific publications on the comprehensive study of metrological characteristics of the PSA national standards have not been found, which makes this paper relevant.

State Measurement Standard of Ukraine of the PSA unit between two voltages

The State Measurement Standard of Ukraine of the PSA unit between two voltages in the frequency range from 0.01 Hz to 10 MHz (DETU 09-07-11), which is maintained at the State Enterprise (SE) "UKRMETRTESTSTANDARD" (Kyiv), was established in 2011. It provides metrological traceability of phases measured in the country. The main components of the standard (meter-converter of PSA and phase measurement standard) were calibrated in 2023 at the PTB, National Metrology Institute of Germany. In Ukraine, numerous measurement standards and measurement instruments for phase measurements are used, in particular, phase calibrators (10 units), phase meters (50 units), phase shifters (500.000 units), synchronoscopes (100 units).

The DETU 09-07-11 measurement standard consists of a complex of measurement standards and measurement instruments (Fig. 1):

- phase measurement standard Clarke-Hess 5500-2;
- phase shift angle meter-converter Clarke-Hess 6000A;
- universal digital oscilloscope Tektronix TDS 2024;
- functional generators Hameg HM 8131-2 (2 units);
- frequency synthesizer Hameg HM 8134-2;
- frequency meter Agilent 53132A;
- calibration bridges Clarke-Hess 5002 (4 units);
- Personal Computer (PC).

Main metrological characteristics of the DETU 09-07-11 measurement standard are:

- range of the PSA reproducible values: (0–360)°;
- main frequency range: 5 Hz–200 kHz;
- expanded frequency range: 0.01 Hz–10 MHz;
- root-mean-square deviation (RMSD) of the measurement result:

  at a frequency of 1 Hz: 0.001°;

  in the extended frequency range: 0.001°–0.01°;
- expanded measurement uncertainty (k = 2; P = 0.95): 0.0044°–0.078°;
- unextracted systematic error:

  at a frequency of 1 Hz: 0.003°;

  in the extended frequency range: 0.003°–0.03°.

Calibration methods of the SE "UKRMETRTESTSTANDARD" MKU 628-11/09-2023 for phase meters, MKU 117-11/09-2023 for phase meters, MKU 629-11/09-2023 for phase generators are used to calibrate measurement standards and phase measuring instruments using the DETU 09-07-11 measurement standard.

Reproduction of the PSA unit in the main frequency range from 5 Hz to 200 kHz

Reproducing the PSA unit between two voltages in the main frequency range is ensured by a phase measurement standard Clarke-Hess 5500-2 and a phase changer Clarke-Hess 6000A (Fig. 2). Voltage U_{REF} is the reference voltage, while voltage U_{VAR} is variable due to the specified PSA. The universal digital oscilloscope Tektronix TDS 2024 is used for monitoring voltages. A PC with a specially developed program in the LabVIEW software environment [14] is used to control the visualization and display of the created PSA.

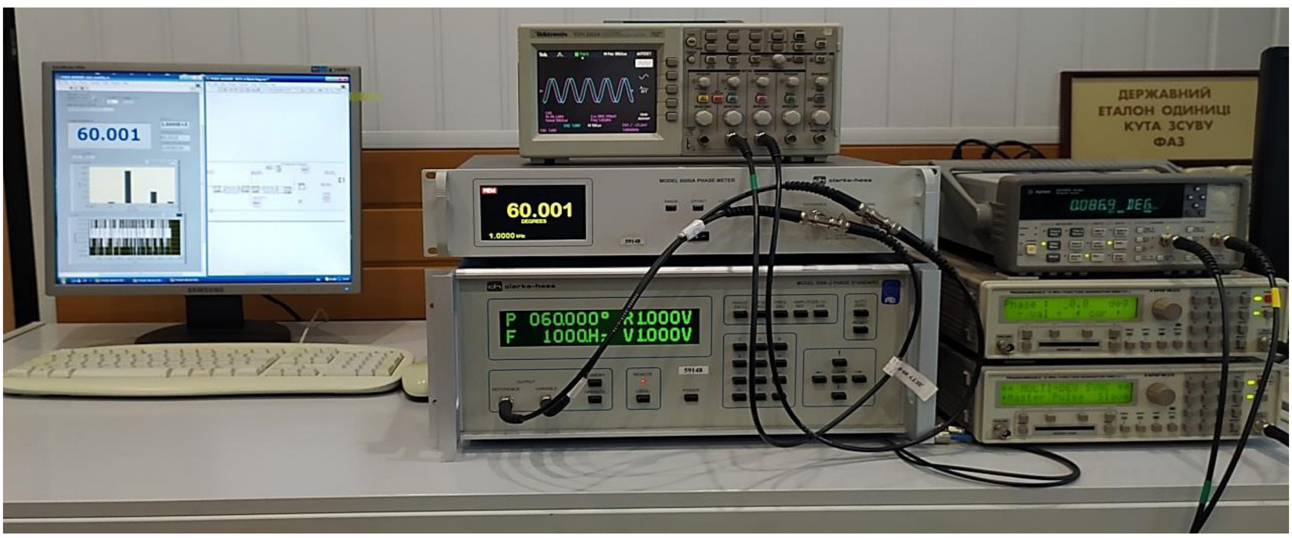

Fig. 1. General view of DETU 09-07-11 measurement standard

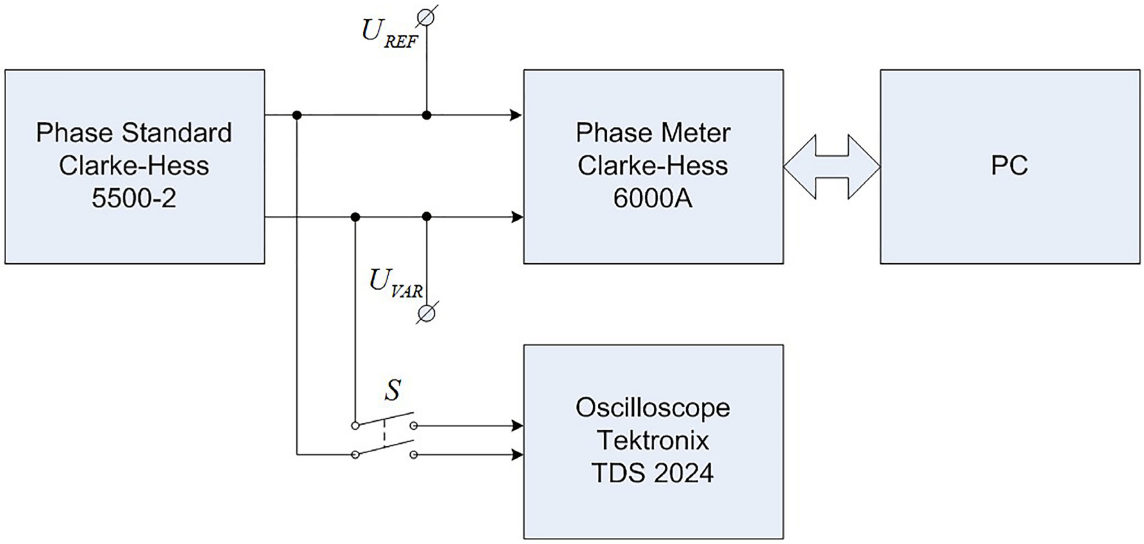

Fig. 2. Structural diagram of the reproduction of the PSA in the main frequency range

One hundred independent observations are systematically carried out for each value of the PSA in the range of values from 0° to 360° with a discreteness of 30°.

For each PSA value, the absolute error is determined by the expression:

$$\Delta\varphi_i = \varphi_{phmi} - \varphi_{phsi}, \qquad (1)$$

where φ_{phmi} is the PSA value according to the readings of the meter, in degrees;

φ_{phsi} is the PSA value according to the readings of the phase measurement standard, in degrees.

RMSD of the results of direct measurements for reproducing the PSA unit is calculated according to the following expression:

$$S = \sqrt{\frac{\sum_{i=1}^{n} \Delta\varphi_i^2}{n-1}} \Bigg/ \sqrt{n}, \qquad (2)$$

where n is the number of observations, n = 100.

Some results of the study of metrological characteristics of the measurement standard DETU 09-07-11 in the main frequency range are shown in the Table 1.

Phase measurement standard calibration using bridges

To eliminate the systematic measurement uncertainty component of the phase measurement standard Clarke-Hess 5500-2, an "auto-calibration" mode is performed using a set of calibration resistive (1:1R) and capacitive (1:1C; 10:1C; 1000:1C) phase

Table 1

Results of the study of metrological characteristics of the measurement standard in the main frequency range

Determined PSA φ, °	5 Hz		1 kHz		200 kHz	
	Average value of PSA φ, °	RMSD, m°	Average value of PSA φ, °	RMSD, m°	Average value of PSA φ, °	RMSD, m°
0	–0.0061	0.6790	0.0024	0.5972	–0.0348	0.8324
30	29.9934	0.7667	30.0022	0.4648	29.9844	0.8040
60	59.9922	0.7255	60.0012	0.4353	59.9713	1.0408
90	89.9940	0.7236	90.0025	0.7175	89.9685	0.8343
120	119.9936	1.2648	120.0022	0.5341	119.9922	0.9395
180	179.9934	0.6765	180.0025	0.6264	179.9766	0.8605
270	269.9922	1.4956	270.0025	0.6889	269.9745	0.9154
300	299.9928	1.3133	300.0021	0.5371	299.9865	0.8217

c *d*

Fig. 3. Resistive and capacitive phase bridges:
a – 1:1R; *b* – 1:1C; *c* – 10:1C; *d* – 1000:1C

bridges Clarke-Hess 5002 (Fig. 3) and a digital multimeter Agilent 34410A, which is used as a zero detector. During this, outputs with voltages U_{REF} and U_{VAR} of the phase measurement standard of 5 V at a frequency of 1 kHz are connected to inputs 1 (U_{VAR}) and 2 (U_{REF}) of the calibration bridge. The output of the calibration bridge is connected to the input of the digital multimeter Agilent 34410A (Fig. 4).

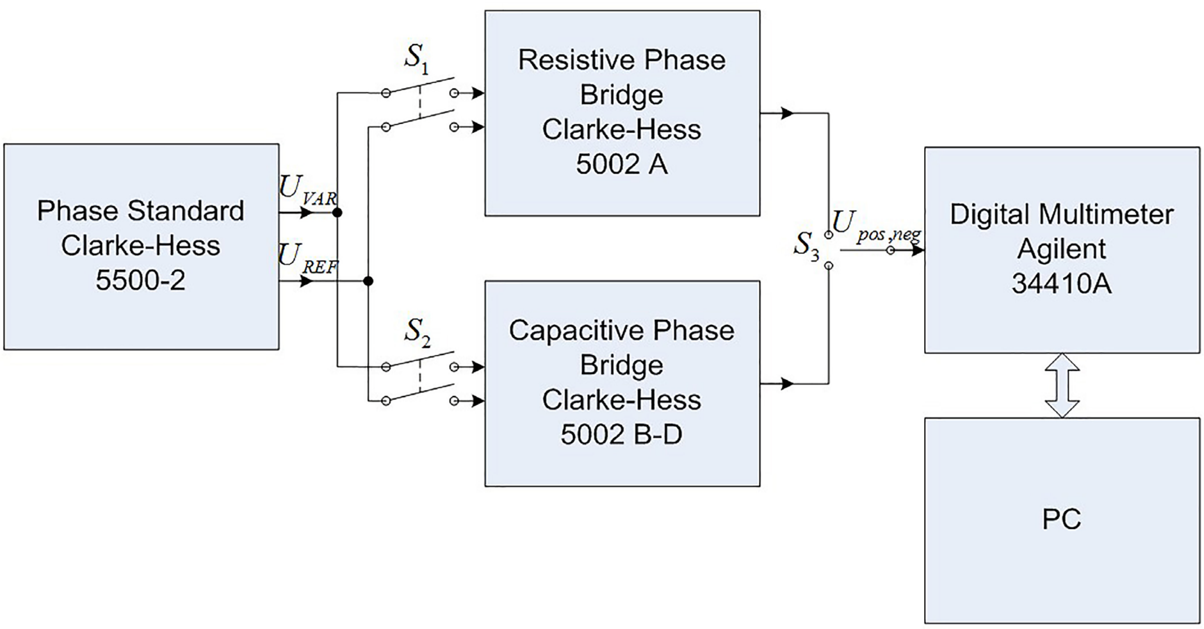

Fig. 4. Structural diagram for calibrating the phase measurement standard

Table 2

Phase measurement standard calibration control points

Amplitude of reference and alternating signals, V	Frequency, kHz	Phase standard deviation, m°	Deviation of PSA		Bridge type
			Permissible limits, m°	Typical value, m°	
5	1	0.58	± 5	± 2	1:1R (Fig. 3, *a*)
	5	–0.02	± 5	± 2	
	50	9.98	± 10	± 5	
	200	–4.96	± 40	± 20	
7	1	0.76	± 5	± 2	
	5	–2.20	± 5	± 2	
	50	1.90	± 10	± 5	
	200	1.67	± 40	± 20	
	1	0.001	± 5	± 2	1:1C (Fig. 3, *b*)
	5	–0.21	± 5	± 2	
	50	–0.05	± 10	± 5	
	200	–0.05	± 40	± 20	

To calibrate the phase measurement standard at frequencies of 5 kHz, 50 kHz, and 200 kHz, the voltage parameters U_{REF} and U_{VAR} of the phase standard are changed according to Table 2 depending on the phase bridge type.

The systematic component of the PSA measurement uncertainty of the phase measurement standard is calculated according to the formula with its subsequent compensation:

$$\delta\varphi = \frac{\theta(U_{neg} - U_{pos})}{U_{neg} + U_{pos}}, \quad (3)$$

where θ is the PSA value, which is 0.1°, by which it was increased/decreased on both sides of the zero of the measurement standards;

U_{neg} is the voltage value observed on the indicator of a digital multimeter when the PSA value of the phase measurement standard is reduced;

U_{pos} is the voltage value observed on the indicator of a digital multimeter for the increased PSA value of the phase measurement standard.

Thus, if negative deviations of –0.1° of the PSA lead to the voltage value of 42.02 mV, and positive deviations of 0.1° lead to the voltage value of 43.17 mV, the deviation of the PSA is 0.00135°.

Fig. 5 shows the change in the deviation of the PSA during the calibration of the phase measurement standard at a frequency of 1 kHz and an amplitude of 5 V using a 1:1R calibration bridge in the period from 2016 to 2023. The specified deviations of the PSA may be approximated by a positive linear trend line, which is accounted for when performing calibrations of phase measurement standards and precision phase meters using the DETU 09-07-11 measurement standard.

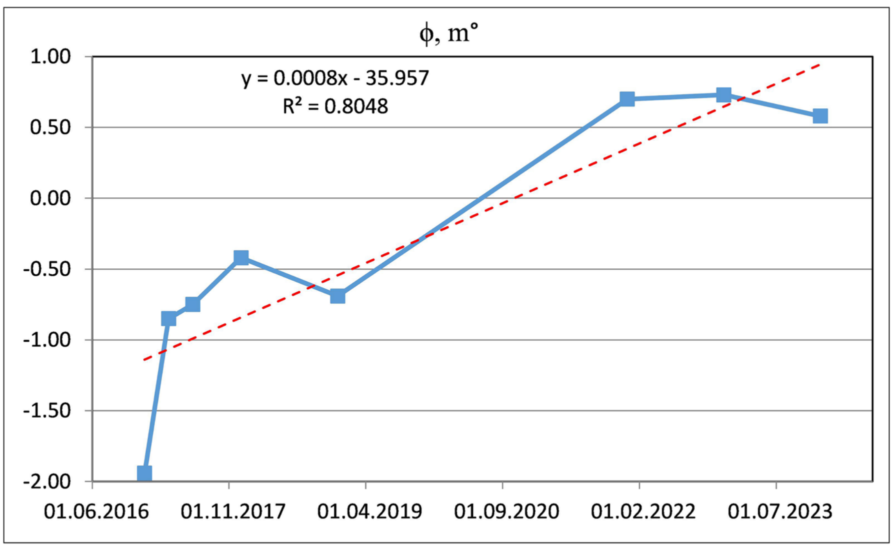

Fig. 5. Deviation of PSA during calibration using a bridge

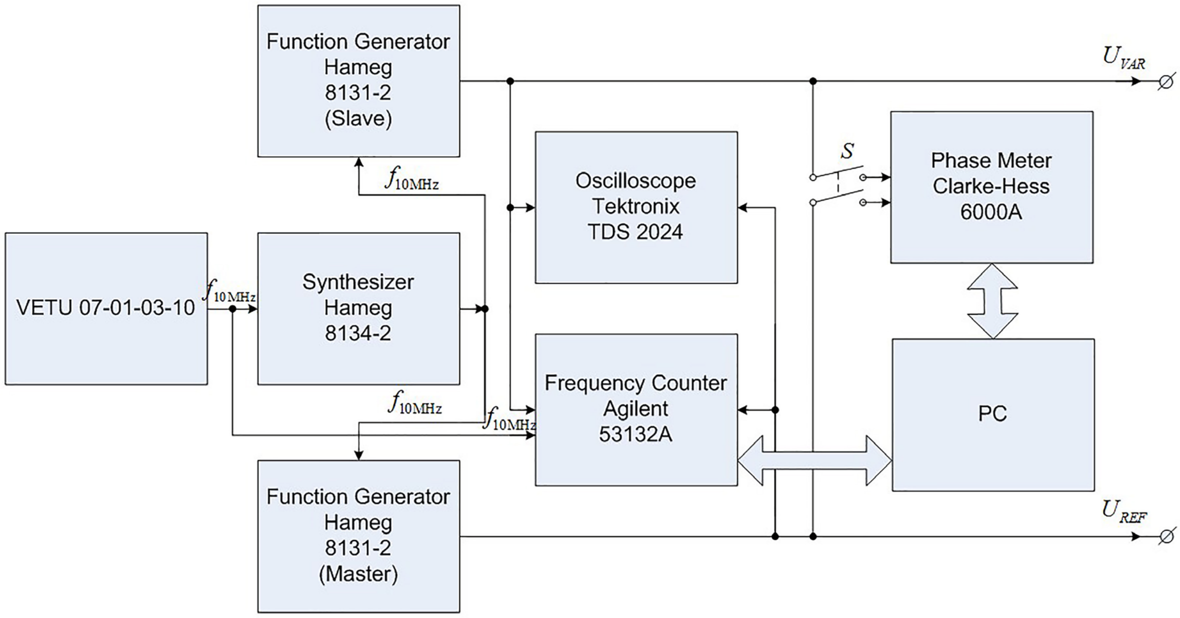

Fig. 6. Structural diagram of the reproduction of the PSA in the expanded frequency range

For equal values of the resistance in two arms of the bridge, the deviation of the PSA of the phase measurement standard is determined by preliminary determining the phase error. The 1:1R PSA deviation of the bridge at 5 V is 0.017°, at 7 V it is 0.023°, and the 1:1C PSA deviation of the bridge at 7 V is –0.010°.

Reproduction of the PSA unit in the main frequency range from 0.01 Hz to 10 MHz

The reproduction of the PSA unit between two voltages in an extended frequency range is implemented by the frequency synthesizer Hameg HM 8134-2, which is synchronized by the Secondary Time and Frequency Measurement Standard of VETU 07-01-03-10 (maintained at the SE "UKRMETRTESTSTANDARD"), two functional generators Hameg HM 8131-2 (main and additional) and a phase shift angle meter-converter Clarke-Hess 6000A (Fig. 6). The universal digital oscilloscope Tektronix TDS 2024 is used to control the parameters of reproduced voltages, and the frequency meter Agilent 53132A is used to control the reproduced frequency. A PC with a specially developed program in the LabVIEW software environment [14] is used to control the meter, the frequency counter, and to display the reproduced PSA.

Some results of the study of metrological characteristics of the DETU 09-07-11 measurement standard in the expanded frequency range are shown in the Table 3.

Table 3

Results of the study of metrological characteristics of the measurement standard in the expanded frequency range

Determined PSA φ, °	1 kHz		500 kHz		1 MHz	
	Average value of PSA φ, °	RMSD, °	Average value of PSA φ, °	RMSD, °	Average value of PSA φ, °	RMSD, °
0	0.0000	0.0006	0.0000	0.0008	0.0000	0.0011
30	29.9937	0.0006	29.9972	0.0021	29.9934	0.0030
60	59.9873	0.0004	59.9881	0.0020	59.9862	0.0034
90	89.9780	0.0009	89.9821	0.0025	89.9795	0.0033
120	119.9718	0.0005	119.9762	0.0015	119.762	0.0040
180	179.9566	0.0008	179.9636	0.0017	179.9627	0.0042
270	269.9351	0.0005	269.9408	0.0016	269.9403	0.0053
300	300.9281	0.0006	299.9332	0.0022	299.9371	0.0037

Conclusions

Regular study of metrological characteristics of the DETU 09-07-11 measurement standard has been conducted both in the main and in the extended frequency range. The PSA values obtained as a result of the study in the main frequency range (from 5 Hz to 200 kHz) do not exceed 0.001° (which is maximum according to measurements at all calibration points 0.00015°), and in the extended frequency range (from 0.01 Hz to 10 MHz) – 0.01° (which is maximum according to measurements at all calibration points 0.0053°). To eliminate the systematic measurement uncertainty component of the phase measurement standard, a special calibration is regularly performed using a set of resistive and capacitive phase bridges.

Дослідження державного первинного еталона одиниці кута зсуву фаз між двома напругами

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Анотація

Фазові вимірювання важливі для визначення основних параметрів коливального процесу в складних електричних мережах. Найчастіше вимірюється саме кут зсуву фаз (КЗФ) між двома коливальними процесами однакової частоти. Важливим показником якості електричної енергії є коефіцієнт несиметрії в трифазній електричній мережі, на який впливає навантаження споживачів у цій мережі. На цей показник впливає КЗФ між двома фазними напругами.

До засобів вимірювання (ЗВ) для вимірювань фази відносяться еталони фази, вимірювачі фази та фазоперетворювачі. Вони широко застосовуються в таких галузях, як радіолокація, радіонавігація, неруйнівний контроль, радіотехніка, телекомунікації, акустика, металургія, машино- та авіабудівна галузь, космічна галузь, а також наукові дослідження та оборона.

Державний еталон України одиниці КЗФ між двома напругами в діапазоні частот від 0,01 Гц до 10 МГц зберігається в ДП "УКРМЕТРТЕСТСТАНДАРТ", м. Київ. Він забезпечує метрологічну простежуваність фаз, виміряних у країні. Основні компоненти еталона були відкалібровані в національному метрологічному інституті Німеччини – PTB. В Україні використовується велика кількість еталонів і засобів для вимірювання фази (понад 500 тис. одиниць), зокрема калібратори фази, фазометри, фазообертачі, синхроноскопи тощо.

Проводяться регулярні дослідження метрологічних характеристик еталона ДЕТУ 09-07-11 як в основному (від 5 Гц до 200 кГц), так і в розширеному (від 0,01 Гц до 10 МГц) діапазоні частот. Отримані в результаті досліджень значення СКВ в основному діапазоні частот не перевищують 0,001° (максимум за вимірюваннями у всіх точках калібрування 0,00015°), а у розширеному діапазоні частот – 0,01° (максимум за вимірюваннями у всіх точках калібрування 0,0053°). Для виключення систематичної складової невизначеності вимірювання еталона фази регулярно проводиться спеціальне калібрування з використанням набору резистивних і ємнісних фазових мостів.

Ключові слова: кут зсуву фази; напруга; вимірювання фази; еталон вимірювання; невизначеність вимірювання.

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