AUTOMATION OF MEASUREMENTS ON THE STATE STANDARD OF THE UNIT OF PHASE SHIFT ANGLE BETWEEN TWO VOLTAGES

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Abstract. The phase is one of the main parameters of the oscillatory process in electric circuits and contains two components – constant and variable. More often, it is not the actual phase that is measured, but the phase shift angle (PSA) between two oscillating processes (voltages or currents) of the same frequency in the range from 0 to 360˚. Then the PSA is equal to the difference between the constant components of the phases of the two oscillations and does not depend on the start of the time count. Most of the modern methods of measuring the phase and PSA are based on the methods of discretization and digital signal processing – complex Fourier transform, least squares, etc. There are many varieties and improvements of these methods, which have different characteristics of measurement accuracy. The LabVIEW graphical programming environment has already become a general-purpose programming environment. Advantages of LabVIEW include simple networking, implementation of common communication protocols, powerful toolkits for process control and data fitting, fast and simple user interface design, and an efficient code execution environment. The article presents the results of the automation of measurements on the State Standard of the PSA between two voltages in the frequency range from 5 Hz to 10 MHz. Automation of precision measurements of PSA using the LabVIEW software environment provides advantages in comparison with manual measurements, in particular, reducing the time of measurement and processing of its results by at least three times. This ensures an increase in the productivity of metrological works; increasing their efficiency and quality, and the possibility of increasing the number of measurements (up to 1000), which allows for improve the root mean square deviation of not less than one and a half times, and reduce the overall standard measurement uncertainty, respectively.

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

1. Introduction

The phase is one of the main parameters of the oscillatory process in electric circuits and contains two components – constant and variable. More often, it is not the actual phase that is measured, but the phase shift angle (PSA) between two oscillating processes (voltages or currents) of the same frequency in the range from 0 to 360˚. Then PSA is equal to the difference between the constant components of the phases of the two oscillations and does not depend on the start of the time count.

Complex electrical networks have become widespread. One of the indicators of the quality of electricity is the asymmetry coefficient in the three-phase power supply network, which is affected by the PSA between the phase voltages. Various consumer loads in the power grid distort the shape of the voltage curve, causing a shift in the angles between the phase vectors of the voltage [1]. The angular error of the measuring transformer intended for large-scale conversion in the power grid is determined by the angle between the primary voltage vector and the secondary voltage vector shifted by 180˚ [2].

The absolute value of the phase for a particular line with an unknown phase at a local site must be determined for the operation and control of a three-phase distribution network. For correct identification, the phase shift for a specific line point compared to the phase reference point at the substation should be in the range of ±60°. However, at a certain point, it can fluctuate depending on the constants of the line, the way the transformer is connected, the length of the line, and the current in the line, etc. [3].

The issue of precise measurement of PSA and the use of appropriate measuring tools and standards is an urgent task.

2. Drawbacks

Many works [1, 3–14] have been devoted to the improvement of methods for measuring the PSA between two voltages, the results of uncertainty assessment in the calibration of phase meters, and the State Standard of the PSA between two voltages in the frequency range from 10 Hz to 10 MHz are presented in [15–18]. In many works, the issues of automating various measurements and processing their results are solved, in particular with the use of the LabVIEW graphical software environment [19–22]. However, there are practically no scientific publications on finding ways to automate phase measurements at the highest level of metrological traceability.

3. Goal

The goal of the research is to establish ways of automating professional measurements on the State Standard of the PSA unit between two voltages using the LabVIEW software environment. At the same time, the main attention is paid to the elimination of any factors that may affect the metrological characteristics of the national standard.

4. Methods of measuring the phase shift angle between two voltages

There are many methods of measuring the short circuit between two voltages, depending on their mathematical models, implementation, and various algorithms. The most common direct conversion methods for measuring the PSA are oscillography methods, methods with the conversion of PSA to current or voltage, and methods with the conversion of PSA to the number of pulses.

When using the balancing transformation method, the measured PSA is compared with the PSA created using a calibrated phase shifter. Parametric, circular phase shifters and phase shifters in the form of a delay line are used. The error of the phase shifter depends on the manufacturing accuracy and stability of its elements, operating frequency, and load resistance.

In the correlation and orthogonal measurement methods, the PSA is determined only at two points, without using other information. The presence of higher harmonics in the signals and noise in the input circuit of the devices leads to a change in the moment of transition through zero of the first harmonics of the signals, i.e., the value of the PSA changes, and significant errors appear.

NIST (USA) has developed methods for measuring phase using bridges [4] and directly using a phase meter. The bridge method allows you to study signals in the frequency range from 10 Hz to 200 kHz and amplitudes from 50 mV to 500 V.

The phase measurement method using 180° bridges is based on the vector distribution of the output signals. If you add two vectors with the same amplitude U_1, which are shifted in phase by 180°, then their sum is zero. Since the angle deviates from 180° by the angle x, it can be shown that the amplitude A of the resulting vector is equal to

$$A = 2U_1 \sin\frac{x}{2} \text{ or } x = 2\Big/ \sin\frac{A}{2U_1}. \qquad (1)$$

Thus, the angle can be defined as the ratio of two amplitudes. The addition of vectors is performed in a bridge, which consists of two identical resistors or capacitors with a common input connection.

The two outputs of the phase standard drive the unconnected ends of the two components, while the voltmeter is connected to the common output. Bridges provide phase determination by subtracting the residual minimum amplitude value from all other measured amplitude values by the square root of the difference of squares method. This method removes noise, and harmonic distortion (which does not depend on the phase) and leaves only the amplitude value, which depends only on the angle x. In addition, measuring the amplitude using two bridge inputs in phase (at x = 180°) allows you to eliminate the influence of the frequency response and the load caused by the voltmeter.

Phase measurement using a phase meter. The measurement method is implemented on a complex Fourier transform approach to obtain the principal component of each of the two signals, and then calculates the phase difference between the home components. Harmonics and noise are effectively "filtered out". This method significantly reduces the number of errors. The high accuracy of the phase meter model CLARKE-HESS 6000A is preserved not only for sinusoidal waves but also for distorted and noisy oscillations [4].

A heterodyne measuring system (HMS) is used to determine phase angles [5]. The method consists in determining the phase angle between two voltages using the complex ratio of frequency-shifted sinusoidal signals. This allows the use of precision sampling methods for signals with frequencies up to the audio frequency range and with rms voltage levels up to 7 V and a maximum voltage ratio of 1:10.

In the French national laboratory LNE, phase measurement is based on two methods: the first part is based on bridges, the content of which is based on the balance of elements such as resistance, capacitance, and inductance; the second part of the measurements is based on methods of sampling and digital signal processing. Digital signal processing is based on the complex Fourier transformation and the method of least squares, which are automated using computer tools [6].

A simple method of measuring the phase difference between sinusoidal signals is described in [7]. The method consists of subtracting two sinusoidal signals with the same frequencies and measuring the amplitude of the resulting signal, which is the minimum whenever there is a coincidence of the two phases of the signal. To test this method, an adjustable phase reference signal was generated using a direct digital synthesizer. Using this method, the KSF between two signals can be estimated with errors of less than 0.3° for signals up to 1.25 MHz

In [8], a phase measurement method based on four-parameter data approximation is used. The uncertainty of the sampling time and the measured voltage is assigned to each sampling point, and the total uncertainty of the phase difference is calculated using the Monte Carlo method. The results showed that the total error for the selected digitizer is lower than 0.5 millidegrees. Noise in the measured signal or digitizer is the largest contributor to the total uncertainty.

To increase the accuracy of estimating the phase difference between two sinusoidal signals with the same frequency, the phase correlation method described in [9] is used. This method uses a two-step calculation – phase-shift autocorrelation and phase-shift cross-correlation.

The effect of frequency drift on the phase difference is also discussed. The experimental results show that the maximum error of the traditional method is about 0.15°, while the estimation error of the proposed method is significantly less than 0.01° under the same conditions.

The phase difference estimation method for sinusoidal signals based on the correlation theory is proposed in [10] to improve the accuracy of the phase difference estimation for sinusoidal signals. This method is not affected by the non-integral period of the sampled signals. It has better estimation performance than Discrete Fourier Transform, Data Augmentation Correlation Method, and Quadrature Delay Estimator.

The digital correlation method for measuring the phase difference between two sinusoidal signals is presented in [11]. FPGA (Field-Programmable Gate Array) is used to implement the measurement algorithm. In FPGA correlation analysis, the CORDIC (Coordinate Rotation Digital Computer) algorithm is used to solve the inverse trigonometric function, and thus the phase difference can be conveniently obtained. Experimental results show that the phase difference between two sinusoidal signals can be estimated with a relative measurement error of less than 1.4% in the phase difference range of 45°.

The phase measurement method for interferograms with a non-uniform phase shift is proposed in [12]. To implement this method, the phase shift between successive interferograms is measured, which is used to change the spectrum of the interferogram data. To analyze this spectrum, an appropriate phase shift algorithm is developed using the formalism of the frequency transfer function. The obtained result is better than the results obtained using the Fourier transform method, the principal component analysis method, and the least squares method.

The study of the possibility of using the method of three amplitudes for measuring the difference in phases and amplitudes of two signals in the systems of dielectrometry and impedance spectroscopy is considered in [13]. A scheme of a broadband amplitude-phase detector with a frequency range from units of hertz to 100 MHz for dielectric spectroscopy systems is proposed. The detector calibration method is presented, which allows for reducing the absolute error of measuring the phase difference to ±0.1°.

The method of measuring the PSA between two voltages using a precision voltage meter of alternating current (AC) is presented in [1, 14]. The method of calibrating AC comparators by the phase component of the error is considered. The dependence of the measured PSA on the RMS values of the two input voltages was determined.

5. Automation of the State Standard of the unit of the phase shift angle between two voltages

The metrological traceability of the PSA measurement between two voltages in Ukraine in the frequency range from 5 Hz to 10 MHz is ensured by the State Standard of the PSA unit between two voltages (DETU 09-07-11), created in 2011, which is keeping in the SE "Ukrmetrteststandard" (Kyiv). To implement this traceability, the main components of the standard were calibrated in national metrological institutes of other countries, in particular in PTB (Germany). The general view of the DETU 09-07-11 standard is shown in Fig. 1.

The purpose of the DETU 09-07-11 standard is to reproduce, keep and transfer the PSA unit to the corresponding working standards. The standard consists of a complex of precision measuring equipment: the CLARKE-HESS 5500-2 phase standard and the CLARKE-HESS 6000A phase meter. The standard uses a phase measurement method implemented using a complex Fourier transform approach.

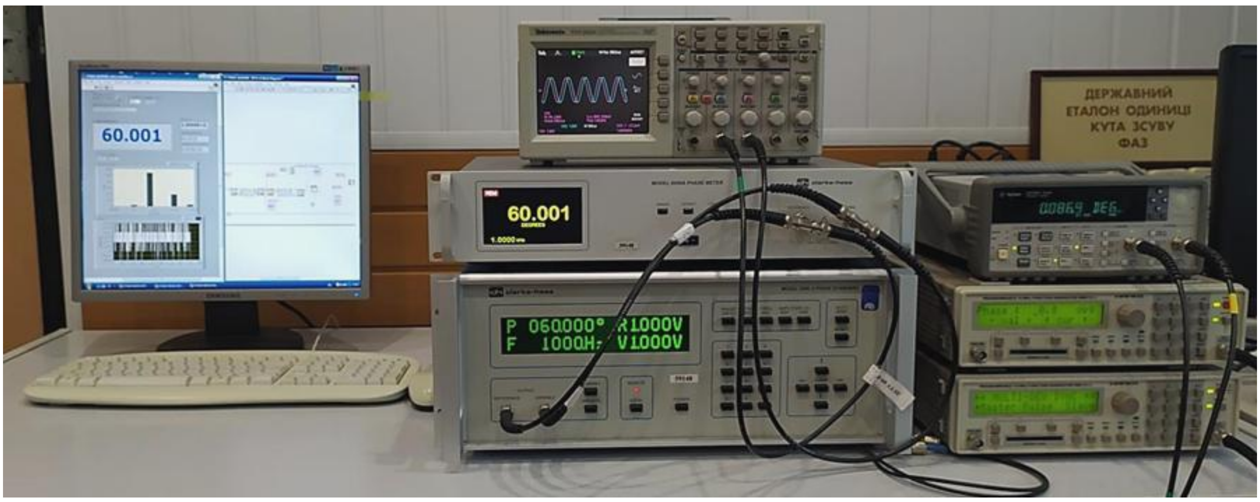

Fig. 1 The general view of the DETU 09-07-11 standard

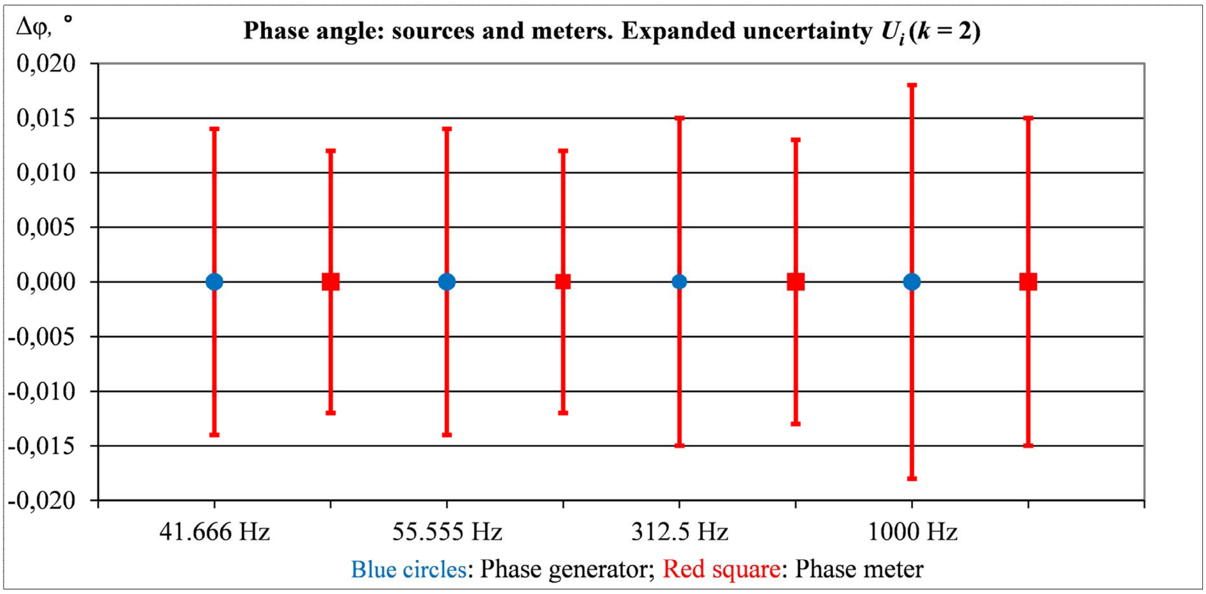

Fig. 2 CMC of Ukraine for the reproduction and measurement of the PSA

In the standard, two groups of reproduction, storage, and transmission of the PSA unit are implemented. The range of values of the PSA unit is from 0° to 360° in the main frequency range from 5 Hz to 100 kHz and the extended frequency range from 0.01 Hz to 10 MHz. The expanded uncertainty of the reproduction of the PSA unit for a frequency of 1 kHz is 0.0044° and for frequencies from 0.01 Hz to 10 MHz - from 0.0044° to 0.078°.

According to the results of studies of the metrological characteristics of the standard, the calibration and measurement capabilities (CMC) of Ukraine (SE "Ukrmetrteststandard") were published in the Key Comparison Database (KCDB) of the International Bureau of Weights and Measures (BIPM) [24]. Fig. 2 shows the extended uncertainties for the reproduction and measurement of the PSA according to the CMC of Ukraine at the frequencies of 41.666 Hz, 55.555 Hz, 312.5 Hz, and 1000 Hz.

Calibration of precision phase calibrators and phase meters according to developed calibration methods is carried out using DETU 09-07-11 standard. The results of the evaluation of the components of the standard uncertainty of the calibration of precision measuring equipment for PSA are given in [16–18]. The estimated expanded calibration uncertainty is 0.0079° at 1 kHz.

In [19], a data collection system for experimental studies of the behavior of alternating current electric circuits is presented. The system was implemented using the LabVIEW graphical programming environment, which allowed to automate the research. Developed applications based on a hierarchical tool structure consisting of user interface and visual programming elements.

The LabVIEW graphical programming environment has matured to become a general-purpose programming environment, as noted in [20]. Advantages of LabVIEW include simple networking, implementation of common communication protocols, powerful toolkits for process control and data fitting, fast and simple user interface design, and an efficient code execution environment.

In [21], a possible application of the LabVIEW integrated environment is shown for the final assessment of the accuracy of the measurement of alternating voltage. The paper presents the results of measurements of selected AC voltage meters, which were obtained at the designed measuring position. It is noted that the analysis of the obtained measurement results should take into account the limitation of the accuracy of the method of processing the measured value, caused, in particular, by the form of the measured signal or the frequency range of the meter.

The use of LabVIEW to automate data collection and data post-processing during structure testing is presented in [22]. LabVIEW can speed up the preparation of test reports, especially during reruns (getting statistics).

In [23] it is noted that LabVIEW is unusual among programming languages and uses such fundamental concepts as "graphic", "structured" and "data flow". LabVIEW is a test and measurement automation tool for non-programmer scientists and engineers.

Taking into account the mentioned advantages of using LabVIEW, it was chosen to automate measurements using the DETU 09-07-11 standard, for which the corresponding LabVIEW applications were developed. Such a decision made it possible to automate the measurement of the PSA, and at the same time significantly increase the number of measurements in comparison with manual control of the standard. This made it possible to increase the accuracy and reliability of the measurement results.

The VISA (Virtual Instrument Software Architecture) interface is used to interact with the LabVIEW software environment with the CLARKE-HESS 5500-2 phase standard and the CLARKE-HESS 6000A phase meter. On the front panel of the developed software interface, the phase standard is controlled and the results of the phase meter measurements are displayed (Fig. 3).

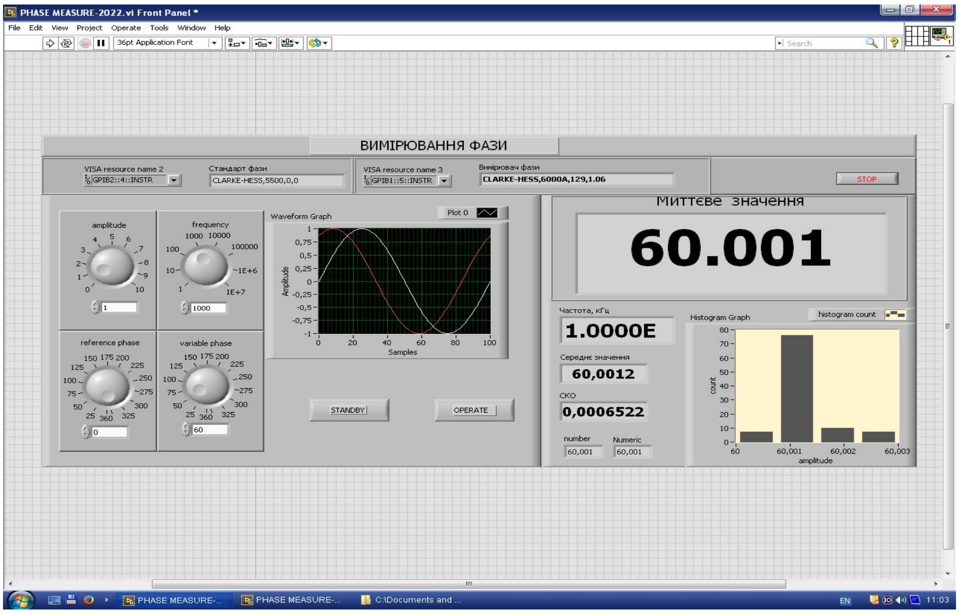

Fig. 3 The front panel of the DETU 09-07-11 standard in the LabVIEW software environment

The front panel contains the numbers and addresses of the phase standard (“Visa Resource Name 2”) and phase meter (“Visa Resource name 3”) interfaces, and next to them are windows with instrument types, serial numbers, and versions, respectively. This information is necessary for monitoring and correcting “feedback” of devices and their readiness for work. Below on the panel on the left are the controls for the phase standard: “amplitude” is setting the amplitudes of the output signals, one value is set for two output signals, functionally paired; “frequency” is setting the frequency of the output signals, one value is set for two signals, functionally paired; "reference phase" - setting the reference phase, by default “0”; “variable phase” is setting the phase to which a shift must be made. “STANDBY” and “OPERATE” functional buttons are responsible for turning off output signals and enabling output signals on the phase standard and coordinating with the physical buttons on the phase standard. “Waveform Graph” is a graphical representation of the phase shift. On the right side of the panel is the display of the PSA unit measurement. The instantaneous value of PSA is read from the phase meter. “Frequency, kHz” window is the value of the frequency of the signals, which was measured by the phase meter; the “Average value” window is the measured average value of PSA; the “RMS” window is the value of the root mean square (RMS) of the sample of PSA measurements. “Histogram Graph” is a histogram of measurement results.

The body of the program is the original graphic text of the virtual device program in the form of a block diagram displayed on the “Block Diagram” panel (Fig. 4).

The block diagram contains subroutines for controlling the phase standard and reading data from the phase meter, combined in a “le loop” that allows the program to run until the operator presses the “STOP” button. The program is launched by pressing the “ ” button on the toolbar or “Operate/Run” of the main menu. During the execution of the program, the operator sets the signal parameters and starts the output signals with the “OPERATE” function button. Data reading from the phase meter occurs every 250 ms, that is, the execution time of the corresponding cycle, which regulates the “Wait Until Next ms Multiple” functional element. This value can be changed at the initiative of the operator. After the set of data sampling, which sets the operator in the data reading subroutine, using the “Write to Spreadsheet File” element, the data is written to a text file in the form of a one-dimensional data array.

The impact of automation on the RMS of a sample of PSA measurements was studied when the number of measurements was increased from 10 to 1000. When measuring a PSA equal to 60° at a frequency of 1 kHz, the RMS of a sample of PSA measurements decreases from 0.000675 at 10 measurements to 0.000425 at 1000 measurements, i.e., by one and a half times. Recalculation of the RMS of a sample of PSA measurements into component uncertainty of type A gives a decrease in value from 0.00021 at 10 measurements to 0.0001 at 1000 measurements. In the manual mode of operation, 20 measurements take approximately 60 seconds, and in the automatic mode – 20 seconds, that is, three times less. In automatic mode, 1000 measurements take approximately 250 seconds, and in manual mode, it is impossible to make such several measurements due to the extremely high labor intensity.

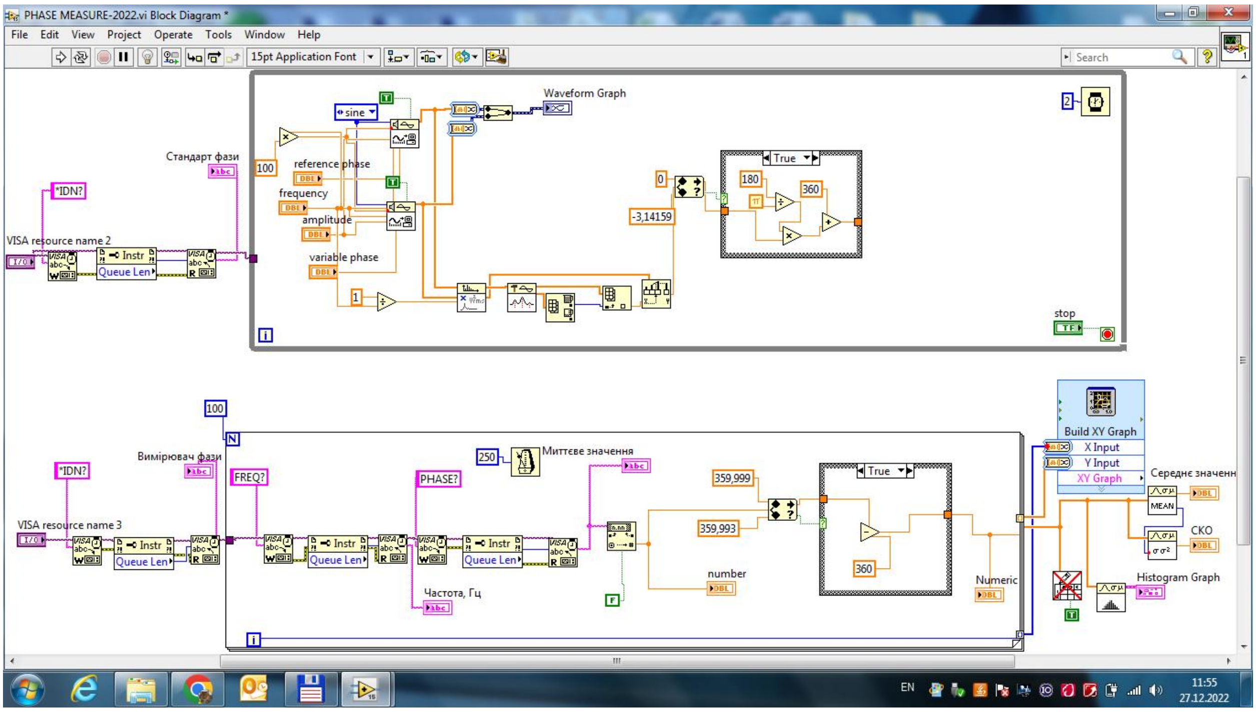

Fig. 4 Block diagram of PSA measurement in the LabVIEW software environment

6. Conclusions

Most of the modern methods of measuring the phase and its shift angle are based on the methods of discretization and digital signal processing – processing by the complex Fourier transform, the method of least squares, etc. There are many varieties and improvements of these methods. Automation of precision measurements of phase shift angle using the LabVIEW software environment provides advantages in comparison with manual measurements, in particular, reducing the time of measurement and processing of its results by at least three times. This ensures an increase in the productivity of metrological works; increasing their efficiency and quality, and the possibility of increasing the number of measurements (up to 1000), which allows for improvement of the RMS of a sample of phase shift angle measurements estimation by at least one and a half times, and reduce the overall standard measurement uncertainty, respectively.

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