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EVALUATING UNCERTAINTY OF UNBALANCE MEASUREMENT DURING CALIBRATION OF MEASURE OF POWER QUALITY PARAMETERS

The article proposes a measurement procedure to calibrate the measure of the power quality parameters for determining the correction of the reproducible negative sequence ratio. The measurement procedure based on the method of indirect measurement of the negative sequence ratio using the precision voltmeter of the alternating voltage. The contribution of the input quantities is analyzed, the analytical expressions for calculating the sensitivity coefficients are obtained and the measurement uncertainty budget is proposed. The measurement results obtained from the calibration of the multifunctional calibrator by using proposed measurement procedure are presented and the expanded uncertainty is estimated.

Keywords: *negative sequence ratio; alternating voltage; precise voltmeter; uncertainty of measurement.*

Introduction

General Problem Statement. The correctness of fulfilling the functions of electrical devices as well as the durability of these means in consistent with the guaranteed lifetime are depending on the supply of certain parameters of the electricity. A large number of problems, associated with exceeding the allowed values of certain parameters of the power grid as well as the basic approaches to solving relevant issues, was described in [1].

The European standard EN 50160 [2] establishes a list of indicators of the quality of electricity and sets the maximum permissible deviations of these parameters from nominal values.

One of the parameters of power quality (PQ) is the negative sequence ratio in the supply voltage unbalance. Various consumer loads connected along the three-phase power supply in one way or another affect the quality of electricity. These factors lead to distorting the voltage curve and causing the displacement of the angles between the phase voltage vectors or the deviation of its amplitude from the nominal value, etc.

A compliance with the established requirements and monitoring of the quality of electricity are also urgent tasks on shipboard power system networks [3].

Measurement instruments, like power network analyzers (for example Fluke 1745, Энергомонитор 3.3, Ресурс ПКЭ, etc.), are used to check compliance with the requirements for the quality of electricity in accordance with [2].

The objective of the metrological support for measuring the unbalance of three-phase power supplies is a determination of the deviation of the readings of the power network analyzers from the corresponding values of the working standard as well as evaluation of the associated measurement uncertainty.

This task is performed with the help of specialized AC calibrators such as Fluke 6100A or Ресурс-К2. It means that the function of such working standard is reproduction with high accuracy of PQ parameters because of its use for determining the metrological characteristics of power network analyzers. Thus, it is a measure of PQ parameters in its essence.

The voltage unbalance is the state of the three-phase system, when the RMS values of line voltages or the phase shift angle between the consecutive line voltages differ from the nominal values according to the definition. In addition to the positive sequence component under the voltage unbalance conditions, at least one of the following components is also present: negative sequence voltage and (or) zero sequence voltage.

According to international standard IEC 61000-4-30 [4], the negative sequence ratio for a three-phase power supply network is determined by the following expression

$$k_2 = \frac{U_2}{U_1} \cdot 100 = \sqrt{\frac{1-\sqrt{3-6\cdot\beta}}{1+\sqrt{3-6\cdot\beta}}} \cdot 100\,, \qquad (1)$$

where U_2 is negative sequence voltage; U_1 is positive sequence voltage; β is line voltage factor that is determined by an expression

$$\beta = \frac{U_{12}^4 + U_{23}^4 + U_{31}^4}{\left(U_{12}^2 + U_{23}^2 + U_{31}^2\right)^2}\,, \qquad (2)$$

where U_{12}, U_{23}, U_{31} are RMS values of line voltage between phases.

The urgent question is a simplification of the expressions for positive and negative sequence components by breaking down into several simpler equations because initial ones are cumbersome.

Analysis of the Recent Research and Publications. The determination of the correction to negative sequence ratio values of the measure of the PQ parameters based on the measurement results of three line voltages using a precise AC voltmeter should be performed during indirect calibration with using formulas (1; 2). The uncertainty of measurements during the calibration of measure of PQ parameters in the part of negative sequence ratio should be evaluated according to guide [5].

The manufacturer of the calibrator Fluke 6100A states that accurate determination of peak values and phase shift angles of output signals ensures high accuracy of all other parameters [6].

Obviously, this is the case, but for the user of final analyzer, it is interesting to have estimates of the quality parameters in accordance with [2], for instance, THD or unbalance factors etc. Evaluated measurement uncertainty of mentioned parameters is also of a metrological interest. In Europe, a study was carried out on the distribution of electricity quality that was analyzed by synchronously measuring PQ parameters using multiple GPS time-stamped digitalisers distributed around the grid [7]. The work was also aimed to improve the accuracy of the calibrator for determining the characteristics of phasor measurement units. At present, research work is under way to establish traceability routs for PQ parameters measurements. The purpose of this work is, in particular, to develop and validate a modular measurement setup for sampled electrical power and PQ parameters measurements [8].

The procedure of measuring the phase shift angle between two voltages of the multifunctional calibrator is proposed in the paper [9] as well as the corresponding measurement uncertainty is estimated. This procedure was tested in practice, and the results of the measurement were compared with the alternative measurement method with a positive result [10]. The uncertainty budget for calibration of such a measure of PQ parameters in the part of the THD is proposed in the paper [11].

The articles about the algorithm features for measuring the supply voltage unbalance by power network analyzers [12] and the influence of the accuracy of voltage and current measurements on a set of PQ parameters [13] are found among publications about the measurement accuracy of this parameter. However, it is difficult to find references to estimating the measurement uncertainty of the negative sequence ratio that is reproduced by means of the measure.

The negative sequence ratio is reproduced with a deviation that does not exceed ± 0.05 percent according to the documentation of universal calibrator Ресурс-К2 [14]. The relation between the metrological characteristics of the standard and the calibrated instrument is recommended to be at least 1:3.

Aim of the Research. The purposes of the article are creation and analysis of the procedure of determining the deviation of the negative sequence ratio as well as evaluation of associated uncertainty of measurements.

Statement of basic materials

Characteristic Features of the Calibration. The calibration at 57,735; 100; 220 V should be carried out in order to reduce the influence of electromagnetic interference on the measurement results. The expediency of selecting the calibration points that are most frequently investigated during the monitoring of the grid quality should be taken into account as well.

It is proposed to set the value of negative sequence ratio equal 0.5; 2.0; 5.0 since the maximum allowable value is 2.0 percent according to EN 50160 [2]. It is necessary to set the required value of the negative sequence ratio and to measure RMS values U_{12}, U_{23}, U_{31} of the line voltages with the precise voltmeter. The specified measured points are set by varying the values of the output phase voltages and the phase shift angles of the calibrator. Measurement and registration of the received data should be carried out automatically as well as readouts of precise voltmeter should be displayed in the formed software protocol. The required number of measurement operations should be repeated depending on the number of measured values of negative sequence ratio.

It is necessary to calculate the arithmetic mean and standard deviation of each line voltage as well as the value of the coefficient from the measurement data array by means of software with the use of actual biases of precise voltmeter by formula

$$\beta = \frac{\left(\overline{U}_{12}+\Delta_{12}\right)^4+\left(\overline{U}_{23}+\Delta_{23}\right)^4+\left(\overline{U}_{31}+\Delta_{31}\right)^4}{\left[\left(\overline{U}_{12}+\Delta_{12}\right)^2+\left(\overline{U}_{23}+\Delta_{23}\right)^2+\left(\overline{U}_{31}+\Delta_{31}\right)^2\right]^2}, \quad (3)$$

where $\overline{U}_{12}$, $\overline{U}_{23}$, $\overline{U}_{31}$ are arithmetic means of line voltages measured with help of precise voltmeter; Δ_{12}, Δ_{23}, Δ_{31} are corrections of precise voltmeter readings considering the temperature of the ambient air.

The purpose of any calibration is determination the interrelation between the indications of the working standard and the calibrated measuring instrument to give a user the capability to calculate the value most approximated to the conventional true value. Since the measure of PQ parameters reproduces the negative sequence ratio which is measured by means of the precise voltmeter by the described procedure, the corrections for the calibration points should be calculated according to the expression

$$K_2 = k_2 - k_{cal}, \quad (4)$$

where k_{cal} is the value of the negative sequence ratio which is reproduced by a measure of PQ parameters.

The final result of the calibration shall be the value of the correction according to (4) and the corresponding expanded uncertainty.

Evaluation of Measurement Uncertainty. In the general case, the uncertainty of measurements should be calculated in accordance with the guide to the expression of uncertainty in measurement [5]. A mathematical expression (2) should be used to calculate the sensitivity coefficients as partial derivatives to further calculating the measurement uncertainty when calibrating the measure of PQ parameters in the part of the negative sequence ratio. In this case, the sensitivity coefficients for each input quantity will be determined by the following expression

$$c_j = \frac{\partial k_2}{\partial U_j} = \frac{\dfrac{\partial U_2}{\partial U_j} \cdot U_1 - U_2 \cdot \dfrac{\partial U_1}{\partial U_j}}{U_1{}^2}, \qquad (5)$$

where j is line voltage index (j = 12 ; 23 or 31).

Tabl. 1 represents characteristic analytical expressions for simplification of defining the sensitivity coefficients. The formulas for calculating sensitivity coefficients in accordance with expressions (6; 10) are taken from expression (5).

Table 1

Analytical expressions for defining the sensitivity coefficients

Characteristic	X^*	Y^*	$\left(\sqrt{3} \cdot U_{12}\right)^*$
$\dfrac{\partial U_1}{\partial U_{12}}$	$-\dfrac{U_{23}^2 - U_{31}^2}{U_{12}^2}$	$2 \cdot \left(\dfrac{U_{23}^2 - U_{31}^2}{U_{12}} + U_{12}\right) \cdot \left(\dfrac{U_{23}^2 - U_{31}^2}{U_{12}^2} - 1\right)$	$\sqrt{3}$
$\dfrac{\partial U_1}{\partial U_{23}}$	$2 \cdot \dfrac{U_{23}}{U_{12}}$	$4 \cdot U_{23} \cdot \left(1 - \dfrac{U_{23}^2 - U_{31}^2}{U_{12}^2}\right)$	0
$\dfrac{\partial U_1}{\partial U_{31}}$	$-2 \cdot \dfrac{U_{31}}{U_{12}}$	$4 \cdot U_{31} \cdot \left(1 + \dfrac{U_{23}^2 - U_{31}^2}{U_{12}^2}\right)$	0

These formulas are converted to a simpler form in order to optimize the formation of the program code. For variants of partial derivatives of positive and negative sequences with respect to each of the measured line voltages, their analytical determination was carried out, and the results are represented by the expressions (6–11).

$$\frac{\partial U_1}{\partial U_j} = \frac{1}{12 \cdot \sqrt{Z}} \cdot \left\{ \begin{array}{l} \left[\sqrt{3} \cdot U_{12} + \sqrt{Y}\right] \times \\ \times \left[\left(\sqrt{3} \cdot U_{12}\right)^* + \dfrac{1}{2 \cdot \sqrt{Y}} \cdot Y^*\right] + \\ + X \cdot X^* \end{array} \right\}, \qquad (6)$$

$$X = \frac{U_{23}^2 - U_{31}^2}{U_{12}} - U_{12}, \qquad (7)$$

$$Y = 4 \cdot U_{23}^2 - \left(\frac{U_{23}^2 - U_{31}^2}{U_{12}} + U_{12}\right)^2, \qquad (8)$$

$$Z = \frac{1}{12} \cdot \left[\left(\sqrt{3} \cdot U_{12} + \sqrt{Y}\right)^2 + X^2\right], \qquad (9)$$

$$\frac{\partial U_2}{\partial U_j} = \frac{1}{12 \cdot \sqrt{Z^*}} \cdot \left\{ \begin{array}{l} \left[\sqrt{3} \cdot U_{12} - \sqrt{Y}\right] \times \\ \times \left[\left(\sqrt{3} \cdot U_{12}\right)^* - \dfrac{1}{2 \cdot \sqrt{Y}} \cdot Y^*\right] + \\ + X \cdot X^* \end{array} \right\}, \qquad (10)$$

$$Z^* = \frac{1}{12} \cdot \left[\left(\sqrt{3} \cdot U_{12} - \sqrt{Y}\right)^2 + X^2\right]. \qquad (11)$$

The characteristics indicated in tabl. 1 need to be subjected to expressions (6) or (10) to calculate the coefficients by the equation (5). Expressions (7–9; 11) should also be used to calculate the sensitivity coefficients.

The standard uncertainty during the measurement of each component according to equations (1; 4) should be calculated as the experimental standard deviation of the mean of the corresponding voltage.

The type B standard uncertainties of corrections Δ_{12}, Δ_{23}, Δ_{31} and the discreteness of the calibrator's indication should be evaluated from calibration certificate and specification.

It is necessary to adopt a uniform distribution law when one of the input quantities of the functional relationship is known only as the interval of possible values in accordance with the recommendations of the guide [5]. Then use the expression given in the fifth row of tabl. 2 to calculate the standard uncertainty of the discreteness.

The uncertainty budget is yielded with use of guide [5] in accordance with the expression (3) for the evaluation of measurement uncertainty in the calibration of the measure of the PQ parameters in the part of negative sequence ratio.

Table 2

Budget of uncertainty to calibrate measure in negative sequence ratio

Input quantity	Estimate of input quantity	Standard uncertainty u_i	Sensitivity coefficient c_i	Contribution to combined uncertainty
U_{12}	$\overline{U}_{12}$, Δ_{12}	S_{12}, u_{12}	c_{12}	$c_{12} \cdot S_{12}$, $c_{12} \cdot u_{12}$
U_{23}	$\overline{U}_{23}$, Δ_{23}	S_{23}, u_{23}	c_{23}	$c_{23} \cdot S_{23}$, $c_{23} \cdot u_{23}$
U_{31}	$\overline{U}_{31}$, Δ_{31}	S_{31}, u_{31}	c_{31}	$c_{31} \cdot S_{31}$, $c_{31} \cdot u_{31}$
k_{cal}	$\hat{k}_{cal}$	$\frac{\Delta_{cal}}{2 \cdot \sqrt{3}}$	-1	$\frac{\Delta_{cal}}{2 \cdot \sqrt{3}}$
Output quantity	Measurement results	Combined standard uncertainty	Coverage factor	Expanded uncertainty
K_2	Equation (4)	$u_{2comb} = \sqrt{\sum_{i=1}^{4} c_i^2 \cdot u_i^2}$	$k \approx 2$, $P = 0.95$	$k \cdot u_{2comb}$

The following notations and their definitions are used in tabl. 2:

S_{12}, S_{23}, S_{31} are experimental standard deviation of the arithmetic mean of measured line voltages;

u_{12}, u_{23}, u_{31} are combined standard uncertainties of the measured RMS voltage values by means of precise voltmeter;

$\hat{k}_{cal}$, Δ_{cal} are the estimate and least significant digit (discreteness) of the indication of the measure.

Practical Application of Proposed Measurement Procedure. Below is an example of the calibrating the measure of the PQ parameters when reproducing the voltage unbalance by measuring the three RMS values of line voltage with help a precise voltmeter. Tabl. 3–4 present the results of the processed measurement data array obtained in the manner described above by means of the software.

Table 3

The results of processing the data of measurement results

Input quantity, V			Sensitivity coefficient, V^{-1}
Line voltage between	Estimate	Standard uncertainty	
for negative sequence ratio 0.6 %			
1 and 2	174,090	0,0070	0,0010
2 and 3	172,783	0,0069	-0,0037
3 and 1	174,522	0,0070	0,0026
for negative sequence ratio 5.0 %			
1 and 2	175.749	0.0070	0.0026
2 and 3	161.097	0.0064	-0.0039
3 and 1	172.403	0.0069	0.0010
for negative sequence ratio 10.0 %			
1 and 2	187.806	0.0075	0.0039
2 and 3	161.065	0.0064	-0.0026
3 and 1	164.310	0.0066	-0.0020

Table 4

The results of calibrating the measure of PQ parameters in the part of negative sequence ratio

Value of negative sequence ratio	Correction to indication	Expanded uncertainty
0.6009	0.0039	0.0066
5.1758	0.0019	0.0064
10.1342	–0.0038	0.0073

How can we see, the values of measurement uncertainty obtained by proposed measurement procedure have a significant margin of accuracy for using the precise voltmeter as a working standard. In this case, measurement uncertainties are more than six times less than corresponding values taking from the specification of the measure.

Conclusions

The first time proposed procedure of calibrating the measure of the PQ parameters in the part of reproducible negative sequence ratio allows determining the deviation of indication from the indirectly measured physical quantity with the help of a precise voltmeter. Evaluating the corresponding measurement uncertainty due to the determined sensitivity coefficients of each input quantity is also could be easily done with help of software. The obtained values of the expanded uncertainty testify to the expediency of using the precise AC voltmeter as a working standard because of high accuracy that was achieved in this way.

Metrological traceability of the measurement results of the final measuring instrument that is the PQ analyzer establishes a connection with the unit of electrical AC voltage, since the proposed procedure of calibration of the measure of PQ parameters at reproduction of the negative sequence ratio is realized using the precise voltmeter.

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ОЦІНЮВАННЯ НЕВИЗНАЧЕНОСТІ ВИМІРЮВАНЬ НЕСИМЕТРІЇ ПРИ КАЛІБРУВАННІ МІРИ ПОКАЗНИКІВ ЯКОСТІ ЕЛЕКТРОЕНЕРГІЇ

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Стаття присвячена вирішенню проблеми метрологічного забезпечення аналізаторів електричної енергії в контексті розроблення процедури визначення метрологічних характеристик робочого еталону. В якості міри показників якості електроенергії (ПЯЕ) використовують трифазні багатофункціональні калібратори, котрі відтворюють напругу та силу змінного струму. Основні ПЯЕ, котрі визначені у національному стандарті ДСТУ EN 50160, розраховуються програмним забезпеченням калібратору та зображуються на екрані монітора. Оскільки аналізатори електричної енергії показують значення цих показників у визначених ДСТУ EN 50160 одиницях, логічним є визначення метрологічних характеристик та невизначеності вимірювань саме в цих одиницях. Одним з ПЯЕ є коефіцієнт несиметрії за зворотною послідовністю, рівняння зв'язку для визначення котрого є складним і містить три вхідних величини. Три лінійних напруги повинні бути виміряні з урахуванням дійсних значень поправок вимірювача. Зазначене рівняння потребує оптимізації з метою визначення коефіцієнтів чутливості при оцінюванні невизначеності вимірювання цього параметру. Метою статті є пропозиція та аналіз методики визначення відхилення коефіцієнту несиметрії, відтворюваного мірою ПЯЕ. Як робочий еталон для калібрування міри ПЯЕ пропонується використовувати прецизійний вольтметр змінної напруги, який опосередковано вимірює коефіцієнт несиметрії. Невизначеність вимірювання під час калібрування пропонується оцінювати відповідно до настанови з вираження невизначеності GUM 1995. У статті проаналізовано внесок вхідних величин, проведено оптимізацію аналітичних виразів для розрахунку коефіцієнтів чутливості та запропоновано бюджет невизначеності. Результати практичного застосування запропонованої методики, отримані під час калібрування багатофункціонального калібратора, свідчать про доцільність використання прецизійного вольтметру як робочого еталону. Бажаний рівень невизначеності вимірювання при калібруванні міри ПЯЕ повинен мати потрійний запас по відношенню до її паспортної метрологічної характеристики, і, з цього погляду, оцінена невизначеність дає удвічі кращі показники.

Ключові слова: *коефіцієнт несиметрії, змінна напруга, прецизійний вольтметр, невизначеність вимірювання.*

ОЦЕНИВАНИЕ НЕОПРЕДЕЛЕННОСТИ ИЗМЕРЕНИЙ НЕСИММЕТРИИ ПРИ КАЛИБРОВКЕ МЕРЫ ПОКАЗАТЕЛЕЙ КАЧЕСТВА ЭЛЕКТРОЭНЕРГИИ

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В статье предлагается процедура измерения для калибровки меры показателей качества электроэнергии при определении поправок воспроизводимого коэффициента несимметрии по обратной последовательности. Методика основана на методе косвенного измерения коэффициента несимметрии с использованием прецизионного вольтметра переменного напряжения. Проанализирован вклад входных величин, получены аналитические выражения для расчета коэффициентов чувствительности и предложен бюджет неопределенности измерений. Представлены результаты измерений, полученные при калибровке трехфазного многофункционального калибратора с использованием предложенной методики, и оценена расширенная неопределенность.

Ключевые слова: *коэффициент несимметрии, переменное напряжение, прецизионный вольтметр, неопределенность измерения.*