Comparison of Approaches for Calibration of Electrical Power Quality Analyzers

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***Abstract* — A comparison of the classical approach using a harmonic signal with the approach of a periodic square wave signal in the first (main) harmonic of the calibration voltage of the electrical power quality analyzers is suggested. The results presented using both approaches for calibrating a Fluke 435 power quality analyzer through a Metrix CX1651 calibrator, provide a quantitative estimate of the degree of equivalence of calibration by both approaches. Evaluation and comparison of the obtained experimental results shows applicability of the approach with a periodic square wave signal of the calibration of power quality analyzers by harmonic voltage in the metrological practice.**

Keywords—power quality analyzer, calibration, harmonic

I. INTRODUCTION

In metrological practice the calibration of power quality analyzers (PQA) is performed by the reference signal method. For calibration of PQA by harmonic voltage it is necessary the calibrator (standard) to generate two or more sinusoidal signals. In case such a calibrator is not available, a new approach is proposed – a calibration using a periodic square wave signal [1, 2, 3]. To prove the applicability of this approach a comparative analysis on the basis of the results of the calibration of the PQA Fluke 435 through calibrator Metrix CX 1651 using the voltage of the first (fundamental) harmonic in both approaches is performed.

The experimental setup is presented in the diagram of Figure 1.

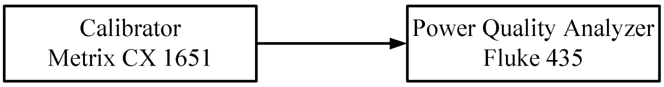

Fig.1. Scheme of calibration

The calibrator Metrix CX1651 used is not calibrated. Therefore, the information in its technical documentation is used, where the maximum error specified with respect to the AC voltage is 0,03% [4]. Fluke 435 is the calibrated PQA by the voltage of the first harmonic [5].

The square wave signal is presented in Fourier series with each of its harmonic constituents being a function of the amplitude U_m and the duty cycle μ of the square wave signal.

The square wave signal generated by the calibrator, which is applied to the input of the calibrated analyzer, contains the sum of the fundamental and infinite series of harmonics. The fundamental harmonic amplitude [1, 2, 3] is:

$$U_{1m} = \frac{4U_m}{\pi}\sin(\pi\mu) \qquad (1)$$

The effective voltage value of the first harmonic is respectively

$$U_1 = \frac{U_{1m}}{\sqrt{2}} = \frac{2\sqrt{2}U_m}{\pi}\sin(\pi\mu)$$

The estimate of the deviation of the effective value of the voltage for the first harmonic of the square wave signal is determined [2, 3] by the expression:

$$\delta U_{1,s.et} = \delta_{U1,et}U_1 = \left(\delta_{Um} + a_{U1,\mu}\delta_\mu\right)U_1 = \left\{\delta_{Um} + \left[\pi\mu.\mathrm{ctg}(\pi\mu)\right]\delta_\mu\right\}\left[\frac{2\sqrt{2}U_m}{\pi}\sin(\pi\mu)\right], \qquad (2)$$

where: δ_{Um} is the relative error of setting of the amplitude of the square wave signal and δ_μ - the relative error of setting of the duty cycle μ of the square wave signal. The parameter $a_{Un,\mu}$ is the factor of influence on the error δ_μ. For the first harmonic it is reset at $\mu = 0,5$, which is the reason for choosing a square wave signal with a duty cycle of 0,5 [1, 2, 3].

II. CALIBRATION OF ELECTRICAL POWER QUALITY ANALYZERS USING A SINUSOIDAL SIGNAL AND A SQUARE WAVE SIGNAL

A. Mathematical models

The mathematical models for the estimation of the actual effective value of the voltage, measured by the analyzer in both approaches are determined by the expressions respectively [2, 6]

$$U_{act} = U_{cal} - \delta U_{s.et} - \delta U_{dr.et} + \delta U_{res.cal} \qquad (3)$$

$$U_{1,act} = U_{1,cal} - \delta U_{1,s.et} - \delta U_{1,dr.et} + \delta U_{1,res.cal} \qquad (4)$$

where:

- U_{cal} and $U_{1,cal}$ are the effective values measured, respectively, of the sinusoidal voltage and of the first harmonic recorded by the analyzer. They are defined as the arithmetic mean of 10 independent measurements;
- $\delta U_{s.et}$ and $\delta U_{1,s.et}$ are the deviations of the set points (points of calibration) from the calibrator, respectively of the sinusoidal voltage and of the first harmonic;
- $\delta U_{dr.et}$ and $\delta U_{1,dr.et}$ are the values of the drift of the calibrator, respectively for the sinusoidal voltage and for the first harmonic;
- $\delta U_{res.cal}$ and $\delta U_{1,res.cal}$ are the deviations from the resolution of the analyzer, respectively for the sinusoidal voltage and for the first harmonic.

B. Determination of the estimates of the input values of the mathematical models

The Fluke 435 analyzer is voltage calibrated for the first harmonic $\mathrm{U_1}= 110\ \mathrm{V}$. The reference signal is set by the Metrix CX 1651 calibrator. When calibrated with a sinusoidal signal, a voltage $\mathrm{U=U_1}= 110\ \mathrm{V}$ is set. In calibration with square wave signal in order to achieve the voltage for the first harmonic $\mathrm{U_1}= 110\ \mathrm{V}$ the amplitude of a square wave signal voltage according to formula (1) is set to $\mathrm{U_m}=\frac{\pi}{4}\mathrm{U}_{1m}\frac{1}{\sin(\mu\pi)}=\frac{\pi}{4}\frac{\mathrm{U_1}}{\sqrt{2}}\frac{1}{\sin(\mu\pi)}=122{,}1793\ \mathrm{V}$, obtained for duty cycle. At the calibration point 110 V, the measured 10 effective voltage values are presented in Table 1.

TABLE I. TABLE TYPE STYLES

i	1	2	3	4	5	6	7	8	9	10
	Sinusoidal voltage, V									
$U_{cal,i}$	109,9525	109,9554	109,9566	109,9490	109,9477	109,9531	109,9589	109,9536	109,9516	109,9519
	First harmonic of square wave signal, V with duty cycle $\mu = 0{,}5$									
$U_{1,cal,i}$	109,9562	109,9566	109,9568	109,9560	109,9562	109,9561	109,9558	109,9560	109,9554	109,9552

The estimates of the measured values of the voltage, read from the analyzer for the sinusoidal signal and the first harmonic of the square wave signal are

$$U_{cal}=\frac{1}{n}\sum_{i=1}^{n}U_{cal.i}= 109{,}95303\ \mathrm{V};$$

$$U_{1,cal}=\frac{1}{n}\sum_{i=1}^{n}U_{cal.i}= 109{,}95603\ \mathrm{V}$$

The estimate of the deviation of the set value voltage from the calibrator for a periodic signal is determined by its specification, through the maximal error $\delta_{U,et}$ at the calibration point.

$$\delta U_{s.et}=\delta_{U,et}.\mathrm{U}=0{,}03\%.110\mathrm{V}=0{,}033\ \mathrm{V}$$

The estimate of the deviation of the effective value of the voltage for the first harmonic of the square wave signal is determined [2, 3] by expression (2), The maximal error in setting of the calibrator alternating voltage [4] represents the error δ_{Um} in setting of the maximal value of square wave voltage set be the calibrator. In addition, the error of setting of a duty cycle is eliminated due to making zero of the parameter $a_{U1,\mu}$. Thus, for the estimate of the deviation of the effective voltage value for the first harmonic of the square wave signal it is obtained:

$$\delta U_{1,s.et}=\delta_{U1,et}U_1=\left(\delta_{Um}+a_{U1,\mu}\delta_{\mu}\right).U_1=\left\{\delta_{Um}+\left[\pi\mu.\mathrm{ctg}(\pi\mu)\right].\delta_{\mu}\right\}.$$
$$.\left[\frac{2\sqrt{2}U_m}{\pi}\sin(\pi\mu)\right]=(0{,}03\%+0).122{,}1793=0{,}03665\ \mathrm{V}$$

The estimates of the calibrator voltage drift for the sinusoidal signal and for the first harmonic of the square wave signal are zero. The drift is a variable with even distribution within certain bounds. These estimates are therefore:

$$\delta U_{dr.et}=0\ \mathrm{V};$$
$$\delta U_{n,dr.et}=0\ \mathrm{V}$$

The estimates of the deviation from the resolution of the analyzer for the voltage sinusoidal signal $\delta U_{res.cal}$ and for the first harmonic $\delta U_{1,res.cal}$ are quantities with even distribution within the bounds of the value of the junior digit of the voltage analyzer and therefore these estimates are:

$$\delta U_{res.cal}=0\ \mathrm{V};$$

$$\delta U_{1,res.cal}=0\ \mathrm{V}$$

C. Determination of the estimates of the actual value of the measured voltage

After accounting of the estimates of the input values in the mathematical models (3) and (4) the following values are obtained for the actual effective value of the voltage, measured by the analyzer in both approaches:

$$U_{act}=U_{cal}-\delta U_{s.et}, \qquad (6)$$

$$U_{1,act}=U_{1,cal}-\delta U_{1,s.et}, \qquad (7)$$

from where it is computed respectively:

$$U_{act}=109{,}95303 - 0{,}033 = 109{,}92003\ \mathrm{V}$$

$$U_{1,act}=109{,}95603 - 0{,}03665 =109{,}91938\mathrm{V}$$

D. Determination of the standard uncertainty of the input values

- the standard uncertainty of the estimate of the measured voltage values for the sinusoidal signal $u(U_{cal})$ and for the first harmonic of the square wave signal $u(U_{1,cal})$ are:

$$u(U_{cal})=\sqrt{\frac{\sum_{k=1}^{n}(U_i-U_{cal})^2}{n(n-1)}}=0{,}001062\ \mathrm{V},$$

$$u(U_{1,cal})=\sqrt{\frac{\sum_{k=1}^{n}(U_i-U_{cal})^2}{n(n-1)}}=0{,}000154\ \mathrm{V},$$

- the standard uncertainty of the estimate of the deviation of the setting point of the sinusoidal voltage $u(\delta U_{s.et})$ and of the first harmonic $u(\delta U_{1,s.et})$ are determined by their estimates from the calibrator specification [4]:

$$\delta U_{s.et}= 0{,}025\%\mathrm{U} + 0.010\%\,\mathrm{U}_{range},$$

where U_{range} is the range of the calibrator, from which it is determined:

$$u(\delta U_{s.et}) = 0{,}025\%.110 + 0.010\%\,240 = 0{,}0275 + 0.024 = 0{,}0515\ \text{V},$$

$$u(\delta U_{1,s.et}) = 0{,}3\%.122{,}1793 + 50\mu\text{V} = 0{,}3665379\ \text{V} + 0{,}00005\ \text{V} = 0{,}36659\text{V}$$

- the standard uncertainty of the calibrator drift estimate for sinusoidal voltage $u(\delta U_{dr.et})$ and for the first harmonic $u(\delta U_{1,dr.et})$ are defined by the specified uncertainty expressions in the instrument specification

$$u(\delta U_{dr.et}) = 0.025\ \%\ \text{U} + 0.010\%\ \text{U}_{range}$$

$$u(\delta U_{dr.et}) = \frac{(0{,}025\%.110\ +\ 0.010\%\ 240)}{\sqrt{3}} = 0{,}02973\ \text{V}$$

$$u(\delta U_{1,dr.et}) = \frac{(0{,}3\%.122{,}1793 + 50\mu\text{V})}{\sqrt{3}} = 0{,}21171\ \text{V}$$

- the standard uncertainty of the deviation of the resolution estimate of the analyzer for the sinusoidal voltage $u(\delta U_{res.cal})$ and for the first harmonic $u(\delta U_{1,res.cal})$ is determined by the value of the least significant digit of the analyzer for voltage $a = 0{,}0001\ \text{V}$, from the expression

$$u(\delta U_{res.cal}) = u(\delta U_{1,res.cal}) = \frac{a}{2.\sqrt{3}} = 0{,}00002887\ \text{V}$$

E. Determination of the combined standard uncertainty of the input values

The combined standard uncertainty is determined by the components of the standard uncertainty of the estimates of all input quantities (where the sensitivity coefficients for the input quantities are equal to one) from the expressions

$$u(U_{act}) = \sqrt{u(\delta U_{cal})^2 + u(\delta U_{s,et})^2 + u(\delta U_{dr.et})^2 + u(\delta U_{res.cal})^2}$$

$$u(U_{1,act}) = \sqrt{u(\delta U_{1,cal})^2 + u(\delta U_{1,s,et})^2 + u(\delta U_{1,dr.et})^2 + u(\delta U_{1,res.cal})^2}$$

$$u(U_{act}) = \sqrt{\left(1{,}127.10^{-6}\right) + \left(2{,}65225.10^{-3}\right) + \left(0{,}88.10^{-3}\right) + \left(8{,}3.10^{-10}\right)} = \\ = 0{,}05947\ \text{V}$$

$$u(U_{1,act}) = \sqrt{\left(2{,}357.10^{-8}\right) + \left(1{,}345.10^{-1}\right) + \left(4{,}482.10^{-2}\right) + \left(8{,}30.10^{-10}\right)} = \\ = 0{,}42333\,\text{V}$$

From the analysis of the components of the input quantities it follows, that the biggest contributors are the uncertainty components of the sinusoidal voltage deviation estimation $u(\delta U_{s.et}) = 0{,}0515\ \text{V}$ and the amplitude of the square wave signal $u(\delta U_{1,s.et}) = 0{,}36670\ \text{V}$. The uncertainty components of the calibrator drift estimate are of the same order, respectively $u(\delta U_{dr.et}) = 0{,}02973\ \text{V}$ and $u(\delta U_{1,dr.et}) = 0{,}21171\ \text{V}$. The uncertainty components of the estimate of the measured voltage value are for sinusoidal voltage - $u(U_{cal}) = 0{,}001062\ \text{V}$ and for the square wave signal $u(U_{1,cal}) = 0{,}000154\ \text{V}$. The uncertainty of the analyzer resolution deviation estimate for both signals is $u(\delta U_{res.cal}) = u(\delta U_{1,res.cal}) = 0{,}00002887\ \text{V}$, and can be ignored.

F. Determination of the extended uncertainty

For the extended uncertainty it can be written

$$\text{U}_{\text{act}} = k.u(U_{act}),$$

$$\text{U}_{1,\text{act}} = k.u(U_{1,act}),$$

where $k = 2$ is a coverage factor of approximately 0,95% probability and a normal distribution law.

$$\text{U}_{act} = 2.\ 0{,}05947 = 0{,}11895\ \text{V}$$

$$\text{U}_{1,act} = 2.\ 0{,}42333 = 0{,}84666\ \text{V}$$

G. Results for the measured voltage

The results for the measured voltage are recorded through the estimates U_{act} and $U_{1,act}$ of the actual value of the measured voltage and their extended uncertainty U_{act} and $\text{U}_{1,act}$.

$$\text{U} = 109{,}92003 \pm 0{,}11895\ \text{V}$$

$$\text{U}_1 = 109{,}91938 \pm 0{,}84666\ \text{V}$$

III. COMPARATIVE ANALYSIS OF FLUKE 435 CALIBRATION RESULTS WITH A SINUSOIDAL SIGNAL AND WITH A SQUARE WAVE SIGNAL

From the results obtained in the calibration of the analyzer Fluke 435 with harmonic voltage with a sinusoidal signal and with a square wave signal at the point of calibration $\text{U} = 110\ \text{V}$ it follows:

- the values for the measured voltage are very close. The difference between the two values is $0{,}65.10^{-3}\ \text{V}$ and the relative error is $5{,}91.10^{-6}\ \text{V}$.
- the expanded uncertainties are $1{,}1.10^{-3}$ times and $7{,}7.10^{-3}$ times smaller than the measured voltage estimates, respectively, when calibrated with a sine wave and when calibrated with a square wave signal.

By the criterion E_N, a quantitative assessment of the degree of equivalence of calibration with the two signals [7] can be obtained.

$$E_N = \frac{|y_1 - y_2|}{\sqrt{U_1^2 + U_2^2}} = \frac{109{,}92003 - 109{,}91938}{\sqrt{0{,}11895 + 0{,}84666}} = 0{,}00066,$$

where: y_1 and y_2 are the estimated values of the measured quantity with a sinusoidal signal and a square wave signal, respectively; U_1 and U_2 are the measurement uncertainty of the corresponding signal.

For $E_N \leq 1$ – a satisfactory equivalence and for $E_N > 1$ - unsatisfactory equivalence are established.

An estimate of $E_N = 0{,}00066$ shows a very good satisfactory equivalence of the results obtained when calibrating the analyzer with both signals.

The results of the comparative analysis show the applicability of the square wave signal approach for the first harmonic voltage calibration of Fluke 435 analyzer.

ACKNOWLEDGMENT

The PQA calibration by voltage harmonics using a periodic square wave signal is appropriate when a calibrator which can generate two or more sine signals is not available.

The approach based on a periodic square wave signal is suitable for calibration of PQA by harmonic voltage - only two variables are specified: amplitude and duty cycle. For a value of the duty cycle $\mu = 0,5$ the relative error of setting of the value of the harmonic is determined only by the error of the set pulse amplitude.

The comparative analysis of the results from calibration of Fluke 435 voltage first harmonic with two signals, demonstrates the feasibility of the approach with periodic square wave signal in calibration of the PQA voltage harmonics in the metrological practice.

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