

Evaluation the Uncertainty Influence Depends on Harmonic Voltage Distortion for Precision Power Measurements

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Abstract – This paper deals with some problems concerning the evaluation of uncertainty depends on harmonic voltage distortion for precision electric power measurements and its further influence on evaluation expanded uncertainty of electric power measurements on National standard of electric power and power factor units of Ukraine. In experimental study cases the authors have modulated harmonic voltage distortions and evaluated the uncertainty depends on it. The paper presents the theoretical framework of the problem as well as the results of measurements, which illustrate the presence of the disturbing voltage harmonics in the low harmonics order such as 3rd, 5th, 7th, 9th, 11th and 13th.

Keywords – *electric power, precision measurements, uncertainty, Total Harmonic Distortion, voltage harmonics distortion*

I. INTRODUCTION

Nowadays the precision electric power (EP) measurements at industrial frequency are the main basis of commercial relations between consumer of electricity and electricity supplier. It will be noted that EP measurements are standard tasks in electrical engineering. Precision of EP measurements is of major interest in the context of energy efficiency.

Deserves to be marked the widespread of power-electronic equipment in Ukrainian EP system is provoking arise of a different type of disturbance that reduce the system's power quality called harmonic distortion [1]. The non-linear feature of this equipment is responsible for the injection of harmonic currents in the electric grid and thus causing the harmonic voltage distortion (HVD).

It is useful to note that most of electrical equipment is very sensitive to distortion of voltage and current waves as well as to the presence of one or more particular harmonics. Consequently the effects of the harmonics in EP networks are reflected by the energy losses that occur

due to the deforming regimes, leading to the increased costs of producing electricity [2]. Unfortunately, EP loss is not directly accessible by electrical measurement. Because of the difference between large input and output EP needs to be determined [3].

Definitely in a three-wire balanced measurement system the 3rd harmonic usually cancels out. However, depending on the type and nature of the nonlinear loads, other voltage harmonics can be present, usually in the order 5th, 7th, 9th, 11th and 13th [4]. Precision EP evaluation has achieved very high accuracy for the sinusoidal case at industrial frequency [5]. Consequently, highly accurate methods for these situations are of great interest.

In experimental study cases the authors have modulated HVDs and evaluated the uncertainty depends on it for precision EP measurements and discovered its further influence on evaluation expanded uncertainty of EP measurements on the National standard of electric power and power factor units of Ukraine (National standard). Therefore, the main aim of this paper is try to evaluate the uncertainty influence depends on HVD which will not exceed 8 % according to standard EN 50160, for precision EP measurements.

II. PRECISION ELECTRIC POWER MEASUREMENTS

A. Measurement model of precision electric power measurements

National standard was designed for reproduction and storage of EP unit from 0.01 W to 72000 W (in single-phase mode) in the frequency range from 40 Hz to 70 Hz [6-8]. The measurement model of precision EP measurements in relative form is the next:

$$P_x = P_0 + \delta P_r + \delta P_{CPM} + \delta P_{CFM} + \delta P_{CDTM} + \delta P_{CACCM} + \delta P_{CACVAM} + \delta P_{CACDCI} + \delta P_{CACDCU} + \delta P_{CTCU} + \delta P_{CTCI} + \delta P_{CTCP} + \delta P_{CTCPA} + \delta P_{CTCF} + \delta P_{STS} + \delta P_{LTS}, \quad (1)$$

where P_0 is the EP mean value of the observation of the differences between the working standard (WS) and the reference value in $\mu\text{W}/\text{VA}$; δP_r is the standard deviation of the mean of EP reproduction; δP_{CPM} is the phase measurement correction; δP_{CFM} is the frequency measurement correction; δP_{CDTM} is the drift of temperature measurements; δP_{CACCM} is the AC current measurements correction; δP_{CACVAM} is the AC voltage amplitude measurements correction; δP_{CACDCS} is the thermal converter AC-DC difference (current channel); δP_{CACDCU} is the thermal converter AC-DC difference (voltage channel); δP_{CTCU} is the influence of temperature coefficient on WS (voltage); δP_{CTCI} is the influence of temperature coefficient on WS (direct AC current); δP_{CTCP} is the influence of temperature coefficient on WS (power); δP_{CTCPA} is the influence of temperature coefficient on WS (power factor); δP_{CTCF} is the influence of temperature coefficient on WS (frequency); δP_{STS} is the short term stability; δP_{LTS} is the long term stability (for the one operation year).

From the formula (1) it can be conclude that the parameter δP_{CACVAM} is the most dependent on the presence of voltage harmonics.

B. Additional measurement model depends on voltage harmonics

The main condition in our research is to provide

Table 1. Additional uncertainty budget depends on harmonic voltage distortions of 8 %, $\mu\text{W}/\text{VA}$.

i	Quantity (unit)	Distribution	x_i	$u(x_i)$	v_i	c_i	$u_i(y)$
1	The differences between the working standard and the fundamental depends on voltage distortion	normal	0.1	2.5	99	1	2.5
2	The influence of 3rd order voltage harmonic	normal	x_{3i}	17.4	99	1	17.4
3	The influence of 5th order voltage harmonic	normal	x_{5i}	17.4	99	1	17.4
4	The influence of 7th order voltage harmonic	normal	x_{7i}	17.4	99	1	17.4
5	The influence of 9th order voltage harmonic	normal	x_{9i}	17.4	99	1	17.4
6	The influence of 11th order voltage harmonic	normal	x_{11i}	17.4	99	1	17.4
7	The influence of 13th order voltage harmonic	normal	x_{13i}	17.4	99	1	17.4
8	The resolution correction of the standard	normal	0	1.0	∞	1	1.0
9	The repeatability correction of the standard	normal	0	10.0	∞	0.1	1.0
y	Standard uncertainty of measurement						42.7

A comparative analysis of the uncertainty budgets of fundamental voltage and voltage with harmonic distortions allows authors to make a general conclusion that the presence of voltage harmonics of 8 % in the order 3rd, 5th, 7th, 9th, 11th and 13th in a harmonic signal are directly proportionally contribute to the uncertainty budget equal 17.4 $\mu\text{W}/\text{VA}$. But if the HVD will be differ from the value of 8 % the standard uncertainty will decreases in direct proportion to level HVD in ideal case. For example if HVD is equal 5 % the standard uncertainty will be 10.9 $\mu\text{W}/\text{VA}$. This means that the presence of each harmonic will add to the budget of uncertainty at least 10.9 $\mu\text{W}/\text{VA}$ for VD of 5 %.

The brief conclusion on Table 1 is the next: the

current stability. Only under this condition the current can be taken as a constant and all the and thus the additional influence of current distortion may not be taken into account in the basic calculations. After analyzing formula (1) the most voltage dependent parameter has been identified and the additional measurement model in relative form of this parameter was written below:

$$\delta P_{\text{CACVAM}} = P_{0U1} + \sum_{n=2}^N \sqrt{\delta P_{nUn}^2} + \delta P_{Ures} + \delta P_{Urep}, \quad (2)$$

where P_{0U1} is the differences between the WS and the reference value depends on influence of fundamental voltage amplitude, in $\mu\text{W}/\text{VA}$; δP_{nUn} is influence of the voltage harmonics, respectively, of the n-order, in $\mu\text{W}/\text{VA}$; δP_{nUres} is the resolution correction of the standard, in $\mu\text{W}/\text{VA}$; δP_{nUrep} is the repeatability correction of the standard, in $\mu\text{W}/\text{VA}$; $N = 13$ is maximum number of harmonics, in $\mu\text{W}/\text{VA}$.

According the main aim of experimental study cases it will be evaluated the influence of HVD for precision EP measurements. By the results of the evaluation components of influence HVD for precision EP measurements, in formula (2) is composed the additional uncertainty budget, which is given in Table 1.

presence of 3rd harmonic implies an increase of uncertainty by 7 times; the presence of combination 3rd and 5th harmonics implies an increase of uncertainty by 10 times; the presence of combination 3rd, 5th and 7th harmonics implies an increase of uncertainty by 12 times; the presence of combination 3rd, 5th, 7th and 9th harmonics implies an increase of uncertainty by 14 times; the presence of combination 3rd, 5th, 7th, 9th and 11th harmonics implies an increase of uncertainty by 16 times; the presence of combination 3rd, 5th, 7th, 9th, 11th and 13th harmonics implies an increase of uncertainty by 17 times. The influence of presence sequential order harmonics is nonlinearly affects increases on uncertainty of measurements.

III. EXPERIMENTAL STUDY CASES

In experimental study cases the authors have decided to discover only HVD. As known the harmonic signals in which distorted voltage signals decompose (with the help of the Fourier transformation) are called harmonics. The formula (3) describes the shape of the voltage in the non-sinusoidal regime accepted in the power quality:

$$u(t) = U_0 + \sum_{n=1}^{\infty} U_n \cdot \sqrt{2} \sin(n\omega t + \alpha_n), \quad (3)$$

where U_0 is the continuous components of the voltage curves; U_n is values of the voltage harmonics, respectively, of the n-order; ω is the pulsations of n-order harmonic; α_n is the phase shift of n-order harmonic component.

For precision EP measurements also were calculated voltage total harmonic distortion (THD_U) which is described according to EN 50160 in next formula:

$$THD_U = \frac{1}{U_1} \cdot \sqrt{\sum_{n=2}^{\infty} U_n^2} \cdot 100\%, \quad (4)$$

where U_n are values of the voltage harmonics, respectively, of the n-order; U_1 is fundamental voltage.

The influence of presence sequential order harmonics is nonlinearly affects increases on uncertainty of measurements. For realization of experimental was chosen reference set of equipment: the highly precision power comparator COM 3003 ZERA GmbH (COM 3003), high stable power source MT 3000 ZERA GmbH (MT 3000). This reference set of equipment is the main part of the National Standard of electrical power and power factor units. The block diagram of the measurement setup is shown in Fig. 1.

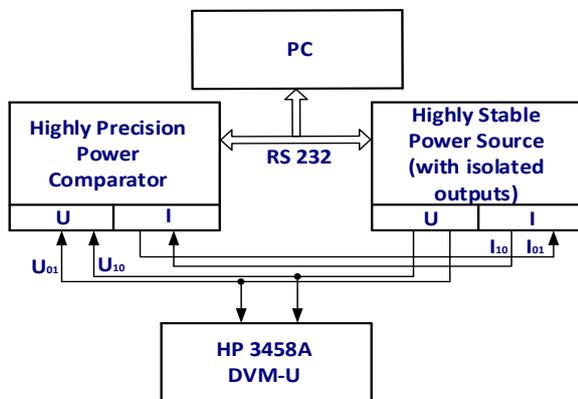


Fig. 1. Block diagram of the measurement setup

The distorted sinewave was generated by the means

of MT 3000 which allows to generate up to the 20th harmonic distortions in voltage and current according to the technical data with THD_U and THD_I less than 0.5 % in a frequency range from 15 Hz to 70 Hz (for 50 Hz 0.1%). It should be mentioned that the declared technical characteristics of the MT 3000 exceed the requirements of the standard EN 50106 with a margin of at least 10 times. The authors to conclude that this device has an ideally pure sine wave and is most suitable for our experimentation. The distorted sinewave was measured by the means of COM 3003 which allows: comparing the EP measured by the COM 3003 with the EP metered by the device under test. Also COM 3003 can display the actual values of the harmonics of all the channels referred to the fundamental harmonic. This enables to detect whether there are harmonic distortions in the current or voltage. Due to the high sampling rate of the COM 3003 harmonic distortions in voltage and current can be measured up to the 40th according to the voltage quality standard EN 50160. The measured harmonic spectrum can be displayed in a chart (Fig. 2) or in a diagram (Fig. 3) with the help of SSM 3000 software.

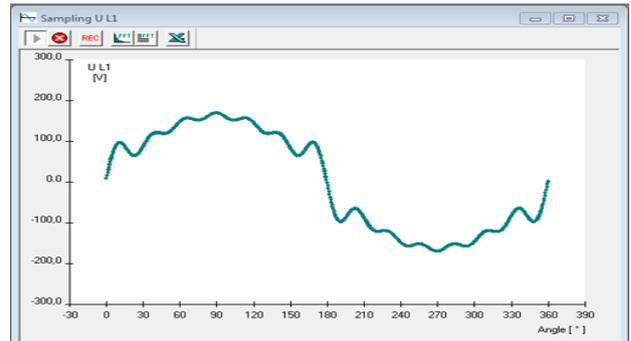


Fig.2. The waveform distortions of the voltage depends on the influence of 7th harmonics

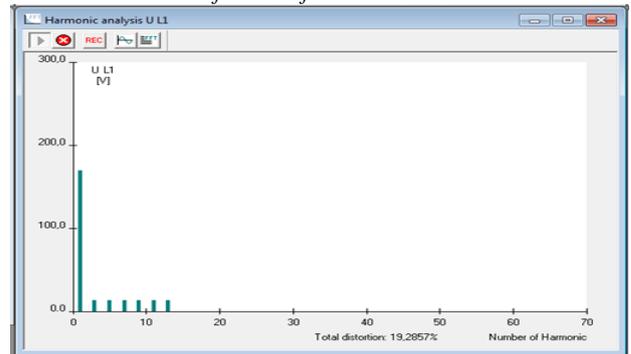


Fig.3. The spectral characteristic on the influence combination of harmonics in the order 1st, 3rd, 5th, 7th, 9th, 11th and 13th

IV. EVALUATION OF THE RESULTS

The first step was to evaluate the standard uncertainty depends on HVD and the next one is to discover its further influence on evaluation expanded uncertainty of

EP measurements. That's why in the framework of research it was decided to modulated combinations of HVDs which will be present like: 1st; 3rd; 3rd and 5th; 3rd, 5th and 7th; 3rd, 5th, 7th and 9th; 3rd, 5th, 7th, 9th

and 11th; 3rd, 5th, 7th, 9th, 11th and 13th with 5 % and 8 % HVD for reference measurement point 120 V, 5 A, PF = 1.0, 50 Hz. All the results of research are listed in Table 2.

Table 2. Results of research for reference signal of active electric power.

Active power mean value, $\mu\text{W}/\text{VA}$	Level of harmonic, %	Voltage harmonic	THD _U , %	Standard uncertainty with influences of HVD, $\mu\text{W}/\text{VA}$	Expanded uncertainty with influences of HVD, $\mu\text{W}/\text{VA}$
1.80	100	U ₁	0.04	2.5	18.5
1.79	5	U ₃	4.99	11.3	28.8
1.78		U _{3,5}	7.06	15.7	36.1
1.76		U _{3,5,7}	8.64	19.1	42.1
1.75		U _{3,5,7,9}	9.97	22.0	47.5
1.74		U _{3,5,7,9,11}	11.14	24.5	52.1
1.69		U _{3,5,7,9,11,13}	12.19	26.9	56.7
1.75		8	U ₃	7.99	17.6
1.75	U _{3,5}		11.25	24.8	52.7
1.74	U _{3,5,7}		13.74	30.3	63.2
1.73	U _{3,5,7,9}		15.82	34.9	72.0
1.72	U _{3,5,7,9,11}		17.64	39.0	80.0
1.60	U _{3,5,7,9,11,13}		19.29	42.7	87.2

Brief analysis of Table 2 makes it possible to draw the following conclusions: contribution to the uncertainty budget of all harmonics make a uniform depending on the level of distortion; harmonic combinations make a non-linear contribution to the uncertainty budget; the presence of harmonics implies the great energy losses that is not suitable for precision EP measurements; the presence of harmonics implies increase expanded uncertainty of precision EP measurements. Also it should be mentioned that odd, multiple 3, harmonics cause overheating and destruction of the zero wire cable line. 5th, 7th, 11th and 13th harmonics in rotating machines cause an oscillatory moment. 3rd and 5th harmonics cause a decrease in noise immunity of single-phase pulsed power supplies. 3rd and 7th harmonics cause lower noise immunity of three-phase rectifiers according to Larionov's scheme. 3rd and 9th harmonics cause overvoltage in voltage transformers.

V. CONCLUSIONS

This article presented the results of modulated HVD and evaluated the uncertainty depends on it for precision EP measurements and also was discovered its further influence on expanded uncertainty. After the analysis of measured data, it was determined that the presence of 3rd harmonic implies an increase of additional standard uncertainty by 7 times and the presence of combination from 3rd to 13th harmonics implies an increase of additional standard uncertainty by 17.4 times.

A general remark is the presence of voltage harmonics in the independent order 3rd, 5th, 7th, 9th, 11th and 13th in a harmonic signal are directly proportionally contribute to the uncertainty budget and equal 10.9 $\mu\text{W}/\text{VA}$ (5 %) and 17.4 $\mu\text{W}/\text{VA}$ (8 %) for each harmonic. The presence of voltage harmonics also implies the great energy losses about 0.2 $\mu\text{W}/\text{VA}$ that are not suitable for precision EP

measurements, increase additional standard uncertainty from 2.5 $\mu\text{W}/\text{VA}$ to 42.7 $\mu\text{W}/\text{VA}$, and as a consequence the expanded uncertainty of precision EP measurements are going to be increased from 18.5 $\mu\text{W}/\text{VA}$ to 87.2 $\mu\text{W}/\text{VA}$. As future works, it will be research current harmonic distortions.

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