ISSN 2226-3780

UDC 621.315.6
DOI: 10.15587/2312-8372.2018.126626

Trotsenko Ye., Brzhezitsky V., Protsenko O., Chumack V., Haran Ya.

EFFECT OF VOLTAGE HARMONICS ON PULSE REPETITION RATE OF PARTIAL DISCHARGES

Об'єктом дослідження є процеси часткового розряду, що моделюються при впливі несинусоїдальної напруги. В контексті дослідження вплив гармонік напруги на часткові розряди, коефіцієнт спотворення синусоїдальності кривої напруги може використовуватися тільки для грубої оцінки. Причина, цього полягає в тому, що коефіцієнт спотворення синусоїдальності кривої напруги не враховує фазові кути окремих гармонійних складових напруги. При несинусоїдній напрузі (с коефіцієнтом спотворення синусоїдальності кривої напруги 10 % і більше) інтенсивність часткових розрядів в ізоляції зростає. Однак при менших значеннях коефіцієнта спотворення синусоїдальності кривої напруги гармоніки також можуть впливати на характеристики часткових розрядів. Для вирішення поставленого завдання необхідно провести дослідження, збільшивши кількість врахованих гармонік напруги. Для цього можна використовувати відому трьох-ємкісну схему заміщення діелектрика з газовим включенням, внісши відповідні зміни в джерело напруги.

Проведено дослідження моделі з використанням спільно з гармонікою основної частоти, гармонік напруги з 2-ї по 30-у включно. Встановлено, що при фіксованій амплітуді фазовий кут гармонік напруги має вирішальний вплив на кількість імпульсів часткових розрядів. При наявності гармонік напруги ця кількість може виявитися такою ж, як і при впливі ідеальної синусоїдальної напруги. Також вона може виявитися на 14,3 % менше і на 14,3 % або на 28,6 % більше. При цьому у всіх випадках коефіцієнт спотворення синусоїдальності кривої напруги залишається одним і тим ж. Проведено експериментальне дослідження можливості використання високовольтних еталонних індуктивних трансформаторів напруги для вимірювання несинусоїдальності напруги. Встановлено, що це доцільно для області максимального значення магнітної проникності їх магнітопроводів, що відповідає діапазону 80–120 % номінальної напруги трансформатора.

Мобільні лабораторії для повірки високовольтних трансформаторів напруги на місцях їх експлуатації при доповненні відповідною апаратурою одночасно можуть бути використані для вимірювання ряду показників якості електроенергії.

Ключові слова: *схемотехнічне моделювання, частковий розряд, гармоніки напруги, фазовий кут, частота слідування імпульсів.*

1. Introduction

The problem of current and voltage harmonics is relevant for electrical networks of various voltage classes. Non-sinusoidal regimes in electrical networks lead to a number of negative consequences, including a reduction in the service life of insulation. Long-term operation of cable and overhead power lines, transformers, generators, switching devices and other equipment depends on reliable operation of electrical insulation. During operation, the insulation is affected by operating voltage and overvoltage. Over time, insulation characteristics deteriorate, insulation resistance decreases, the dielectric loss tangent increases. In the weakened areas of insulation, partial discharges occur. This is one of the reasons that cause accelerated aging of the insulation. Current and voltage harmonics lead to additional losses, heating and accelerated aging of electrical insulation. The appearance of partial discharges of a certain level in the insulation of electrical equipment testifies to the internal defects of this equipment. Therefore, measurement of the partial discharge characteristics has found its application in the high-voltage equipment state diagnosis. At a certain stage of the study, the effect of harmonics on the phenomenon of partial discharge was noted. The study of the influence of voltage harmonics on the partial discharge characteristics showed that under non-sinusoidal voltage (with the total harmonic distortion of 10 % and above) the intensity of partial discharges increases [1]. The permissible values of the total harmonic distortion are set by standards, in particular, GOST 13109, IEC 61000-4-7. These values differ for various rated voltages. For example, at a nominal voltage of 6–20 kV, the maximum permissible value of the total harmonic distortion is 8 % (GOST 13109). As it will be shown later, the authors of the paper believe that even at such values of the total harmonic distortion, the harmonics can significantly affect the characteristics of the partial discharges.

2. The object of research and its technological audit

The objects of the research are partial discharge processes simulated under the influence of non-sinusoidal voltage using capacitive equivalent circuit for a dielectric with a gas cavity. According to GOST 13109, a non-sinusoidal voltage is characterized by the following two factors. The first is the total harmonic distortion, which is given by formula (1). The second is the individual harmonic component, which is given by formula (2).

$$THD_U = \sqrt{\sum_{n=2}^{N}\left(\frac{U_n}{U_1}\right)^2} = \frac{\sqrt{U_2^2+U_3^2+\ldots+U_N^2}}{U_1}, \quad (1)$$

 ISSN 2226-3780

where U_n – root-mean-square value of voltage harmonic component of order n, V; n – order of voltage harmonic component; N – the order of the maximal of the voltage harmonic component taking into account; U_1 – root-mean-square value of fundamental frequency voltage (first order harmonic), V.

According to GOST 13109 or IEC 61000-4-7, it is usually assumed $N=40$, but in a number of publications it is limited to $N=25$ (DSTU EN 50160), since some digital analyzers measure harmonics only up to the 25th order to calculate the total harmonic distortion. In connection with this, in this paper it is accepted $N=30$.

$$U_n(\%)=\frac{U_n}{U_1}\cdot 100\ \%. \tag{2}$$

The permissible value of voltage harmonic component of order n (2) for electrical networks of various rated voltages are given in GOST 13109.

In the context of studying the effect of voltage harmonics on partial discharges, the total harmonic distortion (1) can only be used for rough estimation [2]. The reason for this is that the total harmonic distortion (1) does not take into account the phase angles of the individual voltage harmonic components [2]. In [3] two examples of the dependence of the number of partial discharge pulses on the phase angle of the 5th order voltage harmonic are shown. In the first case, in gas cavity, the same number of partial discharges occurs during a period, as with a pure sinusoidal voltage, but in the second case, the number of partial discharges is greater. The percentage of the 5th order voltage harmonic component in both cases is the same (4 %) and, consequently, the total harmonic distortion is also the same.

Obviously, with the increase in the amplitude of the harmonics, this effect should be manifested more strongly. Study of the influence of voltage harmonics of quite large amplitude on the characteristics of partial discharges was carried out in [1, 2]. The authors of this article believe that it is also necessary to study the effect of voltage harmonics on the number of partial discharges, at such amplitudes of harmonics that do not exceed the permissible values specified in GOST 13109.

3. The aim and objectives of research

The aim of research is analysis of the dependence of the pulse repetition rate of partial discharges in insulation when subjected to the first order harmonic together with voltage harmonics from the 2nd to the 30th order in the programs of circuit simulation. At the same time, it is assumed that the pulse repetition rate of partial discharges is the number of partial discharge pulses over a period multiplied by the network frequency. To achieve this aim, the following tasks were formulated:

1. Selection of a dielectric model with a gas cavity with partial discharge and computation of the number of partial discharges over a period under the influence of a pure sinusoidal voltage of 50 Hz frequency.
2. Computation of the number of partial discharges when subjected to the first order harmonic together with voltage harmonics from the 2nd to the 30th order.
3. Experimental evaluating the possibility of using reference inductive voltage transformers for power quality indices measurements, including non-sinusoidal voltage.
4. Formulating recommendations and drawing conclusions on practical measurements of voltage distortion in high-voltage networks.

4. Research of existing solutions of the problem

In order to study partial discharges at alternating-current voltage, in most cases a three-capacitive equivalent circuit for a dielectric with a gas cavity is used. This circuit is the result of improvements to the circuit proposed in [4]. A brief history of most changes introduced into the circuit is given in [5]. In [6], one of the latest improvements to the circuit for the case of the effect of an impulse voltage on oil-impregnated paper insulation with a partial discharge is also proposed. In general, the good applicability of the three-capacitive equivalent circuit for a dielectric with a gas cavity under the influence of alternating-current voltage is confirmed by articles [7–9]. The influence of voltage harmonics on the characteristics of partial discharges, mainly on increasing their intensity is shown in [1, 2, 10]. The applied voltage in articles [1, 2] is the voltage of the fundamental frequency (the first order harmonic) and several higher-order harmonics. The study was carried out at several fixed values of the phase angle of higher-order harmonics. An example of the combined effect of the 1st and 5th order voltage harmonics on the change in the number of partial discharges over a period is shown in article [3]. At the same time, the percentage of the 5th order voltage harmonic component (4 %) does not exceed the permissible value specified in GOST 13109. In this paper, the authors propose to carry out a wider research by increasing the number of voltage harmonics taken into account together with the fundamental frequency harmonic from the 2nd to the 30th order. In this research, it is possible to use the same model of a dielectric with a gas cavity as in article [3], making appropriate changes to the voltage source.

5. Methods of research

To achieve objectives that were set such research methods were applied: multivariate analysis, circuit simulation on a personal computer, high-voltage testing in a high-voltage laboratory. The initial material of the research is a capacitive equivalent circuit for a dielectric with a gas cavity with partial discharges.

6. Research results

The model for studying the influence of voltage harmonics on partial discharges in a gas cavity is shown in Fig. 1. This model was proposed in article [3]. Modeling was performed in the Micro-Cap Evaluation/Student Version [11].

In Fig. 1 E_1 – a functional voltage source (can represent functions as a voltage source of only the fundamental frequency, and the algebraic sum of the voltage harmonics); R_1 – internal resistance of the voltage source; C_1 – capacitance of a dielectric, without a gas cavity section; C_2 – capacitance of the section of the dielectric connected in series with a gas cavity; C_3 – capacitance of a gas cavity. The remaining elements of the model simulate a spark gap, simulating the breakdown of the gas cavity at partial discharges.

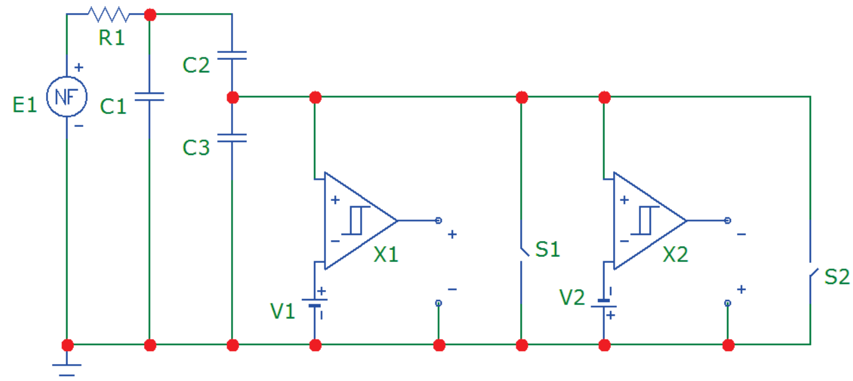


Fig. 1. Circuit-simulation model of a dielectric with a gas cavity with partial discharges, used in research and proposed in article [3]

These elements include:

X_1, X_2 – voltage comparators with hysteresis;

S_1, S_2 – voltage-controlled switches with hysteresis;

V_1, V_2 – reference voltage sources. The resistance of the switches S_1 and S_2 in the open state is $100\,\text{M}\Omega$, and in the close state is $1\,\Omega$. The internal resistance of the voltage source is $1\,\Omega$. It is assumed in the article that $C_1 = 5000$ pF; $C_2 = 200$ pF and $C_3 = 600$ pF [3]. Gas cavity characteristics are following: value of the partial discharge inception voltage is +800 V, and the partial discharge extinction voltage is +400 V. Analogously for a negative half-cycle of a sinusoidal voltage, these values are –800 V and –400 V. It is assumed in the article that the amplitude of the fundamental frequency voltage harmonic is $U_{1m} = 10000 \cdot \sqrt{2} / \sqrt{3}$ V.

Prior to studying the influence of non-sinusoidal voltage on the model of a dielectric with a gas cavity, the model was tested using an undistorted sinusoidal voltage, the corresponding results are shown in Fig. 2. These results are shown on the same plot, but with different vertical axis scales. Here and below, the blue color corresponds to the voltage applied to the dielectric. The red color corresponds to the voltage that arises on the gas cavity in solid insulation.

Thus, it was found that, in the absence of harmonic distortions for specified parameters of the model, 14 partial discharge pulses over one period of 50 Hz frequency occur in the gas cavity. All further results will be compared to this number.

To vary the value of the phase angle (φ_n) of the voltage $u_n(t)$ of each harmonic component of order n:

$$u_n(t) = U_{1m} \cdot \left(\frac{U_n}{U_1}\right) \cdot \sin\left(n \cdot 2 \cdot \pi \cdot f \cdot t + \varphi_n\right),$$

where $f = 50$ Hz, it was decided to use a random number generator. Accordingly, the phase angle of each harmonic is given by the formula:

$$\varphi_n = 2 \cdot \pi \cdot RNDR, \tag{3}$$

where φ_n – phase angle in radians; $RNDR$ – function that returns a random real number in the range from 0 to 1 each time a transient analysis is run [11]. Thus, each time a transient analysis is launched, the phase angle of each individual voltage harmonic is equal to a random number in the range from 0 to $2 \cdot \pi$. After a multiple launch of the transient analysis, all possible variants of the number of partial discharge pulses that can occur over a period in the given model were found. These values are 12, 14, 16 or 18 partial discharge (PD) pulses over one period. Examples are shown in Fig. 3–6. Counting starts from the second half-cycle, when each subsequent period of the applied voltage contains the same number of partial discharge pulses.

The phase angle and the percentage U_n (%) of each voltage harmonic component of order n, corresponding to the graphs in Fig. 3–6, are given in Table 1.

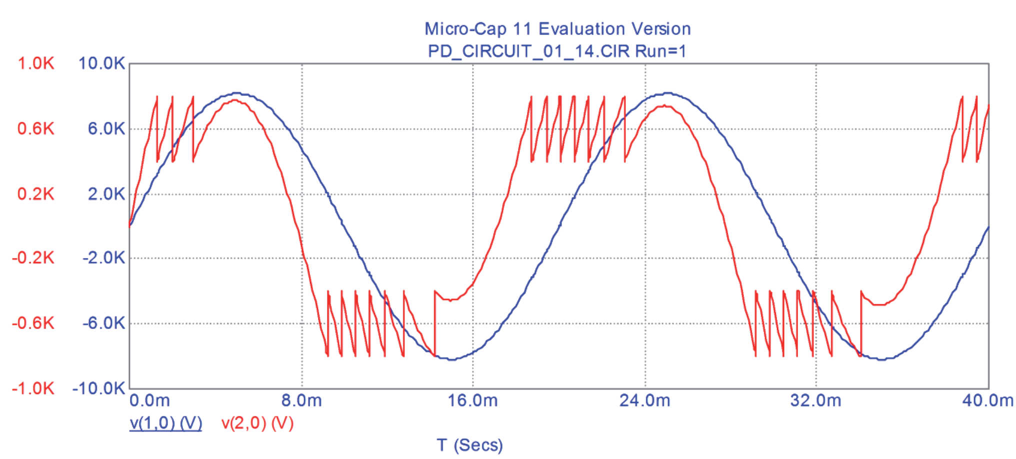


Fig. 2. The appearance of 14 partial discharges over a period at a pure sinusoidal voltage of 50 Hz frequency

 ISSN 2226-3780

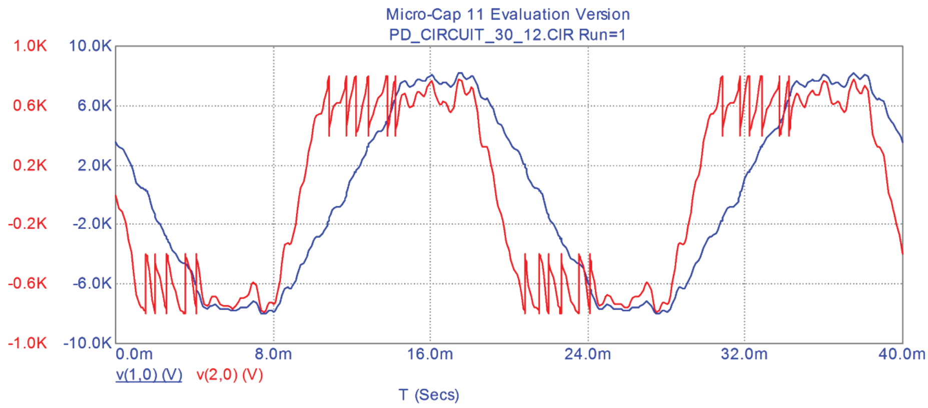


Fig. 3. The appearance of 12 partial discharges over a period for given values of the amplitudes and a combination of the phase angles of the voltage harmonics in accordance with Table 1

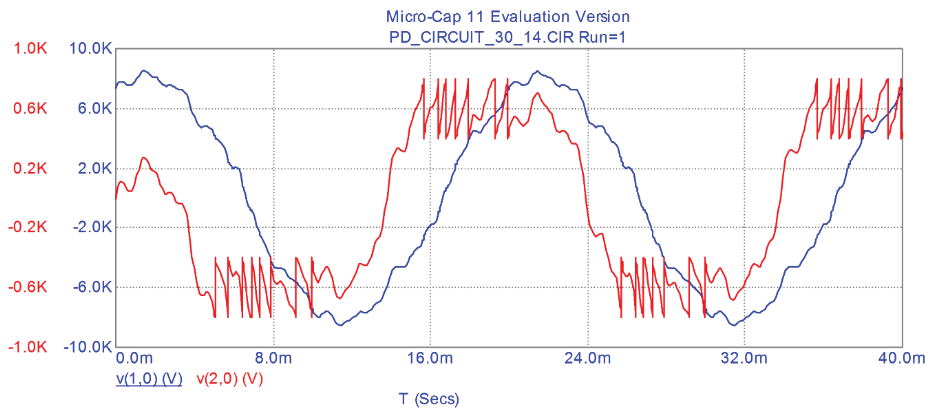


Fig. 4. The appearance of 14 partial discharges over a period for given values of the amplitudes and a combination of the phase angles of the voltage harmonics in accordance with Table 1

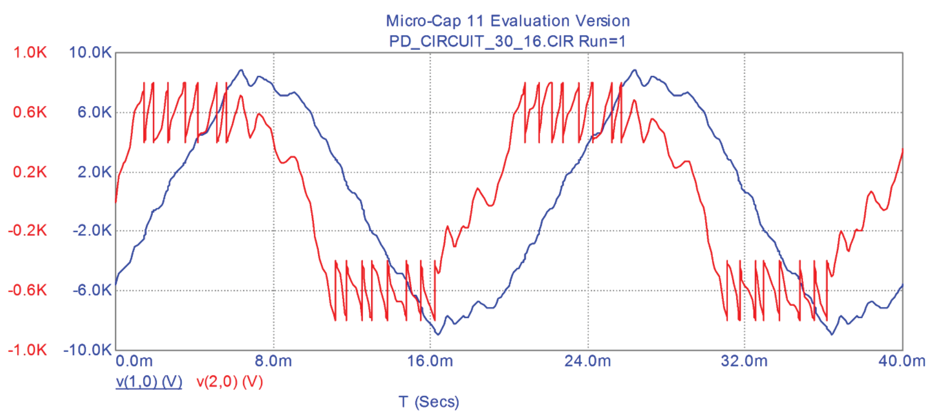


Fig. 5. The appearance of 16 partial discharges over a period for given values of the amplitudes and a combination of the phase angles of the voltage harmonics in accordance with Table 1

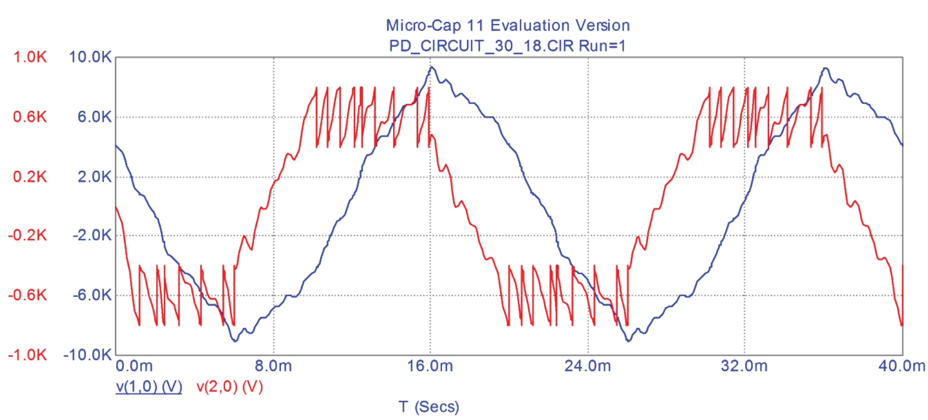


Fig. 6. The appearance of 18 partial discharges over a period for given values of the amplitudes and a combination of the phase angles of the voltage harmonics in accordance with Table 1

Table 1

Simulation results

Order of voltage harmonic component (n)	Percentage U_n (%) of each voltage harmonic component of order n, %	Phase angle j_n of each voltage harmonic component of order n, rad			
		12 PD pulses over a period (Fig. 3)	14 PD pulses over a period (Fig. 4)	16 PD pulses over a period (Fig. 5)	18 PD pulses over a period (Fig. 6)
1	100.00	2.664	1.075	5.554	2.621
2	1.50	2.670	5.161	2.179	4.462
3	1.50	1.480	2.642	1.969	6.207
4	0.70	1.619	1.368	4.721	2.981
5	4.00	4.065	5.099	4.474	1.158
6	0.30	1.002	1.669	4.027	4.152
7	3.00	5.915	0.742	0.120	3.572
8	0.30	0.339	4.095	0.617	5.440
9	0.50	3.701	0.441	3.726	1.981
10	0.30	0.766	2.388	1.820	1.492
11	2.00	2.121	2.431	0.176	1.731
12	0.20	0.397	1.012	4.502	2.497
13	2.00	5.157	0.910	1.730	5.486
14	0.20	0.556	4.405	1.382	4.844
15	0.30	0.848	4.576	3.405	0.348
16	0.20	3.360	2.541	3.461	5.717
17	1.50	5.966	0.416	4.842	5.003
18	0.20	4.200	3.878	2.248	3.567
19	1.00	4.457	0.216	2.507	0.784
20	0.20	1.451	0.221	4.653	5.328
21	0.20	3.269	2.438	1.276	6.076
22	0.20	1.440	2.672	1.300	5.207
23	1.00	2.834	0.267	6.041	5.255
24	0.20	0.011	2.881	0.487	4.947
25	1.00	2.625	3.407	0.362	1.626
26	0.20	1.980	2.437	1.421	3.982
27	0.94	3.982	4.943	3.823	2.207
28	0.20	5.065	3.800	4.119	3.394
29	0.88	5.818	0.892	5.415	5.294
30	0.20	0.578	5.977	5.736	0.916

It should be noted, that in this research, the values of the percentages of individual voltage harmonic component (Table 1) are assumed to be equal to the maximal permissible values, given in GOST 13109. Analysis of the graphs in Fig. 2–6 shows that for the fixed amplitude, the phase angle of the voltage harmonics has a decisive influence on the number of pulses of partial discharges in the gas cavity. In the presence of voltage harmonics, this number can be the same as under the influence of a pure sinusoidal voltage (14 partial discharges over a period). It can also be 14.3 % less (12 partial discharges over a period) and 14.3 % or 28.6 % greater (16 or 18 partial discharges over a period, respectively). At the same time, for all these cases, the total harmonic distortion calculated according to formula (1) gives the same value $THD_U = 6.78$ %.

The obtained results are of great importance for the theory of partial discharges in high-voltage electrical equipment. Not at once, but gradually partial discharges lead to deterioration of insulation properties, its physical destruction and, ultimately, to the electrical breakdown. The increase in the intensity of partial discharges with deterioration of the power quality indices contributes to the acceleration of this process.

In connection with the results obtained above, it becomes important to measure power quality indices in high-voltage networks not only in amplitude, but also in phase characteristics. Power quality control systems, in addition to the specialized power quality meters themselves (digital amplitude-phase analyzers), also require the use of appropriate primary scale current and voltage transducers.

The authors carried out the study of the possibility of using reference inductive voltage transformers to measure the quality of electrical energy, in particular, the non-sinusoidal voltage. A schematic diagram of the installation is shown in Fig. 7. The experiment consisted of comparing the output voltages of the reference toroidal voltage transformer with the standard capacitive voltage divider.

In Fig. 7 *SPVR* – single-phase voltage regulator; *VT* – step-up voltage transformer; *RVT* – reference toroidal inductive voltage transformer which is being studied; *RVD* – reference voltage divider; *USB-Oscill* – digital oscilloscope.

The installation shown in Fig. 7, allows applying a sinusoidal signal of the fundamental frequency to the input of the reference voltage transformer which is being studied (with some distortions existing in the network and brought by the voltage regulator and by the step-up voltage transformer).

In the installation, reference toroidal inductive voltage transformer of class 110 kV and of accuracy class 0.05 was used as the transformer under test. The transformer is manufactured at the Department of High Voltage Engineering and Electrophysics of the National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute» [12]. A photograph of the transformer is shown in Fig. 8, *a*. The parameters of the reference capacitive voltage divider are as follows. Capacitance of high-voltage arm $C_3 = 75$ pF (MCF-75/350 type high-voltage measuring capacitor manufactured in Germany). Capacitance of low-voltage arm $C_4 = 0.87$ μF (P-5025 type capacitor bank manufactured in Ukraine).

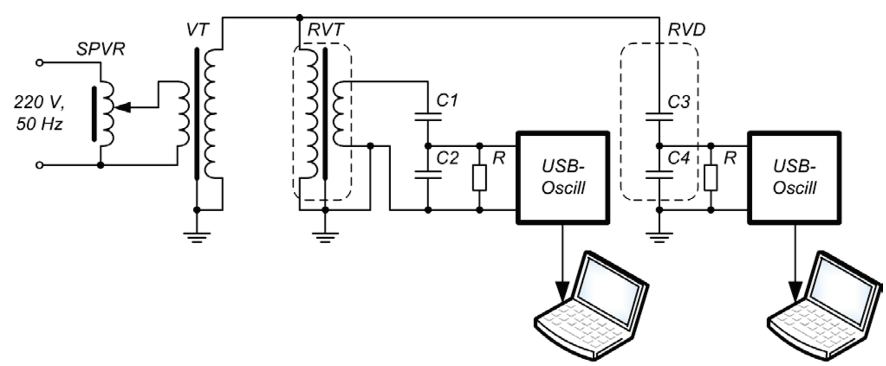
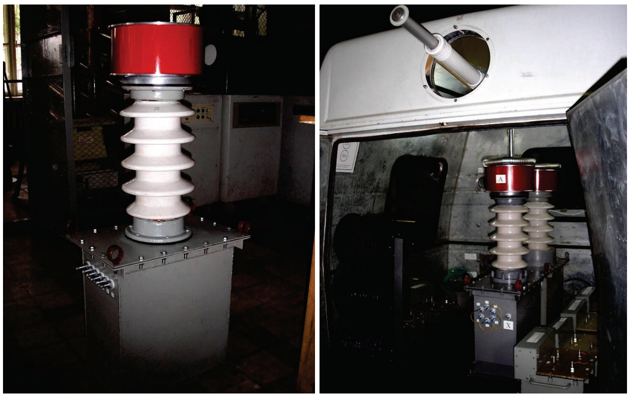


Fig. 7. Schematic diagram of the installation for studying the frequency characteristics of the inductive voltage transformer

 ISSN 2226-3780



a b

Fig. 8. Reference toroidal inductive voltage transformer of class 110 kV: *a* – preparation of the transformer for testing in the laboratory hall; *b* – transformer is mounted inside the mobile testing laboratory [13]

To observe the measurement results on the notebook screen, the USB-Oscill oscilloscope (manufactured in Ukraine) with the function of spectral analysis of the voltage signal up to 25th harmonic, with an input resistance of 1 MΩ was used. To reduce the amplitude of the signal from the terminals of the low voltage winding of the *RVT* transformer, a capacitive voltage divider with the capacitances of $C_1 = 0.1111\,\mu\text{F}$ and $C_2 = 0.9999\,\mu\text{F}$ (P-5025 type capacitor banks) was used.

Capacitors C_3, C_4, together with the input impedance R of the USB-Oscill oscilloscope, form a resistive-capacitive voltage divider with the division ratio K dependent on the angular frequency ω:

$$K(\omega) = \sqrt{1 + \frac{C_4^2}{C_3^2} + \frac{2C_4}{C_3} + \frac{1}{C_3^2 R^2 \omega^2}} = \sqrt{1.346\cdot 10^8 + \frac{1.778\cdot 10^8}{\omega^2}}.$$

Due to the large resistance R, the division ratio $K(\omega)$ is practically independent of the angular frequency ω. That is, the aforementioned resistive-capacitive voltage divider is not a filter of voltage harmonic components. For example, at frequencies of the fundamental (1st order harmonic) and 40th harmonics (at $\omega_1 = 314.159$ rad/s and $\omega_{40} = 12566.4$ rad/s, respectively), $K(\omega)$ is equal to $K(\omega_1) = 11601.80$ and $K(\omega_{40}) = 11601.72$, respectively.

The study was carried out at 20 %, 50 %, 80 %, 100 % and 120 % of the rated voltage of the reference inductive voltage transformer $U_r = 110/\sqrt{3} = 63.5$ kV (root-mean-square voltage). The results of an experimental research of the transformation of higher-order voltage harmonic components by a high-voltage reference voltage transformer in a wide range of its primary voltage are shown in Fig. 9–13. It can be seen that the transformation approaches the standard high-voltage voltage divider in the region of the maximum value of the magnetic permeability of the magnetic core of the transformer, that is, at 80–120 % of the rated voltage (Fig. 11–13).

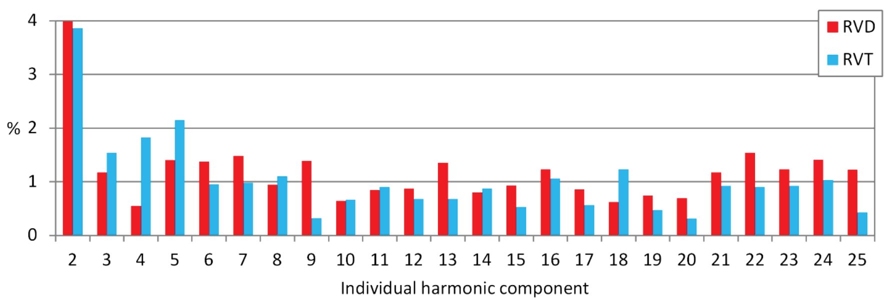


Fig. 9. Histograms of individual harmonic components of the test voltage at 20 % of U_r

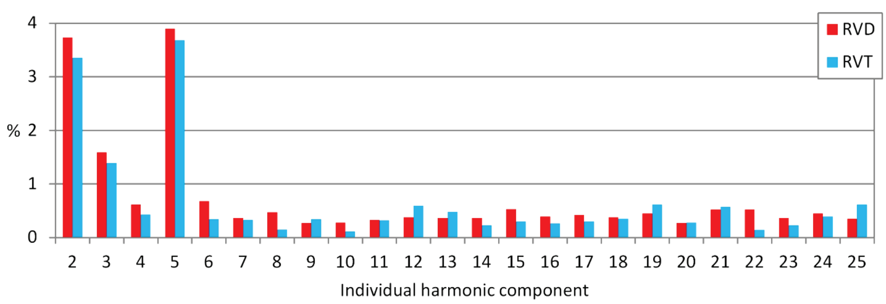


Fig. 10. Histograms of individual harmonic components of the test voltage at 50 % of U_r

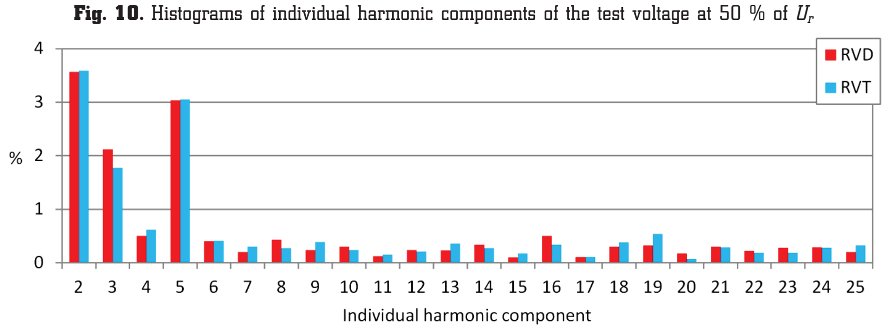


Fig. 11. Histograms of individual harmonic components of the test voltage at 80 % of U_r

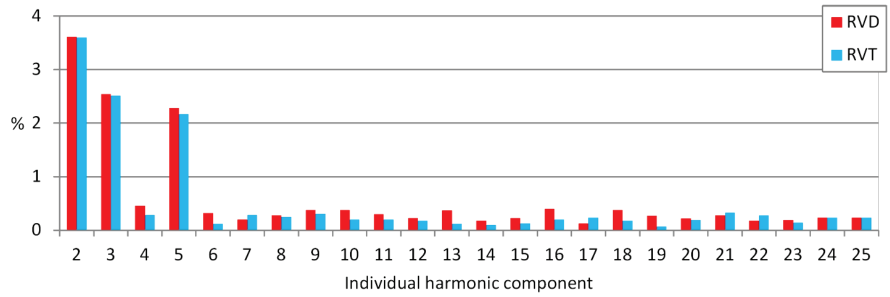


Fig. 12. Histograms of individual harmonic components of the test voltage at 100 % of U_r

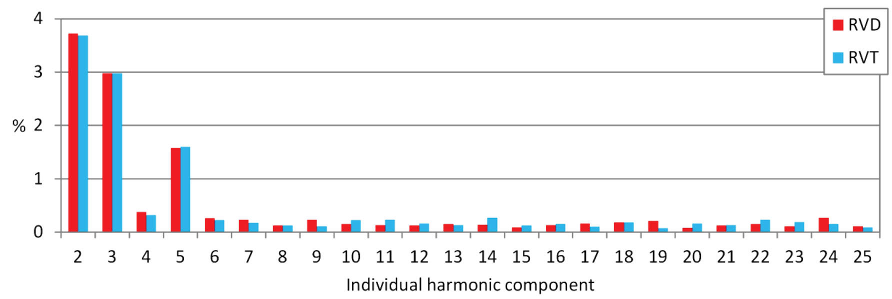


Fig. 13. Histograms of individual harmonic components of the test voltage at 120 % of U_r

In Fig. 9–13 *RVD* – histograms for the reference voltage divider; *RVT* – histograms for the reference toroidal inductive voltage transformer which is being studied.

Thus, the research showed the possibility of using reference instrument voltage transformers for measurement of power quality indices, in particular, the voltage harmonic components of higher orders. At the same time, it was shown in [14] that typical voltage transformers (not reference transformers), used in high-voltage electrical networks, unsatisfactorily transform voltage harmonic components of higher orders under conditions close to the saturation of their magnetic cores.

7. SWOT-analysis of research results

Strengths. The strengths of this research are:

– unlike other works, the proposed approach takes into account, together with the harmonic of the fundamental frequency, all harmonics from the 2nd to the 30th order;

– the possibility to accurately determine all possible variations in the number of partial discharge pulses that can occur in each particular model of a dielectric with a gas cavity. To obtain a similar result in a physical experiment, taking into account so many voltage harmonics is very difficult and is unlikely possible in practice;

– the possibility of using reference inductive voltage transformers to measure the amplitude of voltage harmonics directly in high-voltage networks was confirmed experimentally.

Weaknesses. The weak sides of this research are:

– the influence of the reference inductive voltage transformers on the phase angle of the voltage harmonics was not studied. This requires digital analyzers having the function of measuring not only the amplitude, but also the phase characteristics of individual harmonics;

– the measurement of the amplitude of voltage harmonics was performed up to the 25th order harmonic component. While in the standards the number of harmonics that have to be measured is 40. As in the previous paragraph, the reason lies in the limited capabilities of digital analyzers.

Opportunities. The additional opportunities that this research provides include:

– the possibility of further studying the influence of voltage harmonics on the characteristics of partial discharges and the identification of individual «critical» harmonics leading to an increase in the intensity of partial discharges;

– the continuation of work on improvement of reference inductive voltage transformers for measurement of power quality indices, including non-sinusoidal voltage characteristics.

Threats. Partial discharge is a very complex physical phenomenon, therefore, modeling is accompanied by certain assumptions and simplifications. In practice, partial discharge inception voltage and extinction voltage in each separate discharge can be different. During the study of partial discharge, these parameters were assumed unchanged. For this and other reasons, the quantitative characteristics of the result obtained in the simulation may, to some extent, differ from the one obtained in the experiment.

8. Conclusions

1. To study partial discharges under the influence of non-sinusoidal voltage, a traditional three-capacitive equivalent circuit of a dielectric with a gas cavity was chosen. The model was studied using an undistorted sinusoidal voltage. It was found that in the absence of harmonic distortions for the given parameters of the model and the rated voltage $10/\sqrt{3}$ kV, 14 pulses of partial discharges occur over a period of 50 Hz frequency in the gas cavity.

2. The model was studied using voltage harmonic of the fundamental frequency together with voltage harmonics from the 2nd to the 30th order included. It was found that for the fixed amplitude the phase angle of the voltage harmonics has a decisive influence on the number of partial

ISSN 2226-3780

discharge pulses. In the presence of voltage harmonics, this number can be the same as under the influence of a pure sinusoidal voltage (14 partial discharges over a period). It can also be 14.3 % less (12 partial discharges over a period) and 14.3 % or 28.6 % greater (16 or 18 partial discharges over a period, respectively). At the same time, for all these cases, the total harmonic distortion remains the same. In the context of studying the influence of voltage harmonics on partial discharges, the total harmonic distortion can only be used for rough estimation, since it does not take into account the phase angles of the individual voltage harmonics.

3. The possibility of using high-voltage reference inductive voltage transformers for voltage distortion measurements was studied experimentally, in particular, for non-sinusoidal voltage measurements. It was found that this is expedient for the region of the maximum value of the magnetic permeability of their magnetic cores, which corresponds to a range of 80–120 % of the transformer rated voltage.

4. Work to improve the reference inductive voltage transformers for the aim of measurement of non-sinusoidal voltage has great potential. In addition, digital analyzers having the function of measuring not only amplitude, but also phase characteristics of individual voltage harmonics are required. In connection with this, mobile laboratories (Fig. 8, *b*) for checking high-voltage transformers on-site [13, 15] with the addition of appropriate equipment can simultaneously be used to measure a number of power quality indices.

References

1. Florkowski M., Florkowska B. Distortion of partial-discharge images caused by high-voltage harmonics // IEE Proceedings – Generation, Transmission and Distribution. 2006. Vol. 153, No. 2. P. 171–180. doi:10.1049/ip-gtd:20050008
2. Impact of high voltage harmonics on interpretation of partial discharge patterns / Florkowski M. et al. // IEEE Transactions on Dielectrics and Electrical Insulation. 2013. Vol. 20, No. 6. P. 2009–2016. doi:10.1109/tdei.2013.6678848
3. Trotsenko Ye. et al. Simulation of partial discharges under influence of impulse voltage // Technology Audit and Production Reserves. 2018. Vol. 1, No. 1 (39). P. 36–41. doi:10.15587/2312-8372.2018.123309
4. Gemant A., Philippoff W. Die Funkenstrecke mit Vorkondensator // Zeitschrift für Technische Physik. 1932. Vol. 13, No. 9. P. 425–430.
5. Lemke E. A critical review of partial-discharge models // IEEE Electrical Insulation Magazine. 2012. Vol. 28, No. 6. P. 11–16. doi:10.1109/mei.2012.6340519
6. Partial discharge characteristics of uniform gap in oil-impregnated paper insulation under switching impulse voltage / Deng J. et al. // IEEE Transactions on Dielectrics and Electrical Insulation. 2016. Vol. 23, No. 6. P. 3584–3592. doi:10.1109/tdei.2016.005508
7. A Matlab Simulink model for a partial discharge measuring system / Gunawardana S. D. M. S. et al. // Electrical Engineering Conference. 2015. P. 29–34.
8. Arief Y. Z., Izzati W. A., Adzis Z. Modeling of Partial Discharge Mechanisms in Solid Dielectric Material // International Journal of Engineering and Innovative Technology. 2012. Vol. 1, No. 4. P. 315–320.
9. Patel U. D., Patel J. A., Patel H. R. Simulation and mathematical analysis of partial discharge measurement in transformer // International Journal of Emerging Technology and Advanced Engineering. 2015. Vol. 5, No. 1. P. 585–592.
10. Florkowska B., Florkowski M., Zydron P. The Role of Harmonic Components on Partial Discharge Mechanism and Degradation Processes in Epoxy Resin Insulation // IEEE International Conference on Solid Dielectrics. 2007. P. 560–563. doi:10.1109/icsd.2007.4290875
11. Micro-Cap 11. Electronic Circuit Analysis Program. Reference Manual. Sunnyvale: Spectrum Software, 2014. 1040 p. URL: http://www.spectrum-soft.com/down/rm11.pdf
12. Brzhezytskyi V. O., Brzhezytskyi V. V., Voloshchenko V. V., Kikalo V. M., Masliuchenko I. M., Trotsenko Ye. O. Etalonni vysokovoltni transformatory napruhy toroidalnoho typu: proceedings // Metrolohichne zabezpechennia obliku elektrychnoi enerhii v Ukraini. Kyiv: AVEHA, 2007. P. 96.
13. Mobilna povirochna laboratoriia klasiv napruhy 0,22...110 kV / Brzhezytskyi V. O. et al. // Metrolohichne zabezpechennia obliku elektrychnoi enerhii v Ukraini. Kyiv: AVEHA, 2007. P. 202–204.
14. Brzhezytski V. O., Garan Y. O., Maslychenko I. M. Transforming the higher harmonic components of the electromagnetic transformers (experimental study) // Scientific Works of National University of Food Technology. 2013. Vol. 49. P. 98–103.
15. Application of high voltage dividers for power quality indices measurement / Anokhin Y. L. et al. // Electrical Engineering & Electromechanics. 2017. No. 6. P. 53–59. doi:10.20998/2074-272x.2017.6.08

Trotsenko Yevgeniy, *PhD, Associate Professor, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: y.trotsenko@kpi.ua, ORCID: http://orcid.org/0000-0001-9379-0061*

Brzhezitsky Volodymyr, *Doctor of Technical Sciences, Professor, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: v.brzhezitsky@kpi.ua, ORCID: http://orcid.org/0000-0002-9768-7544*

Protsenko Olexandr, *PhD, Associate Professor, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: apro54@ukr.net, ORCID: http://orcid.org/0000-0002-7719-3336*

Chumack Vadim, *PhD, Associate Professor, Department of Electromechanics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: chumack_kpi@ukr.net, ORCID: https://orcid.org/0000-0001-8401-7931*

Haran Yaroslav, *Assistant, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: y.garan@kpi.ua, ORCID: http://orcid.org/0000-0003-3242-9218*