ARCHIVES OF ELECTRICAL ENGINEERING VOL. 67(2), pp. 231–246 (2018)

DOI 10.24425/119637

High voltage harmonics induced modifications of PD phase-resolved patterns

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(Received: 01.02.2017, revised: 31.01.2018)

Abstract: Partial discharges (PD) are influencing electrical insulating systems of high voltage electrical devices. Typically, in laboratory and diagnostics AC tests focused on measuring and analysis of PD, a pure sinusoidal voltage waveform is assumed. However, in practice the spectral content of the working voltage is rarely so ideal and additional spectral components have a significant impact on the discharge behaviour in electrical insulation systems. In this paper the influence of voltage harmonics on PD behaviour and phase-resolved PD patterns evolution is analysed. The presented experiments were conducted on a specimen representing a gaseous inclusion embedded in electrical insulation. The experimental results showed that various harmonic compositions superimposed on the fundamental sinusoidal waveform have a significant impact on PD intensity and maximum charge. In consequence, the derived patterns of PD phase, and magnitude distributions are distorted, and statistical parameters calculated on their basis are changed. In certain environments, neglecting harmonic content in the testing voltage may lead to a misleading interpretation and assessment of PD severity.

Key words: electrical insulation system, diagnostics, harmonics, partial discharges, phase-resolved patterns

1. Introduction

The influence of harmonics on insulation systems in terms of losses, lifetime and dielectric material degradation has been considered in many research papers. A novel aspect in this research area relates to the influence of harmonics on partial discharge (PD) phenomena, especially with regard to their mechanism and the interpretation of measurements [1–8]. PDs are influencing electrical insulation. An awareness of the impact of harmonics is especially important both in laboratory measurements [9] and in modern diagnostics of high voltage equipment, which is increasingly based on partial discharge phase-resolved patterns analysis. In power grids and networks, sinusoidal voltage usually contains various harmonics caused by nonlinear loads and resonances in the system. Higher harmonic content in voltage waveforms is usually associated with dielectric heating in insulating materials which has accelerated the aging process of the material. Increased power losses, in comparison to the power frequency excitation, result in increased temperature. Thermal, electrical, ambient, and mechanical (TEAM) stresses are usually combined to form life time models of insulation systems. In the advanced models also the harmonic content is taken into account, replacing pure sinusoidal voltage in simplified models [10]. The voltage peak is usually treated as the dominating factor for the accelerating degradation of insulation systems fed by both low frequency and high frequency harmonics. The additional factors are voltage rms (root-mean-square), shape and thermal stress for low frequency harmonics [11]. The presence of harmonics has an effect on the design rules of electric insulation withstand. For example, the degradation of power capacitors under the influence of harmonics was demonstrated in [1, 12]. The superimposed harmonics resulted in a shorter lifetime of those capacitors. The impact of voltage harmonics on the breakdown of insulation through influence on electrical tree growth in epoxy resin [13], and in XLPE samples [14] was also investigated. The effects of harmonics on parameters of PD raised in insulating systems are observed and analysed by different, complementary measurement methods. For example, in addition to the electrical method described in IEC standard [15] electromagnetic detection of PD signals using wideband sensors working in the UHF range was also used for investigation of PD generated by a conducting particle in transformer oil [16], and electrical trees in XLPE [17]. For PD testing and assessment of electrical insulating systems, both PD phase-resolved distributions and patterns [18–20], as well as the characteristic clusters parameters evaluated by the Pulse Sequence Analysis method [21] are used.

Transformer insulation is designed to withstand the effects of impulse test voltages like BIL (Basic-Insulation-Level) and abnormal system voltages like switching surges [22–24]. However, during normal operation the transformer insulation is also subjected to harmonic stresses on transmission and distribution levels as well as in industrial applications. The growing importance of this problem is related to the widespread use of non-linear loads, at different voltage levels. This is due to the common use of power electronic switching devices, including high power impulse-controlled ones. They work in AC power systems using e.g. phase angle control or the PWM (Pulse Width Modulation) method for required power flow control. The resulting distortions of the working voltages are characterized by time-varying harmonic content with different amplitudes and phases of individual harmonics, which can significantly influence electrical insulation degradation processes [25–28].

The harmonic contents of voltages and currents in electric networks are usually analysed due to requirements for assessment of the quality of electrical energy supplying different electric devices and equipment (motors, transformers, capacitors, etc.) [26, 29]. These analyses take into account the percentage value of the amplitude of individual harmonics with respect to the amplitude of fundamental 50/60 Hz component and/or ratio of their total rms value to fundamental component rms value, i.e. THD (Total Harmonic Distortion) parameter [26]. During PD measurement calculated $\mathrm{THD_U}$ value can be treated only as a rough estimation of test voltage quality in the context of its impact on PD activity, because it does not carry information about the shape of the voltage waveform. In real electric power networks, where transformers are exposed, additionally varying operating conditions result in various combinations of harmonics in voltage with dynamic modulation of their amplitudes and phase angles. The literature of the subject does not have many sources concerning the ranges of variation of individual harmonics phases, because in harmonic related studies the shape of the distorted voltage is usually not analysed. The presented problem is specific to the PD phenomenon sensitive to changes in the shape of the voltage, which is the basic operational stress for insulating systems of electric equipment. Thus, in modern diagnostics it is of utmost importance to properly understand and interpret the presence of harmonics when measuring, processing, and analysing PD arising at insulating systems. This aspect of harmonics is described in the paper, with particular emphasis on the effect of test voltage $u(t)$ and its derivative $\mathrm{d}u/\mathrm{d}t$ on measurement results. In presented studies, the influence of the percentage of selected harmonics and their phases (changed in the full range of angles, from 0° to 360°) on the recorded PD phase-resolved patterns is analysed.

2. Influence of harmonics on partial discharge mechanism

Partial discharge is a localized electrical discharge which occurs only in part of the volume or on a part of the surface of the insulation system. Such discharge partially bridges the insulation between conductors and can arise adjacent to a conductor [15]. Among the various forms of PD, discharges occurring in gaseous inclusions (cavities) can be distinguished, the presence of which is usually a factor that significantly diminishes the quality of the insulation system. The development of internal PDs occurring because of voids presence is an important reason leading to a reduction of the lifetime of insulation systems. Due to the fact that the basic cause of the PDs is the electric field stress, therefore the influence of the voltage waveform shape on the inception and development of PDs, and on the diagnostic parameters determined from PD measurement data is still an important research problem.

Typically, in laboratory and diagnostics tests focused on measuring partial discharges, a pure sinusoidal voltage waveform is assumed. However, in practice the spectral content of the applied voltage is rarely so ideal and additional spectral components have a significant impact on the discharge behaviour in electrical insulation systems. In consequence, PD phase-resolved patterns, and also PD phase, and PD magnitude distributions are distorted. As a result, the calculated statistical parameters of mentioned distributions are also changed.

To illustrate the harmonics impact, a specimen representing a gaseous inclusion in the high voltage insulating system was considered. The mechanism for PD depends on the type of defect in the insulation system, the defect itself being a source of discharges. For example, the mechanism of electrical treeing occurring in cable insulation subjected to voltage stresses containing harmonics was studied in [14], mainly in term of time-to-breakdown. The conditions for PD inception are related to the electric field distribution and its absolute value. In the oil-paper impregnated insulation, one can distinguish the characteristic defects, representing distinct conditions for PD initiation and development. For example, gaseous inclusions in the laminar insulation or created due to oil decomposition with gas emission. The PD inception mechanism is related to ionization in gas, comprising the electric charge transfer in an avalanche or streamer discharge. The geometry of the insulation system, including the thickness of the dielectric, the height of a gaseous inclusion in the direction of the external electric field, the surface perpendicular to the field, and the shape of the inclusion e.g. flat, spherical, oval etc., impacts the electric field in the source of discharges and the charge, transferred in the consecutive cycles. The electric field in the cavity is the resultant of the field coming from the time-varying test voltage and the field generated by charges distributed on its walls. These charges on the surface of the inclusion decay with a time constant depending on several factors (e.g. surface conductivity, recombination processes, etc.). Partial discharge arises when the value of the field in the inclusion exceeds the breakdown strength of the gas and the initiating electron is also available [30–33]. The variability and randomness of the factors determining the generation of discharges make the occurrence of PDs a stochastic process [28].

A simple PD triggering mechanism related to voltage condition in a PD source is illustrated in Fig. 1, where the applied voltage represents pure sinusoids and a distorted waveform. In the first case, assuming inception and extinction thresholds, two PD pulses are observed at specific phase locations (Fig. 2a). In the latter case, where harmonics are present, the void voltage is distorted and as a result PD pulses phase locations are changed into a half period (Fig. 2b). Thus the PD parameters and attributes are modulated/changed by harmonics [17–20].

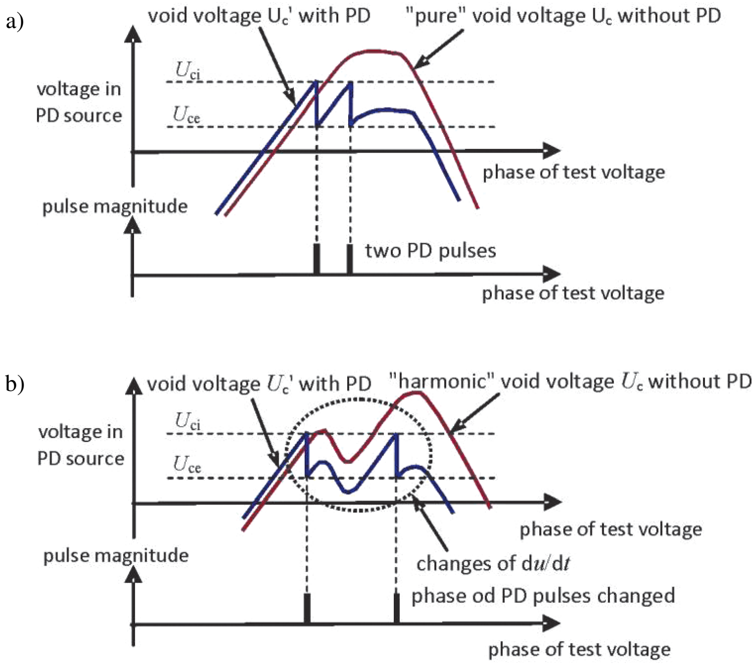

Fig. 1. Changes of voltage in PD source at “pure” and “harmonic” voltage: a) PD mechanisms at “pure” sinusoidal test voltage, b) example of effect of harmonics in applied voltage on void voltage U'_{c} and PD; (U_{ci} – PD inception voltage, U_{ce} – PD extinction voltage)

3. Specimen, measurement setup and experimental conditions

3.1. Gaseous inclusion specimen

An experimental specimen was prepared for laboratory investigations of PD behaviour in the presence of harmonics in HV insulating systems. The geometry of oil-impregnated sample is shown in Fig. 2.

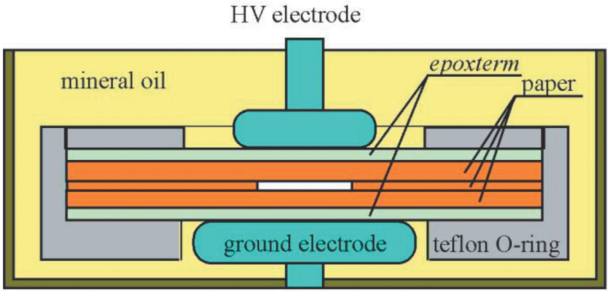

Fig. 2. Cross-section of O-ring specimen mimicking gaseous inclusion defect

The associated PD inception mechanism was discussed above. The specimen took the form of a radial gaseous inclusion with a diameter of 8 mm and a height of 0.5 mm, cut in two layers of *Kraft paper*. The whole specimen contained 12 paper layers, i.e. 5 below and above the inclusion. The paper specimen was placed between *epoxterm* insulating sheets and pressed in the *Teflon*® ring, as shown in Fig. 2. The samples were placed during the measurements in an oil tank. The high voltage and ground electrodes were placed centrally over the void. All the measurements were performed at room temperature (23°C–25°C).

3.2. Partial discharge detection and acquisition

For PD pulses acquisition a wideband detection system, meeting requirements of IEC 60270 standard [15] has been used (Fig. 3). It consisted of a signal conditioning unit (SCU) with two preamplifiers, working in PD signal and synchronizing voltage paths, together with a PD recorder (*ICMsystem*) operating in two different acquisition modes:

- *phase-resolved mode* with $\mathrm{D}(\varphi, q, n)$ pattern acquisition, PD pulses at every period of testing voltage were synchronized with its zero phase angle and accumulated in 256×256 matrix during a 60 second measurement period. Each phase slot corresponds to 78.1 μs time window,
- *time-resolved mode* for $\mathrm{D}(t, q, n)$ pattern acquisition, PD pulses were registered continuously during 60 seconds within 256 channels. Duration of each channel was equal to 234 ms.

The sequence of harmonic compositions, including a phase angle position, was created in an arbitrary waveform generator (*Analogic 2030*), driving a high voltage, solid-state amplifier (*TREK 20/20B*). The synchronization signal for PD acquisition was obtained from a resistive HV divider.

The presence of harmonics in voltage has several implications like higher dielectric losses, depending on the combination of a harmonic number, magnitude and phase angle but also an

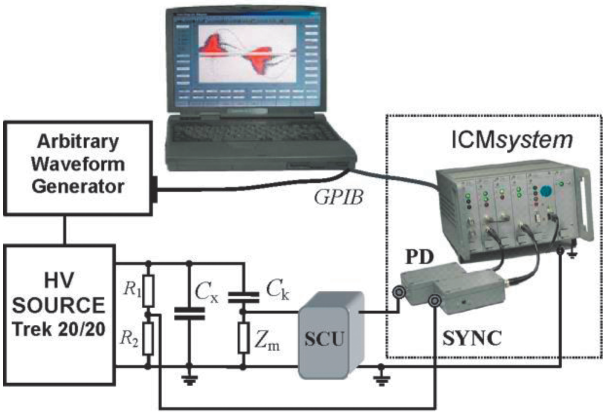

Fig. 3. Measuring setup for PD acquisition: R_1, R_2 represents the resistive divider providing synchronization signal, C_x is the test object, C_k is the coupling capacitor, Z_m is the measuring impedance, SCU is the signal conditioning unit

impact on internal discharges. This paper illustrates the influence of harmonics on PD attributes. Selected combinations of the 3rd, 5th and 7th harmonics, including phase angle variations are investigated. This aspect, highlighted in this paper on tested specimens, is especially important as the same combination of harmonics, i.e. the same value of waveform distortion measured in terms of THD, can generate different PD levels and deliver substantially different PD patterns.

4. Results

4.1. Tests with selected harmonics compositions

Partial discharge measurements were performed on a specimen containing a flat radial gaseous inclusion, placed symmetrically between adjacent electrodes. The PD patterns reveal a dominating gaseous inclusion-like shape; however it should be noted that micro voids can also occur in laminar paper layer insulation.

The PD patterns obtained on the specimen with the gaseous inclusion subjected to a voltage comprised of selected harmonics is shown in Fig. 4. The corresponding voltage waveforms are superimposed on the plot. Fig. 4a represents the reference obtained for a spectrally pure sinusoidal waveform. Adding the 3rd, 5th, 7th and 11th harmonic components significantly modifies the original pattern obtained from a purely sinusoidal excitation. The composition of those harmonics can attenuates the discharge intensity as in the case of the 3rd harmonic at 5% (Fig. 4b) in terms of maximum charge. Almost the same pattern as for pure sinusoidal reference voltage, obtained for the composition of the 3rd and 5th harmonics at 5% and 7th harmonic at 3% is shown in Fig. 4d. However, the discharge intensity is clearly attenuated in terms of the number of discharges. Interesting observation provides comparison of Fig. 4e and 4f, obtained for the set of the same harmonics: 3rd, 5th and 11th, however incorporating also individual phase shifts of the 3rd and 11th harmonics.

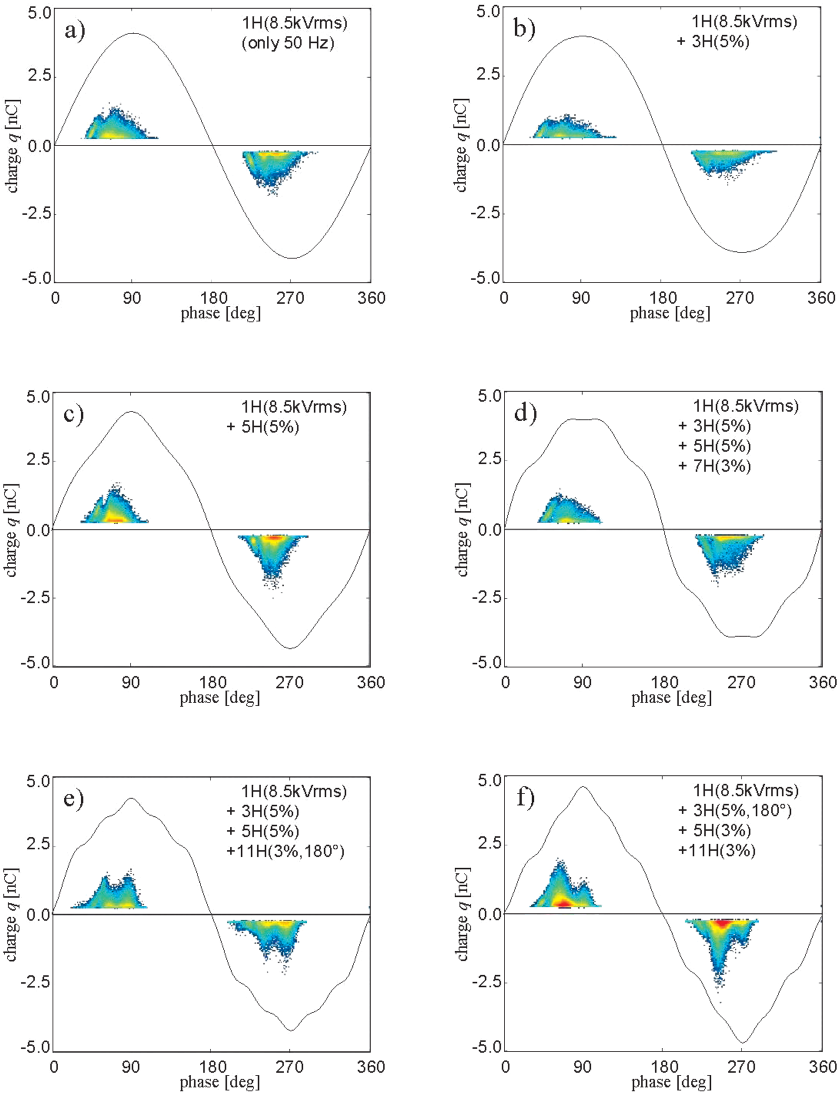

Fig. 4. PD patterns obtained at $U_{\mathrm{rms}} = 8.5$ kV for selected harmonic compositions for a specimen containing a gaseous inclusion for following voltage waveforms: a) sinusoidal (S); b) S + 3H5%; c) S + 5H5%; d) S + 3H5% + 5H5% + 7H3%; e) S + 3H5% + 5H5% + 11H3%180°; f) S + 3H5%180° + 5H5%0° + 11H3%0°

4.2. Influence of selected harmonics phase angle on PD phase-resolved patterns

As has been stated, distortions of the working voltages in electrical networks are characterized by varying harmonic content. The variability of voltage harmonics over time applies to both the amplitudes of individual harmonics and also their phases. In the literature, there are no descriptions of extended analyses regarding phases of voltage harmonics, except for single publications. The conference paper [34] presents results of voltage harmonic measurements and analyses performed in a 400 kV AC transmission network. For example, the authors provide the range of observed values of the phase angle for the 5th harmonic of voltage, which together with the 7th harmonic had the greatest influence on the voltage distortion. This angle during the measurements varied from about 78° to 160°. The widest ranges of phase angles were observed for the 7th and 9th harmonics, they reached almost a full angle. During laboratory experiments, it was possible to create harmonics at selected frequencies with controlled amplitudes and phases. Considering the wide variability of the harmonic component phases, the effects of individual harmonics were observed in the maximum range of their phase angles (from 0° to 360°).

In order to highlight the impact of the phase angle on PD phase-resolved patterns, an investigation was carried out for a sinusoidal voltage waveform with an U_{rms} value of 10 kV, containing the 3rd harmonic (150 Hz) at 5%. The evolution of the PD pattern for four phase positions 0°, 90°, 180°and 270° is presented in Fig. 5, with the waveforms superimposed on the plot.

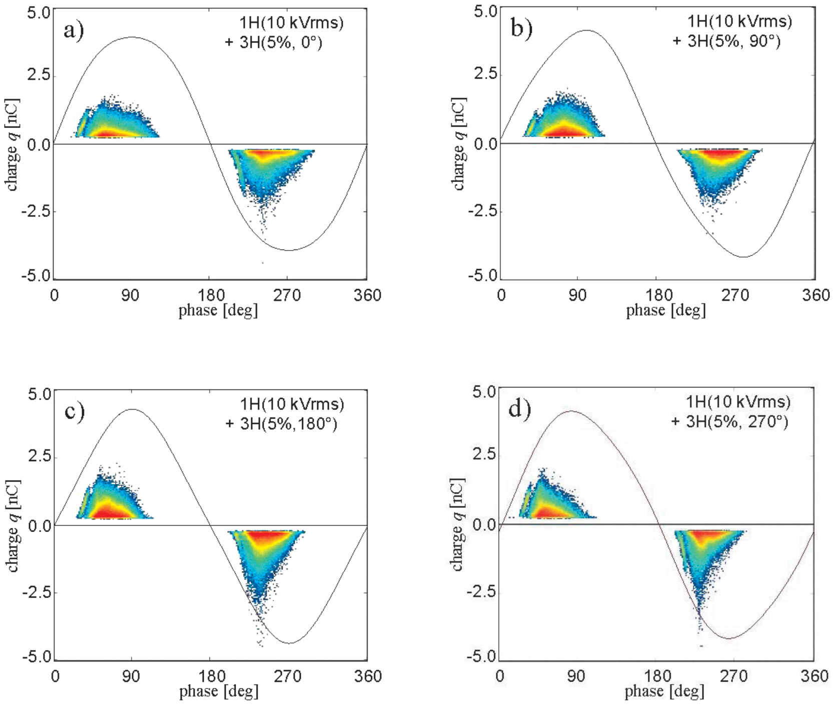

Fig. 5. Evolution of PD pattern at 10 kV, voltage containing the 3rd harmonic at 5% and phase angle: a) 0°, b) 90°, c) 180°, d) 270°

The number of PD pulses and maximum charge magnitudes in positive and negative half periods for 4 phase angle positions are summarized in Table 1. During the transition of the phase angle of the 3rd harmonic from 0° to 180° (Fig. 5c), the discharge intensity increases by 50%. One can observe elongation of the PD cluster and the increase of $Q_{\max}$ from 1.3 nC to 2.0 nC for the positive half period and from 2.6 nC to 3.7 nC for the negative half period.

Table 1. Influence of the 3rd harmonic phase on PD parameters

No.	3rd harmonic phase	N_+ [s^{-1}]	N_- [s^{-1}]	$Q_{\max+}$ [nC]	$Q_{\max-}$ [nC]
1	0°	784	833	1.3	2.6
2	90°	1260	1323	1.8	2.5
3	180°	1434	1558	2.0	3.7
4	270°	1000	1043	1.8	3.3

A similar experiment was performed for a sinusoidal voltage waveform with a magnitude of 10 kV, containing the 5th harmonic (250 Hz) at 5%. The evolution of the PD pattern for four phase positions 0°, 90°, 180° and 270° is presented in Fig. 6, with waveforms superimposed on the plot. The number of PD pulses and maximum charge magnitudes in positive and negative half periods for four phase angle positions are summarized in Table 2. During the transition of the phase angle of the 5th harmonic from 0° to 270°, one can observe a lower degree of intensity in terms of maximum charge comparing to the 3rd harmonic case. However there is an evident impact on the shape of the PD pattern, especially the one that introduced asymmetry at 90° (Fig. 6b) and 180° (Fig. 6c).

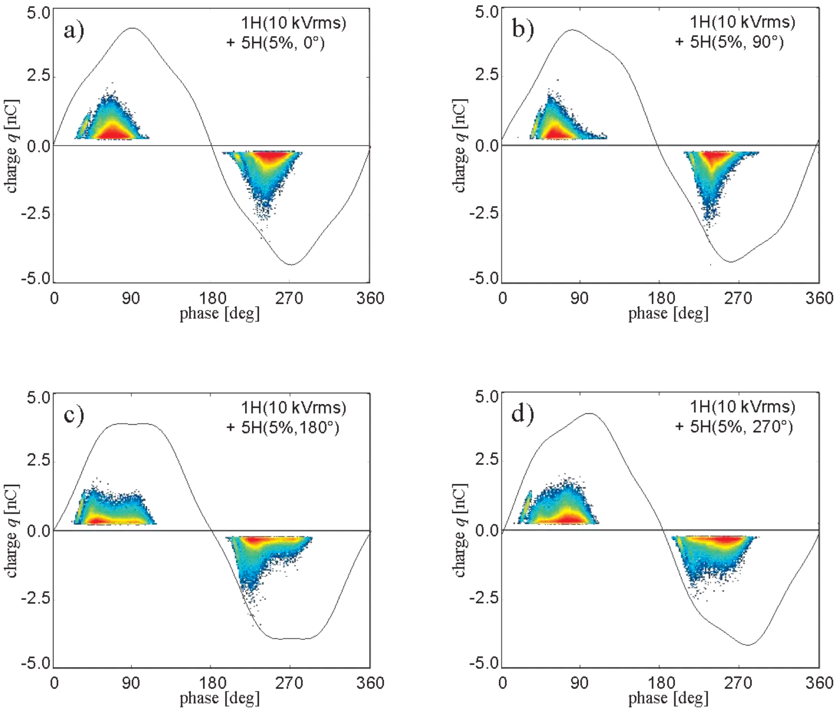

Fig. 6. Evolution of PD pattern at 10 kV, voltage containing the 5th harmonic at 5% and phase angle: a) 0°; b) 90°; c) 180°; d) 270°

Table 2. Influence of the 5th harmonic phase on PD parameters

No.	5rd harmonic phase	N_+ [s^{-1}]	N_- [s^{-1}]	Q_{max+} [nC]	Q_{max-} [nC]
1	0°	1283	1336	2.0	3.1
2	90°	1011	1031	1.8	3.2
3	180°	878	927	1.6	3.0
4	270°	1179	1187	1.9	2.5

4.3. Continuous phase shift of selected harmonic component

To visualize the influence of phase shift of an individual harmonic on the transition of PD intensity and maximum charge, the special technique of continuous sweep of the phase angle of the 3rd harmonic in the range from 0° to 180° within a 60 second time period was used as shown in Fig. 7. The applied voltage was constant both in terms of U_{rms} and THD_U, and the level of the

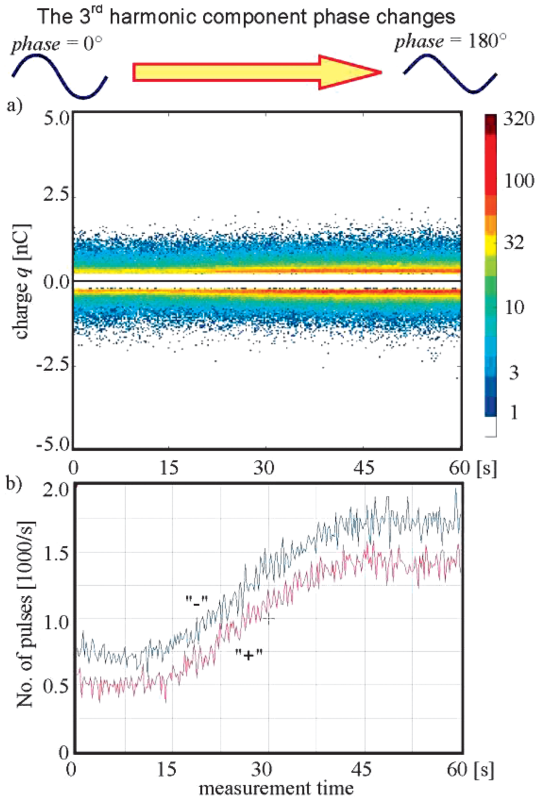

Fig. 7. Variation of PD charge (a) and intensity (b) at the continuous sweep of the 3rd harmonic phase angle in the range from 0° to 180°, superimposed on sinusoidal component, within time 60 seconds; a specimen representing a gaseous inclusion, $U_{rms} = 10$ kV

3rd harmonic was maintained at 5% of the fundamental. Thus, only the continuously changed phase angle influences the shape of a time waveform. The addition of these harmonics to the main sinusoidal component results in variation of crest voltage and time derivative $\mathrm{d}u/\mathrm{d}t$ along the phase. The charge distribution and number of pulses are shown.

The analysis of Fig. 7 shows, that variation of the 3rd harmonic phase from 0° to 180° results in an increase of PD intensity, both in charge and the number of discharges. An increase of PD activity can be correlated with the influence of the U_3 component phase angle causing the increase of the crest value $U_{\max}$ of composed $U_1 + U_3$ waveform, from $0.95U_{1\max}$ to $1.05U_{1\max}$ (Fig. 8).

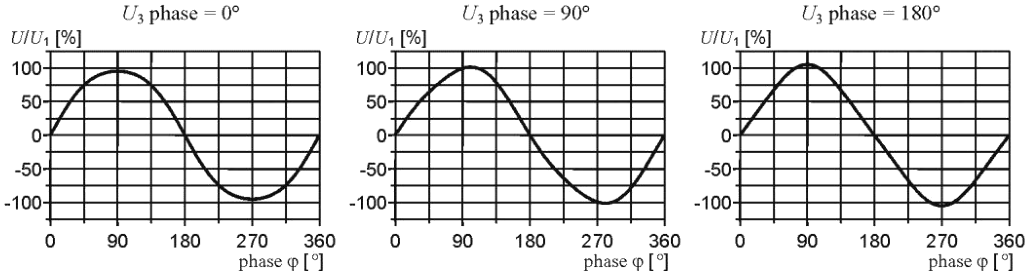

Fig. 8. Influence of the 3rd harmonic phase angle on the shape and the crest value $U_{\max}$ of composed $U_1 + U_3$ voltage waveform for three selected cases $(U_3 = 5\%U_1)$

5. Discussion

The presented results show how the underlying influence of harmonics, occurring in the applied voltage during measurements, can influence experimental PD data results. The tests performed on a specimen containing characteristic defect presents in high voltage insulation showed the impact of harmonics on PD in the following aspects:

- maximum charge $Q_{\max}$,
- PD inception voltage (PDIV),
- intensity (the number of discharges N per period).

A plot of the intensity of PD pulses versus the applied voltage for various compositions of harmonics is shown in Fig. 9.

Standards are not precise with respect to PDIV determination. Using a phase-resolved digital PD acquisition, we assumed in this paper recording of two stable PD pulses in an AC period as a PDIV level. For AC frequency equal to 50 Hz, it results in 2 pulses per period. Following the methodology for PDIV determination, the spread of inception voltage levels in relation to harmonic composition is illustrated. During experiments, the effective voltage U_{rms} and $\mathrm{THD_U}$ were kept constant. Harmonics content and phases of individual harmonics influence the $U_{\max}$ value of composed testing voltage, changing voltage waveform and modifying locally $\mathrm{d}u/\mathrm{d}t$. Registered phase-resolved PD patterns depend on the above listed parameters. Experiments show that for the positive half period partial discharges exist in phase ranges where voltage is greater than inception voltage and $\mathrm{d}u/\mathrm{d}t > 0$. If $\mathrm{d}u/\mathrm{d}t$ locally diminishes to 0 or $\mathrm{d}u/\mathrm{d}t < 0$ PD pulses are not generated even for voltages greater than inception voltage, so the voltage gradient is a significant

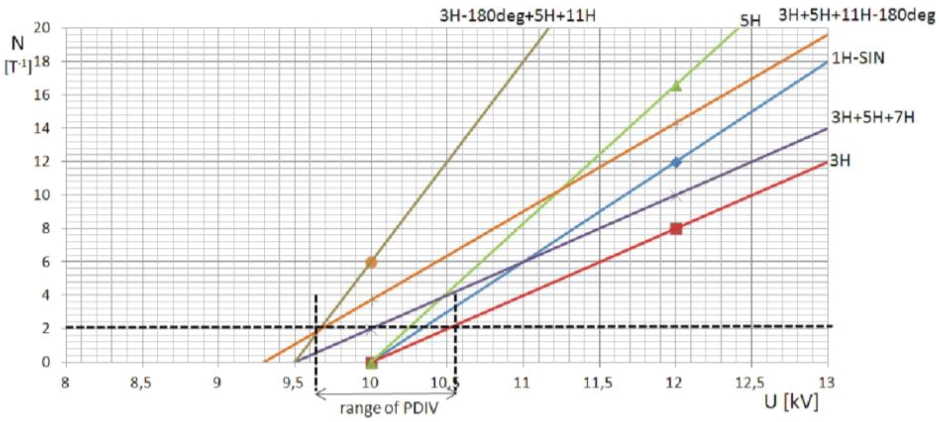

Fig. 9. Number of PD pulses per period versus applied voltage for various compositions of harmonics

parameter for PD generation at distorted voltages. This effect is presented in Fig. 10 where testing voltage is a sum of fundamental a 50 Hz component and the 11th harmonic at the level of 8%. The derivative $\mathrm{d}u/\mathrm{d}t$ indicates the regions o PD activities. After each PD in a gaseous inclusion the next one may occur when the internal electric field rises to a value sufficient for its generation. For this reason, PD pulses in the positive half period are grouped in these time intervals, where the test voltage increases $(\mathrm{d}u/\mathrm{d}t > 0)$. The number of PDs and their charges are related to the value of the test voltage derivative and the statistical lag time of PD generation [33]. If the voltage derivative increases, then the time intervals between subsequent PD pulses decrease, so the repetition rate of PDs rises. The observed effect is the same as during PD tests realised with increasing voltage frequency [31]. In this case, however, there is modulation of the shape of the fundamental voltage component, which leads to changes in the location of PD pulses in its period.

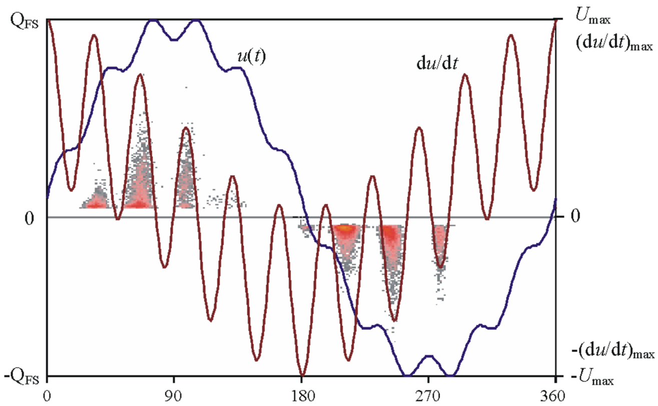

Fig. 10. Influence of testing voltage $u(t)$ and its derivative $\mathrm{d}u/\mathrm{d}t$ on PD patterns at harmonically distorted voltage (fundamental component + 8% of the 11th harmonic)

As it is seen from the presented results, the harmonic combination may increase or attenuate the PD intensity in reference to measurement for pure sinusoidal test voltage. The sinusoidal waveform, modulated by harmonics, may exhibit higher crest value $U_{\max}$ than the fundamental sinusoidal wave and poses several local extrema. The maximum charge $Q_{\max}$ is associated with the locally increased voltage slew rate $\mathrm{d}u/\mathrm{d}t$ and follows $U_{\max}$. It can be observed that local extrema in the voltage waveform are reflected in the PD pattern. Thus, the presented results underline the high sensitivity of PD measurements to voltage harmonics. The basic reason for such results are dynamic physical processes occurring in the inclusion located in the insulating system leading to PD inception and development.

On-site measurements should involve simultaneous monitoring of voltage distortion. The rough parameters reflecting the waveform spectral quality like $\mathrm{THD_U}$, are rather superficial and do not provide a unique and reliable signature of the applied voltage especially with regard to phase angle variations. Thus it is recommended, for example, for PD trend analysis, that voltage spectrum including higher harmonics will be considered. In addition, in the case of phase-resolved measurements, voltage magnitude and phase can be dynamically modulated during the PD acquisition and influence the proper interpretation of patterns and derived statistical parameters.

Special care should be also taken in PD diagnostics based on a reference signature obtained at sinusoidal voltage and comparison with actual obtained on-site at distorted voltage.

6. Conclusions

In AC electric power systems due to the non-linear phenomena of different kind the voltage distortions changing shape of voltage waveform can occur. Their analysis in the frequency domain, performed using the Fourier transform, allows describing this phenomenon by means of harmonic analysis. Measurements of PDs, which are very sensitive to changes in peak and slew rate of voltage, are very important for assessment of high voltage insulating systems integrity. The influence of harmonics is not considered usually, however it might have significant influence on measurement data interpretation. This is a novel research aspect neglected in many PD related interpretations. Experimental results highlighted that various harmonic compositions superimposed on the fundamental sinusoidal waveform have a distinct impact on PD intensity and maximum charge. The presence of harmonics modifies the shape of the testing voltage and influences the local value of its derivative in time. These factors change the electric field conditions for the inception and development of discharges in gaseous inclusions. In consequence, PD patterns, phase and magnitude distributions are distorted and influence the derived statistical parameters as well. Because during the measurements in real situations, the shape of the testing voltage, i.e. harmonic amplitudes and phases, often dynamically change, therefore the relationship between them and the acquired PDs can not be clearly described.

The intention of the paper was not to analyse the impact of individual harmonic compositions but rather underline the importance of the awareness of spectral purity of the applied voltage, especially when the PD measurements are associated with acceptability criteria and compatibility with the standards. Changes of the shape of the voltage (interpreted in the frequency domain as the presence of higher harmonics) modify the PD distributions and statistical parameters in a way that cannot be explicit. This results in an increase of diagnostic uncertainty in the study of the state of electrical isolating systems based on the interpretation of statistical parameters of PD pulses sets. It is concluded that knowledge of harmonic content of applied AC voltage is essential and critical in proper assessment of PD impact on insulating systems. The current version of the IEC 60270 standard [15] in informative Annex E recommends that the applied voltage waveform should be sampled with a frequency that allows registering not less than 100 voltage samples per period. Theoretically, this enables the analysis of the harmonic content up to the 50th harmonic. For 50 Hz AC voltages and for standard PD tests with duration of 30 or 60 seconds, this causes that the total number of recorded voltage samples is no less than 150 000 samples or 300 000 samples, respectively. Related information may help in the analysis of changes in the shape of the AC voltage during the test and in the estimation/assessment of measurement uncertainty of the parameters characterizing PD phase-resolved patterns, but they do not allow their backward correction.

In recent years, investigations of the influence of voltage harmonics on the inception and development of PD in the insulation of HVDC transmission systems are also carried out [35, 36]. This is related to intensive development of this technology in electric energy transmission. Simultaneously, this opens up new directions of research in this field.

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