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Application of a Phase Resolved Partial Discharge Pattern Analysis for Acoustic Emission Method in High Voltage Insulation Systems Diagnostics

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An alternative method for analysis of acoustic emission (AE) signals generated by partial discharges (PD), based on a correlation between voltage phase run and AE pulses, so called phase resolved PD pattern (PRPD), is presented in the paper. PRPD pattern is a well-known analysis tool commonly used in such PD diagnostic methods as conventional electrical and UHF ones. Moreover, it yields various signal analysis abilities and allows a direct correlation indication between measurement results achieved using different methods. An original PRPD measurement methodology applied for AE method as well as some exemplary measurement results and further data analysis capabilities are presented in the paper. Also a comparative analysis of PRPD patterns achieved using various measurement methods and different PD source configurations have been investigated. All presented experiments were done under laboratory conditions using PD model sources immersed in the insulation oil. The main purpose of the presented research is to indicate an all-embracing analytical tool that yields an ability to direct comparison (qualitative as well as quantitative) of the AE measurement results with other commonly applied PD measurement methods. The presented results give a solid fundamental for further research work concerning a direct correlation method for AE and other described in the paper diagnostic techniques, mainly in order to continue PD phenomena analysis and assessment in real life high voltage apparatus insulation systems under normal onsite operation conditions.

Keywords: acoustic emission; partial discharge; transformer diagnostics; insulation system.

1. Introduction

Nowadays application of non-invasive and non-destructive diagnostic methods for industry apparatus technical condition assessment has been one of the crucial aspects of a fleet maintenance. Current diagnostics and technical condition assessment of the main devices have become the priority in terms of reliable and continuous supply of electric power energy (Carneiro *et al.*, 2012; Lima *et al.*, 2015; Takahashi *et al.*, 2016). In the electrical power distribution system, high voltage (HV) distribution transformers present one of the most crucial apparatus. Exploitation of every HV electrical device is accompanied by the common and destructive PD phenomenon which appears due to insulation system ageing process. Long duration PD activity usually results in some degradation of dielectrics and may cause some serious apparatus faults and even catastrophic events. A significant share of all electric power distribution system failures are directly or indirectly associated with the PD (Borucki, 2012; Chaidee *et al.*, 2007; Kunicki *et al.*, 2016; Vahidi, Tenbohlen, 2014). Hence, adequately early detection and recognition of any insulation faults of the primary apparatus such as generators or power transformers, not only allows to provide a reliable electric power delivery but also may reduce some potential costs related to uncontrolled failures of the infrastructure or overhaul process (Borucki *et al.*, 2017; Kunicki, Cichoń, 2016; Wang *et al.*, 2015; Wotzka *et al.*, 2012). The AE method has been recognised as one of the most popular and effective technical contemporary diagnostic methods. The AE phenomenon is widespread and relatively well described in the modern scientific literature. Generally, AE phenomenon may be simply described as an ultrasound (20 kHz – 1.5 MHz) wave emitted by the source into a springy resilient environment. Various different AE sources are commonly recognised, and some of them are e.g.: crystal structure defects motions in solids, cracks, and micro cracks forming and shifting; local environment motions combined with internal friction, chemical reactions; some biological process; and partial discharges (Boczar *et al.*, 2014; Chen *et al.*, 2014; Kunicki *et al.*, 2016; Wotzka, 2012). Apart from the AE method there are a few other PD detection, identification and localisation methods. The most often applied are: electrical method, ultra-high frequency (UHF) method, optical method. Every method is based on a different physical phenomenon that is accompanied by the PD generation: current pulse propagation for the electrical method, electromagnetic wave emission in UHF range (300 MHz – 3 GHz) for the UHF method, light emission in ultra violet range (UV) for the optical method (Álvarez *et al.*, 2015; Boczar *et al.*, 2017; Boczar, Zmarzly, 2006; Coenen, Tenbohlen, 2012; Frącz *et al.*, 2012; Nagi *et al.*, 2016; Zheng *et al.*, 2014). Despite a number of advantages in terms of PD detection applications the AE method is characterised by a few significant weaknesses, such as: lack of PD charge calibration capability and lack of a common PD signal analysis domain, according to the simultaneous applications with electrical and UHF methods (Coenen, Tenbohlen, 2012; Kraetge *et al.*, 2013; Kundu *et al.*, 2012). Regarding the electrical and UHF methods it is characteristic that a fundamental analysis tool of the signals generated by the PDs is the PRPD – supply voltage phase is used as a common signal analysis domain, while AE method uses time, time-frequency, or frequency domains (Boczar *et al.*, 2009; Cichoń *et al.*, 2008; Harbaji *et al.*, 2015; Ramírez-Niño, Pascacio, 2009; Rubio-Serrano *et al.*, 2012). Various different qualitative and quantitative collations of the measured physical phenomena (e.g., apparent charge for the electrical method vs UHF voltage for the UHF method) may be obtained when common signal analysis domain is supported. Also, some correlation analysis of the achieved values' distributions may be carried out for further advanced analysis. Bearing in mind that the AE method has been one of those three contemporary leading PD measurement methods, a proposal of an AE analysing tool supporting the PRPD measured data layout seemed to be a crucial issue (Deshpande *et al.*, 2013; Majidi, Oskuoee, 2015; Wang *et al.*, 2015). A direct phase distribution collations of the AE amplitudes and the apparent charge values as well as the UHF amplitudes would be realisable by such a tool. Furthermore, formulation of the model for reciprocal correlation analysis and a charge calibration algorithm for AE method may be proposed.

An original PD measurement methodology based on the correlation of AE signals with the phase of the supply voltage has been presented in the paper, resulting in support of the PRPD analysis for AE signals received support. Further measurement results analysis allowing a direct electrical method as well as UHF method measurement results collation has also been pointed out. An exemplary measurement setup and equipment supporting the proposed methodology applications as well as various exemplary measurement results achieved for different PD model sources have been presented in the research. The main purpose of the presented research is to indicate an all embracing analytical tool that yields an ability of direct comparison (qualitative as well as quantitative) of AE measurement results with electrical and UHF methods. The presented results give a solid fundamental for further research work concerning a direct correlation method for the AE and other mentioned in the paper diagnostic methods, mainly in order to carry out PD phenomena analysis and assessment in real life high voltage apparatus insulation systems under normal onsite operation conditions.

2. Research methodology

All the presented research has been done under laboratory conditions. However, a proposed methodology onsite application capabilities during apparatus real life normal exploitation should be also considered, according to the authors intention. Due to the above assumption a typical measurement equipment and lay out commonly used for PD detection in electric power transformers have been supported for the research. Fundamental measurement equipment applied for registration of AE signals generated by PDs during research have been: wide range piezoelectric joint transducer WD AH 17, installed on the outer wall of the oil filled tank where the PD model source has been immersed, 2/4/6 preamplifier and AE2 amplifier (all from Physical Acoustic Corporation), and Acquitek interface CH3160 installed on a PC (Fig. 1). A frequency range of the WD AH17 sensor amounted to 100–1000 kHz (± 10 dB), sensitivity was 55 dB ± 1.5 dB. Additional external distortion reduction was achieved by a differential output applied in the AE sensor. A sampling rate of the measuring interface was set to 1 MHz, which allowed to register signals in the range from 20 kHz to 500 kHz – according to the authors' personal experience and other publications, it is a relevant band for acoustic PD measurements (Głowacz, Głowacz, 2017; Shang *et al.*, 2017; Witos *et al.*, 2011). A constant clamp force and repeatable sensor and tank coupling were achieved by a dedicated magnetic grip applied additionally for measurements. A total voltage gain of the measuring track was set to 75 dB, and it was not adjusted during all measurements. Also the PD source and sensor locations were not adjusted during the research.

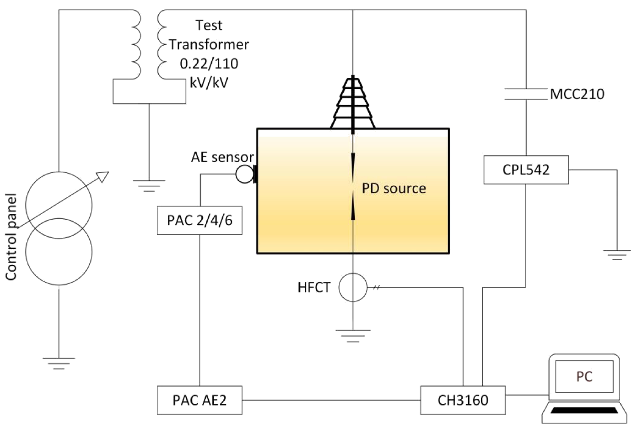

Fig. 1. Layout of the measuring set up.

An additional measurement track was also used during the research for measurements on the supply voltage phase. A capacitive voltage divider originally designed for MPD600 measuring system was applied for phase measurement. The divider consisted of a coupling capacitor MCC210 with the capacity of 1 nF and a quadripole CPL542A with the capacity of 30 μF, and fed the second input channel of the CH3160 interface. Both AE and electric (supply voltage phase) signals were captured simultaneously. A measurement window was set to 20 ms, equalling one 50 Hz voltage supply period, which supported an AE activity registration within a whole voltage supply period. After choosing such metrological conditions, a series of AE signals generated by the PDs and adequate supply voltage time runs were registered. Two different spark gap configurations immersed in insulation oil were selected for PD sources modelling during research: point to point (PP) and surface type (SFR), with 8 mm thick pressboard paper plate used as a solid dielectric. All measurements were conducted under a constant supply voltage level ensuring a stable PD generation for each applied spark gap configuration. 250 signals have been captured for each spark gap. Additionally simultaneous electrical method (according to IEC60270) and UHF method signals for further comparative and correlative analysis purposes were captured also.

A dedicated Matlab based software was created and applied for post processing and measurement data analysis. A proper data formatting, phase domain analysis, and PRPD data layout have been supported by the software. Two key algorithms were created for relevant software operations: AE peak amplitude extraction algorithm (PAE) and supply voltage phase correlation with AE signals algorithm (PCA). Also an additional AE signal delay compensation algorithm (DCA) was created and implemented as an optional software and hardware block. In general, the DCA is based on the comparison of the cumulative partial energy curves minimums of the registered relevant AE and electrical signals, which correspond with the signals onset (Markalous *et al.*, 2008). The energy curve S_i of the sampled signal x is defined as a cumulative sum of amplitude values. A partial energy S_j of the j-th sample may be defined as shown in (1):

$$S_j = \sum_{k=0}^{j} x_k^2, \tag{1}$$

where x_k is the amplitude of the k-th sample. In order to separate the partial signal S_j from the noise, the so called S'_j criterion shown in Eq. (2) may be used:

$$S'_j = S_j - j\delta = \sum_{k=0}^{j} x_k^2 - j\delta, \tag{2}$$

where δ is defined as the mean value of the squared all N samples, and may be calculated with Eq. (3):

$$\delta = \frac{S_N}{\alpha \cdot N}, \tag{3}$$

where α is the correction factor – in the presented research set to 1 (Markalous *et al.*, 2008).

In order for the DCA to be launched, an electrical PD pulse measurement needs to be provided, e.g. high frequency current transformer (HFCT) may be applied that feeds the third CH3160 interface channel. An exemplary graphical layout of the DCA process is presented in Fig. 2. According to presented research, the DCA was not used due to the PD source location and the sensor position, and measurement setup geometry was known, so the AE signal delay could be calculated manually. Also, a homogeneous AE wave propagation environment was supported during experiment. The absolute distance between the sensor and PD source amounted 0.2 m, which corresponds to about 0.144 ms for the average velocity of sound in transformer mineral insulation oil, which is approx. 1390 m/s. Thus, the relevant AE signal phase shift according to 50 Hz voltage

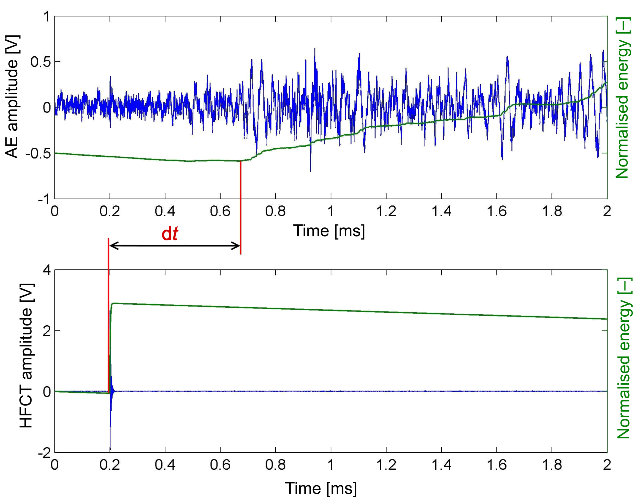

Fig. 2. Exemplary graphical layout of the DCA process using HFCT.

is about 2.8°. However, the DCA needs to be used in so that the presented methodology could be applied for the measurements on the onsite apparatus under normal operation conditions.

3. Results and discussion

First presented are the measurement results in the form of the most popular contemporary analysis tools according to the AE method: time domain, frequency domain, and time-frequency domain analysis. Some exemplary AE time runs and power density spectrograms generated by the PP and SRF spark gap configurations are shown in Fig. 3. Registered signals are presented within 20 ms, which is as long as one 50 Hz supply voltage period.

a)

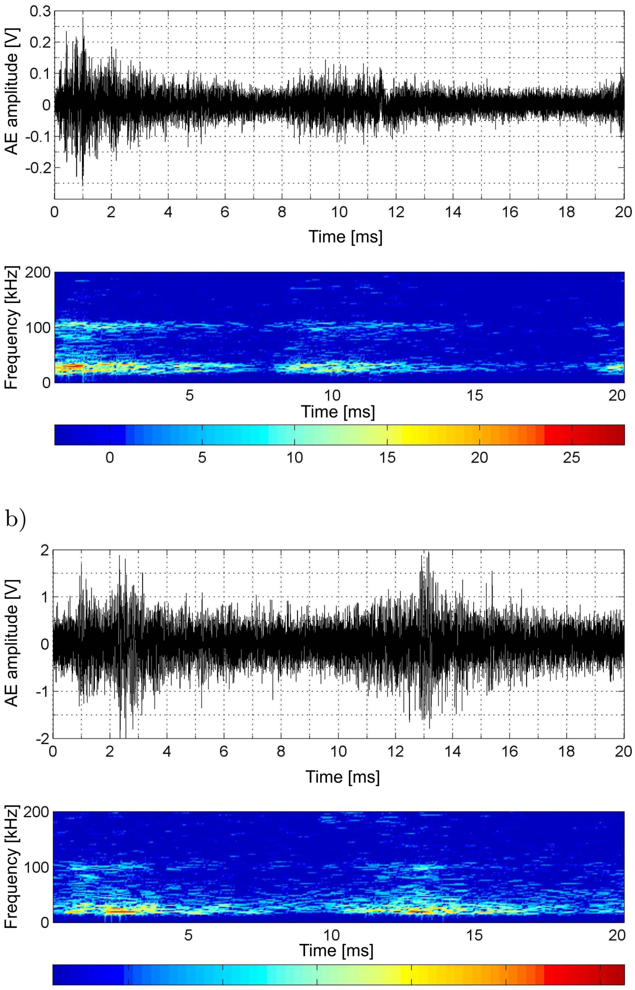

Fig. 3. Exemplary time run and power density spectrogram of PD generated AE signals: a) PP spark gap configuration, b) SRF spark gap configuration.

Some exemplary amplitude spectrums and power density spectrums of the AE signals generated by the PDs, achieved for the selected spark gaps are shown in Fig. 4, respectively. Such conventional measurement results layout allows various fundamental descriptors of the AE signal to be indicated. Also, the PD source identification as well as limited rating of the intensity analysis are yielded by such an approach. Various analysis possibilities based on time, frequency, and time-frequency domain have been described in (Boczar *et al.*, 2009; 2014; Kunicki *et al.*, 2016).

a)

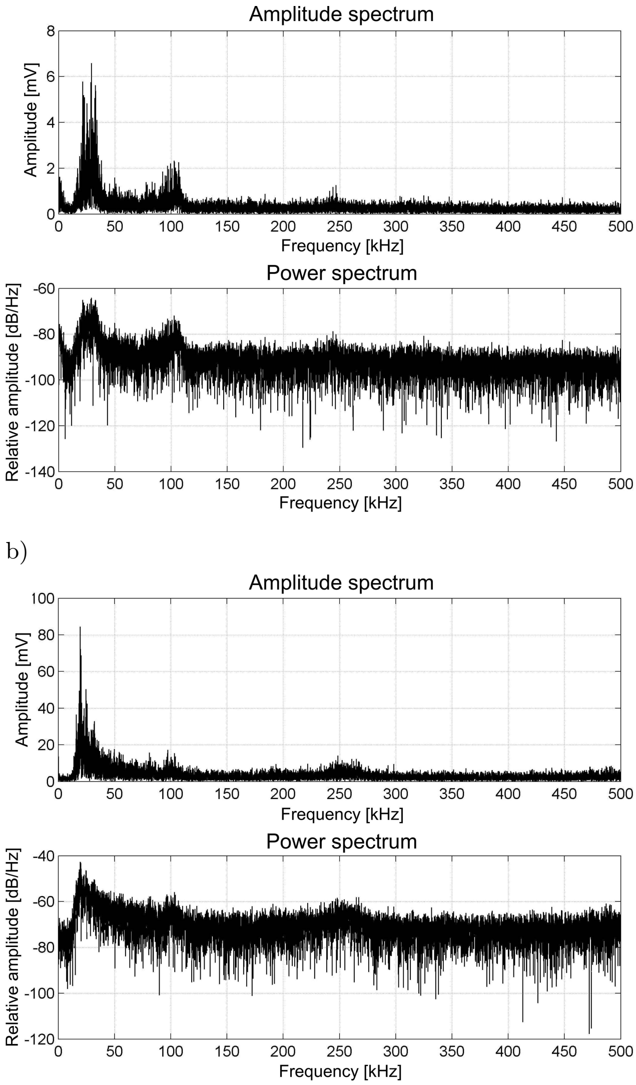

Fig. 4. Exemplary amplitude spectrum and power density spectrum of PD generated AE signals: a) PP spark gap configuration, b) SRF spark gap configuration.

As mentioned above, the PRPD is recognised as a major PD generated signal analysis tool provided by the UHF and electrical methods. Some exemplary PRPD patterns achieved for the selected spark gaps using the electrical method are shown in Fig. 5. Apparent charge amplitudes and PD events density (counts) dependency on supply voltage phase have been illustrated in the plots.

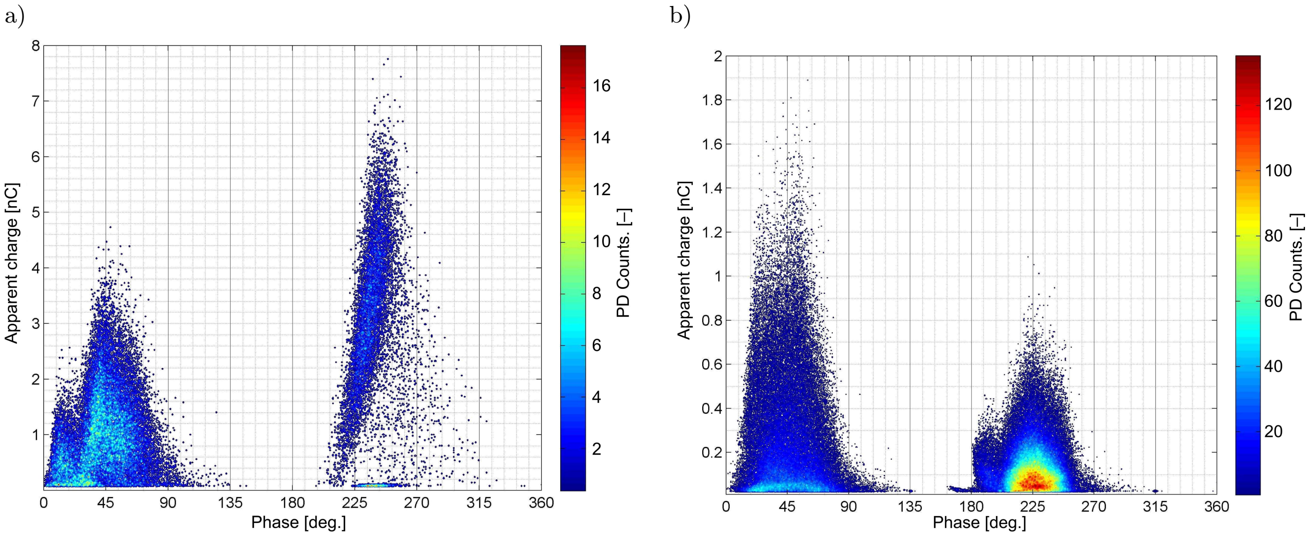

Fig. 5. Exemplary PRPD patterns achieved using the electrical method:
a) PP spark gap configuration, b) SRF spark gap configuration.

Furthermore, some representative UHF measurement results presented in the PRPD form have been showed for applied spark gaps in Fig. 6 – detailed instruction how to perform the UHF measurements may be found in (Boczar *et al.*, 2017; Siegel *et al.*, 2017; Tenbohlen *et al.*, 2016). PD common structures appearance in relevant voltage half-periods may be obviously noticed – rising slopes, start right after a voltage wave zero crossing. It has been known as one of the essential properties of PD signals according to PRPD analysis.

In Fig. 7 some representative PRPD patterns of the AE signals achieved using the methodology, described in Sec. 2 of the paper, are presented. An amplitude criterion was investigated in the example, so PAE was applied for AE pulse amplitude peaks extraction. Phase angle assignment of every extracted AE peak is also supported by PCA.

Some obvious convergence between results achieved using three applied methods may be pointed out even at this stage of the experiment. On the other hand, the amplitude criterion has been known as non-optimal according to the AE signals analysis, while the energy criterion has been commonly recognised as a more efficient factor – energy is proportional to the squared AE signal amplitude. Results of the PAE application for energy based peaks extraction are illustrated in Fig. 8. A convergence between such presented data and those achieved by using other methods seems to be more accurate. It needs to be emphasised that PRPD patterns assignment should be read as an initial stage being preliminary for further

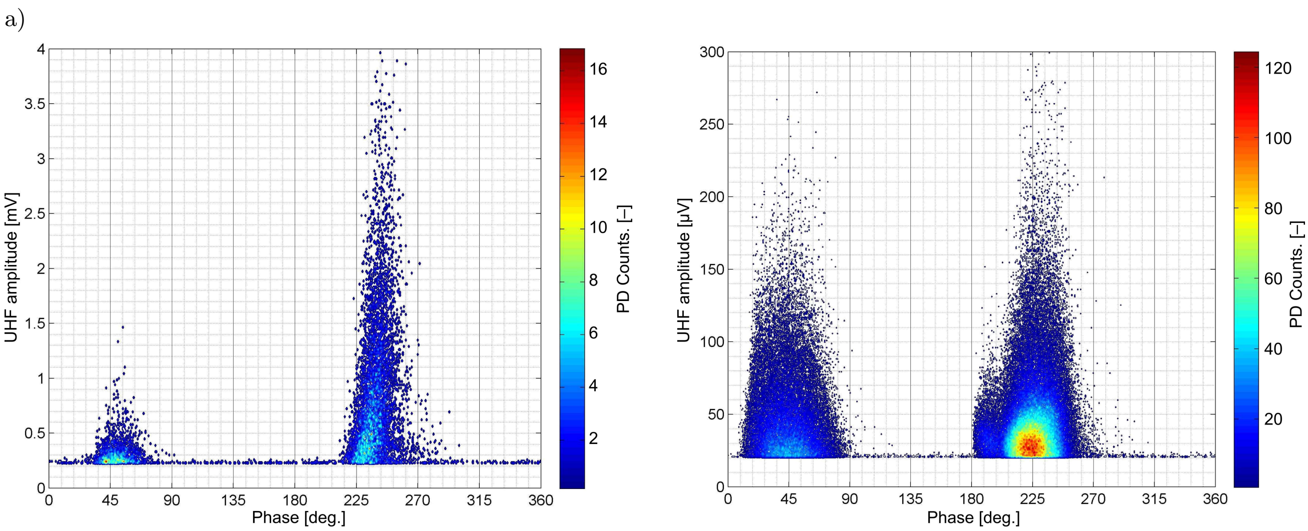

Fig. 6. Exemplary PRPD patterns achieved using the UHF method:
a) PP spark gap configuration, b) SRF spark gap configuration.

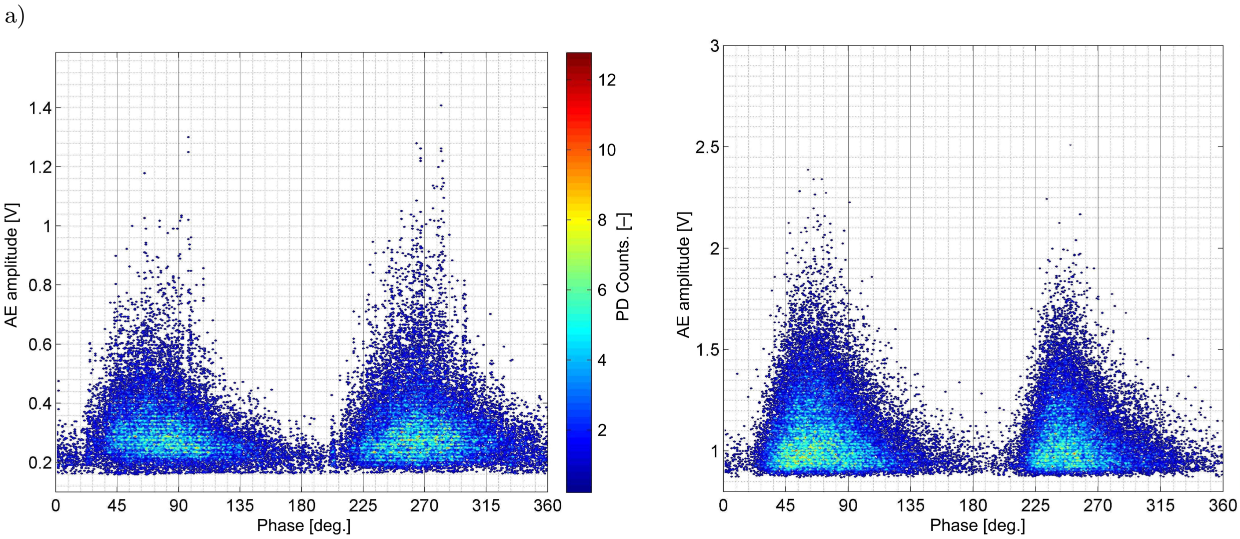

Fig. 7. Exemplary PRPD patterns achieved using AE method – amplitude criterion applied: a) PP spark gap configuration, b) SRF spark gap configuration.

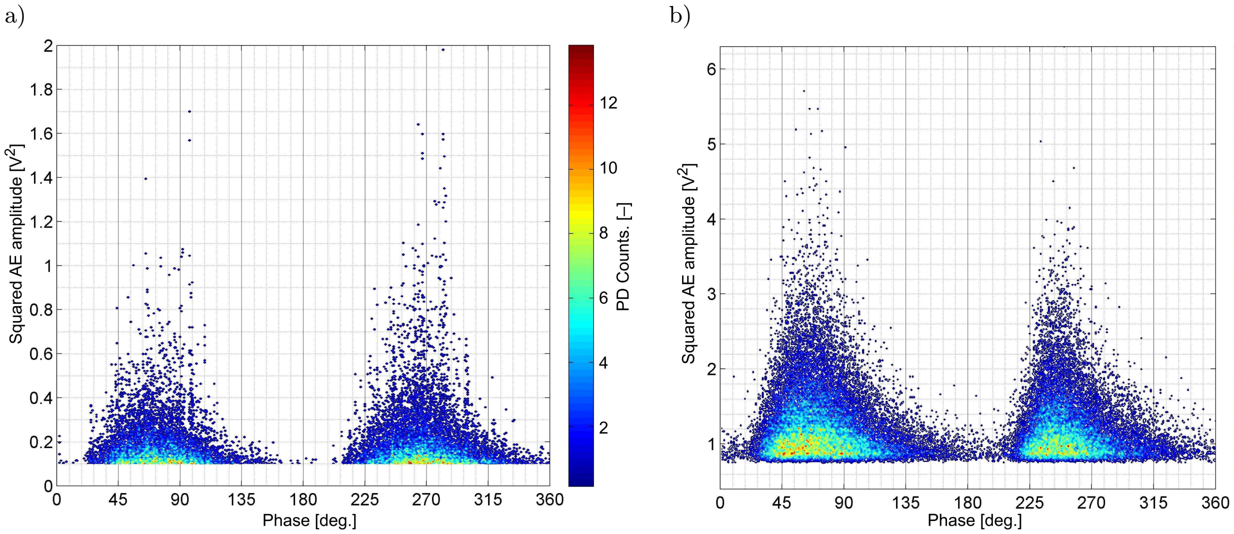

Fig. 8. Exemplary PRPD patterns achieved using the AE method – energy criterion applied: a) PP spark gap configuration, b) SRF spark gap configuration.

advanced analysis of the achieved results. Despite this, there may be noticed some similarities between Fig. 5, Fig. 6, and Fig. 8. It is also evident that PRPDs achieved using different methods are not equal. It is due to the fact that each method measures different kind of signals – different form of the energy emitted by the PD. Also, each signal is captured in a different environment, so different couplings need to be supported: an electric signal travels within the galvanic parts and is captured using the capacitive or inductive sensors, an UHF signal is emitted to the surrounding oil volume and is captured by the UHF probe coupled with the oil, AE signals travel within the oil and steel tank and are captured by the joint sensor coupled with the tank. As a result, each finally registered signal is deformed in relation to the original one, and affected by different disturbances, including reflections, dissipations, absorptions, attenuations, etc., and various kinds of external noise.

A phase domain layout of the measurement results is supported by the original PEA and PCA application for the AE signals analysis. Having such formatted data various statistical descriptors related to the particular phase domain distributions of any assigned quantities may be defined. Some exemplary descriptors referring to selected AE signals phase distributions (maximum amplitude phase distribution and PD count phase distribution) are presented in Fig. 9.

Further advanced statistical analysis may be applied for the phase distributions of the selected descriptors, e.g. skewness or kurtosis of the selected quantities distributions may be assigned, which are com-

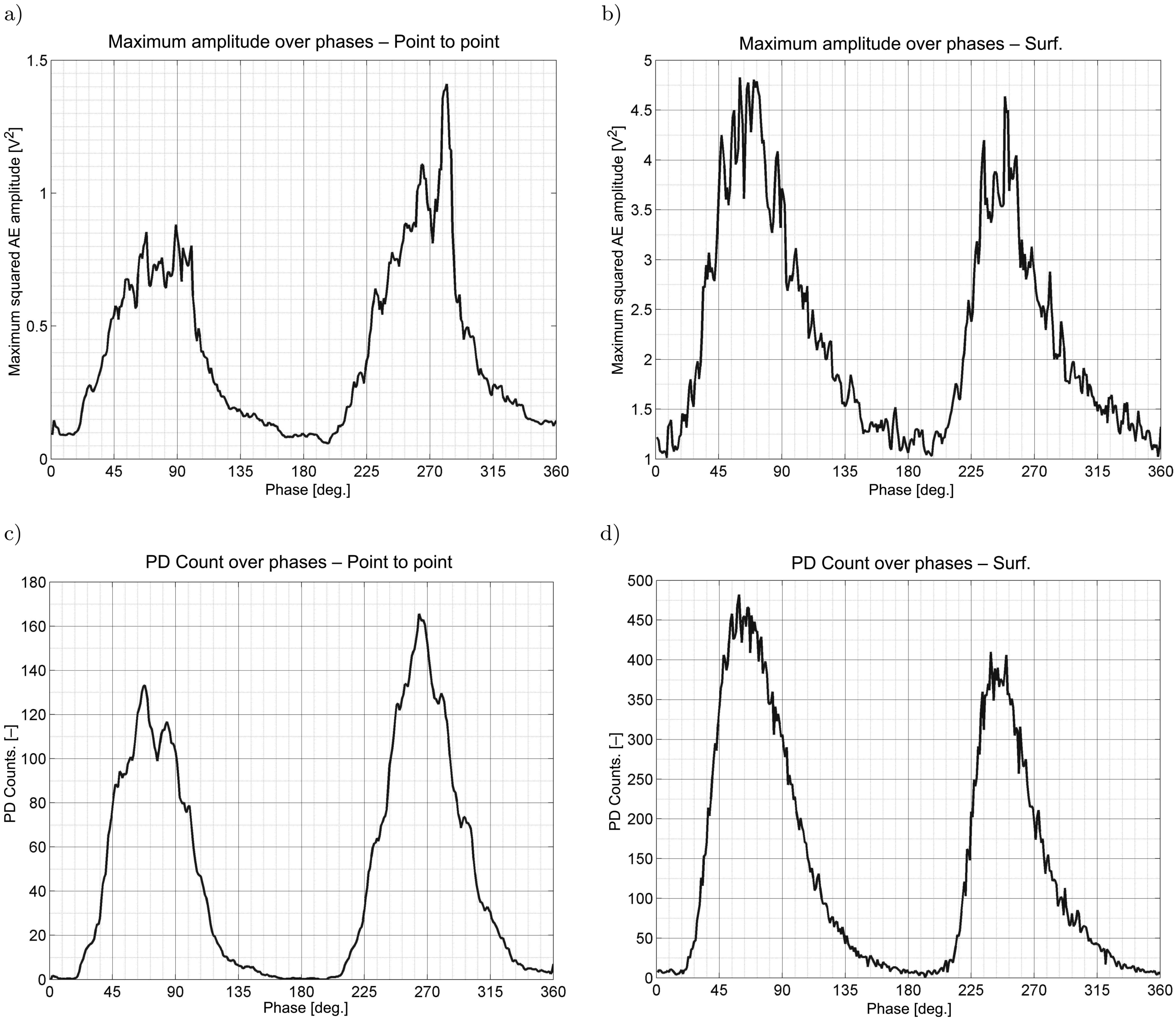

Fig. 9. Exemplary phase distribution descriptor runs of the AE signals (PRPD based) for relevant spark gap configurations: a) PP – maximum squared amplitude over phases, b) SRF – maximum squared amplitude over phases, c) PP – PD count over phases, d) SRF – PD counts over phases.

monly used for phase distribution analysis and PD source identification in diagnostic expert systems designed for industry applications, based on both electrical and UHF methods. In Table 1 presented are exemplary descriptors of the phase domain distributions (of max amplitude, mean amplitude, PD counts) achieved for both applied spark gaps using the AE method and the methodology proposed in the paper. A potential PD source identification possibilities have been initially confirmed by the results presented in Table 1.

Table 1. Exemplary selected phase distribution descriptors values achieved for different PD source configurations.

Descriptor	Surface spark gap	Point to point spark gap
Kurtosis of mean value phase distribution	2.61	3.75
Skewness of mean value phase distribution	1.30	0.72
Kurtosis of max value phase distribution	2.80	7.22
Skewness of max value phase distribution	0.76	1.65
Kurtosis of PD counts phase distribution	2.16	2.45
Skewness of PD counts phase distribution	0.72	0.94

4. Conclusion

An original method for measurement and analysis on the AE signals generated by the PDs in an insulation oil has been presented in the paper. Analysis of the phase domain distributions of the various quantities describing the AE signals receives support thanks to this method. Furthermore, direct comparison and correlation of the measurement results achieved using different methods (electrical, UHF, and AE ones) are provided by the presented method, which seems to be a crucial result of the research. Not only the application possibilities of the AE method become broadened but also some wide correlation analysis conduction capabilities between the three mentioned methods are yielded by such an approach, in terms of the AE method based PD measurements. Also, some significant fundamentals for charge calibration algorithm formulation according to the AE method have been pointed out by the research. The electrical method has been known as the only one that supports the charge calibration of the PD measurement so far. The AE method application areas for the electric power apparatus under onsite normal operation conditions were practically limited to the PD detection and localisation. The relative nature of all commonly applied PD analysing tools based on acoustic signals (e.g. FFT, STFT, wavelet analysis) has resulted in limited or even lack of practical applications of the AE method for qualitative PD phenomenon assessment. Significant extension of the measurement results interpretation capabilities as well as application of proven analysing tools widely used by electrical and UHF method only so far, is provided by the proposed signal analysis algorithm. Furthermore, the proposed method may be potentially applied for the tests on the onsite transformers under normal operation conditions, because it is based on typical measurement instruments commonly used for PD detection according to the electric power industry applications. The authors' further research work is to be focused on real life object onsite verification of the results and method presented in the paper. On the other side, correlation analysis of the achieved results with particular consideration of possibilities of charge calibration algorithm formulation for PD measurements based on the AE method will also be one the main scientific future tasks for the authors.

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