Influence of additional dielectric coatings on the electrode surfaces on selected parameters of acoustic emission signals in high-voltage gas insulation systems

Arkadiusz Dobrzycki¹ · Władysław Opydo² · Sebastian Zakrzewski³

Received: 3 May 2021 / Accepted: 25 October 2021 / Published online: 16 November 2021
© The Author(s) 2021

Abstract

The paper is devoted to the study of impact of additional dielectric coatings placed on the surface of the electrodes on the operation of a high-voltage insulation system with air as insulating medium. The study mainly focused on measurement of partial discharges (PDs) with the use of acoustic emission method. Tests were conducted in various levels of chamber pressure. Applicable parameters of recorded signals were analyzed with the use of applications developed in the environment of MATLAB software. The results of analyses clearly show that presence of additional coatings has impact on signal parameters and thus indirectly on PDs. The use of coatings reduces the duration of a single pulse (event) and increases its amplitude. Furthermore, the influence of degradation of the coating caused by individual discharges on the values of the analyzed parameters was analyzed. The study has shown, however, that this effect is negligible.

Keywords High-voltage gas insulated systems · Partial discharges · Acoustic emission · Dielectric coatings

1 Introduction

At present, continuous increase in demand for electricity is observed, which is also accompanied by increasingly higher requirements of consumers regarding the quality and reliability of its supplies. These requirements result from growing number of electrical and electronic devices in households as well as electric vehicles. The former require a relatively small power unit, but their nonlinear nature can affect the parameters of electricity, e.g., by generating higher harmon-

ics of current and voltage [1]. As far as electromobility is concerned, in order to be able to charge batteries of electric vehicles efficiently and quickly, it is necessary to provide power ranging between several kW for one car and several hundred kW for a bus, depending on a charging method, or a charging station capable of charging several vehicles simultaneously [2].

These trends, including progressive miniaturization of high-voltage electrical apparatus and increasingly smaller area available for construction of transmission stations, especially near cities, necessitate optimal design of the entire transmission and distribution system. This optimization consists in minimizing dimensions of the working system with the highest technical parameters while maintaining acceptable costs for the implementation of such a system. Design activities and subsequent operation require development of models and methods of modeling their operation appropriate for a given system or its element [3–5]. They also must take into account further possible increase in transmitted power, which may negatively affect transmission efficiency [2].

In the case of high-voltage electrical insulation systems, one of the indicators providing information about their condition is the level of PDs [4–11]. Most of PD energy is converted into electricity, heat and chemical resistance. It is assumed that during discharge the incomplete conversion gates por-

✉ Arkadiusz Dobrzycki
arkadiusz.dobrzycki@put.poznan.pl

Władysław Opydo
wladyslaw.opydo@put.poznan.pl

Sebastian Zakrzewski
zakrzewski@hvexpert.com

¹ Institute of Electrical Engineering and Electronics, Poznan University of Technology, Piotrowo 3A, 60-965 Poznan, Poland

² Institute of Electrical Engineering, Bydgoszcz University of Science and Technology, Al. prof. S. Kaliskiego 7, 85-796 Bydgoszcz, Poland

³ Tele-Fonika Kable S.A., H. Cegielskiego 1, 32-400 Myślenice, Poland

tion of the electrical energy to mechanical energy, with an efficiency of 1–5%. From the physical perspective, individual PD can be compared to microexplosion that takes place in the dielectric. Assuming that PDs occur in a homogeneous medium, they can be treated as a point source of elastic disturbances.

This is the reason why the level of these discharges can be measured and analyzed on the basis of non-invasive methods, e.g., the Acoustic Emission (AE) method [7, 12–14]. This method is constantly developed, and thanks to increasingly efficient measuring equipment and advanced methods of analysis of recorded signals, its accuracy is constantly improving [15, 16].

Researchers point to the significant impact of the presence of PDs in diagnosing Gas Insulated Systems (GIS) [17, 18]. Furthermore, correlation between the results of tests by electrical methods and AE measurements [19], especially with proper selection of signal descriptors, can be demonstrated [20, 21]. Artificial neural networks are also used in the analysis of AE signals [22, 23]. One can notice that topics like presence of PDs in high-voltage insulation systems [24], coatings influence of arc deposition [25], improving electrical parameters with the use of nanocoatings [26] and mainly using AE method with diagnostics of high-voltage equipment [27], especially transformers [28, 29], are now in the center of attention of researchers.

Planar electrodes used in high-voltage electrical insulation systems are characterized by the presence of asperities from the tops, in which, due to a local increase in the electric field, electron emission occurs. Attempts can be made to reduce the emission by machining consisting in thorough grinding of this surface. However, even the application of the above process does not completely eliminate the presence of this electron emission, i.e., PDs.

Therefore, work has begun to develop the method of "smoothing out" the surface of the electrodes even further using electrochemical processes. It was assumed that coating the electrodes with an additional thin layer of dielectric will fill the micro-craters appearing on the surface and increase the microspike radii, which will reduce the local gain of electric field strength.

This paper describes the effect that presence of additional dielectric coatings placed on the surface of electrodes in the GIS high-voltage insulation system has impact on parameters of AE signals accompanying the PD.

Increasingly, compressed gases are used as electrical insulation - sulfur hexafluoride and air. The interest in SF₆ is mainly due to the electrical properties such as the center of a large electric resistance and its good extinguishing the arc. The non-toxicity of this medium is also of great importance; only the degradation products of SF₆ are toxic to some extent, but with low chemical activity and non-flammability; this is usually not significant [30–34].

Even in a relatively strong electric field, the hexafluoride conducts electricity poorly. As the field intensity increases, it loses its insulating properties and eventually an electric discharge develops in it, which adversely affects the technical condition of the devices—they cause degradation of materials and power losses and in the extreme case short circuit. In addition, they are a source of electromagnetic interference. For this reason, these devices are designed and constructed in such a way as to eliminate electrical discharges in them or at least reduce their intensity and duration.

The advantage of using compressed air as an insulating medium is its availability and no negative impact on the environment. The emphasis on ecological aspects of the energy industry meant that the research was carried out for cases in which the air was an insulating medium.

The research presented in the paper concerns the effect of additional dielectric coatings on the surface of the electrodes on PD. The conducted experiment concerns a system with flat electrodes coated with a layer of Al₂O₃. This coating was chosen for its physicochemical properties, such as: high abrasion and corrosion resistance and very good electrical insulating properties.

The tests were carried out to verify whether this material would have the same effect on the parameters of AE signals accompanying PD at different air pressures in the insulation chamber. It was also checked whether the mechanical damage resulting from multiple discharges significantly influenced the parameters of the recorded AE signals accompanying PD.

The remainder of the paper is organized as follows. The second part of the article describes the construction and presents the main components of the test setup. Then, in the third part, methods of analyzing the recorded AE signals and the obtained results of these analyses are shown. This part also includes the results of statistical analyses of selected AE signal parameters. The discussion includes the authors' thoughts on the relationship between the results of the analyses and the physical phenomena occurring in the tested electrical insulating system. The article ends with conclusions from the research.

2 Measurement setup

Experimental research was carried out on a test setup, the block diagram of which can be found in Fig. 1a. This setup has enabled measurement and recording of AE signals and electrical strength of the tested insulation system. Insulation plate system was formed with flat aluminum electrodes with a diameter of 50 mm with rounded corners according to the Rogowski formula. The process of electrode surface preparation and a method for producing oxide coatings on them are shown in [5].

Fig. 1 **a** Block diagram for measuring the AE signals and the dielectric strength of the insulation system [14], **b** view of test setup for measuring the AE signals and the dielectric strength of the insulation system [14] and **c** detailed view of test chamber

Table 1 Physicochemical conditions of the process of aluminum oxide coating obtained at the aluminum electrodes

Coating symbol (–)	Thickness of the oxide layer (μm)	Chemical composition of the bath (–)	Density of direct current (A/m ²)	Oxidation time (s)	Temperature of the bath (K)
P1	5...10	20% H ₂ SO ₄	200	600	293
P2	12...16	20% H ₂ SO ₄	400	600	293
P3	14...19	20% H ₂ SO ₄	200	1800	293

Electrodes were made of aluminum (99.95%). Their surface has been mechanically ground until achieving its bright polish. Afterward, the electrodes were washed many times in distilled water, acetone, and ethyl alcohol, with the use of an ultrasonic washer.

The dielectric coating of the polished aluminum electrodes was obtained as follows: first of all the electrodes were etched in a 30% solution of potassium hydroxide for about one minute and, afterward, accurately rinsed in distilled water. The aluminum oxide layer at the electrode surface has been obtained in the process of anodic oxidation in a 20% solution of sulfuric acid under the temperature 20°C. Variation of the current flowing during the anodic oxidation process and duration of the oxidation the flowing oxide coatings have been obtained: P1 of 5...10 μm thickness, P2 of 12...16 μm thickness, and P3 of 14...19 μm thickness. Physicochemical conditions of the oxide coating obtained at the aluminum electrode surfaces with the anodic oxidation method are specified in Table 1.

After the anodic oxidation, the electrodes have been carefully rinsed in distilled water. Then the oxide layer at the surface has been hardened by several-minutes boiling of the electrode in distilled water and dried in the temperature 110°C for 10 min.

In the present study, the thickness of aluminum oxide layer on the surfaces of the electrodes has varied between 5 and 10 μm.

The resulting oxide coating exhibits some porosity which reduces the corrosion resistance of the anodized aluminum. Therefore, after the anodic oxidation step, the obtained oxide coatings applied to the electrodes should be sealed (filled). Therefore, the Al₂O₃ coatings were additionally saturated, with the use of spraying technique, with a thin layer of insulating material (polyurethane varnish). This process was intended to increase the electrical and mechanical strength of the electrode surfaces.

The layers were subsequently hardened at 150 °C for 10 to 60 min—depending on the instructions of the manufacturer.

Electrodes prepared this way were then placed inside a stainless steel cylindrical pressure vessel with the diameter of 40 cm and height of 70 cm. Detailed description of the chamber is shown in [5].

Fig. 2 Characteristics of R3α sensor, calibration based on ASTM E1106 (—○—), calibration based on ASTM E976 (—△—) [32]

Electric strength was tested in the systems with air at $1 \cdot 10^5$, $3 \cdot 10^5$ and $5 \cdot 10^5$ Pa. The distance between the electrodes had a constant value of 3 mm.

Compressed air was obtained from an oil-free compressor and forced into the chamber through a silica gel filter to remove any air contaminants. Figure 1b shows the setup of a constructed chamber for testing gas insulated systems. The body is closed with upper and lower covers and two sides sealed with rubber o-rings. High voltage was obtained from the Haefely Trench RS-700-30-50 resonance system (with a voltage of 700 kV and power 500 kVA) powered from the mains voltage of 0.4 kV via the auto-transformer. One of the terminals of the test transformer was grounded and combined with the lower electrode insulation system under test, and the other via a resistor with a resistance of 40 kΩ and bushing in the flange of the chamber was connected to the high-voltage electrode. High voltage was measured with the use electrostatic kilovoltmeter. Additionally Fig. 1c shows detailed view of the chamber.

Figure 2 shows frequency characteristics of used piezo-electric acoustoelectric broadband sensor type R3α made by Physical Acoustics. Because of preliminary FFT analysis (see Fig. 3b) [31], it has been expected that during the tests frequencies would range between 0 and 100 kHz. Before analysis sensor's frequency characteristic was normalized.

AE signals were transferred to a preamplifier (with gain equal 20 dB) integrated with filter with a passband from 20 to 1000 kHz. After filtering, the signals were sent to the amplifier and were recorded on the PC via a measuring card

Fig. 3 Registered AE signal and its envelope **(a)** and spectrum **(b)** for the case when the electrodes were covered with additional coatings

with a frequency of 1 MHz sampling rate and 16 bit resolution.

Before the measurements were taken, the system was calibrated according to standard procedure adopted for tests with the use of the AE method, i.e., the Hsu-Nielsen method [33, 34].

Each test was performed until a short circuit occurred in the system. Five tests were performed for each distance-pressure set. This amount was considered as sufficient, as no significant differences were observed between them.

3 Analysis of measurements

3.1 Analyzing method and analyzed parameters

A computer program has been developed for recording signals, enabling the configuration of measurement card operation parameters, saving data in binary form, and also saving measurement parameters in the file header.

Recorded signals were analyzed with the use of functions developed in MATLAB, which operate according to the following algorithm:

- removing noise from signals (using wavelet transform),
- calculation of selected parameters of AE signals [15, 16].

Among many parameters of the AE signals, the following have been adopted for the purpose of description of the measured values:

- a sum and rate of AE counting;
- a sum and rate of AE events;
- duration of AE;
- duration of AE events;
- amplitude of AE signals;
- RMS value of the electric signal leaving the converter.

The sum of AE count is a sum of signal amplitudes exceeding an arbitrarily assumed discrimination threshold, counted in a definite period of time. On the other hand, the counting rate ($AE/\Delta t$) is a counting sum referred to the measuring time (t).

The sum of acoustic events (N) is defined as the number of the events counted in a definite period of time the envelopes of which (as opposed to the amplitudes as in case of the sum of counting) exceed an arbitrarily assumed discrimination

Fig. 4 Sum of AE counts for 3 mm electrode distance and pressures $1 \cdot 10^5$ Pa, $3 \cdot 10^5$ Pa and $5 \cdot 10^5$ Pa

threshold. On the other hand, the rate of the events ($N/\Delta t$) is a sum of the events referred to the measuring time (t).

The root-mean-square value A_{RMS} of the electric signal leaving the electroacoustic converter (briefly called an RMS signal) was analyzed.

Additionally, statistical analyses were performed. Calculated parameters were skewness and kurtosis.

Skewness, as the probability distribution asymmetry measure, is identified in the following way:

$$\text{skew} = \frac{\bar{x} - \text{med}(x)}{\sqrt{\sigma}} \quad (1)$$

where $\bar{x}$ —mean value of analyzed parameter, $\text{med}(x)$ —median value of analyzed parameter, and σ —analyzed parameter variance.

Kurtosis, which is the measure of the results' concentration around the mean, amounts to:

$$\text{kurt} = \frac{\mu_4}{\sigma^4} - 3 \quad (2)$$

where μ_4 —the fourth central moment of analyzed parameter and σ —analyzed parameter variance.

3.2 Results of measurements

Figure 3 shows an example of a registered AE signal along with its numerically determined envelope.

The above course of AE signal indicates the points of emission limits (beginning and end) that are relatively difficult to identify, or unambiguous definition rising and falling forehead of emissions, which can be a problem in the proper

evaluation of signal parameters. Hence, despite significant denoising of signals, the level of discrimination of signals was set at a value much higher than the noise level of the apparatus. Denoising parameters were: db5 wavelet, Donoho and I. M. Johnston filtration method with hard thresholding method at 6 mV level—the level of noises generated by apparatus (according to its documentation).

Figures 4, 5, 6, 7 and 8 present signal parameters, respectively: sum and rate of counts, sum and rate of events, and RMS for case without and with coating. The examples presented concern the case where the inter-electrode distance was 3 mm, and the air pressure was $1 \cdot 10^5$ Pa, $3 \cdot 10^5$ Pa and $5 \cdot 10^5$ Pa.

The use of dielectric coatings significantly affects the registered sum of AEs only at the smallest inter-electrode pressure tested. In other cases, for values greater than $1 \cdot 10^5$ Pa, the values are similar for every pair, with or without coatings of electrodes.

About 45 s, you can see a marked increase in the number of counts. This is due to the fact that Townsend's discharge mechanism was dominant at the time. This mechanism can be compared to the emission of single electrons from the electrodes so that more individual acoustic emissions are registered; in contrast to the channel discharge mechanism where the acoustic emissions are more concentrated because the number of discharges per unit time is lower. The same relationship will be seen in the following figures.

As in the case of the sum of counts, in the case of the counts rate also the use of dielectric coatings significantly affects this parameter only at the smallest inter-electrode pressure tested. In other cases, the impact is small. It should be noted,

Fig. 5 Rate of AE counts for 3 mm electrode distance and pressures $1 \cdot 10^5$ Pa, $3 \cdot 10^5$ Pa and $5 \cdot 10^5$ Pa

Fig. 6 Sum of AE events for 3 mm electrode distance and pressures $1 \cdot 10^5$ Pa, $3 \cdot 10^5$ Pa and $5 \cdot 10^5$ Pa

however, that changes in counts rate were smaller during tests for coated electrodes.

In the case of the sum and rate of events, one can observe a similar relationship as the one observed for counts, i.e., a large decrease in the sum and rate of events for the smallest inter-electrode pressure and no significant changes for larger ones.

Analyzing the impact of the presence of dielectric coatings on the RMS of AE signals, it can be seen that for all the tested pressures, this parameter achieves lower values for cases where the electrodes were covered with additional dielectric coatings.

To obtain more complete information on the impact of dielectric coatings on AE signals, an extended analysis of single counts and single events parameters was carried out. The mean and median duration of a single count and event were determined, as well as the mean and median amplitude of counts and events. Additionally, statistical parameters were determined, i.e., kurtosis and skewness. The results of these calculations are provided in Figs. 9 and 10 and Tables 2 and 3.

An increase in pressure in system increases the duration of a single count. The use of coatings reduces these times by several dozen percent. Furthermore, as the pressure increases,

Fig. 7 Rate of AE events for 3 mm electrode distance and pressures $1 \cdot 10^5$ Pa, $3 \cdot 10^5$ Pa and $5 \cdot 10^5$ Pa

Fig. 8 RMS of AE counts for 3 mm electrode distance and pressures $1 \cdot 10^5$ Pa, $3 \cdot 10^5$ Pa and $5 \cdot 10^5$ Pa

the kurtosis value increases, i.e., the results are concentrated around the mean after applying the coatings. At lower pressures ($1 \cdot 10^5$ Pa), the spread increases, and at higher pressures it takes lower values than for a system without coatings.

From the analysis of the duration of events, it can be seen that the increase in air pressure in the chamber results in extension of the duration of the event. On the other hand, the presence of coatings significantly reduces the average duration of the event while reducing the spread of these changes with increasing pressure.

Afterward, the count and event amplitudes were analyzed. The results of the analyses are presented in Figs. 11 and 12 and Tables 4 and 5.

The significant impact of the presence of coatings on the count amplitudes relates to the case for the highest pressure value—the average amplitude drops by more than 20%, and the median amplitude by more than 8%. At atmospheric pressure and $3 \cdot 10^5$ Pa changes are small. As for statistical parameters, a larger dispersion of amplitudes can be observed—a decrease in the skewness value with increasing pressure.

The use of additional dielectric coatings significantly increases the average and median amplitude of events for a pressure of $1 \cdot 10^5$ Pa several times. Increasing the pressure in the system results in increasing the signal amplitudes in the case of a system without coatings, while the signal

Fig. 9 Counts duration parameters for 3 mm electrode distance and pressures 1·10⁵ Pa, 3·10⁵ Pa and 5·10⁵ Pa

Fig. 10 Events duration parameters for 3 mm electrode distance and pressures 1·10⁵ Pa, 3·10⁵ Pa and 5·10⁵ Pa

amplitudes decrease for the case in which the coatings were applied.

3.3 Impact of multiple discharges on AE signal parameters

The next stage of the research was to verify the impact of dielectric coatings on the parameters of AE signals in repeated use of a pair of electrodes under given voltage conditions. This test was carried out by performing three measurements for a given pair of electrodes with a constant distance between electrodes, while maintaining the airtightness of the measuring chamber. In this process, the voltage was increased cyclically to the level at which there was a discharge in the inter-electrode space causing power cut. The purpose of this test was to verify whether the dielectric coating damage that occurs during breakdown is significant enough to affect the intensity of PD, i.e., the parameters of the AE signals. Figures 13, 14 and 15 show the count rate, event rate and RMS, respectively, with an electrode distance of 3 mm and a pressure of 1·10⁵ Pa.

The calculations carried out indicate that individual discharges in the system do not significantly affect either the rate of counts or the rate of events in the analyzed high-voltage system. There are some differences between individual measurements; however, they are small and the nature of their changes does not show any regularity.

As before, there are discontinuities (peaks) in the waveforms. Here, we can also notice Townsend's mechanism dominance in the formation of PDs.

In the case of RMS, not only do the discharges have no effect on the values of this coefficient, but also, as shown

Table 2 Statistical AE signals duration parameters—counts

Pressure	Average count duration (ms)	Median count duration (ms)	Skewness count duration (–)	Kurtosis count duration (–)
1·10 ⁵ Pa				
Without coatings	0.2249	0.1740	2.0495	8.6069
With coatings	0.1450	0.1160	5.0300	38.1965
Relative change	– 35.53%	– 33.33%	145.43%	343.79%
3·10 ⁵ Pa				
Without coatings	3.1854	2.2250	2.0321	9.2602
With coatings	2.2429	1.5800	2.0134	8.9586
Relative change	– 29.59%	– 28.99%	– 0.92%	– 3.26%
5·10 ⁵ Pa				
Without coatings	5.1000	1.9000	3.5885	20.1503
With coatings	2.3000	1.6000	2.0342	9.3760
Relative change	– 54.90%	– 15.79%	– 43.31%	– 53.47%

Table 3 Statistical AE events duration parameters

Pressure	Average event duration (ms)	Median event duration (ms)	Skewness event duration (–)	Kurtosis event duration (–)
$1 \cdot 10^5$ Pa				
Without coatings	0.2856	0.2740	1.8864	8.9903
With coatings	0.1768	0.1270	7.0650	78.9055
Relative change	– 38.10%	– 53.65%	274.52%	777.67%
$3 \cdot 10^5$ Pa				
Without coatings	20.1887	14.1155	1.9149	8.1774
With coatings	12.5904	8.7660	1.8893	7.7497
Relative change	– 37,64%	– 37,90%	– 1,34%	– 5,23%
$5 \cdot 10^5$ Pa				
Without coatings	30	8.7	4.2571	26.6504
With coatings	12.8	8.9	1.9454	8.3929
Relative change	– 57.33%	2.30%	– 54.30%	– 68.51%

Fig. 11 Counts amplitude parameters for 3 mm electrode distance and pressures $1 \cdot 10^5$ Pa, $3 \cdot 10^5$ Pa and $5 \cdot 10^5$ Pa **Fig. 12** Events amplitude parameters for 3 mm electrode distance and pressures $1 \cdot 10^5$ Pa, $3 \cdot 10^5$ Pa and $5 \cdot 10^5$ Pa

above, these values do not depend on the presence of coatings. It can be noticed that the dispersion of this parameter

value for the conducted analyses does not exceed 10%. For a more detailed description of the results obtained, a statistical analysis of selected signal parameters for individual tests was performed, which is presented in Table 6. The signal parameters are shown at an electrode distance of 3 mm and a pressure of $1 \cdot 10^5$ Pa.

The statistical analysis presented above confirms the lack of significant changes in AE signal parameters associated with single discharges in the insulation system.

4 Discussion

The research presented in this paper relates to systems with air as high-voltage insulation. Systems in which the air pressure p had the following values $1 \cdot 10^5$ Pa, $3 \cdot 10^5$ Pa or $5 \cdot 10^5$ Pa and the distance between electrodes d was 3 mm were tested. Thus, the product of pressure and electrode spacing pd were, respectively, $0.3 \cdot 10^5$ Pa·cm, $0.9 \cdot 10^5$ Pa cm and $1.5 \cdot 10^5$ Pa cm. These values are close to the value of the product $pd = 10^5$ Pa cm, which is commonly regarded as the boundary between the Townsend's mechanism and the streamer discharge mechanism. Thus, in the studied systems, the development of the discharge was probably caused by the interaction of both mechanisms. The increase in air pressure in the systems within the scope of the experiment ($1 \cdot 10^5$ Pa, $3 \cdot 10^5$ Pa, $5 \cdot 10^5$ Pa) probably caused a decrease in the participation in the initiation of the Townsend's mechanism shift and an increase in the share of the streamer mechanism.

In the Townsend's mechanism, it is assumed that the main source of free electrons is their emission from the cathode, which is the result of bombardment of the cathode by positive ions, which are formed during the formation of an electron avalanche. These ions accelerate in an electric field, bombard the cathode surface and penetrate its surface layer, where

Table 4 Statistical AE signals amplitude parameters

Pressure	Average count amplitude (mV)	Median count amplitude (mV)	Skewness count amplitude (–)	Kurtosis count amplitude (–)
1·10 ⁵ Pa				
Without coatings	25.3	18.6	1.7922	12.4533
With coatings	26.5	18.8	2.0742	9.0811
Relative change	4.74%	1.08%	15.73%	– 27.08%
3·10 ⁵ Pa				
Without coatings	25.0	18.6	16.2746	406.8270
With coatings	24.8	18.7	15.8199	545.4866
Relative change	– 0.80%	0.54%	– 2.80%	34.08%
5·10 ⁵ Pa				
Without coatings	32.6	20.5	20.1519	430.5184
With coatings	24.9	18.7	13.8273	385.3488
Relative change	– 23.62%	– 8.78%	– 31.38%	– 10.49%

Table 5 Statistical AE events amplitude parameters

Pressure	Average event amplitude (mV)	Median event amplitude (mV)	Skewness event amplitude (–)	Kurtosis event amplitude (–)
1·10 ⁵ Pa				
Without coatings	225.5	144.7	0.7081	3.4737
With coatings	820.6	713.3	0.6370	3.6626
Relative change	263.90%	392.95%	– 10.04%	5.44%
3·10 ⁵ Pa				
Without coatings	316.0	317.4	0.1279	3.7961
With coatings	322.5	321.5	0.1471	3.7423
Relative change	2.06%	1.29%	15.01%	– 1.42%
5·10 ⁵ Pa				
Without coatings	370.6	351.3	1.8672	15.3050
With coatings	318.9	320.6	0.1475	3.7648
Relative change	– 13.95%	– 8.74%	– 92.10%	– 75.40%

they collide with its atoms and transfer their kinetic energy to them. Many physical processes can take place as a result of this bombardment. One of these processes is the emission of secondary electrons by the cathode. It can be very intense and plays a major role in the Townsend mechanism initiating shocks. Moreover, bombardment of the cathode with positive ions may cause sputtering of the bombarded material, production of defects in its crystal structure, doping and complete destruction of its structure. These processes can be sources of acoustic emission signals.

The tests of acoustic emission signals generated by the insulation systems in the stage preceding the flashover showed that for the lowest pressure of 1·10⁵ Pa and the inter-electrode distance of 3 mm, the result in the product $pd = 0.3 \cdot 10^5$ Pa cm, which is significantly below the limit of $pd = 1 \cdot 10^5$ Pa cm. In this case, the influence of the coatings on the emission of electrons is an additional smoothing of the surface and reduction of local irregularities constituting the source of the emission. Therefore, electron emissions are less

frequent, but of higher energy, as shown by the amplitudes of the recorded AE events.

The second and third measurements concern the product pd equal to $0.9 \cdot 10^5$ Pa cm and $1.5 \cdot 10^5$ Pa cm. In these cases, we are either on the verge of mechanisms or with the dominant avalanche mechanism. The obtained results suggest that, in accordance with Paschen's law, for a constant inter-electrode distance, the electrical strength of the system increases with increasing pressure in the system. Thus, the mere increase in pressure results in a decrease in the intensity of the PD. However, the influence of the coatings can be compared in this case to an additional resistor in the circuit—it 'hinders' the formation of an avalanche at the cathode and 'extinguishes' it at the anode. In the parameters of the AE signals, these are the time parameters of the pulses, especially the average duration of the pulse and the event.

When examining the effect of dielectric coatings on the electrode surfaces of the systems on the RMS of the generated acoustic emission signals, it was found that the presence of

Fig. 13 Rate of AE counts for 3 mm electrode distance, pressure $1 \cdot 10^5$ Pa during multiple discharges

Fig. 14 Rate of AE events for 3 mm electrode distance, pressure $1 \cdot 10^5$ Pa during multiple discharges

the coatings, regardless of the value of air pressure in the system, decreased the value of this descriptor. With the increase in the value of air pressure in the systems, which increased the dominance of the streamer discharge initiation mechanism over the Townsends mechanism, an increase in the amplitudes of the recorded acoustic emission signals was observed. The presence of coatings on the electrode surfaces resulted in a decrease in these amplitudes, the stronger the higher the air pressure value. In addition, the increase in air pressure in the tested systems, which changed the type of discharge initiation mechanism into a streamer, caused the extension

of individual acoustic emissions from the tested system and the simultaneous stabilization of the duration of individual acoustic emissions (there was a significant reduction in the value of kurtosis and the skew duration of individual acoustic emissions).

It seems that the dielectric coatings on the electrodes at a higher air pressure of $5 \cdot 10^5$ Pa ($pd = 1.5 \cdot 10^5$ Pa cm) have a particularly favorable effect on the electrical insulating properties of the tested systems. In this case, the presence of dielectric coatings on the electrodes meant that the amplitudes of the observed acoustic events were smaller and were

Fig. 15 RMS for 3 mm electrode distance, pressure $1 \cdot 10^5$ Pa during multiple discharges

Table 6 AE signals parameters during multiple discharges

	Average count amplitude (mV)	Average event amplitude (mV)	Average count duration (ms)	Average event duration (ms)	Average RMS (V)
Without coatings					
Attempt 1	25.3	227.8	0.225	0.375	0.887
Attempt 2	24.8	224.0	0.209	0.331	0.833
Attempt 3	25.2	227.8	0.222	0.365	0.857
With coatings					
Attempt 1	26.5	820.6	0.145	0.177	0.858
Attempt 2	26.2	828.4	0.131	0.157	0.863
Attempt 3	27.0	843.1	0.134	0.159	0.832

characterized by a much smaller dispersion (skewness and kurtosis).

Summarizing, the above research shows that the application of 14–19- μm thick dielectric coatings on the electrode surfaces of the insulating system with air as insulation effects positively on the electrical insulating properties of the insulating system, especially when the flashover in the system occurs as a result of the streamer mechanism, i.e., when the product of the air pressure value and the distance between the electrodes is greater than 10^5 Pa·cm.

5 Conclusions

Verification of hypothesis that adding additional coatings influences on AE signals and thus on PD activity involved conducting a series of measurements. The studies were connected with registration and analysis of AE signals for the various system conditions and electrical insulation, i.e., different pressures in the chamber for cases where the electrodes

were both coated with electric insulation and without these coatings.

These studies led to the following conclusions.

1. When comparing long-term parameters, i.e., the sum and rate of counts as well as the sum and rate of events, it can be observed that the presence of dielectric coatings significantly reduces the values of these parameters only for atmospheric pressure, increasing the pressure does not cause any significant changes to these parameters.
2. Analysis of individual acoustic events and counts results in significant changes in the signals after the application of the coatings.
 - a. regardless of the level of pressure in the system, the duration of individual counts is significantly reduced (such as from 29 to 55 percent, depend on the pressure),
 - b. higher system pressure is accompanied by a reduction in kurtosis and skewness of the duration of a single pulse or AE event,

- c. count amplitudes at lower pressures are slightly higher than in systems without coatings, but with increasing pressure they decrease and become smaller than for systems without coatings,.
 - d. amplitude events have a similar pattern as the amplitude of the count, but in this case the relationship is even clearer; initially, at the lowest pressures the signal amplitudes increase several times after applying the coatings. With the increase in pressure, they reach the same level as for the case without coatings, while with a further increase in pressure they become less than the level achieved by the signals in the uncoated system—both average and median amplitude.
3. Multiple single discharges do not significantly affect the performance of individual counts and events while maintaining consistence, depending on higher counts and events amplitudes and shorter count and events duration for systems with coatings.

In conclusion, one should indicate the potentially main effect of using dielectric coatings, which may be associated with the impact of these coatings on PD. This impact is associated with the change in the shape of a single AE signal. These signals become shorter with a simultaneous increase in their amplitude, which may suggest changes in emerging PD consisting in the concentration of energy during discharge. This is confirmed by slight changes in RMS during the whole measurement. It can therefore be concluded that this has been achieved thanks to further smoothening of the electrode surface, which resulted from the intense emission of electrons together with smaller amounts of other asperities.

Additionally, a sudden increase in the intensity of emissions could be observed (shown in Figs. 5, 7). This phenomenon is believed to result from influence of the measuring system and the presence of transients occurring during tap switching of transformer while increasing the voltage) or presence of a single corona discharge observed during some of the tests.

The lack of influence of individual discharges on AE signals allows to hypothesize that damage to coatings due to single discharges is insignificant.

In order to verify above hypothesis, it is necessary to conduct further research and analyses regarding the impact of additional dielectric coatings on the operation of high-voltage insulation system.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material

is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Putz Ł, Bednarek K, Nawrowski R (2019) Disturbances generated by lighting systems with LED lamps and the reduction in their impacts. *Appl Sci* 9:4894
- Jajczyk J, Dobrzycki A, Filipiak M, Kurz D (2017) Analysis of power and energy losses in power systems of electric bus battery charging stations. *Proc E3S Web Conf* 19:1027
- Bednarek K, Nawrowski R, Tomczewski A (2002) Electromagnetic compatibility in the neighborhood of high-current lines. *Electromagn Fields Electr Eng Stud Appl Electromagn Mech* 22:363–368
- Wu M, Cao H, Cao J, Nguyen HL, Gomes JB, Krishnaswamy SP (2015) An overview of state-of-the-art partial discharge analysis techniques for condition monitoring. *IEEE Electr Insul Mag* 31:22–35
- Zakrzewski S, Opydo W (2010) Effect of electrode material on electric strength of compressed air in uniform electric field. *Pozn Univ Technol Acad J* 64:71–77
- Bartnikas R (2002) Partial discharges their mechanism, detection and measurement. *IEEE Trans Dielectr Electr Insul* 9(5):763–808
- Achatz N, Gorablenkow J, Schichler U, Hampton B, Pearson J (2008) Features and benefits of UHF partial discharge monitoring systems for GIS
- Okubo H, Nishizawa K, Okusu T, Hayakawa N, Endo F, Yoshida M, Uchida K (2008) Partial discharge detection techniques under the condition of metallic particle adhering to solid spacer in SF₆. In: *Proceedings of the annual report—conference on electrical insulation and dielectric phenomena, CEIDP*
- Li J, Han X, Yao X (2018) A novel GIS partial discharge detection sensor with integrated optical and UHF methods. *IEEE Trans Power Deliv* 33:2047–2049. <https://doi.org/10.1109/TPWRD.2016.2635382>
- Abdel-Gawad NM, Dein AZ, Lehtonen MK (2017) Experimental measurements of partial discharge activity within LDPE/TiO₂ nanocomposites. In: *19th International Middle-East Power Systems Conference, MEPCON 2017—Proceedings*. Institute of Electrical and Electronics Engineers Inc., pp 811–816. doi:<https://doi.org/10.1109/MEPCON.2017.8301273>
- Hussain GA, Shafiq M, Lehtonen M, Hashmi M (2015) Online condition monitoring of MV switchgear using D-dot sensor to predict arc-faults. *IEEE Sens J*. <https://doi.org/10.1109/JSEN.2015.2474122>
- Boczar T, Cichon A, Wotzka D, Kunicki M, Kozioł M (2017) Indicator analysis of partial discharges measured using various methods in paper-oil insulation. *IEEE Trans Dielectr Electr Insul*
- Dobrzycki A, Mikulski S, Opydo W (2014) Analysis of acoustic emission signals accompanying the process of electrical treeing of epoxy resins. In: *Proceedings of the ICHVE 2014–2014 international conference on high voltage engineering and application*. doi:<https://doi.org/10.1109/ICHVE.2014.7035500>
- Dobrzycki A, Opydo W, Zakrzewski S (2019) Influence of dielectric coatings on AE signals generated in high voltage gas insulated systems. In: *Proceedings of the ICHVE 2018–2018 IEEE international conference on high voltage engineering and application*. doi:<https://doi.org/10.1109/ICHVE.2018.8642212>
- Dobrzycki A, Mikulski S (2016) Using of wavelet transform in the analysis of AE signals accompanying the process of epoxy

- resins electrical treeing. *PRZEGLĄD ELEKTROTECHNICZNY* 92(5):221–223. <https://doi.org/10.15199/48.2016.04.4>
16. Mikulski S, Dobrzycki A (2016) Using of continuous wavelet transform for de-noising signals accompanying electrical treeing in epoxy resins. *PRZEGLĄD ELEKTROTECHNICZNY* 92(4):26–29. <https://doi.org/10.15199/48.2016.04.07>
 17. Morshuis PH (1993) *F Partial discharge mechanisms*. Delft University Press, Delft
 18. Kreuger FH, Gulski E, Sonneveld WA (1992) Diagnosis in GIS by statistical analysis of discharges. *CIGRE* 15/23–04
 19. Skubis J (1998) Relationships between acoustic and electric descriptors of partial discharges. *Arch Electr Eng XLVII*:120–126
 20. Skubis J (1998) Spectrum of acoustic emission pulses generated by electric slide surface discharges in oil. *Arch Electr Eng XLVII*:25–38
 21. Skubis J, Lorenc M (1998) Measurements and analysis of acoustic emission standard pulses generated in Hsu–Nielsen source. *Arch Electr Eng XLVII*:13–24
 22. Tian Y (2005) PD pattern identification using acoustic emission measurement and neural networks
 23. Dobrzycki A, Mikulski S, Opydo W (2019) Using ANN and SVM for the detection of acoustic emission signals accompanying epoxy resin electrical treeing. *Appl Sci* 9:1523. <https://doi.org/10.3390/app9081523>
 24. Suwarno S (2016) Partial discharge in high voltage insulating materials. *Int J Electr Eng Inform* 8(1):147–163. <https://doi.org/10.15676/ijeei.2016.8.1.11>
 25. Syed B, Zhu J, Polcik P, Kolozsvari S, Håkansson G, Johnson L et al (2017) Morphology and microstructure evolution of Ti–50 at.% Al cathodes during cathodic arc deposition of Ti–Al–N coatings. *J Appl Phys*. <https://doi.org/10.1063/1.4990425>
 26. Fabiani D, Cavallini A, Sacconi A, Toselli M (2013) XLPE with hybrid nanocoating showing improved electrical properties. *IEEE Trans Fund Mater* 133:116–120. <https://doi.org/10.1541/ieejfms.133.116>
 27. Yaacob MM, Alsaedi MA, Rashed JR, Dakhil AM, Atyah SF (2014) Review on partial discharge detection techniques related to high voltage power equipment using different sensors. *Photonic Sens*. <https://doi.org/10.1007/s13320-014-0146-7>
 28. Markalous SM, Tenbohlen S, Feser K (2008) Detection and location of partial discharges in power transformers using acoustic and electromagnetic signals. *IEEE Trans Dielectr Electr Insul* 15(6):1576–1583. <https://doi.org/10.1109/TDEI.2008.4712660>
 29. Castro B, Clerice G, Ramos C, Andreoli A, Baptista F, Campos F, Ulson J (2016) Partial discharge monitoring in power transformers using low-cost piezoelectric sensors. *Sensors (Switzerland)*. <https://doi.org/10.3390/s16081266>
 30. Brochure prepared for U.S. Environmental Protection Agency: Byproducts of Sulfur Hexafluoride (SF6) Use in the Electric Power industry, ICF Consulting, Fairfax 2002.
 31. Chalmers TD, Qiu XQ, Coventry P (1999) The study of SF6 mixtures, gaseous dielectrics VIII. In: Christophorou LG (ed), USA
 32. Słowikowska H, Słowikowski J (1999) Podstawy diagnozowania urządzeń z SF6 w oparciu o badania stanu gazu, VII Sympozjum "Problemy Eksploatacji Układów Izolacyjnych Wysokiego Napięcia", Zakopane
 33. Christophorou LG, Van Brunt RJ (1996) SF6 insulation: possible greenhouse problems and solutions, *CIGRE*, paper 15.03.06 IWD4
 34. Wootton RE (1982) Gases superior to SF6 for insulation and interruption, Report ERRI EL-2620. Electric Power Research Institute
 35. Dobrzycki A, Zakrzewski S, Opydo W (2010) Acoustic emission signals associated with prebreakdown state in air high voltage insulating systems. *Comput Appl Electr Eng* 13:278–286
 36. Datasheet of R3α sensor, <https://www.physicalacoustics.com/by-product/sensors/R3a-30-kHz-Low-Frequency-AE-Sensor>
 37. Witos F, Szerszeń G, Opilski Z, Setkiewicz M, Olszewska A, Duda D, Maźniewski K, Szadkowski M (2017) Calibration and laboratory testing of computer measuring system 8AE-PD dedicated for analysis of acoustic emission signals generated by partial discharges within oil power transformers. *Arch Acoust* 42(2):297–311. <https://doi.org/10.1515/aoa-2017-0032>
 38. Hsu N, Breckenridge F (1981) Characterization and calibration of AE sensors. *Mater Eval* 39(1):601

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.