Research Article

Diagnosis of High Voltage Insulators Made of Ceramic Using Spectrophotometry

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The paper presents results of comparative analysis of optical signals emitted by partial discharges occurring on three types of high voltage insulators made of porcelain. The research work consisted of diagnosis of the following devices: a long rod insulator, a cap insulator, and an insulating cylinder. For optical signal registration a spectrophotometer was applied. All measurements were performed under laboratory conditions by changing the value of partial discharges generation voltage. For the cylindrical insulator also the distance between high voltage and ground electrodes was subjected for investigation as a factor having influence on partial discharges. The main contribution which resulted from the studies is statement that application of spectrophotometer enables faster recognition of partial discharges, as compared to standard methods.

1. Introduction

This research concerns a field of science which is related to the generation and development of electric discharges on surfaces of high voltage (HV) insulation systems. An important problem of insulation systems is the ageing process progressing during their operation and causing deterioration of insulating properties [1–3]. Important ageing factors that occur in operational practice include UV radiation, ozone and nitrogen oxides, temperature fluctuations, rain-fall (including acid rain), rime deposition, dirt, and partial discharges (PD). The origin of research and scientific studies conducted by our team is the need to analyze the physical phenomena that occur during electric discharges on the surface on nonorganic (ceramic) dielectrics. The main objective of research conducted within this scope is to determine as accurately as possible how, when, and at what pace a process of deterioration of insulation elements is progressing. Another issue is to determine the conditions under which the complete breakdown occurs. The studies involved measurements of optical emission spectra of electric discharges occurring on the surface of ceramic insulation using spectrophotometer. Based on the gathered data, the initial voltage values of electric discharges U_{10} were estimated

with a greater sensitivity and faster than previously possible, based on the measurement of initial corona voltage U_0 . The presented study results were aimed at confirming the hypothesis that measurement of emission spectra, especially in the range from 250 nm to 280 nm, generated by electric discharges occurring on surfaces of ceramic dielectrics, can serve as a sensitive and effective indicator of their surface strength.

2. Materials and Methods

2.1. Metrological Parameters of the Measuring System. Nowadays, there are many measurement methods of detecting PD occurring in the insulating systems of electrical power equipment. Diagnostic methods can be divided into invasive methods and noninvasive methods. Invasive methods involve detection and recording PD currents using special measuring probes that express PD value in pC. The disadvantage of such methods is the need to disconnect the tested device from the power supply during connection and disconnection of the measuring apparatus [4–6]. Alternative methods do not require invasion in the operation of the device, making them safer for people performing measurements with measuring equipment, usually hand-held and portable [7, 8].

The acoustic method allows the detection of ultrasound (sound pressure) within the range of up to 500 kHz generated in the early stage of surface PD using the specialized devices [9, 10]. The electromagnetic method, depending on the instrument used, allows the recording of the intensity of spectrum for varying radiation range. The knowledge available today in the literature allowed us to conclude that the emitted spectrum is in the range from ultraviolet to infrared radiation [11, 12] and in X-rays in the range 10 pm to 10 nm [13].

This paper concerns electromagnetic method, and particularly recording of UV and visible radiation. The properties of electromagnetic radiation emitted during the PD depend on the type of insulating material and parameters of the propagation medium and the environment surrounding the area of PD generation, such as pressure, temperature, and humidity [14, 15].

The basic technique for measuring optical radiation is spectrophotometry. Its main advantage is the galvanic separation of the measuring position from the tested device, which is under high voltage [16]. Thanks to that, the obtained results do not affect external electromagnetic fields with high intensity and other types of disturbances that have negative impact on the signals recorded using electric or acoustic method. A condition necessary for the detection of PD with the use of optical method is a direct line of sight. A method for recording optical radiation is the spectrophotometry technique, allowing the recording of not only the radiation intensity but, above all, the occurrence and shape of the spectrum present in the emitted signals [17]. In this technique spectrophotometers are used, which are currently being constructed from sets of photodiodes with variable wavelengths, light-sensitive CCD detectors, and special software for processing [18, 19]. An important parameter affecting the accuracy and efficiency of the obtained results of measurements is the amount of attenuation and dispersion of optical signals depending, among other things, on the distance of the recording equipment from the point of PD generation and the propagation medium itself.

Table 1 presents basic technical parameters of the Ocean Optics HR4000 spectrophotometer used in the measurements. Measurement data archiving and processing were performed using numerical procedures implemented in the MATLAB programming environment.

All the measurements were conducted in a darkened room of the laboratory. The measurement procedure included increase of the PD generation voltage from 0 to 100 kV while recording the intensity of optical radiation. For each of the considered voltage levels, five measurements using a spectrophotometer were made. The power supply system consisted of a testing transformer and a control panel, which included an autotransformer, an overcurrent protection system, and a voltmeter for measurement of the momentary voltage value. The voltage values were controlled by the autotransformer and forwarded to primary winding of the single-phase testing transformer. The output of the secondary winding was connected to a water resistor for limitation of the short-circuit current with which the tested insulator was powered.

TABLE 1: Characteristics of technical parameters of spectrophotometer applied in the study.

Parameter	Value	Unit
CCD detector	Toshiba TCS1304AP - 3648	Pixel
Integration time (counting time)	from 3.8×10^{-3} to 20	s
Type of optical link	SMA 905	
Width of apertures lit	5, 10, 25, 50, 100, 200	μm
Optical resolution	$\sim 0.02\text{--}8.4$	nm FWHM
Light scattering	$<0.05\%$ for 600; $<0.1\%$ for 435	nm
Visible light range	190–1100	nm
UV spectral range	200–1100	nm
Dynamic range	1300 : 1	
Corrected linearity	>99.8	%
A/D resolution	14	bits
Maximum pixel digitalization range	1	MHz
Size of pixel, CCD element	8×200	μm
Sensitivity	100 per count for 800 nm	Photons

Measurement cycles were conducted for supply voltage varying in the range from initial voltages U_0 to U_p . The initial voltages U_0 and U_{01} were determined based on voltmeter reading, while the spectrophotometer showed intensity exceeding 300.

The breakdown voltage depended on the type of tested porcelain and the distance between electrodes. An optical transducer was placed in a specially designed holder mounted on a stand, allowing us to adjust height, angle, and distance between the measuring head and the area of PD occurrence on the tested dielectric. For each tested dielectric, a value of initial voltage U_0 and a breakdown voltage U_p was determined five times prior to the measurement of PD. Measurements of emission spectra were conducted for averaged values relative to U_0 and U_p .

The tests involved the preparation of three ceramic insulation systems for PD generation, that is,

- (i) LS-type long rod insulator (Figure 1(a)),
- (ii) WPK-type porcelain cylinder, filled with quartz (Figure 2(b)),
- (iii) LK-type cap insulator (Figure 2(a)).

For the WPK-type insulator, PD measurements were performed at various distances between the HV and ground electrodes in the range from 3 cm to 11 cm. In consequence, the following definitions are used in this paper: WPK3, WPK5, WPK7, WPK9, and WPK11, where the numbers correspond to the distance between electrodes in cm.

2.2. Numerical Methods Applied for Measurement Results Analysis. The obtained results of measurements of emission spectra were analyzed statistically in order to determine differences and similarities between signals and to determine

FIGURE 1: (a) The long rod insulator, type LS, and (b) the spectrophotometer applied in the study.

FIGURE 2: (a) The cap insulator, type LK, and (b) the cylindrical insulator, type WPK.

the effect of PD generation voltage on the obtained emission spectra. Light emission intensity spectra were visualized for various PD generation voltages, as well as using cumulative graph for all tested voltages. Histograms showing the number of variable intensity radiation I were calculated for individual wavelengths. A histogram is a graphical method to present the empirical distribution, which is determined by calculating the frequency distribution. Histograms were presented on cumulative graphs showing the dependence of obtained values on PD generation voltage. Wavelength ranges were determined for the light emission of the highest intensity. These values are dependent on the voltage of PD generation and the type of studied insulation system. Recorded characteristics underwent a process of mathematical regression. For that, components of linear spectrum were determined using a series of Gaussian functions. The developed procedures use Nelder-Mead Simplex method to look for optimal parameters of the function in question, that is, parameters that would provide minimum deviations between theoretical and empirical data (3). A final effect was the sum of spectral components in the form of relation designated as M2

$$M2(\lambda) = \sum_{i=1}^N A_i * e^{-((\lambda-B_i)/C_i)^2}, \quad (1)$$

where λ is independent variable wavelength, A_i is amplitude of component (spectral line) of width C_i , N is varying number of components in the model, and A , B , and C are model parameters.

In order to determine most predominant components of the linear spectrum, a mathematical model M1 was developed that can be described using relation (2). M1 model is a sum of eight Gaussian functions:

$$M1(\lambda) = \sum_{i=1}^8 A_i * e^{-((\lambda-B_i)/C_i)^2}, \quad (2)$$

where λ is independent variable wavelength, A_i is amplitude of component (spectral line) of width C_i , and A , B , and C are model parameters:

$$\delta = \sqrt{\sum_{i=1}^n (x_i - \tilde{x}_i)^2}, \quad (3)$$

where x_i is i th empirical variable value and $\tilde{x}_i$ is i th theoretical variable value (estimated).

In order to perform analysis of obtained regression results, values of coefficients which are the measures of matching the studied models to the studied dependence were

FIGURE 3: Summary of spectrum intensity histograms for different voltages: (a) $I > 500$ and (b) $I > 1000$.

determined, including SSE (4), RMSE (5), R -square (6), and adj- R -square (7).

(a) SSE is the sum of squares of residuals. It determines the total deviation of estimated values from empirical data. A value close to zero indicates that the model has a smaller random error component, and the fitting can be more useful for prediction:

$$\text{SSE} = \sum_{\forall i} (y_i - \tilde{y}_i)^2, \quad (4)$$

where y_i is i th empirical variable value and $\tilde{y}_i$ is i th theoretical variable value (estimated).

(b) RMSE is the standard error of regression constituting the root mean square error. The value close to one means higher utility of the considered model for prediction:

$$\text{RMSE} = \sqrt{\frac{\sum_{\forall i} (y_i - \tilde{y}_i)^2}{n - p}}, \quad (5)$$

where y_i is i th empirical variable value, $\tilde{y}_i$ is i th theoretical variable value (estimated), n is number of samples contained in estimated course/dependence, and p is number of model parameters.

(c) R -square (R^2) determines the variability in the data. This value is the square of the correlations between empirical and estimated data. Values close to one indicate that most of the variance is included in the model. In this study, we apply R^2 as a fitting indicator. Values above 0.6 and 0.8 indicate well and very well fitting results, respectively. Values equal or less than 0.5 indicate poor or no fitting, respectively:

$$R\text{-square} = 1 - \frac{\sum_{\forall i} (y_i - \tilde{y}_i)^2}{\sum_{\forall i} (y_i - \mu)^2}, \quad (6)$$

where y_i is i th empirical variable value, $\tilde{y}_i$ is i th theoretical variable value (estimated), and μ is arithmetic mean of the empirical data.

(d) Adj- R -square (adj- R^2) is a determination coefficient adjusted by the number of degrees of freedom. It is an indicator that allows the comparison of results obtained by models with different numbers of parameters. The values are in the range below one. Values close to one indicate a good matching of the model to empirical data. Negative values indicate that the model contains elements that do not help in predicting model response:

$$\text{adj-}R\text{-square} = 1 - \frac{\text{SSE}(n-1)}{\text{SST}(n-p)}, \quad (7)$$

where n is number of samples contained present in estimated curve/dependence and p is number of model parameters:

$$\text{SST} = \sum_{\forall i} (y_i - \mu)^2, \quad (8)$$

where y_i is i th empirical variable value and μ is arithmetic mean of the empirical data.

M1 and M2 models, despite apparent similarities, are very different in terms of number of parameters and parameter estimation method. The paper presents fit coefficients calculated using regression for both models, that is, SSE, R -square, and RMSE in form of 3D graphs visualizing dependence as a function of PD generation voltage.

3. Example Results and Discussion

3.1. Analysis of Emission Spectra of Discharges Occurring on the Surface of Porcelain Insulation Cylinder Filled with Quartz: Example Distance between Electrodes Is 3 cm. Figure 3 presents a cumulative comparison of histograms calculated for spectra of the highest intensities obtained during measurements as a function of PD generation value. The graph on the left refers to the intensity exceeding the value of 500 ($I > 500$), while the graph on the right indicates intensity exceeding the value of 1000 ($I > 1000$). On the basis of this analysis, it is possible to determine the frequency of light emission generated by PD for a given wavelength.

TABLE 2: Dominant wavelengths present in light emission of value $I > 1000$.

Wavelength interval (nm)	Dominant wavelengths and intervals present in light emission of value $I > 1000$ (nm)
$\lambda = [200-299]$	203, 296–298
$\lambda = [300-399]$	311–318, 333–340, 351–360, 369–382, 390–396, 397–399
$\lambda = [400-499]$	400–401, 404–407, 420, 425–428, 434–435
$\lambda > 500$	745, 933, 1073

Based on the obtained histograms for intensities of values exceeding 1000, dominant light wavelengths occurring in the recorded signals were determined for the individual intervals and presented in Table 2.

Figure 4 presents the results of modeling intensity spectra using Gaussian series, model M2 for selected values of PD generation voltage. A red color denotes measurement results, while blue denotes modeling results. The legend contains value of determination coefficient R^2 .

Figures 5 and 6 present graphically the values of fitting parameters, R^2 , RMSE, and SSE obtained from the regressions using Gaussian series M2 for data recorded during each of five measurements conducted for various PD generation values.

Based on the R^2 coefficient analysis, it was found that the M2 model was performed with an excellent adequacy level in the majority of cases, which was confirmed by the obtained values, close to 1. No fitting was obtained for lower PD generation voltages. This is due to a lack of dominant wavelengths emitted by PD at these voltages.

Based on the analysis of the values of the coefficients RMSE and SSE that reached values above 100, it was concluded that the model should not be used for prediction.

Figure 7 presents the results of modeling intensity spectra using a sum of eight Gaussian functions, model M1 for selected values of PD generation voltage. The red color denotes measurement results and blue corresponds to modeling results. The legend contains the value of determination coefficient R^2 .

Figures 8 and 9 present graphical values of fitting parameters, R^2 , RMSE, and SSE obtained by the regression of model M1 for all data recorded during each five measurements conducted by different PD generation values.

It was found that the M1 model was performed in a very similar way to the M2 model with an excellent adequacy level in the majority of cases, which was confirmed by the obtained values of R^2 , close to one. Only in individual cases for the lowest PD generation voltages, poor fitting or no fitting was observed.

The application of the M1 model allowed precise determination of intensity and wavelength of dominant light waves in recorded spectrum emitted by PD. Figure 9(b) presents intensity of individual wavelengths depending on the value of voltage supplying given system.

FIGURE 4: Intensity spectra of recorded and modeled light emission for selected values of PD generation voltages: (a) $0.75 U_p = 15$ kV and (b) $0.94 U_p = 19$ kV.

3.2. Analysis of Emission Spectra of Discharges Occurring on the Surface of LK-Type Cap Insulator. Figure 10 depicts cumulative comparison of histograms calculated for spectra of highest intensities obtained during measurements as a function of PD generation value. Figure 10(a) refers to the intensity exceeding the value of 500 ($I > 500$) and Figure 10(b) intensity exceeding the value of 1000 ($I > 1000$).

For intensities of values exceeding 1000, dominant light wavelengths occurring in the recorded signals were determined for the individual intervals and presented in Table 3.

Figure 11 shows the results of modeling (blue line) intensity spectra using model M2 for selected values of PD

FIGURE 5: Comparison of values of R^2 coefficient obtained by the regression of the model M2 for all the recorded signals.

FIGURE 6: Comparison of values of coefficients RMSE (a) and SSE (b) obtained by the regression of the model M2 for all the recorded signals.

TABLE 3: Dominant wavelengths present in light emission of value $I > 1000$.

Wavelength interval (nm)	Dominant wavelengths and intervals for $I > 1000$ (nm)
$\lambda = [200-299]$	243
$\lambda = [300-399]$	312-317, 329, 333-339, 352-371, 373-382, 398-399
$\lambda = [400-499]$	400, 404-406, 435, 460
$\lambda > 500$	724, 933

generation voltage compared to measurement results (red line).

Figures 12 and 13 present values of fitting parameters, R^2 , RMSE, and SSE obtained from the regressions using model M2 for data recorded during each five measurements conducted by different PD generation values.

It was found that model M2 obtained an excellent adequacy level for PD generation voltage values of 60 kV and 70–80 kV. However, no fitting was obtained for other voltages. The coefficients RMSE and SSE that reached values above 100 indicate that the model cannot be used for prediction.

Figure 14 shows the results of modeling intensity spectra using model M1 for all selected values of PD generation voltage.

Figures 15 and 16(a) depict values of fitting parameters: R^2 , RMSE, and SSE obtained by the regression using model M1 for data recorded during each five measurements conducted by different PD generation values.

Model M1 for PD generation voltage values of 65 kV and 70–80 kV obtained an excellent adequacy level, which was confirmed by the obtained values, over 0.6. However, no fitting was obtained for other voltages. The coefficients RMSE and SSE that reached values above 100 indicate that the model cannot be used for prediction.

FIGURE 7: Intensity spectra of recorded and modeled light emission for selected values of PD generation voltages: (a) $0.75 U_p = 15$ kV and (b) $0.94 U_p = 19$ kV.

FIGURE 8: Comparison of values of R^2 (a) and RMSE (b) coefficients obtained by the regression of the model M1 for all the recorded signals.

Figure 16(b) presents the intensity of individual wavelengths depending on the value of voltage supplying given system.

3.3. Analysis of Emission Spectra of Discharges Occurring on the Surface of LS-Type Long Rod Insulator. Figure 17 depicts a cumulative comparison of histograms calculated for spectra of highest intensities obtained during measurements as a function of PD generation value. Figure 17(a) refers to the intensity exceeding the value of 500 ($I > 500$) and Figure 17(b) to the intensity exceeding the value of 2000 ($I > 2000$).

For intensities of values exceeding 2000, dominant light wavelengths occurring in the recorded signals were

TABLE 4: Dominant wavelengths present in light emission of value $I > 2000$.

Wavelength interval (nm)	Dominant wavelengths and intervals present in light emission of value $I > 2000$ (nm)
$\lambda = [200-299]$	—
$\lambda = [300-399]$	315–317, 335–338, 353–358, 379–381
$\lambda = [400-499]$	—
$\lambda > 500$	724

determined for the individual intervals and presented in Table 4.

FIGURE 9: (a) Voltage dependency on SSE obtained by model M1 for all data samples. (b) Intensity of wavelength components obtained by model M1 as a function of PD generation voltage.

FIGURE 10: Summary of spectrum intensity histograms for different voltages: (a) $I > 500$ and (b) $I > 1000$.

Figure 18 presents the results of modeling (blue line) intensity spectra using model M2 for selected values of PD generation voltage and experimental results (red line).

Figures 19 and 20 show values of fitting parameters: R^2 , RMSE, and SSE obtained from the regressions using model M2 for data recorded during each five measurements conducted by various PD generation values. It was found that model M2 obtained an excellent adequacy level in most cases, which was confirmed by the obtained values, R^2 above 0.6. Only for the 37.5 kV no fitting was obtained. From Figure 20 it is to conclude that the model cannot be used for prediction.

Figure 21 presents results of modeling (blue color) intensity spectra using model M1 for selected values of PD generation voltage. Red dots denote experimental results.

Figures 22 and 23 depict values of fitting parameters: R^2 , RMSE, and SSE obtained by the regression using model M1 for data recorded during each of five measurements conducted for various PD generation values.

It was found that model M1 gives very good fitting for signals registered in voltage values over 40 kV, which was proven by the R^2 values over 0.8. No fitting was obtained at 37.5 kV in 4 of 5 samples. Figure 23(b) depicts the PD generation voltage dependency on the intensity of individual wavelengths.

4. Conclusions

Conducting tests with spectrophotometer allowed precise determination of lines length and corresponding intensities

FIGURE 11: Intensity spectra of recorded and modeled light emission for selected values of PD generation voltages: (a) $0.56 U_p = 60$ kV and (b) $0.89 U_p = 80$ kV.

FIGURE 12: Comparison of R^2 obtained by regression of model M2 for all the recorded signals.

in the recorded optical signals. Based on the obtained dependencies of intensities of emission spectrum emitted by PD generated on studied dielectrics and insulation system the following was concluded:

- (i) During PD generation on the surface of a porcelain insulating cylinder filled with quartz, while the distance between electrodes was 3 cm, the highest intensities reaching 10,000 were obtained for spectral lines in a wavelength range of 333–340 and 351–360 nm, when the system was supplied with voltage in a range from 16.5 kV to 19 kV.
- (ii) During PD generation on the surface of a porcelain insulating cylinder filled with quartz, while the distance between electrodes was 5 cm, the highest

intensities reaching 10,000 were obtained for spectral lines in a wavelength range of 331–341 and 349–362 nm, when system was supplied with voltage in a range from 25.5 kV to 27 kV.

- (iii) During PD generation on the surface of a porcelain insulating cylinder filled with quartz, while the distance between electrodes was 7 cm, the highest intensities reaching 6000 were obtained for spectral lines in a wavelength range of 335–339 and 352–359 nm, when the system was supplied with voltage in a range from 31.5 kV to 33.5 kV.
- (iv) During PD generation on the surface of a porcelain insulating cylinder filled with quartz, while the distance between electrodes was 9 cm, the highest

FIGURE 13: Comparison of RMSE (a) and SSE (b) obtained by regression of model M2 for all data samples.

FIGURE 14: Intensity spectra of recorded and modeled light emission for selected values of PD generation voltages: (a) $0.56 U_p = 60$ kV and (b) $0.89 U_p = 80$ kV.

- intensities reaching 2000 were obtained for spectral lines in a wavelength range of 336–338, 354, and 356–359 nm, when the system was supplied with voltage in a range from 39 kV to 41 kV and 43 kV to 46 kV.
- (v) During PD generation on the surface of a porcelain insulating cylinder filled with quartz, while the distance between electrodes was 9 cm, the highest intensities reaching 2000 were obtained for spectral lines in a wavelength range of 335–339 and 353–359 nm, when the system was supplied with voltage in a range from 44 kV to 45 kV and for approximately 50 kV.

- (vi) By analyzing the influence of distance on the obtained results, one can conclude that the range of components decreases with increasing distance, which is probably a result of the suppression of individual spectral lines in the air.
- (vii) During PD generation on a cap insulator made of porcelain, the highest intensities, over 9000, were obtained for spectral lines in ranges 333–339 and 352–371. The insulator was supplied with voltage of values in a range from 72 kV to 76 kV.
- (viii) During PD generation on an individual cap of porcelain long rod insulator, the highest intensities, over

FIGURE 15: Comparison of R^2 (a) and RMSE (b) obtained by regression of model M1 for all data samples.

FIGURE 16: (a) Comparison of SSE coefficient obtained by regression of model M1 for all recorded signals. (b) Voltage dependence of intensity of individual wavelengths obtained by model M1.

6000, were obtained for spectral lines in ranges 335–338 and 353–358. The insulator was supplied with voltage of values in a range from 42.5 kV to 46 kV.

Table 5 shows a comparison between PD initial voltage values U_0 and U_{01} , during which the measurement device recorded first light emission waves (U_{01}) or when the recorded spectra included the most components of increased (over 300) intensities (U_0), depending on the test system. The analysis of the values presented in Table 5 allows one to conclude that the application of the spectrophotometer enables earlier recognition of PD generation, which confirms the thesis of the study. On average, the increased performance was estimated as a lower level of voltage, 42%.

Based on the obtained results, Table 6 presents a comparison of dominant wavelengths contained in light emission of intensities exceeding 1000, obtained for individual dielectrics and ceramic insulators.

The comparison of the data presented in Table 6 allows one to formulate the following general conclusions:

- (i) PD emitted electromagnetic waves in a range of 300–400 nm regardless of in which dielectric and insulator system they are generated.
- (ii) PD emitted waves of 203 nm length on a porcelain cylinder filled with quartz, except when the HV electrode was placed at a distance between electrodes of 11 cm.

FIGURE 17: Summary of spectrum intensity histograms for different voltages: (a) $I > 500$ and (b) $I > 2000$.

FIGURE 18: Intensity spectra of recorded and modeled light emission for selected values of PD generation voltages: (a) $0.81 U_p = 39$ kV and (b) $0.95 U_p = 46$ kV.

TABLE 5: Comparison of PD initial voltages for tested insulation systems, during which emission spectra may have increased intensity and the broadest range.

Values of initial voltages U_0 and U_{01} for tested insulation systems							
	WPK 3 cm	WPK 5 cm	WPK 7 cm	WPK 9 cm	WPK 11 cm	LK —	LS —
U_0	9.9%	18.2%	23.6%	24.3%	25.7%	23.3%	12%
U_{01}	15.5%	25.5%	30.5%	37%	39%	72%	37.5%
<i>Difference</i>	36.2%	28.6%	22.6%	34.3%	34.1%	67.6%	68%

FIGURE 19: Comparison of R^2 coefficient obtained by regression of model M2 for all the recorded signals.

FIGURE 20: Comparison of RMSE (a) and SSE (b) obtained in model M2 for all the recorded signals.

TABLE 6: Comparison of the dominating wavelengths present in light emission of value $I > 1000$ for all tested dielectrics and ceramic insulators.

System symbol		Values and ranges of recorded optical waves λ (nm) exhibiting intensity $I > 1000$		
WPK 3	203, 296–298	311–318, 333–340, 351–360, 369–382, 390–396, 397–399	400–401, 404–407, 420, 425–428, 434–435	745, 933, 1073
WPK 5	203, 295–299	309–318, 328–329, 331–341, 349–362, 366–383, 386, 388–399	400–407, 414, 416, 418–421, 424–428, 431–435, 449, 456–458	607, 653–654, 658–663, 667–671, 676–678, 724, 745, 774, 793, 913, 933, 1062, 1073
WPK 7	203	306–317, 335–339, 352–359, 374–382, 386, 393–394, 399	400, 405–406, 423	587–594, 640, 720, 745, 766–768, 770–771, 793, 933
WPK 9	203	315–317, 336–338, 354, 356–359, 375–376, 379–381	—	660, 724, 813, 933
WPK 11	—	313–317, 335–339, 353–359, 374–377, 379–382, 399	400, 406	660, 724, 739
LS	—	315–317, 335–338, 353–358, 379–381	—	724
LK	243	312–317, 329, 333–339, 352–371, 373–382, 398–399	400, 404–406, 435, 460	724, 933

FIGURE 21: Intensity spectra of recorded and modeled light emission for selected values of PD generation voltages: (a) $0.81 U_p = 39$ kV and (b) $0.95 U_p = 46$ kV.

FIGURE 22: Comparison of R^2 (a) and RMSE (b) coefficient obtained in model M1 for all the recorded signals.

- (iii) PD occurring on the surface of the tested cap insulator are characterized by the presence of waves of 243 nm length.
- (iv) PD occurring on the porcelain cylinder with a HV electrode placed at distances between electrodes of 3 cm and 5 cm emitted waves of 295–299 nm length.
- (v) PD emitted many waves in a range of 400–500 when they occurred on a porcelain cylinder with a HV electrode placed at distances between electrodes of 3 cm and 5 cm. Single waves in this range were emitted on cap insulators and other types of insulating cylinders, except for cylinder tested at a distance between electrodes of 9 cm. PD occurring on the

porcelain long rod insulator did not emit any optical waves in this range.

- (vi) EM waves in visible light range, above 500 nm, were present in spectra in different ways. Most components from this range were recorded on porcelain roll insulators during PD generation at distances of 5 cm and 7 cm.
- (vii) The lowest number of spectral components was generated by PD occurring on the long rod insulator made of porcelain.

Figures 24–26 present a comparison showing the averaged values of fitting coefficients of regression models M1 and M2 to empirical data: SSE (4), R^2 (6), and RMSE (5).

FIGURE 23: (a) Comparison of SSE coefficient values obtained in model M1 for all the recorded signals. (b) Dependence of the intensity of individual wavelengths as a function of PD generation voltage.

FIGURE 24: Comparison of the averaged values of the SSE coefficient obtained by the regression of models M1 and M2 for all the tested dielectrics and insulation systems.

FIGURE 25: Comparison of the averaged values of the R^2 coefficient obtained by the regression of models M1 and M2 for all the tested dielectrics and insulation systems.

The comparative analysis of models M1 and M2 fitting coefficients, which describe the dependency of intensity of emission spectra as a function of wavelength, may serve as a justification for the following statements:

- (i) The values of coefficients SSE and RMSE are similar in both models. The tested insulation system exhibited high values of these parameters, which proves that these models are not optimal for prediction applications.
- (ii) Regarding the comparison of determination coefficient values, R^2 , obtained for the M1 model, we may conclude that good fitting was observed only

in selected insulation models, including porcelain cylinder at distances of 3, 7, and 11 cm and in LS-type insulator. The rest of values indicate rather moderate and poor fitting. In case of model M2, all the fitting coefficient values had results of R^2 below 0.7, except for the WPK3 system, which also indicates poor fitting of the model to empirical data.

- (iii) It should be noted that all of the conclusions mentioned above apply to values that have been averaged “twice”; that is, firstly, the results from five measurements were averaged and then a second averaging was conducted for all PD generation voltages. Therefore, it seems more reasonable to take into consideration

FIGURE 26: Comparison of the averaged values of the RMSE coefficient obtained by the regression of models M1 and M2 for all the tested dielectrics and insulation systems.

the results obtained for values averaged just “once” for individual voltages, which are depicted in Figures 5, 6, 8, 9(a), 12, 13, 15, 16(a), 19, 20, 22, and 23(a).

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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