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Quantitative Analysis of Surface Partial Discharges through Radio Frequency and Ultraviolet Signal Measurements

Michał Kozioł [1,*], Łukasz Nagi [1], Tomasz Boczar [1,*] and Zbigniew Nadolny [2]

1 Faculty of Electrical Engineering, Automatic Control and Informatics, Opole University of Technology, 45-758 Opole, Poland
2 Institute of Electrical Power Engineering, Poznan University of Technology, 60-965 Poznań, Poland
* Correspondence: m.koziol@po.edu.pl (M.K.); t.boczar@po.edu.pl (T.B.)

Abstract: In high voltage insulation systems, dielectric materials may be exposed to partial discharges (PD), which can lead to equipment failures and safety hazards. Therefore, it is crucial to detect and characterize PD activity on the surface of insulation systems. Techniques such as radio frequency signal analysis and ultraviolet radiation emission detection are commonly used for this purpose. In this research study, an analysis was conducted on the signals emitted by surface PD in the radio frequency and ultraviolet radiation emission ranges. The goal was to indicate possible directions for further basic research aimed at building a knowledge base and improving measurement methods. The analysis confirmed that radio frequency and ultraviolet signal analysis can provide important information about the activity and location of PD on the surface, including the intensity and nature of PD. The experimental investigation presented in this paper provides valuable insights into the potential for using radio frequency and ultraviolet signals to enhance diagnostic techniques for monitoring the condition of insulation systems in high-voltage equipment.

Keywords: surface partial discharges; radio frequency analysis; ultraviolet signals; camera UV

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1. Introduction

The insulation systems of power equipment are typically made of dielectric materials and are often located in areas with gas or liquid dielectrics. However, the boundary between these dielectrics can create a plane that generates surface electrical discharges, also known as surface partial discharges, sometimes early corona discharges [1]. These discharges can contribute to equipment failure and, in extreme cases, lead to the destabilization of the power grid and cause power outages. The maintenance of power transformers' reliability requires regular monitoring and assessments of their condition, and the diagnosis of any faults [2].

Surface partial discharges usually occur at alternating voltage and initially take the form of luminous discharges, emitting low-intensity optical radiation. The formation and development of these discharges depend mainly on the technical condition of the solid dielectric and the applied supply voltage of the system. The presence of a dirt layer on the surface of the dielectric can also provide a surface with reduced electrical strength, which is conducive to the development of surface partial discharges. Examples of systems that are exposed to the formation and development of such discharges include insulation systems of power machines and devices, and high-voltage cable heads.

Partial discharges emit signals that are commonly used to test high-voltage insulation systems. These discharges are accompanied by the emission of acoustic and electromagnetic waves in various spectral ranges, as well as the formation of various types of chemical compounds [3–7]. Based on these emissions, various measurement methods have been developed and implemented to detect and localize the source of partial discharges during the operation of the device (online) and during standstill of the device (offline). These methods are also used to assess the technical condition of insulation in high-voltage power devices [8–12].

The analysis of radio signals emitted by partial discharges (PD) is a non-invasive technique for detecting PD activity in electrical insulation systems. It works by measuring the electromagnetic waves generated by PD and propagating through the insulation material. This technique has the advantage of being able to detect PD activity without the need to physically access the insulation system, which can be particularly useful for high-voltage equipment in operation. The signals captured by the probe can provide information about the type and location of the PD, as well as the severity of the insulation degradation. For example, the amplitude and frequency of the signals can be used to estimate the energy of the discharge and the distance from the PD source to the probe, respectively. In addition, the phase angle between the signals measured by different probes can be used to localize the PD source in three dimensions, which is an important advantage of this method.

However, radio signal analysis has its limitations. It requires careful calibration of the measurement system to ensure accurate registration and interpretation of signals. External electromagnetic interference can affect the measurement of radio signals, causing distortion of PD signals and reducing measurement sensitivity. Therefore, it is important to carefully choose the measurement location and apply appropriate shielding and filtering techniques to minimize the impact of external interference.

One commonly used method for detecting partial discharges is the analysis of radio signals, particularly in the VHF and UHF ranges [13,14]. This technique involves measuring the electromagnetic waves emitted by partial discharges in the insulation system [15]. Monitoring of partial discharges (PD) using ultra-high frequency (UHF) is gaining popularity due to its advantages over electrical methods. One of these advantages is the possibility of three-dimensional localization of the PD source [16]. The amplitude and frequency of the signals can provide information on the type and location of the partial discharge [17]. However, the influence of winding construction on signal propagation is poorly understood [18]. In one study [19], a compact, wideband, two-arm Archimedean slotted spiral with coplanar waveguide feed was presented for PD detection. Another method for detecting partial discharges is through the analysis of ultraviolet (UV) radiation. This technique involves using a UV camera to detect the optical emissions generated by partial discharges [20]. In some studies, two methods based on optical and electrical methods are used [8], indicating that there are many combinations of methods.

The UHF method is characterized by high resistance to external interference and a good level of sensitivity of measurement devices. It is commonly used in the diagnosis of paper-oil insulation systems of power transformers or gas-insulated switchgear. These signals are less affected by external interference and provide a more accurate indication of the location and severity of the partial discharge. Due to the complex characteristics of PD signals in the UHF range, the choice of an appropriate antenna for use becomes the main problem in PD diagnostics. An interesting solution is to print an antenna with parameters that meet the requirements of a given measurement [17].

The ultra-high frequency (UHF) method for detecting and analyzing partial discharge (PD) phenomena is also used in oil insulation. One study presented the results of research conducted under laboratory conditions on three model sources of PD: the blade-to-blade system, the surface system, and the multi-blade-plate system [21]. A detailed analysis of the measurement results was described, from which methods for identifying selected forms of PD were proposed.

Analysis of UV radiation emitted by partial discharges is most commonly conducted using UV cameras, which visualize them in real-time images of the tested equipment. This image can be analyzed to determine the location and severity of partial discharge present.

One paper [22] described an exemplary method of locating partial discharges using a partial discharge camera. This method was utilized by the authors, among other things, to investigate medium voltage switchgear and cable joints.

Another paper [23] presented the results of optical signals recorded by a UV camera, emitted by surface partial discharges occurring on various insulator models. The study specifically focused on the impact of the camera's relative sensitivity value on the number of surface partial discharge counts.

A method for identifying the intensity of discharges based on ultraviolet sensors was also developed [24], which was combined with a time-frequency method, texture analysis, and a support vector machine (SVM) classifier to classify the intensity of partial discharges for ceramic insulators. The visible images and root mean square values of leakage currents detected simultaneously are used to classify UV signals into different types of discharges. The authors demonstrated that the integration of frequency and amplitude of UV pulses is minimal in the case of corona discharges and greater in the case of arc discharges.

The aim of the research presented in this paper was to record and analyze radio signals emitted in the VHF and UHF frequency ranges, as well as optical radiation in the ultraviolet range, generated by surface partial discharges (SPDs). The experimental study was conducted on electrode systems that modeled surface discharges on solid dielectrics in laboratory conditions. The primary focus of the study in analyzing radio signals was on their frequency spectra and their characteristic components, which were recorded for four different generation sources. The study on optical radiation involved the quantitative analysis of phenomena accompanying surface partial discharges, which were recorded in the ultraviolet range. The novelty of this research lies in its contribution to the development of characteristic patterns and indicators emitted by surface partial discharge signals in the radio wave and optical radiation range. These studies represent the first stage of planned research aimed at developing characteristic patterns and indicators emitted by surface partial discharge signals in the radio wave and optical radiation range.

2. Materials and Methods

2.1. Sample Preparation

A laboratory experiment was conducted to model surface partial discharges with different sources of generation. Four types of electrodes were used in the experiment: three aluminum electrodes with diameters of 6.0 cm, 8.0 cm, and 12.0 cm, and a height of 7.0 cm, as well as a pointed electrode. The system used a solid dielectric made of a glass plate with a thickness of 2 cm. The experimental studies used a solid dielectric in the form of a glass plate due to its structure, which does not actively participate in the formation and development of surface partial discharges.

The high voltage source used was a TP110 test transformer, which can generate a maximum secondary voltage of 110 kV. An alternating voltage (AC) with a frequency of 50 Hz and adjustable voltage level was applied to the aluminum electrode. Surface discharges were generated at the point of contact between the high voltage electrode, the solid dielectric, and air, also known as the triple point. The general schematic of the measurement system is shown in Figure 1.

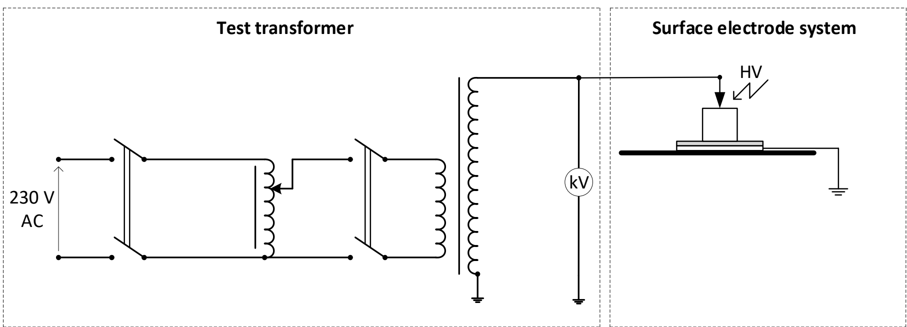


Figure 1. Schematic of the measurement system.

The use of electrodes with different dimensions enabled the modeling of surface partial discharge sources with different generation areas. The choice of a needle electrode as one of the electrodes allowed for the modeling of a point source of discharge generation. On the other hand, the use of a cylindrical electrode enabled the creation of different lengths of edges in contact with a solid dielectric. In the study, three different lengths were used, measuring 18.84 cm, 25.12 cm, and 37.68 cm, respectively. By using these different electrode configurations, it was possible to investigate the influence of electrode geometry on the characteristics of the generated surface partial discharge signals.

2.2. Experimental Setup and Measurement

An experimental analysis was conducted to investigate the signals emitted in the VHF and UHF bands. The PDS100 portable analyzer was used for this purpose, which records signals in the radio frequency range (the device's measuring range is 50 MHz–1000 MHz). The device scans radio frequencies, which is a non-invasive method and allows measurements to be carried out during the operation of the tested device. It enables the recording and analysis of the amplitude of electromagnetic wave signals emitted by partial discharges both in the time and frequency domains. This measurement is a relative value and only indicates the presence of energy, which is expressed in dB. A broadband Watson W-889 telescopic antenna with a length of 310 mm was used to receive radio signals, which operates in the frequency range from 25 MHz to 1900 MHz. The basic parameters of the PDS100 analyzer are presented in Table 1.

Table 1. Basic parameters of PDS100 analyzer [25].

Parameter	Range
Range of measurement	50–1000 MHz
Resolution	120 kHz/6 MHz
Display unit	MHz/dBm or MHz/dBμV
Frequency sweep method	Continuous, Counted, and Single Mode
Detection modes	Peak, Average, and Separate Peak and Average Mode (SPAM)

In addition, measurements were carried out using an Ofil DayCor Superb camera with detectors that allow for the simultaneous recording of images of partial discharges in two bands: UV (in the range of 250 nm to 280 nm) and visible light. The measurement principle is based on counting the number of detected partial discharges by a UV-sensitive matrix, from which the number of active photons in the UV range can be obtained. The result is combined with the real image of the tested object obtained using a CCD matrix sensitive to visible light. This enables an accurate image of the partial discharge intensity on the insulation elements seen in visible light to be obtained, and has a sensitivity of 1 pC for detecting phenomena in the UV range from a distance of 10 m [26].

This camera can detect and locate the occurrence of a discharge, and allows for the relative quantitative measurement of partial discharge activity. It is also equipped with a noise reduction algorithm that eliminates single, sporadic UV signals. Measurement results are presented directly on a color LCD display and saved as images on an SD memory card. An overall view of the measurement station is presented in Figure 2.

During the experiment, measuring devices were positioned around the tested object at a distance of 4.5 m. The measurements were conducted under constant environmental conditions, including an air temperature of 19 °C, humidity of 51%, and pressure of 997 hPa. As the measurements were experimental in nature, the effect of environmental conditions on the phenomena under study was not specifically analyzed.

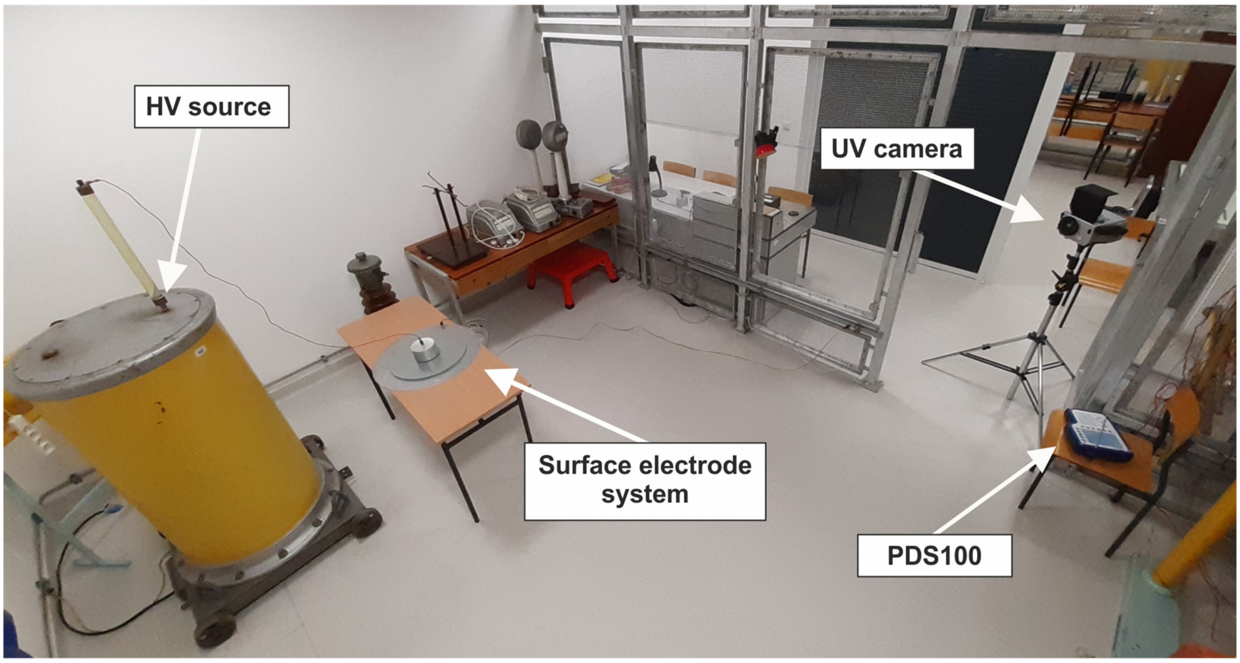


Figure 2. View of the measuring station.

In order to conduct a thorough analysis of signals within the radio frequency (RF) band, it is imperative to first characterize the environmental background noise. To achieve this, a 10-min measurement of background noise was performed in order to isolate any frequency components that occur continuously and could potentially affect the measurement of signals emitted by surface partial discharges. The repetitive background noise spectrum is presented in Figure 3.

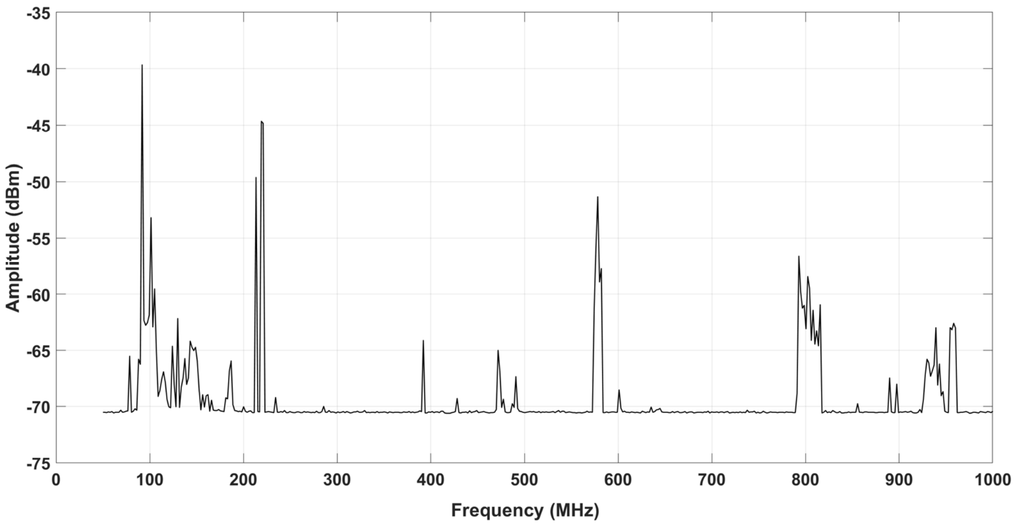


Figure 3. Background noise spectrum.

During the analysis of the recorded background noise, various interferences were identified, mainly within the frequency ranges associated with radio stations, terrestrial digital television, and LTE (4G) technology. These interferences were found to have a significant impact on the quality and accuracy of the measurements of the desired signals.

The measurements were carried out on all four systems using supply voltages that ranged from 30 kV to 80 kV, with a 10 kV increment between each voltage level. The purpose of using varying supply voltages was to model surface partial discharges at different intensities and the resulting emission of both radio signals and ultraviolet (UV) signals. The experiments were conducted under controlled laboratory conditions, with the systems being tested individually and sequentially to ensure accurate and reliable results.

3. Results and Discussion

3.1. Results of Radio Frequency Signal Measurements

To ensure accurate measurements, it was necessary to isolate the frequency components of the background noise that occur continuously and could have a significant impact on the measurement of the signals emitted by the surface partial discharges. To achieve this, a 10-min background noise measurement was conducted prior to the measurement of the signals emitted by the discharges. The repetitive background noise spectrum was then analyzed to identify and isolate the frequency components that could affect the measurement of the signals emitted by the surface partial discharges. In Figure 4, example spectra of recorded signals and background noise spectra are presented.

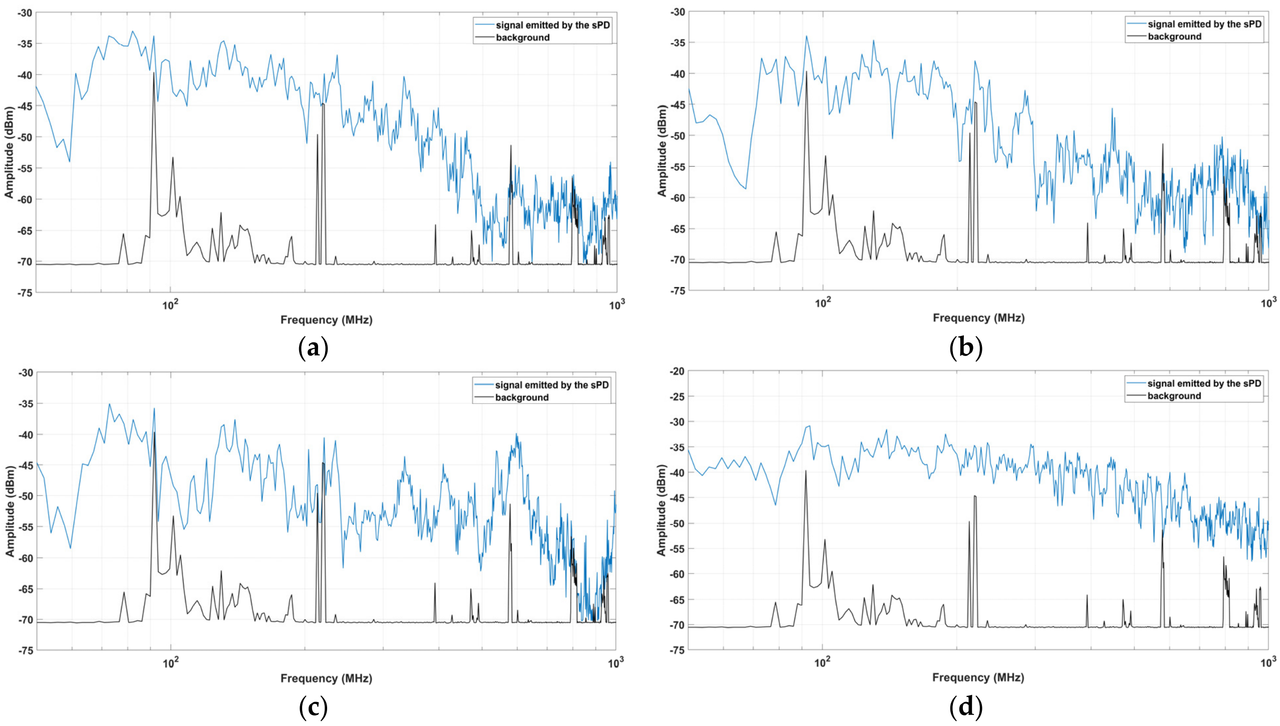


Figure 4. Radio frequency spectra emitted by surface partial discharges recorded for: systems using a cylindrical electrode with a diameter of (**a**) 6 cm, (**b**) 8 cm, and (**c**) 12 cm; and (**d**) a system using a needle electrode.

In the next step of the signal processing, the recorded signal was filtered to remove background noise and then subjected to a nonlinear approximation (model) for the interpretation and analysis of the signals. Based on the obtained results, frequency areas were identified in which signals emitted by surface partial discharges were characterized by the highest intensity (amplitude). The results, presented in Figures 5–10, shows the amplitude spectra for all electrode configurations examined, powered by a voltage from 30 kV to 80 kV. The spectra exhibit distinct peaks, indicating the presence of dominant frequency components.

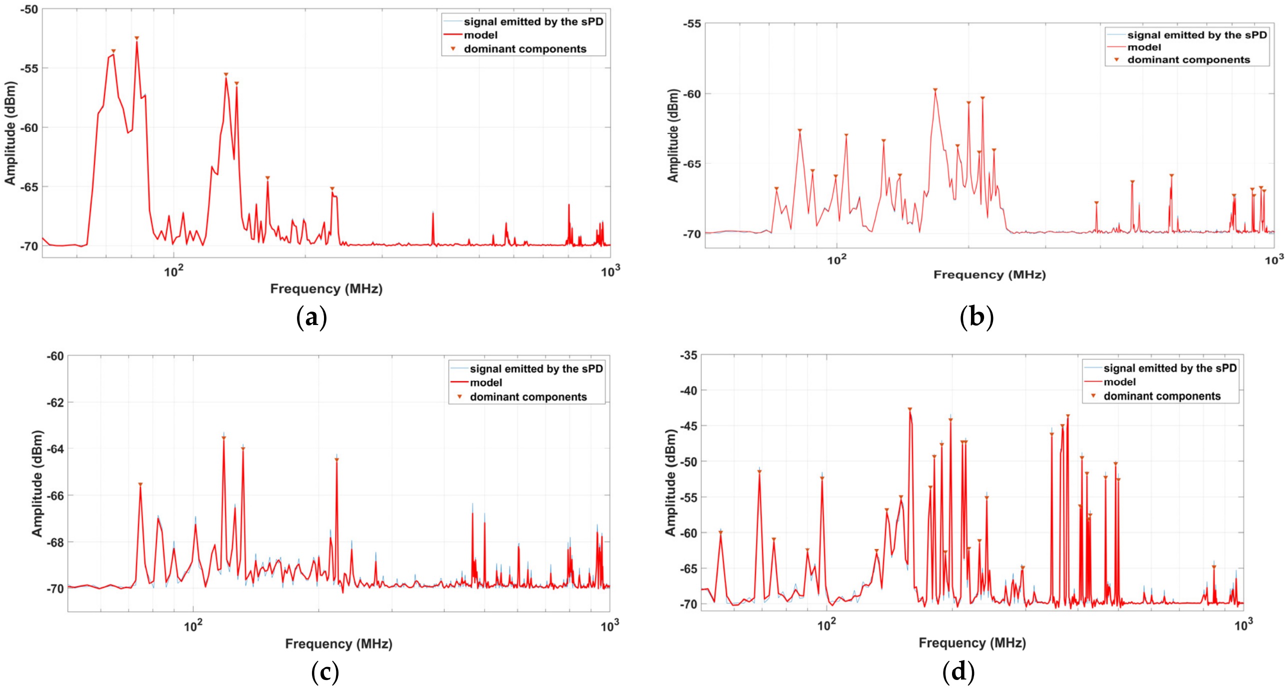


Figure 5. Frequency components of the signals emitted by surface partial discharges generated at a supply voltage of 30 kV: systems using a cylindrical electrode with a diameter of (**a**) 6 cm, (**b**) 8 cm, and (**c**) 12 cm; and (**d**) a system using a needle electrode.

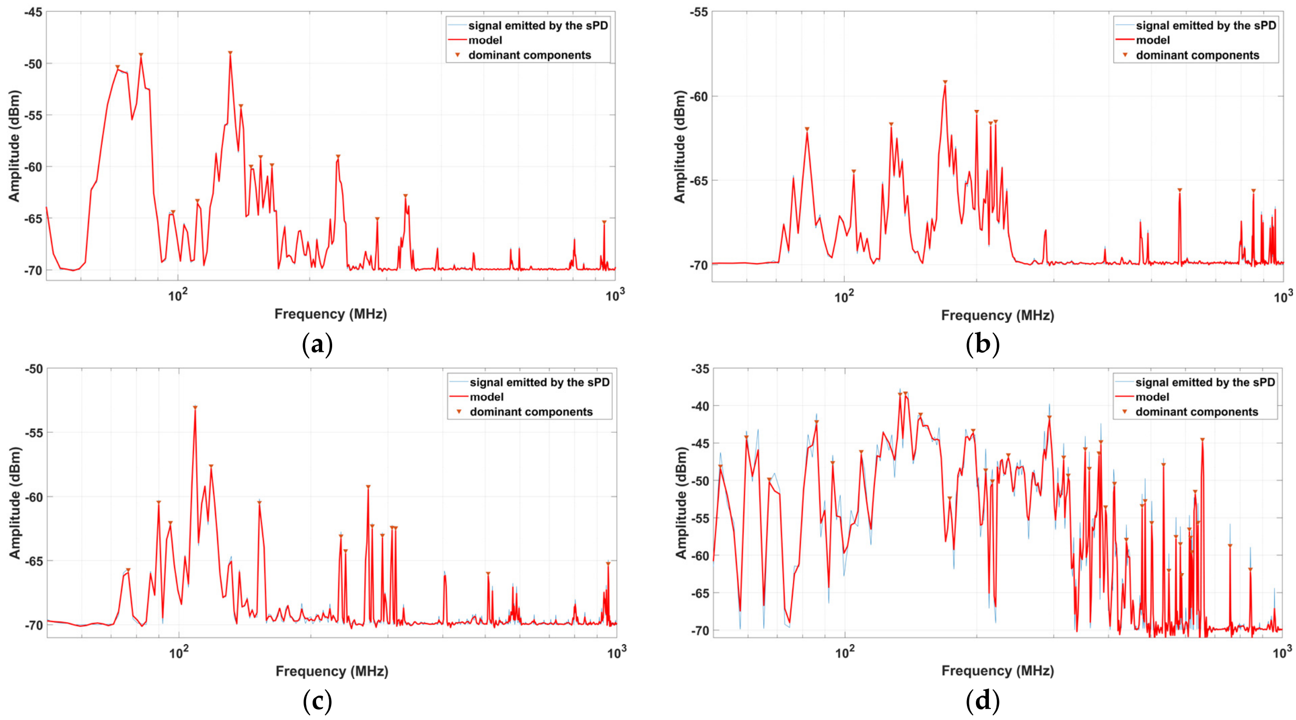


Figure 6. Frequency components of the signals emitted by surface partial discharges generated at a supply voltage of 40 kV: systems using a cylindrical electrode with a diameter of (**a**) 6 cm, (**b**) 8 cm, and (**c**) 12 cm; and (**d**) a system using a needle electrode.

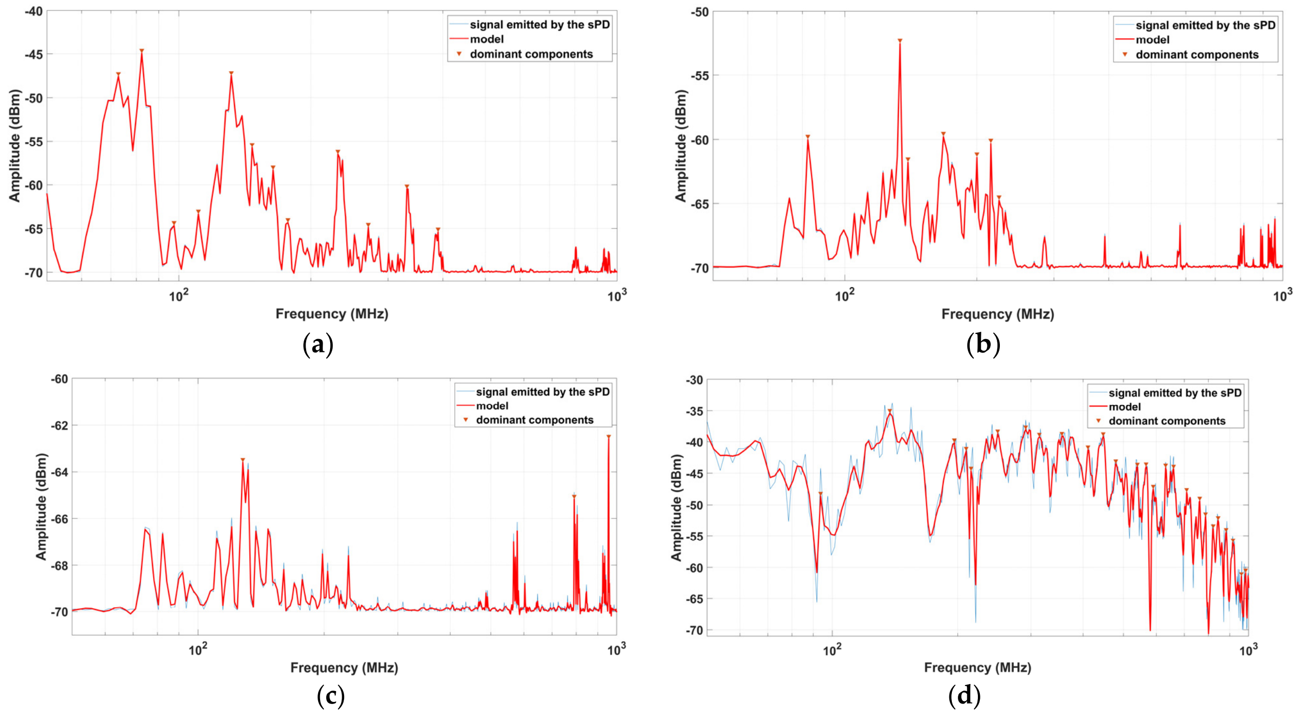


Figure 7. Frequency components of the signals emitted by surface partial discharges generated at a supply voltage of 50 kV: systems using a cylindrical electrode with a diameter of (**a**) 6 cm, (**b**) 8 cm, and (**c**) 12 cm; and (**d**) a system using a needle electrode.

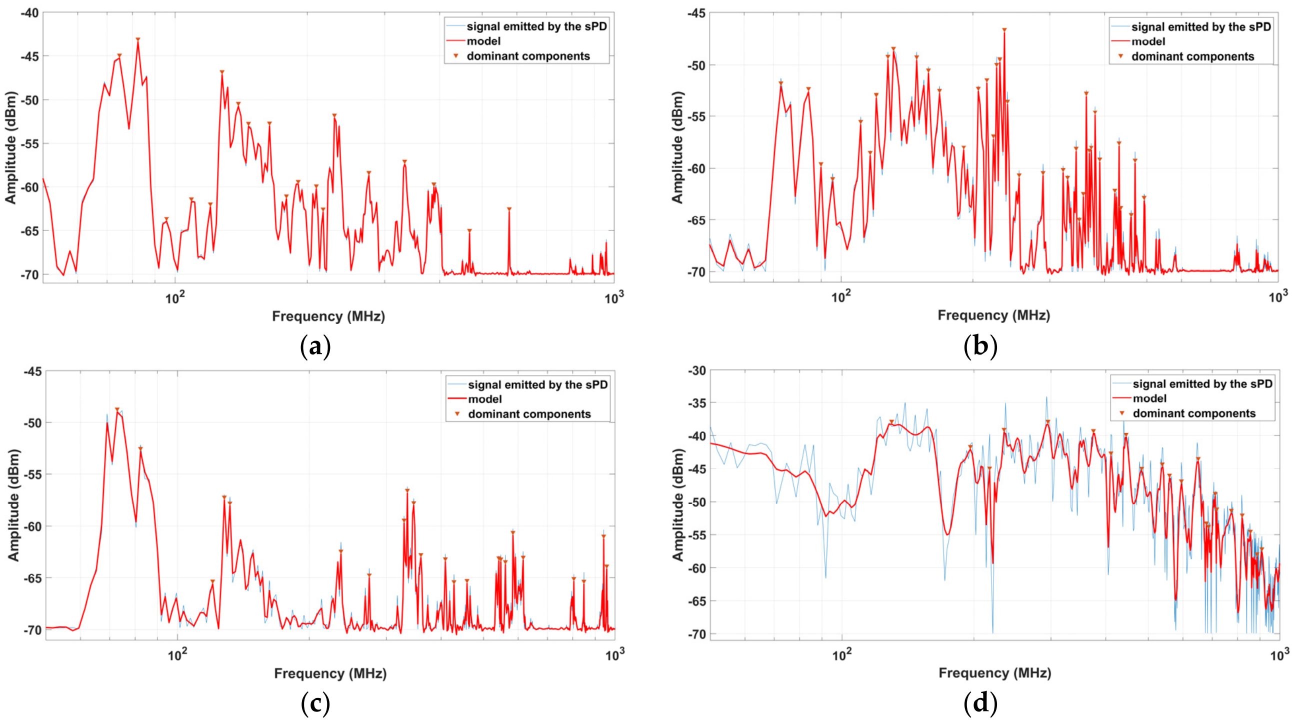


Figure 8. Frequency components of the signals emitted by surface partial discharges generated at a supply voltage of 60 kV: systems using a cylindrical electrode with a diameter of (**a**) 6 cm, (**b**) 8 cm, and (**c**) 12 cm; and (**d**) a system using a needle electrode.

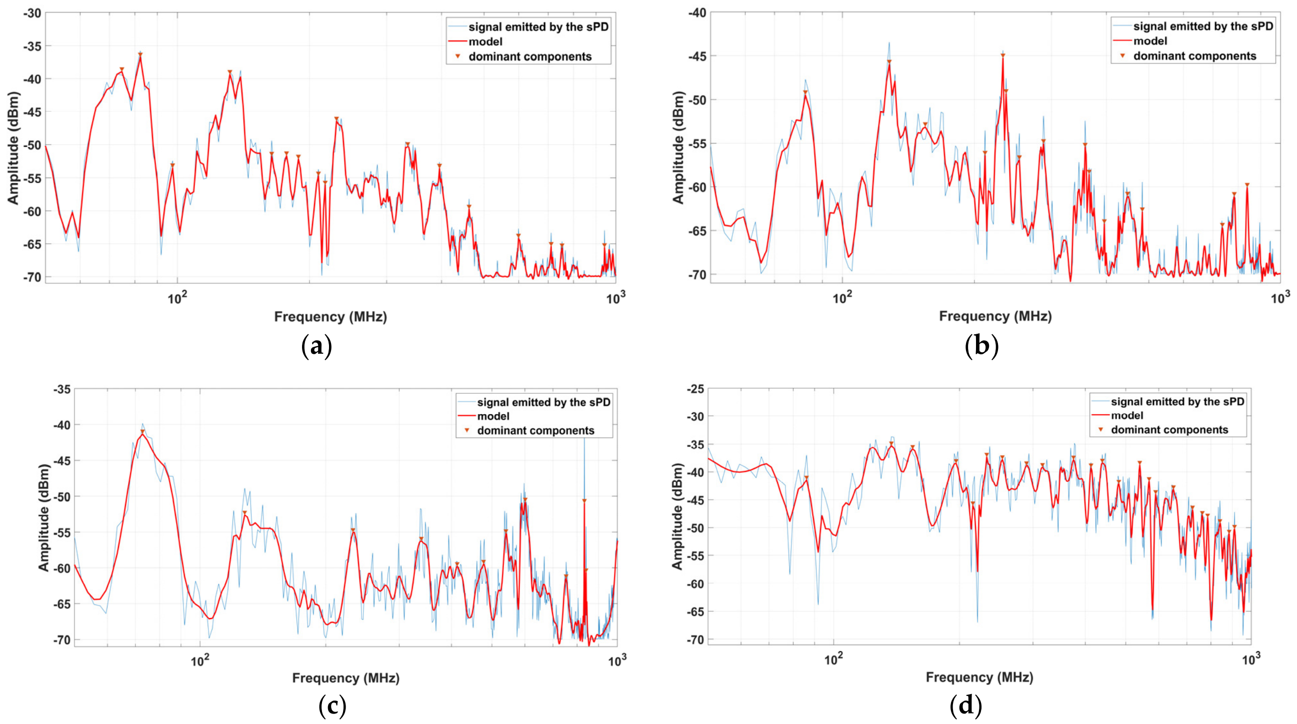


Figure 9. Frequency components of the signals emitted by surface partial discharges generated at a supply voltage of 70 kV: systems using a cylindrical electrode with a diameter of (**a**) 6 cm, (**b**) 8 cm, and (**c**) 12 cm; and (**d**) a system using a needle electrode.

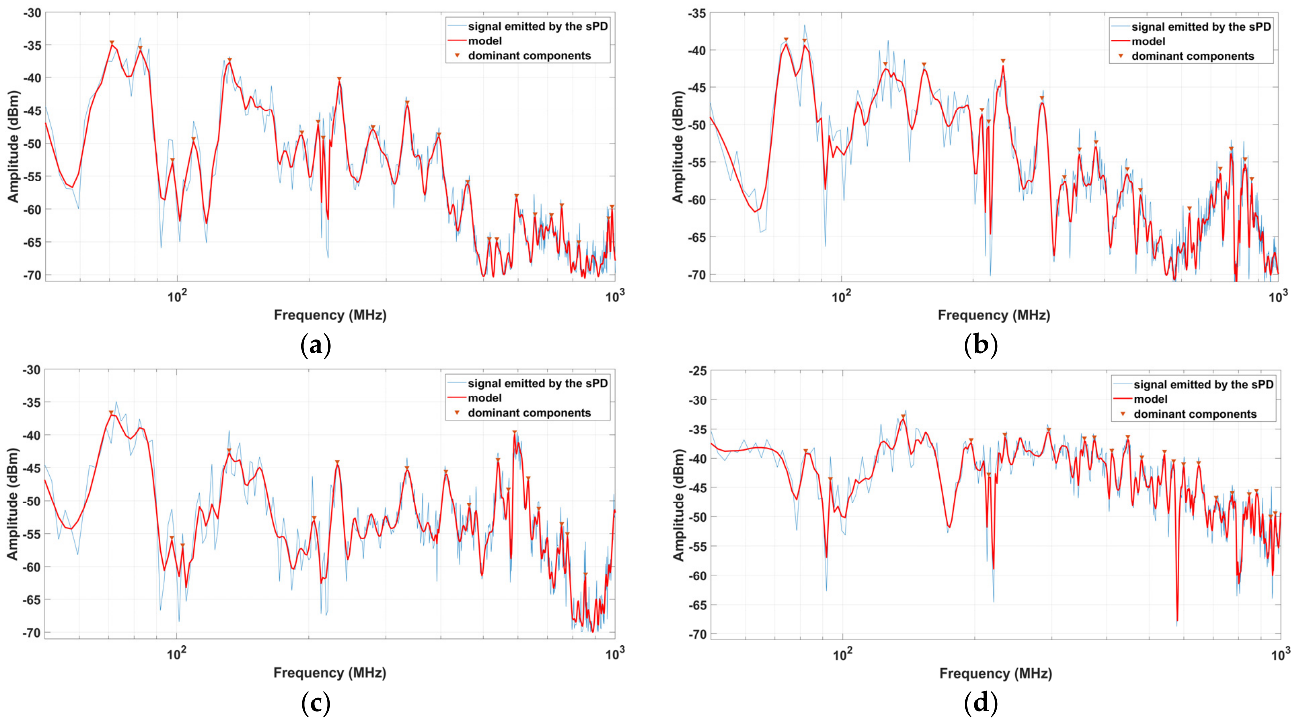


Figure 10. Frequency components of the signals emitted by surface partial discharges generated at a supply voltage of 80 kV: systems using a cylindrical electrode with a diameter of (**a**) 6 cm, (**b**) 8 cm, and (**c**) 12 cm; and (**d**) a system using a needle electrode.

By analyzing the components of the radio frequencies emitted by surface partial discharges (Figures 5–10), it was possible to identify certain characteristic frequency bands within the very high frequency (VHF) and ultra-high frequency (UHF) ranges (Table 2). Spectra were analyzed for all electrode configurations, and based on this, dominant center frequencies were determined that represent the bands with the highest amplitude of radio waves emitted by surface partial discharges. The dominant center frequencies were determined based on the amplitude of radio waves emitted by partial discharges. These frequencies represent the bands with the highest activity of partial discharges in terms of emitted radio waves. The study found that in the VHF band (50 MHz–300 MHz), two characteristic frequencies were consistently present in all analyzed spectra: 74.7 MHz and 120.3 MHz (Table 2). In the UHF band (300 MHz–1 GHz), a frequency of 336.9 MHz showed repeatability (Table 2).

Table 2. Characteristic components of a frequency band.

Range	Frequency Band (MHz)				
			Electrode diameter 6 cm		
VHF	**74.7**	**120.3**	135.5	228.6	279.9
UHF	**336.9**	460.4	-	656.1	-
			Electrode diameter 8 cm		
VHF	**74.7**	**120.3**	133.6	222.9	285.6
UHF	**336.9**	445.2	540.2	682.7	-
			Electrode diameter 12 cm		
VHF	**74.7**	**120.3**	131.7	232.4	298.3
UHF	**336.9**	412.9	538.3	635.2	-
			Needle electrode		
VHF	**74.7**	**120.3**	137.4	226.7	295.1
UHF	352.1	443.3	536.4	648.5	-

It’s worth noting that in the analyzed frequency range, the VHF band was the most active in terms of surface partial discharge activity. This confirms that surface partial discharges in the VHF band show more activity than in the UHF band up to 1 GHz.

The identification of characteristic frequency bands of radio signals that appear during surface discharges can be valuable in further recognizing the nature of these phenomena. By determining the characteristic and repeatable frequency bands, the patterns of emitted radio signals from surface discharges can be developed. These patterns can be used as a basis for creating a knowledge base that will be useful for high-voltage diagnostics. For example, analyzing radio signals can help detect abnormalities in high-voltage systems, which will enable the prompt implementation of appropriate corrective actions.

The results of these studies emphasize the importance of identifying and eliminating interferences in order to obtain accurate and repeatable measurements in various applications. The need for accurate signal measurement is crucial in many fields, and understanding the nature and sources of interferences, as well as developing effective methods to minimize their effects, is of great importance in obtaining reliable and accurate measurements in practical conditions.

3.2. Results of UV Camera Measurements

Figure 11 presents the results of measurements recorded using a UV camera. These measurements were carried out on all four systems with supply voltages ranging from 30 kV to 80 kV, and were performed simultaneously with radio signal measurements. The measurements consisted of counting the number of photons emitted by partial surface discharges in the ultraviolet range, and displaying the average value over a 5-s counting time. The UV camera was used for the visualization of surface discharges and the measurements were used to determine the quantitative intensity of events emission in the UV range generated during partial surface discharges.

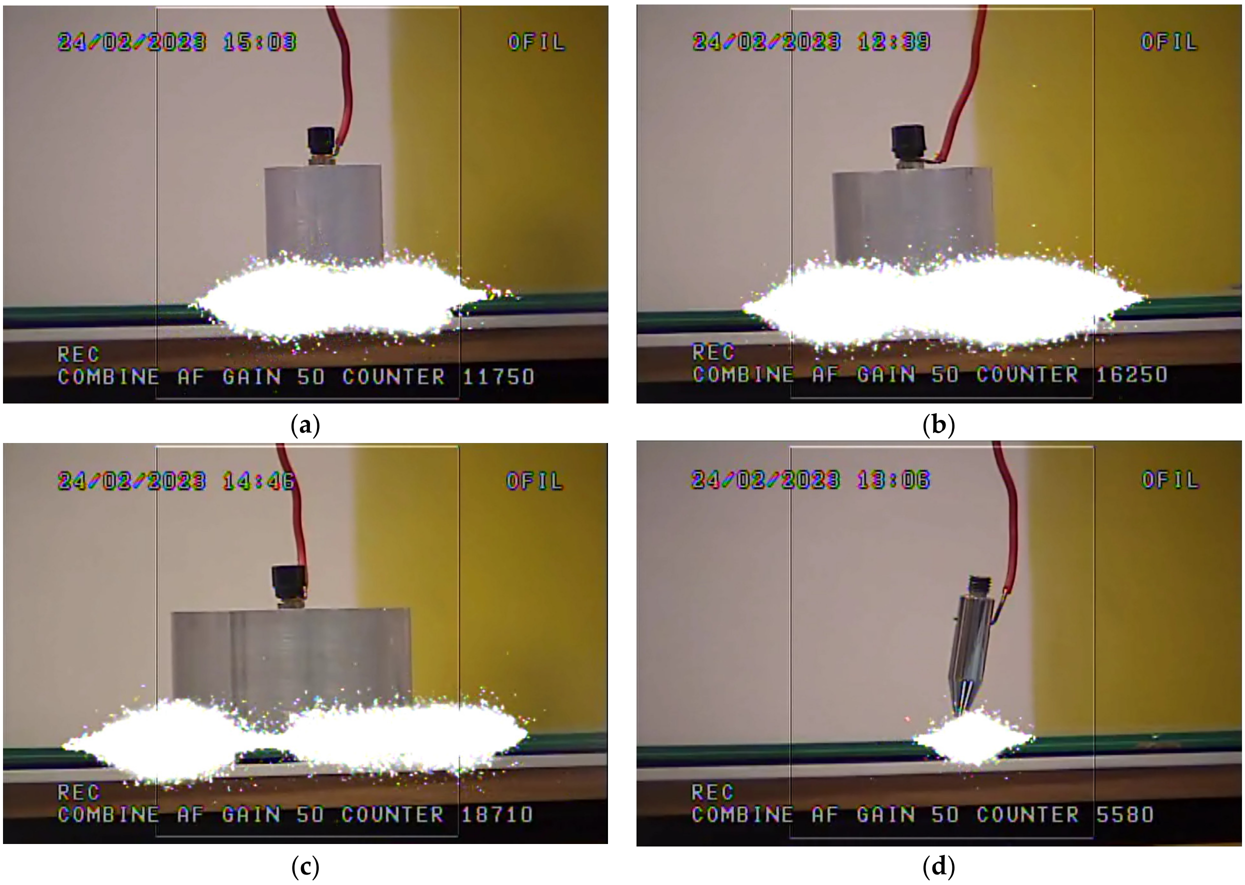
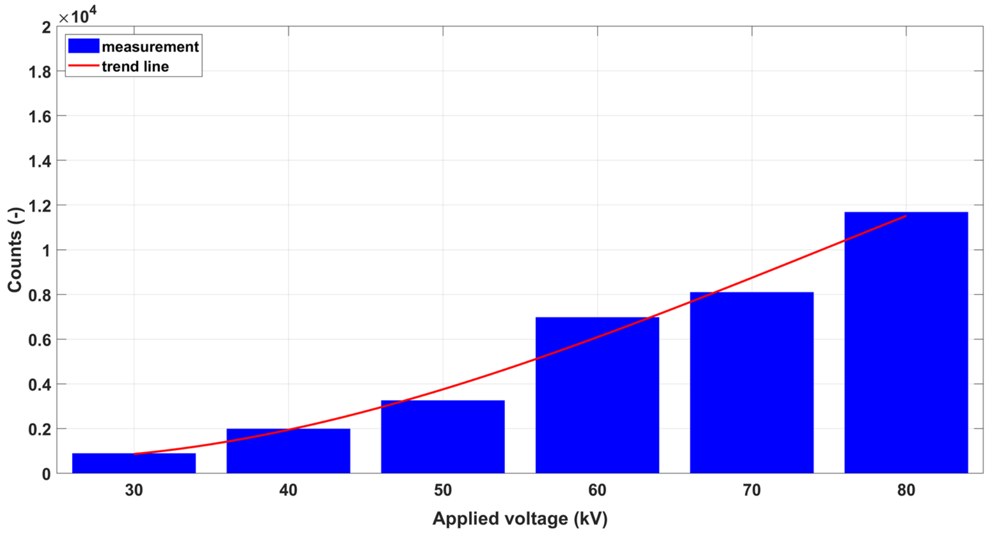


Figure 11. Example images from the UV camera: systems using a cylindrical electrode with a diameter of (**a**) 6 cm, (**b**) 8 cm, and (**c**) 12 cm; and (**d**) a system using a needle electrode.

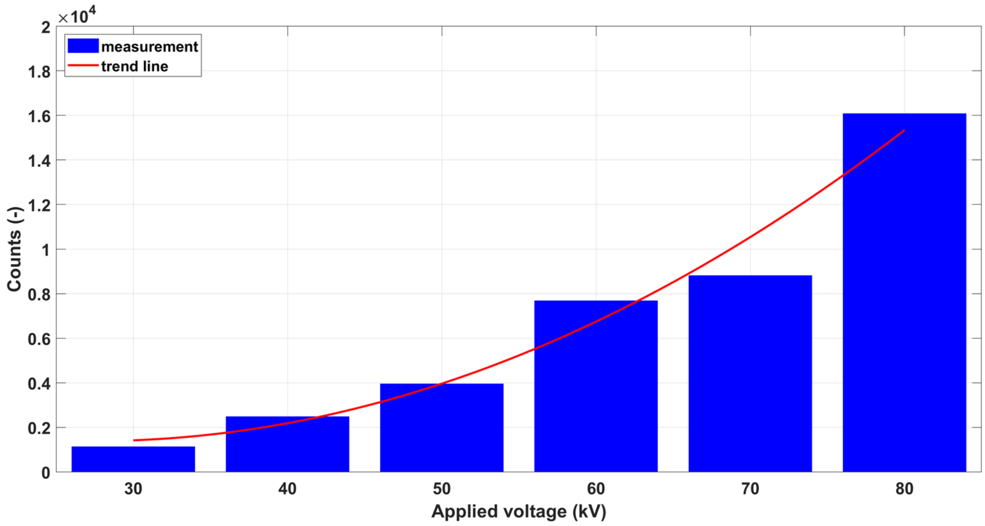
These measurements provide information on the location and intensity of partial discharges on the surface of solid dielectrics. The images shown in Figure 11 illustrate examples of registered measurements of surface partial discharges for a voltage of 80 kV. The white markers depict the intensity of the registered discharges, while their numerical interpretation is shown at the bottom of each image. Depending on the type of electrode system used to model surface partial discharges, different graphical interpretations of intensity can be observed. The electrode system with the largest base—the longest edge in contact with the solid dielectric (Figure 11c)—is characterized by the highest intensity of surface partial discharges, while the smallest intensity occurred in the case of a pointed electrode with a point contact.

During the study, a clear correlation was observed between the voltage applied to the electrode and the number of emitted events in the UV range, as shown in Figure 12. As the voltage increased, the number of partial discharges in the insulating material also increased. This trend was expected because higher voltages can cause higher electric field strength, which can activate partial discharges in areas where the insulation is damaged. Over time, these partial discharges can cause further insulation degradation and ultimately lead to its complete destruction. Observing this trend emphasizes the importance of monitoring and controlling the intensity of surface partial discharges to prevent damage to electrical equipment and ensure their safe and reliable operation.

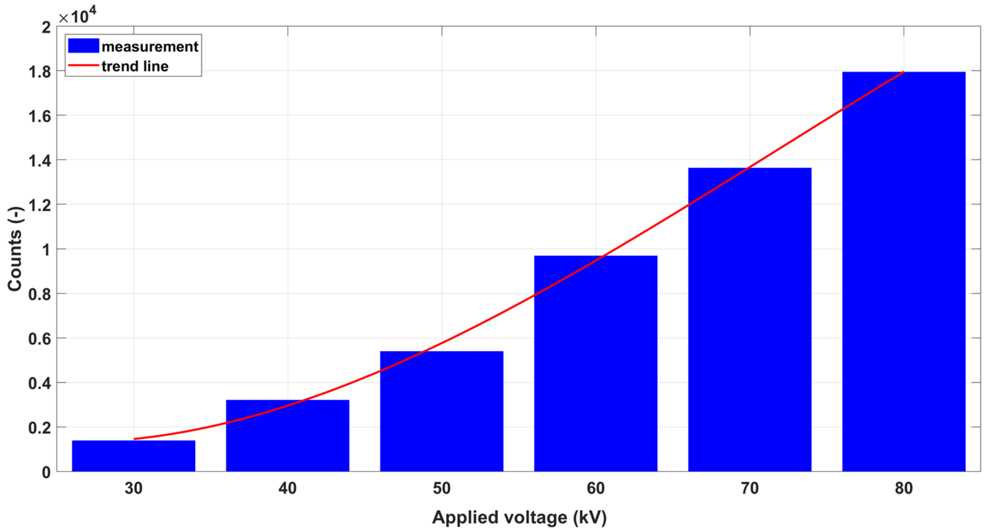
An important aspect of the measurement was the ability of the UV camera to not only collect quantitative data but to also provide spatial information on the location and development of surface partial discharge sources. This information is critical in diagnosing electrical power equipment, as it can help identify areas of high partial discharge activity and potential sources of equipment failure.



(a)

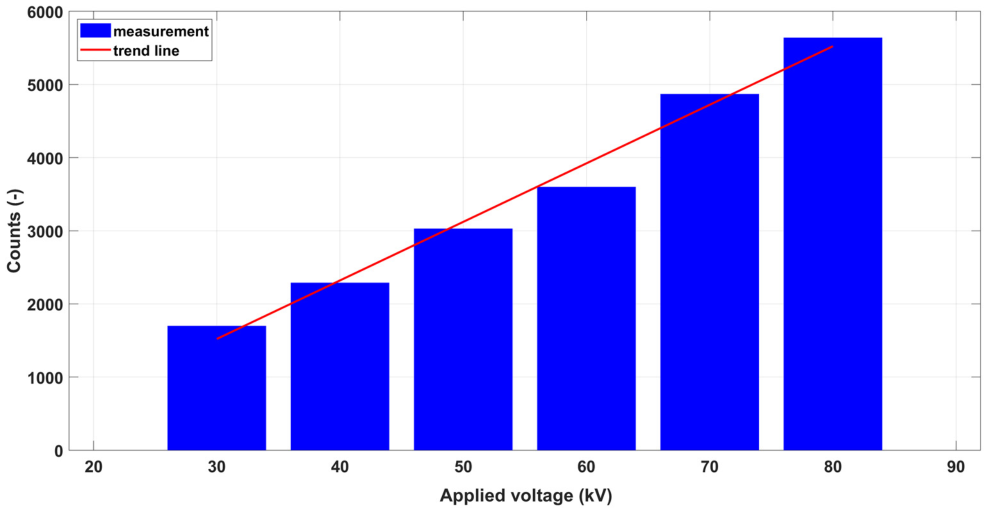


(b)



(c)

Figure 12. *Cont.*



(**d**)

Figure 12. Measurements of surface partial discharges recorded with a UV camera: systems using a cylindrical electrode with a diameter of (**a**) 6 cm, (**b**) 8 cm, and (**c**) 12 cm; and (**d**) a system using a needle electrode.

Although there are no standard interpretations for counting results, the data obtained from the UV camera measurement can still be very useful for comparing the intensity of surface partial discharges and for observing trends in the defects that cause them. This analysis can provide insights into the temporal and spatial patterns of surface partial discharge activity and can help identify underlying factors that may be contributing to the development and propagation of these events.

In addition to the above, it is important to note that the use of UV cameras can also be helpful in the development of predictive maintenance strategies for electrical power equipment. By detecting and analyzing surface partial discharges early on, potential equipment failures can be identified and corrected before they escalate into more serious problems. This can ultimately lead to increased safety, improved reliability, and reduced downtime in electrical power systems. Additionally, the use of UV cameras can be a valuable tool for research and development, as it allows for the observation and analysis of surface partial discharge behavior in a controlled laboratory environment. This can lead to a better understanding of the underlying physics of the phenomena, which can be applied to the development of improved electrical insulation materials and different types of system solutions.

4. Conclusions

The paper presents the findings of an experimental investigation focused on analyzing the radio frequency (RF) and ultraviolet (UV) signals emitted by surface partial discharges. The study revealed distinct RF characteristics in the VHF and UHF frequency bands, which could serve as valuable features for developing and enhancing diagnostic techniques based on radio signal analysis. Specifically, such techniques would be valuable for monitoring the condition of insulation systems in high-voltage transformers, switchgears, and cables, and could help prevent equipment failure or damage.

To develop reliable diagnostic algorithms and models, further research is needed to identify key features such as peak amplitudes, rise times, and spectral content. Signal processing techniques can be applied to extract these features from the measured RF and UV signals. Real-time monitoring systems based on wireless sensor networks and machine learning algorithms can be developed to classify different types of partial discharges and provide early warnings of potential equipment failures.

Further studies should also consider the technical condition of the solid dielectric surface, particularly its level of contamination. The presence of a semi-conductive contamination layer on the solid dielectric surface promotes the development of surface partial discharges. Therefore, it is essential to ensure that the solid dielectric surface is free from any contaminations that may affect its insulating properties. Additionally, investigating the effect of different types of contamination on the occurrence and characteristics of partial discharges can provide valuable insights into the behavior of insulation materials in practical applications.

Regarding the UV camera measurements, methodological validation is necessary to overcome limitations in the quantitative and qualitative analysis of the data. In particular, comparative measurements with the conventional electrical method can help validate the sensitivity and specificity of the UV camera for detecting partial discharges and establish a calibration curve for the camera. This can enhance the accuracy, reliability, and reproducibility of the count values obtained from the UV camera measurements, and enable more standardized and consistent analysis of the data.

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References

1. Javandel, V.; Akbari, A.; Ardebili, M.; Werle, P. Simulation of Negative and Positive Corona Discharges in Air for Investigation of Electromagnetic Waves Propagation. *IEEE Trans. Plasma Sci.* **2022**, *50*, 3169–3177. [CrossRef]
2. Jin, L.; Kim, D.; Abu-Siada, A. State-of-the-art review on asset management methodologies for oil-immersed power transformers. *Electr. Power Syst. Res.* **2023**, *218*, 109194. [CrossRef]
3. Klein, L.; Seidl, D.; Fulneček, J.; Prokop, L.; Mišák, S.; Dvorský, J. Antenna contactless partial discharges detection in covered conductors using ensemble stacking neural networks. *Expert Syst. Appl.* **2023**, *213*, 118910. [CrossRef]
4. Zmarzły, D.; Nagi, Ł.; Borucki, S.; Boczar, T. Analysis of Ionizing Radiation Generated by Partial Discharges. *Acta Phys. Pol. A* **2014**, *125*, 1377–1379. [CrossRef]
5. Rozga, P.; Stanek, M.; Cieslinski, D. Comparison of properties of electrical discharges developing in natural and synthetic ester at inception voltage. In Proceedings of the 2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Chenzhen, China, 20–23 October 2013; IEEE: Piscataway, NJ, USA, 2013; pp. 891–894.
6. Nagi, Ł. Detection of ionizing radiation generated by electrical discharges in the air using sphere-sphere system. *E3S Web Conf.* **2017**, *19*, 01045. [CrossRef]
7. Malažinskas, V.; Raišutis, R.; Morkvėnas, A.; Gudžius, S.; Jonaitis, A.; Vaičys, J.; Daukšys, G. Evaluation of the insulation condition of high-voltage transformers by detecting partial discharges using the electromagnetic wave radiation method. *Mater. Tehnol.* **2021**, *55*, 253–261. [CrossRef]
8. Riba, J.-R. Application of Image Sensors to Detect and Locate Electrical Discharges: A Review. *Sensors* **2022**, *22*, 5886. [CrossRef] [PubMed]
9. Wotzka, D.; Koziol, M.; Nagi, L.; Urbaniec, I. Experimental analysis of acoustic emission signals emitted by surface partial discharges in various dielectric liquids. In Proceedings of the 2018 IEEE 2nd International Conference on Dielectrics—ICD 2018; Budapest, Hungary, 1–5 July 2018.
10. Martinovic, T.; Fulnecek, J. Fast Algorithm for Contactless Partial Discharge Detection on Remote Gateway Device. *IEEE Trans. Power Deliv.* **2022**, *37*, 2122–2130. [CrossRef]
11. Witos, F. Application of Acoustic Emission Method for Partial Discharge Research in Selected Elements and Devices of Electric Power Systems. In Proceedings of the 2018 Joint Conference—Acoustics, Ustka, Poland, 11–14 September 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 1–6.
12. Binotto, A.; de Castro, B.A.; Ardila-Rey, J.A.; Andreoli, A.L. Partial Discharge Detection of Transformer Bushing Based on Acoustic Emission and Current Analysis. In Proceedings of the 2021 IEEE XXVIII International Conference on Electronics, Electrical Engineering and Computing (INTERCON), Lima, Peru, 5–7 August 2021; IEEE: Piscataway, NJ, USA, 2021; pp. 1–4.
13. Uwiringiyimana, J.P.; Khayam, U.; Suwarno; Montanari, G.C. Comparative Analysis of Partial Discharge Detection Features Using a UHF Antenna and Conventional HFCT Sensor. *IEEE Access* **2022**, *10*, 107214–107226. [CrossRef]

14. Kaziz, S.; Said, M.H.; Imburgia, A.; Maamer, B.; Flandre, D.; Romano, P.; Tounsi, F. Radiometric Partial Discharge Detection: A Review. *Energies* **2023**, *16*, 1978. [CrossRef]
15. Tenbohlen, S.; Beura, C.P.; Sikorski, W.; Sánchez, R.A.; de Castro, B.A.; Beltle, M.; Fehlmann, P.; Judd, M.; Werner, F.; Siegel, M. Frequency Range of UHF PD Measurements in Power Transformers. *Energies* **2023**, *16*, 1395. [CrossRef]
16. Beura, C.P.; Beltle, M.; Wenger, P.; Tenbohlen, S. Experimental Analysis of Ultra-High-Frequency Signal Propagation Paths in Power Transformers. *Energies* **2022**, *15*, 2766. [CrossRef]
17. Azam, S.M.K.; Othman, M.; Illias, H.A.; Abdul Latef, T.; Tariqul Islam, M.; Fadzil Ain, M. Ultra-high frequency printable antennas for partial discharge diagnostics in high voltage equipment. *Alex. Eng. J.* **2023**, *64*, 709–729. [CrossRef]
18. Beura, C.P.; Beltle, M.; Tenbohlen, S. Study of the Influence of Winding and Sensor Design on Ultra-High Frequency Partial Discharge Signals in Power Transformers. *Sensors* **2020**, *20*, 5113. [CrossRef] [PubMed]
19. Ghanakota, K.C.; Yadam, Y.R.; Ramanujan, S.; Prasad V. J., V.; Arunachalam, K. Study of Ultra High Frequency Measurement Techniques for Online Monitoring of Partial Discharges in High Voltage Systems. *IEEE Sens. J.* **2022**, *22*, 11698–11709. [CrossRef]
20. Skubis, J.; Kozioł, M. Assessment of Partial Discharges in the Air by Application of Corona Camera. *Appl. Sci.* **2021**, *11*, 8595. [CrossRef]
21. Kunicki, M. Zastosowanie metody UHF do detekcji i analizy zjawiska wyładowań niezupełnych. *Przegląd Elektrotech.* **2016**, *1*, 60–64. [CrossRef]
22. Durak, S.; Partyka, J.; Gustaw, M. Pomiary i analiza wyładowań niezupełnych przy użyciu kamery wyładowań koronowych. *Przegląd Elektrotech.* **2020**, *1*, 158–161. [CrossRef]
23. Frącz, P.; Zmarzły, D.; Boczar, T. Characteristic of Surface Partial Discharges Measured with Ultraviolet Camera. *Acta Phys. Pol. A* **2015**, *127*, 715–718. [CrossRef]
24. Ma, D.; Jin, L.; He, J.; Gao, K. Classification of partial discharge severities of ceramic insulators based on texture analysis of UV pulses. *High Volt.* **2021**, *6*, 986–996. [CrossRef]
25. Doble Engineering Company. PDS100 Datasheet. Available online: https://www.doble.com/wp-content/uploads/PDS100_US_HR_web.pdf (accessed on 13 April 2023).
26. Ofil Systems DayCor Superb Datasheet. Available online: http://www.tectra.hu/pdf-docs/Ofil-SUPERB.pdf (accessed on 13 April 2023).