

Article

Insulation Defect Modelling and Partial Discharge Typology Identification: A Robust and Automatic Approach

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Abstract: This paper has a twofold aim. On one side, it aims to show a paramount application of an innovative approach to automatic partial discharge (PD) monitoring and analysis, referring to types of cable defects that can trigger internal and surface discharges. The type of defect generating PD is automatically identified, which is of fundamental importance to develop condition maintenance tools of any electrical asset component. On the other side, the way to create artificial defects, namely using a tool to test any PD measurement approach, is illustrated and discussed, relying upon partial discharge inception field and voltage modelling. Also, the so-called three-leg approach, which is capable of achieving the optimal and reliable design of electrical insulation systems, was applied and successfully validated for simple test objects and real electrical assets such as cable with artificially developed defects.

Keywords: partial discharges; automatic PD monitoring; electrical insulation systems; cable defects; surface and internal discharges; defect typology identification



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1. Introduction

Electrified transportation (including aerospace, aviation, and ships), renewable energy generation, and medium voltage (MV) electrical grids have necessitated advanced electrical insulation designs that can improve the reliability and lifespan of these systems [1–3]. Partial discharges (PD) are unarguably one of the most common reasons for premature breakdown of organic electrical insulation systems [4–7].

To face the difficulty of reaching insulation system designs that can assure specified life and reliability irrespective of the type of waveform, i.e., AC or DC, and in the presence of PD, one must first understand and model PD phenomena, especially the PD-inception mechanism. Then, the theoretically obtained partial discharge inception voltage (PDIV) needs to be validated by PD measurements performed on the electrical component under investigation. The inclusion of power electronics has modified the type of supply voltage waveform from sinusoidal AC to modulated AC and DC [8,9]. Since the electric field distribution along/across the insulation defects is significantly different in the case of AC and DC [10–13], it is essential to validate the PD-inception model by artificial defects created on the tested object.

Dealing with diagnostics and condition maintenance based on PD, it is of fundamental importance not only to measure signals that can be associated to PD but even more so to understand (identify) which type of defect generated the detected PD [4,14,15]. Diagnostic studies that comprise of a series of assessments ranging from residual life estimation [16] to health condition or health index [17] can be effective following the proper identification of the PD-source typology.

It is reasonable to assume that the primary motivation for establishing PD monitoring and condition-based maintenance (CBM) systems is the cost and the complex analysis of

PD measurement results, which generally require the assistance of experts. As long as interpretation of PD in terms of understanding their typology and therefore harmfulness is still dependent on experts, long wait periods and often significant costs can be expected in relation to condition maintenance action related to PD measurement or monitoring procedures. Furthermore, PD analysis performed by expert systems such as those utilizing artificial intelligence (AI) can be ineffective if the PD is not separated properly from noise and other sources of PD [18]. Therefore, the focus of any automatic PD-based diagnostic system method must be on effective separation and recognition of PD and noise, followed by proper PD identification.

As regards identification, which is directly associated with maintenance action, PD phenomena can consist of surface/interface discharges (e.g., at cable splices) or internal discharges occurring in insulation bulk. In terms of harmfulness, internal discharges cause a faster degradation rate than surface discharges; thus, the former can be related to higher risk in insulation health condition evaluation [19].

In order to check the validity of any approach trying to add the above-mentioned information to PD measurement/monitoring, insulation system objects endowed with replicable artificial defects that are able to provide the desired type of PD, i.e., internal and surface discharges, must be designed and manufactured for the purpose of developing extensive lab experiments.

Acquisition and analysis, the latter focused on identification, are all managed automatically by the PD detection system. Defects generating PD are artificially created on a cable, and the way to model and manufacture them is the main contribution of this paper. As known by lab researchers, generating artificial defects in test objects is always a challenge: We propose here an approach based on PD-inception modelling and electric field simulation, which is validated in the paper by PD measurements.

In addition, the application of the three-leg approach for the PD-free design of insulation systems [20,21] to polymeric material specimens (the same insulating material as for most cables, that is, cross-linked polyethylene, XLPE) is demonstrated.

2. Three-Leg Approach

A recently proposed new framework for the PD-free design of insulation systems, the so-called “three-leg approach” [18,22], can be exploited for the estimation of bulk, surface, or interface PDIV of an insulation system. This approach is valid for both AC and DC systems, and it is based on three steps (the “legs”):

1. Electric field simulation of the insulation system/object under study;
2. Modelling of the PD-inception field and voltage, PDIE and PDIV, respectively;
3. Performance of PD measurements to validate the results predicted by leg 2.

Specifically, the voltage at which the maximum (approximately) electric field in an insulation system (calculated at leg 1) matches the PD-inception field estimated by the model at leg 2 is the partial discharge inception voltage (PDIV) [22]. Eventually, the experimental PDIV value determined from leg 3 is used to validate the estimated PDIV thus obtained from leg 2.

The generalized PD-inception model, namely leg 2, can be expressed as follows [21,22] (based on [20]):

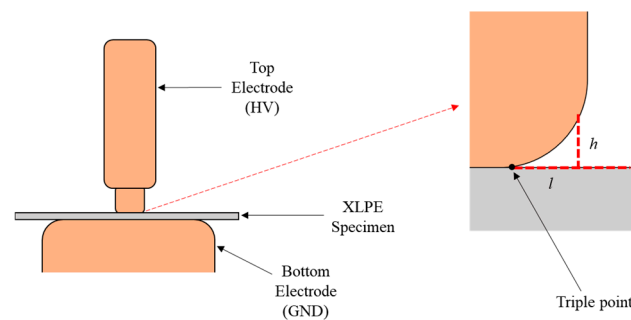
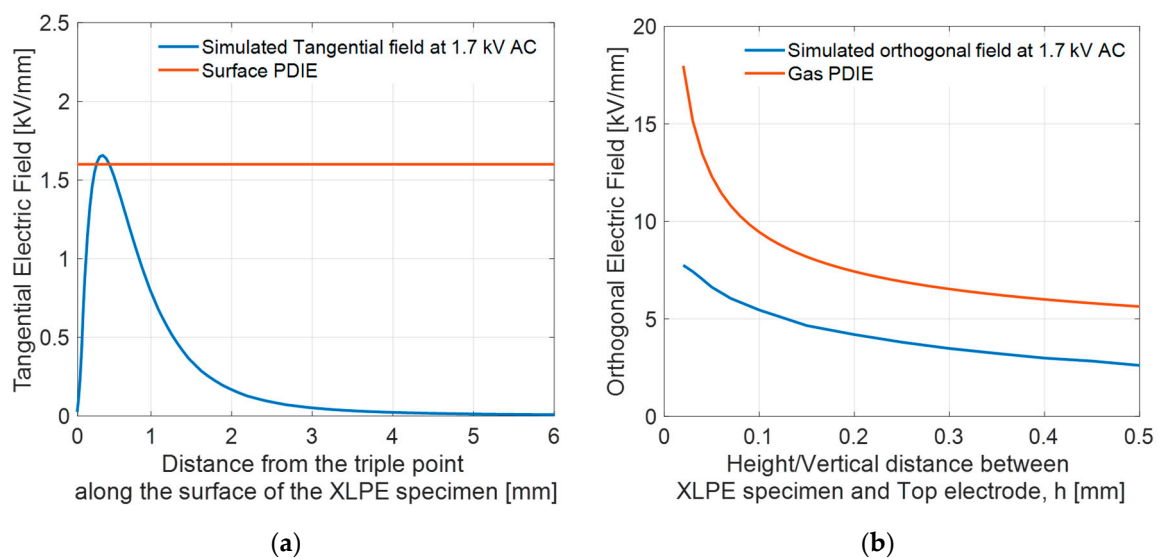
$$PDIE \text{ or } E_i = (E/p)_{cr} p \left(1 + \frac{B}{(pk_s l)^{1/\beta}} \right) \quad (1)$$

which is valid for a gas at pressure p . $(E/p)_{cr}$ is the critical reduced field, B and β are empirical parameters (based on the discharge mechanism and Meek number, [21,22]), and k_s is a scale factor that considers the field gradient in the volume/surface where the electric field is maximum. Table 1 displays the parameters of each type of discharge (surface or internal) in air.

Table 1. Parameter values of the generalized partial discharge model (1) for air.

Discharge Type	$(E/p)_{cr}$	B	β	k_s
Internal/Gas discharge	25.2	8.6	2.0	1
Surface discharge	8.0	4.3	2.0	<1

Before creating model-driven artificial defects on the cable, the above-mentioned three-leg approach was applied on commercial XLPE flat specimens (which is the material of insulation of the MV cable used in the present study) by the test electrode setup shown in Figure 1, under AC. The modelled value of AC PDIV was calculated by using the PD-inception model (Equation (1)) and estimating the value of k_s by means of the tangential electric field profile from the triple point (Figure 2). The tangential and orthogonal electric field profiles, near the triple point of the top electrode, are depicted in Figure 2. Even though the orthogonal field component (which causes gas discharges) is larger than the tangential field (which promotes surface discharges), PDIV in the case of surface PD is lower than that of gas discharges because of different model parameter values (see Table 1). As can be seen in Figure 2a, the simulated tangential field at 1.7 kV is slightly higher than the surface PDIE, satisfying the condition for the inception of surface PD. On the other hand, the simulated orthogonal field at the same voltage (1.7 kV) is significantly lower than the corresponding gas PDIE (Figure 2b). Hence, surface discharges are predominant with the type of the electrodes shown in Figure 1. The validation of the estimated surface PDIV of XLPE flat specimen with test electrode setup, by means of performing PD measurements, is discussed in Section 4.

**Figure 1.** Sketch of the test electrode configuration.**Figure 2.** (a) Simulated tangential and (b) orthogonal electric field profiles near the triple point of the top electrode (Figure 1) at 1.7 kV AC along with surface and gas PDIE.

3. Creating Artificial Defects on MV Cable

Two types of PD are considered here for developing artificial defects on the cable, that is, internal PD generated by bulk defects/cavities and surface PD occurring at the insulation surface or interfaces. In order to design and manufacture surface geometries and bulk defects able to incept PD of specific phenomenology, that is, surface or internal PD, the type of defect that generates PD must be designed, manufactured, and then identified through proper PD measurements. Reference is made in the following to MV cables as the test object where defects are created.

3.1. Surface Defect

To deploy a surface defect, an aluminum (Al) tape was wrapped around the surface of the XLPE insulation of the MV cable, separated by a distance of 10 mm from the edge of the cable. The cable conductor was connected to HV and the Al tape to the ground. The borders of the Al tape were folded in order to control the electric field divergency at the triple point (Al tape, cable, and air). The field divergency was devised such that it could be large enough, even at relatively low voltage, to incept surface PD around the triple point, giving rise to a stable surface PD phenomenon that does not cause flashover.

This electrode configuration has the significant component of a tangential field on the surface, which is able to effectively trigger surface discharges. Figure 3 displays the normal field calculated (by COMSOL) near to the triple point of the Al tape (point C) and the tangential field starting from the triple point to the edge of the cable insulation (from C to B of Figure 4). The PD-inception voltage obtained from the surface discharge model described in [22] is 3.3 kV, as shown in Figure 3b, which is lower than the PDIV related to the orthogonal field or gas discharge (i.e., 8.1 kV at a height, $h = 0.05$ mm; Figure 3a). A photo of the artificial surface defect is shown in Figure 4.

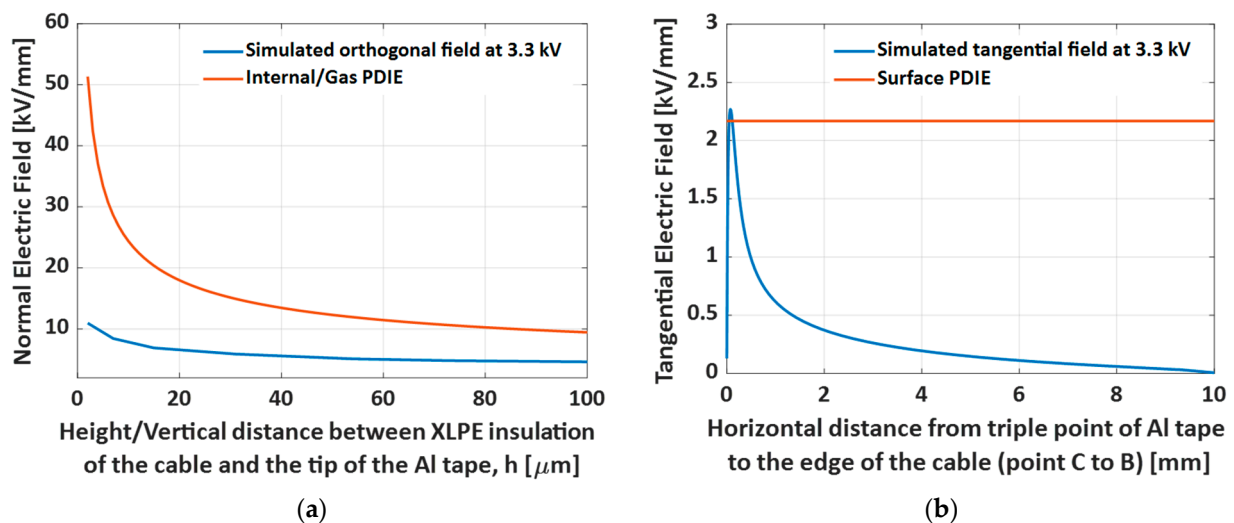


Figure 3. (a) Normal field near the triple point of the Al tape (point C; Figure 4), and (b) tangential field from the triple point C (as in Figure 4) to the edge of the cable insulation, point B, and PD-inception field plots obtained from the PD-inception field model (gas (a) and surface discharges (b)). Applied voltage = 3.3 kV, that is, PDIV for surface discharges.

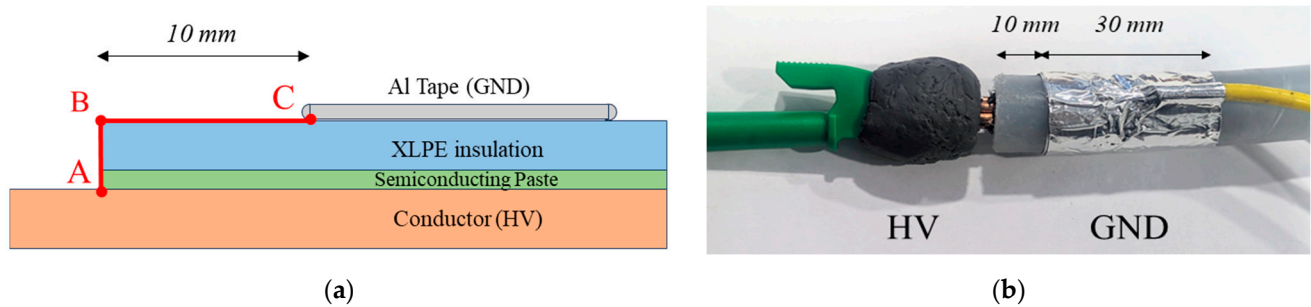


Figure 4. (a) Cross-sectional view of MV cable with surface defect and (b) photo of the MV cable with manufactured surface defect. Path ABC represents the creepage line. A is the point of contact of cable conductor (HV electrode) with XLPE insulation through semiconducting paste, B is the edge of the cable insulation, and C is the triple point of the Al tape (ground electrode).

3.2. Internal Defect

As for internal defect, a cylindrical cavity was modelled inside the cable insulation and we calculated the electric field profile (leg 1) by COMSOL. The defect is modelled such that a portion of the cavity is filled with semicon material, and the remaining portion contains air, as shown in Figure 5, with the purpose of giving rise to a sudden change in permittivity value from the semicon ($\epsilon_r = 1000$) to air ($\epsilon_r = 1$). This results in a significant intensification of the orthogonal electric field at the boundary of the air and semicon (Figure 6a), which can incept gas internal discharges at a relatively low voltage. In the present study, a cylindrical cavity (with height of 3 mm and diameter of 6 mm) was carved onto the cable insulation (thickness 4.8 mm). A 2/3rd portion of the cavity was filled with semicon material. Matching the electric field distribution (Figure 6a) with the internal PD-inception model [21], the PDIV is estimated to be 4.0 kV. The size of the cavity and the filled portion of the semicon material inside the cavity were selected in order to design an internal defect that generates internal discharges at a voltage lower than that of the PD-inception voltage of the surface discharges that occur along the triple point (cable insulation, semicon tape, and air) and cable termination (as shown with red dotted line in Figure 5). By matching this simulated tangential electric field profile (Figure 6b) with the surface PD-inception field calculated from PD-inception model [21], the estimated surface PDIV is 5.3 kV. This confirms that the internal discharges across the cavity will occur at a relatively lower voltage than that of the surface discharges. Hence, the present configuration of the defect (as in Figure 5) is validated as a proper internal defect.

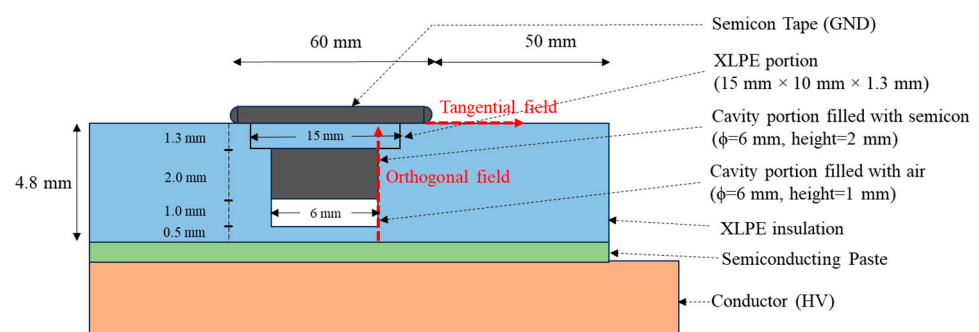


Figure 5. Cross-sectional view of MV cable with internal defect (cylindrical cavity).

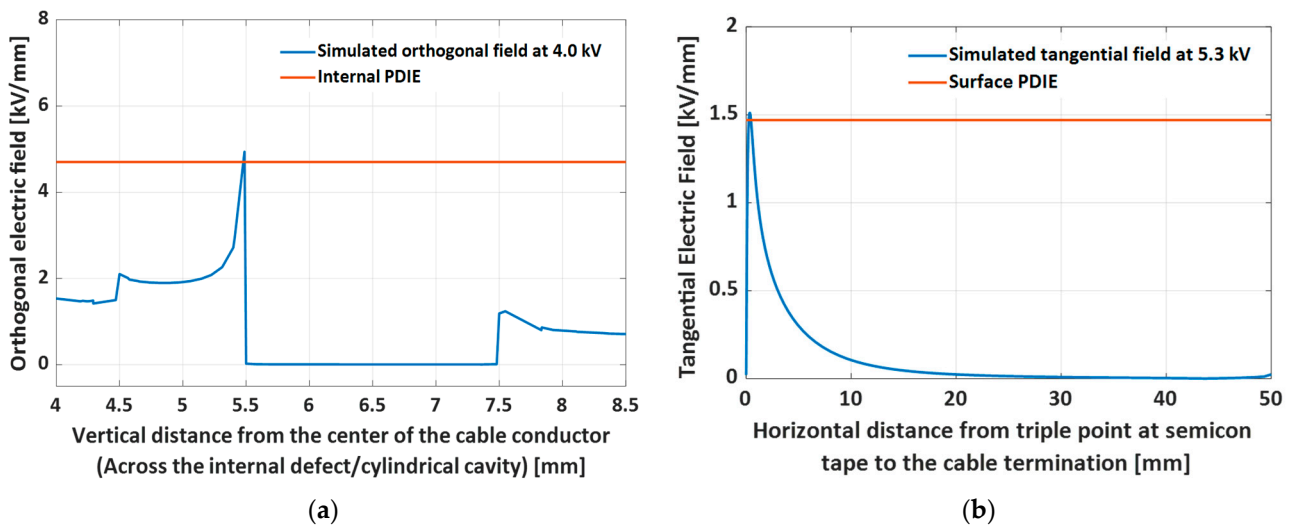


Figure 6. (a) Simulated orthogonal electric field across the edge of the cavity and (b) tangential electric field along the cable surface from outer semicon tape to cable termination (as shown with red arrow in Figure 5) and PD-inception field obtained from the PD-inception field model (gas (a) and surface discharges (b)).

For manufacturing the internal defect on a MV cable, semicon is peeled off, and a portion of XLPE insulation ($15 \text{ mm} \times 10 \text{ mm} \times 1.3 \text{ mm}$) is cut from the cable insulation. After drilling the cavity, the XLPE portion is glued to the remaining part of insulation. Then, a semicon tape is wrapped around the cable above the internal defect, and it is connected to the ground, while the conductor of the cable is connected to HV.

4. PD Measurement and Analysis

This section shows the validation of the capability of a specific defect to trigger the wanted type of PD (i.e., validation according to the 3rd leg of the three-leg approach).

For this purpose, it is necessary to have a PD measurement system that is not only capable of detecting PD signals coming from the object under test but also should be able to identify which type of defect is generating the PD. The PD system used for this research was developed recently and is fully automatic for both acquisition and analytics [18,23]. The analysis features are based on SRI technology, that is, with the separation of acquired signal having different features and the creation of a multi-dimensional clustering map, recognition of clusters corresponding to noise and PD and noise rejection from the PRPD global pattern, and identification of the typology of PD based on sub-patterns as separated through the clustering map and considering three categories (in descending harmfulness order), i.e., internal, surface, and corona PD.

AC PD measurements were performed on XLPE flat specimens by the electrode setup of Figure 1 as the test object, using a signal generator (RIGOL, Portland, OR, USA; DG952, 50 MHz, 250 MSa/s) plus high-voltage amplifier (Matsusada Precision, Otsu, Japan; AMPS series, 0 to $\pm 30 \text{ kV}$) setup as the supply (which is able to generate different types of voltage waveforms). A high-frequency current transformer (HFCT) with a large bandwidth of 100 kHz to 50 MHz was employed to sense PD, and the PD pulses were acquired and processed using an automatic PD acquisition and detection system of 10 kHz to 100 MHz bandwidth. The schematic of the experimental setup used to perform AC PD measurements is displayed in Figure 7. Five measurements were carried out to determine PDIV_{AC} , and the corresponding values along with mean value are represented in Table 2. As can be seen in Table 2, the mean value of measured PDIV_{AC} is closer to the estimated PDIV_{AC} value. Thus, the estimated surface PDIV_{AC} value in the case of XLPE with the test electrode setup are validated with the help of experimentally determined PDIV_{AC} value.

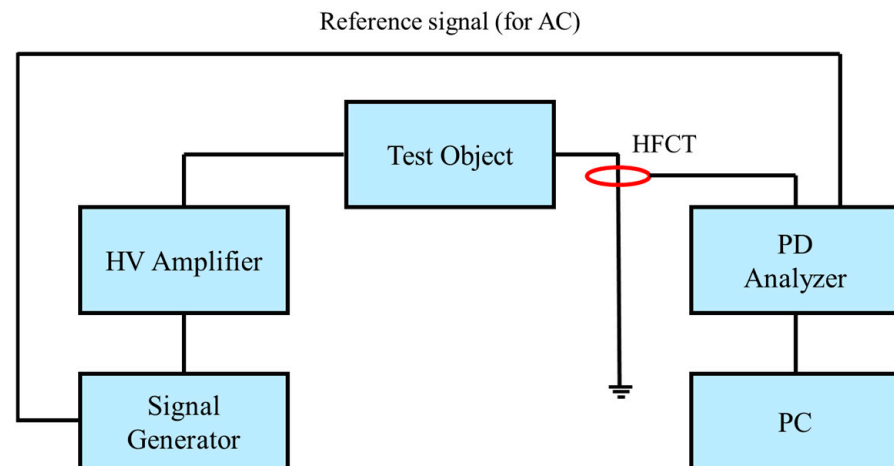


Figure 7. Schematic of the experimental setup used to perform AC and DC PD measurements. Test object is either XLPE specimen with test electrode setup or cable with artificial defects.

Table 2. Measured and modelled AC PDIV values of XLPE specimen with test electrode setup as in Figure 1, along with the PDIV values of cable with surface and internal defects in case of AC and DC.

Measured Values	XLPE Flat Specimen	MV Cable with Surface Defect		MV Cable with Internal Defect	
	PDIV _{AC} [kV]	PDIV _{AC} [kV]	PDIV _{DC} [kV]	PDIV _{AC} [kV]	PDIV _{DC} [kV]
Reading-1	1.7	3.0	10.7	3.9	7.9
Reading-2	1.8	3.4	11.3	3.6	7.7
Reading-3	1.7	3.1	10.8	3.7	7.7
Reading-4	1.8	3.2	11.0	3.8	7.8
Reading-5	1.8	3.0	10.8	3.7	8.0
Mean measured value	1.8	3.1	10.9	3.7	7.8
Modelled value	1.7	3.3	11.1	4.0	7.7

Then, AC PD measurements were performed on the MV cable specimen of 5 m long as the test object featuring surface and internal defects, using the same test setup as in Figure 7. The results of the measurements (five) that were performed to determine PDIV_{AC} are summarized in Table 2. The mean measured PDIV_{AC} is in accordance with the modelled values in case of the cable with surface as well as internal defects.

Figure 8 depicts the typical screenshot of an XLPE flat specimen with the test electrode setup obtained by the innovative SRI automatic PD software (PDNOVA, Seiktron, Weston, FL, USA; version: 1.2.3.2) at 1.1 PDIV_{AC}, and Figures 9 and 10 display the screenshots obtained by the same PD software at 1.1 PDIV_{AC} for both types of defects on MV cable.

The innovative, fully automatic, PD analytics algorithm is based on SRI logic, i.e., separation, recognition, and identification [18,24].

Separation is based on quantities extracted from pulse shape and projected on a 2-dimensional space by principal component analysis (PCA). Clusters of homogenous pulse characteristics would separate different types of PD sources and noise from PD, assuming that the acquired signal characteristics are partly or totally different (which happens in most cases). Recognition relies upon statistical algorithms and points out noise and PD clusters, thus obtaining sub-patterns of the global one, each one pertinent to a specific phenomenon.

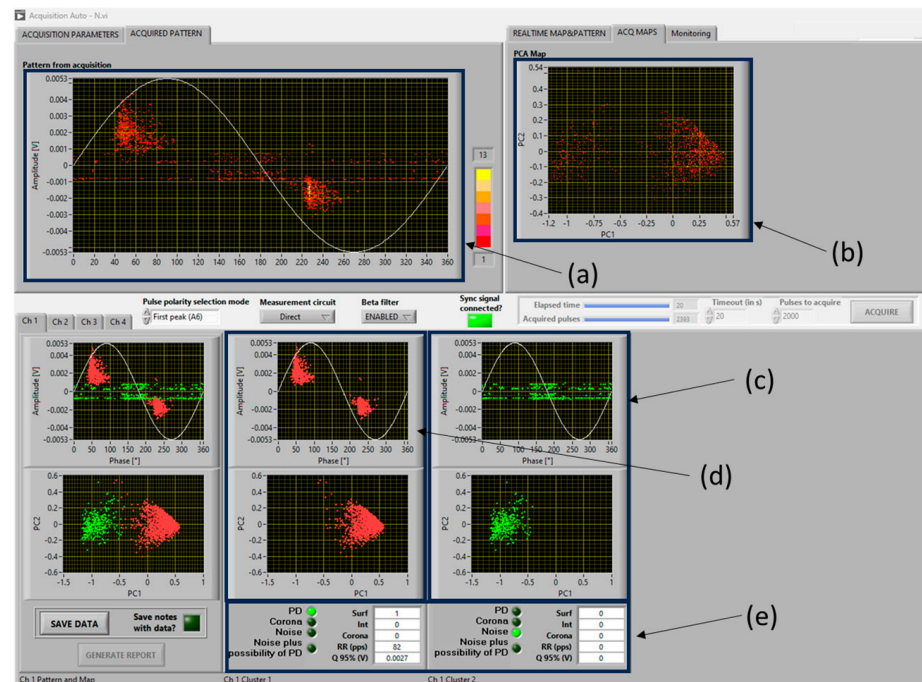


Figure 8. Typical screenshot from analytics software that illustrates how SRI works for XLPE with test electrode configuration, shown in Figure 1, at 1.1 PDIV_{AC}: (a) global pattern, (b) separation map, (c) sub-pattern and cluster corresponding to noise, (d) sub-pattern and cluster corresponding to PD, and (e) recognition (PD or noise) and identification (type of defect generating PD).

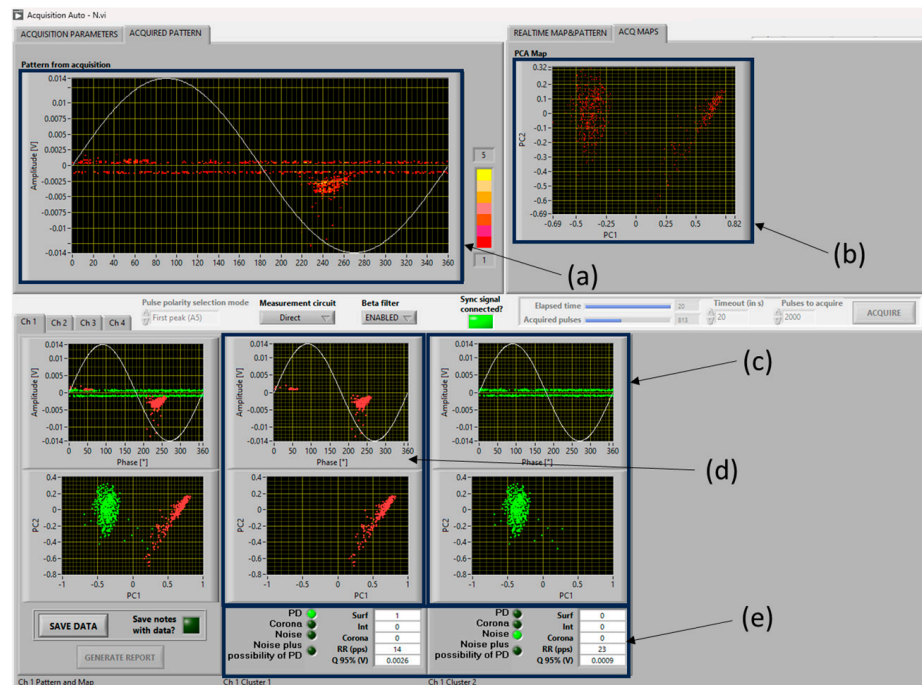


Figure 9. Typical screenshot from analytics software that illustrates how SRI works for cable with surface defect at 1.1 PDIV_{AC}: (a) global pattern, (b) separation map, (c) sub-pattern and cluster corresponding to noise, (d) sub-pattern and cluster corresponding to PD, and (e) recognition (PD or noise) and identification (type of defect generating PD).

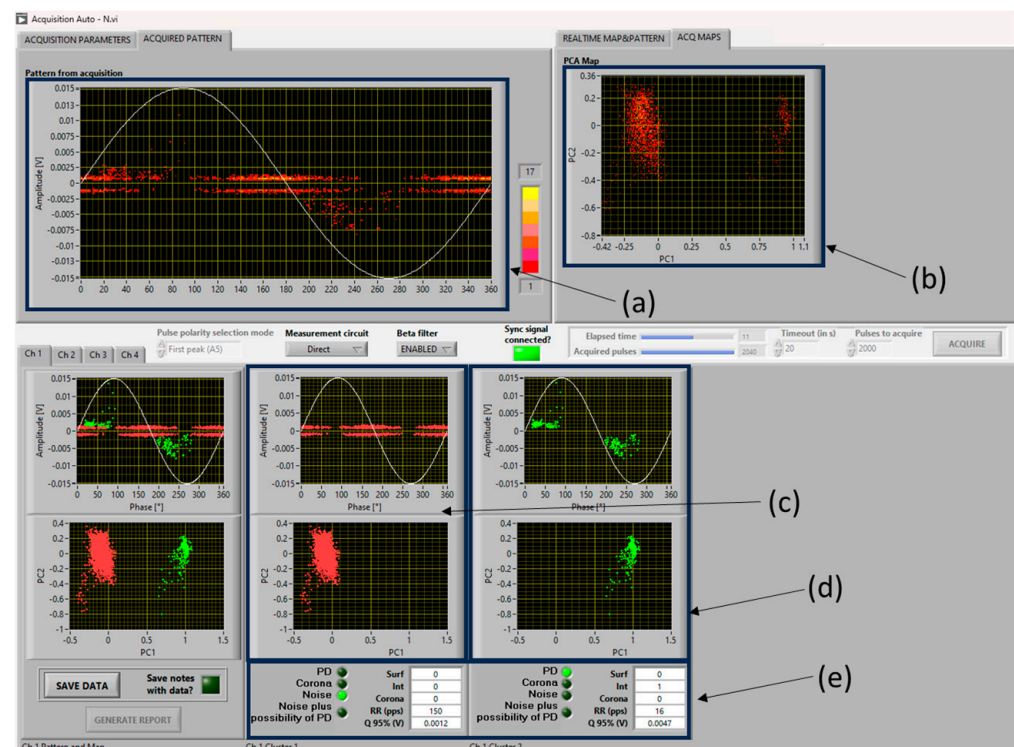


Figure 10. Typical screenshot from analytics software that illustrates how SRI works for cable with internal defect at 1.1 PDIV_{AC}; (a) global pattern, (b) separation map, (c) sub-pattern and cluster corresponding to noise, (d) sub-pattern and cluster corresponding to PD, and (e) recognition (PD or noise) and identification (type of defect generating PD).

As can be seen from Figures 8–10, the PD and noise pulses were successfully separated and recognized properly. The sub-patterns related to one or more PD sources were then identified by means of artificial intelligence (fuzzy logic), whether belonging to internal, surface, or corona discharge phenomenology (in descending order of harmfulness for electrical insulation reliability). Identification is associated with a likelihood degree. As an example, identification (ID) of 80% internal and 20% surface means that the PD phenomenon can be largely ascribed to internal PD, but these are some inherent features that could be also associated, with low probability, with surface discharges. This mimics the way an expert operator generally explains PD patterns.

As regards the experiments of Figure 8, in the case of XLPE with the test electrode configuration as in Figure 1, the PD analytics provided PD identification of 1 (i.e., 100% probability) for surface PD, thus confirming the occurrence of surface discharges. In the case of the cable with the surface defect, the screenshot of the PD analytics from the Figure 9 highlights the typology corresponding to the acquired PD pulses of 100% surface discharge. Therefore, it is certain that the designed and manufactured surface defect actually provided surface discharges. Similarly, in the case of the internal defect, the analytics summarized in Figure 10 were obtained. The automatic acquisition and analysis algorithm provides an identification of 100% internal, near PDIV, for the designed and manufactured defect, thus confirming that both design and manufacturing are appropriate for the specific wanted PD phenomenology. Then, a voltage of 5.8 kV AC (which is 1.1 times the PDIV of surface discharges from triple point near semicon tape) was applied across the same internal defect. Figure 11 depicts the screenshot of PD analytics at 5.8 kV, and it was noticed that the PD identification is 50% surface and 50% internal. This confirms the presence of two types of discharges (surface and internal PD).

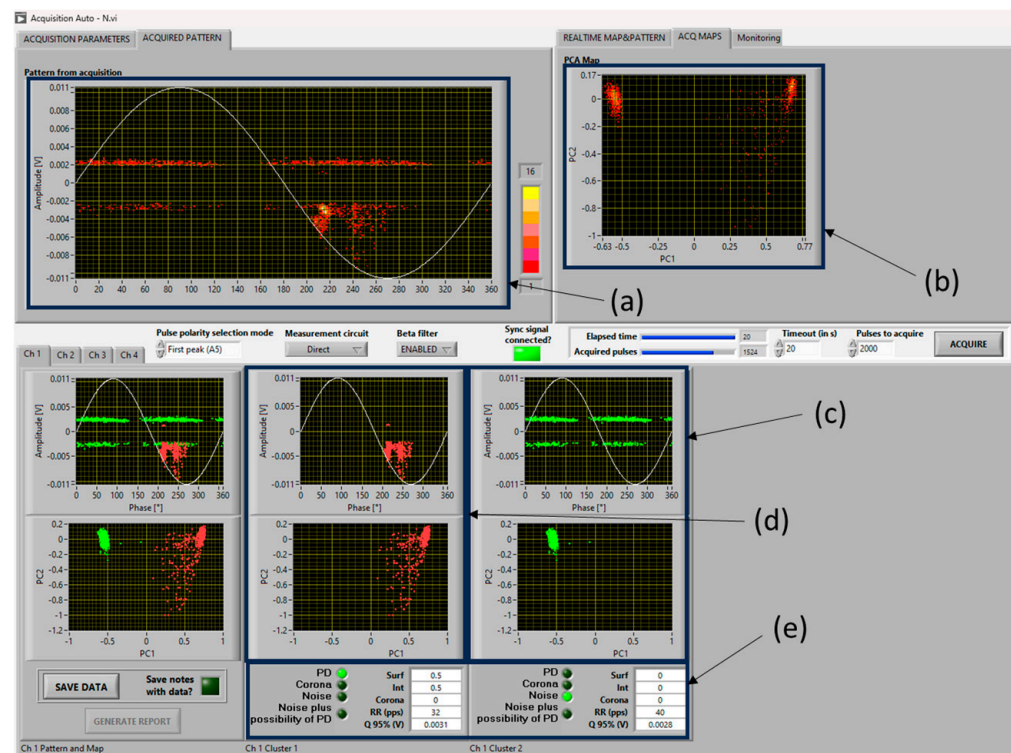


Figure 11. Typical screenshot from analytics software that illustrates how SRI works when both internal and surface PD are present; (a) global pattern, (b) separation map, (c) sub-pattern and cluster corresponding to noise, (d) sub-pattern and cluster corresponding to PD, and (e) recognition (PD or noise) and identification (type of defect generating PD).

5. DC PD Measurements on Cable with Surface and Internal Defects

DC PD measurements were also performed on an MV cable with surface and internal defects, separately, by means of the experimental setup depicted in Figure 7, which consists of a typical HV amplifier plus signal generator setup to generate a high-voltage DC supply and HFCT to sense PD. In case of the surface defect, the same configuration shown in Figure 4 was considered. As regards the internal defect, a configuration similar to that shown in Figure 5 but with a different cavity dimension was created. The details related to the manufacturing of the cavity and the simulated electric field profile, which was matched with the corresponding internal PDIE in case of DC, are reported in [25].

The automatic PD detection and analytics software used to acquire and process the DC PD pulses follows the same SRI algorithm, but it is enhanced by means of additional software noise filters (to reduce repetition rate and magnitude of noise) [24]. $PDIV_{DC}$ is generally indicated by the automatic DC PD software through the sentence “Noise plus possibility of PD”, which is activated when even few PD pulses are collected together with overwhelming noise. Steady-state DC PD measurements were performed in a time window of 2 to 10 min to achieve robust estimates of $PDIV_{DC}$. Figure 12 depicts the screenshot of PD analytics corresponding to the cable with surface defect at $PDIV_{DC}$, where the presence of PD was detected even through there was only one PD pulse present along with large number of noise pulses. Five measurements were carried out for each defect to detect $PDIV_{DC}$. The mean value of the measured $PDIV_{DC}$ in the case of the surface defect and the internal defect were determined as 10.9 and 7.8 kV, respectively, which were noticed to be very close to the modelled/estimated $PDIV$ values of 11.1 and 7.7 kV. This confirms that the designed surface and internal defects are valid in the case of DC along with AC.

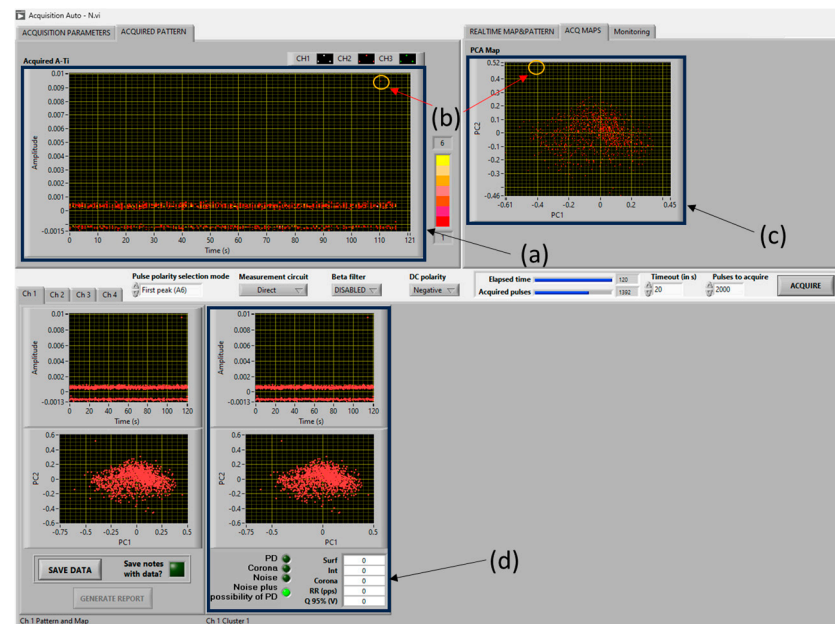


Figure 12. Typical screenshot from DC PD analytics software that illustrates how SRI works for surface defect at PDIV_{DC} ; (a) global TRPD pattern, (b) PD pulse (c) separation (PCA) map, and (d) recognition of presence of PD by highlighting the option “Noise plus possibility of PD”.

6. Discussion and Conclusions

Having ascertained the effectiveness of the three-leg approach through studying simple insulation test objects such as XLPE specimen, as seen by the test cell as in Figure 1, real electrical assets such as MV cables with artificially developed defects can be designed and investigated. In the first part of the paper, controlled surface discharges were generated on a simple XLPE flat specimen with a test electrode configuration that promotes surface PD. AC PD measurements were performed to determine the PDIV_{AC} as well as the type of generated PD. The obtained results confirmed the occurrence of surface PD with 100% probability, and the determined AC PDIV_{AC} value was used to validate the modelled PDIV_{AC} that was calculated with the help of a generalized PD-inception model (Equation (1)) and simulated electric field profile.

Reproducing artificial defects in insulation systems to investigate the phenomenology, time trend, and damage rate of PD is a diffused practice in university and industrial labs. However, it is also a common experience that defects not engineered properly either do not activate PD or do it at voltage levels that are not of interest for the testing purpose. Also, they might not incept the type of PD that is wanted.

The above-mentioned three-leg approach, which is based on a modelled PD-inception field and calculates electric field distribution and validation through measurement analytics that can identify the type of source generating PD, was also proven to be successful in the case of real electrical insulation systems such as cable with artificially developed defects. The analytics software screenshots displayed by Figures 9 and 10 provide clear and unambiguous identification of PD sources as surface and internal, respectively, in case of AC, thus validating defect design and manufacturing technology. Also, Figure 11 highlights the operation of the automatic PD analytics software, which is able to identify the presence of different types of PD (surface and internal) at the same time, while Figure 12 indicates that defects can also be properly designed and manufactured for DC PD phenomena.

The possibility of having available analytics and acquisition software that are fully automatic conforms to the proper and ineludible direction, that is, to make PD measurements not only simple but, particularly, to promote PD diagnostic and condition inference as an open asset for condition and maintenance operators that does not need experts or suffer the related delay times. In such a way, PD monitoring can become a part of an inte-

grated condition monitoring global process that can interact with central control systems of electrical assets (as SCADA) in a smart and effective way [26].

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