A New Inference System for the Robust Identification of Defects Supporting PD in MV Cables

Johnny Borghetto
R.S.E. s.p.a.
Milano, Italy
Johnny.borghetto@rse-web.it

Giovanni Pirovano
R.S.E. s.p.a.
Milano, Italy
Giovanni.pirovano@rse-web.it

Sergio Chiarello
R.S.E. s.p.a.
Milano, Italy
Sergio.chiarello@rse-web.it

Manuel Sozzi
R.S.E. s.p.a.
Milano, Italy
Manuel.sozzi@rse-web.it

Alfredo Contin
DEI University of Trieste
Trieste, Italy
contin@units.it

Andrea Pegoiani
UnaReti - s.p.a.
Brescia, Italy
Andrea.pegoiani@unareti.it

***Abstract*— A method for the identification of a large number of defects supporting Partial Discharges (PD) in MV cables is presented in the paper. A specific set of parameters that summarize features related to the shape of the Phase-Resolved PD (PRPD) patterns, is organized in a tree structure on the assumption of a correlation between the PRPD shapes and the defect typologies. Tree inspection resorts to the Fuzzy-Logic to take into account the inherent uncertainty of the identification results. Predicates that address PRPD to the defect typologies and the relevant membership values are provided as the output taking into account even more than one option. Both training and working examples obtained testing artificial defects and real cables, are presented and discussed.**

***Keywords*— MV cables, insulation system, diagnostics, partial discharges**

I. Introduction

The identification of defects supporting Partial Discharges (PD) is an important step to prevent failures in insulation systems of MV cables since different defects can affect in different ways the insulation reliability. The shape analysis of the Phase Resolved PD (PRPD) patterns is largely diffused to discriminate the different defect typologies, [1]. This empirical method implicitly assumes that the PRPD shapes are characteristics of the different defects and these shapes remain quite similar varying the measurement set-up, the applied voltage, and the location of the defect along the cable. Different statistical and artificial intelligence methods for an automatic defect-identification, have been proposed but most of these methods has been applied considering a limited number of defects typologies, mainly artificially reproduced and these investigations were addressed to evaluate the algorithm accuracy instead of the defect-identification efficiency.

A new algorithm for the automatic identification of defects supporting PD in MV cables that emulates the visual inspection approach (evaluation the phase symmetry/asymmetry of the dominant positive/negative half-pattern), is presented in this paper. The proposed algorithm is based on parameters derived from the analysis of statistical distributions derived from the PRPD patterns and organized in a tree-structure. Past investigations shown that values of these parameters (Identification Markers, IM) range in well defined intervals and these intervals can be associated to features related the pattern shape. It was also found that these intervals remain almost constant varying the applied voltage, the location of the defect along the cable and the measurement set-up (bandwidth and gain of the PD instrument and the relevant coupler), [2].

Due to the inherent stochastic behavior of PD signals and to the partial overlapping of the interval values of the IM, the defect identification is not completely deterministic. Thus, the Fuzzy-Logic has been adopted to take into account the residual uncertainty of the identification results and to consider more than one option.

Both training and a working examples obtained testing real cables, are discussed to show the algorithm efficiency and robustness.

II. PD Sources (Defects) and Their Classification

In insulation systems of MV-HV cables, defects that can support PD sources can be classified into several categories, [3]. In this work, the following defect typologies are taken into account as possible outputs for the identification tool:

- void embedded within the main insulation,
- internal delamination (flat cavities surrounded by insulation),
- delamination between conductor and insulation or between insulation and outer conductive layer or shield,
- corona discharges due to metallic protrusions,
- inner/outer stress grading deterioration,
- surface tracking.

The inclusion of the electrical trees in the automatic recognition method is under investigation.

Each one of these defect typologies can be associated to PRPD patterns whose shapes are characteristics of the different defects. The physical reasons behind this experimental evidence are still under investigation.

The identification of a defect typology is an inference process that addresses a given PRPD pattern to a specific defect typology. Using this approach, the defect typology is the target of the diagnostic procedure and PD signals are the medium to achieve such a result. In this context, the concept of "measure of PD charge" is not valid any more (e.g., calibration of PD signals in pC is not required). Since the defect typology is the target, the identification output must remain the same even if PD signals change in amplitude and shape due to the different location of the defect, when a different set-up is used (different instruments and couplers), changing the applied voltage or during ageing.

Investigations performed in the past allowed to select a sub-set of parameters that fit these identification properties, [2]. Among the statistics derived from the analysis of PRPD patterns, only the shape parameter of the two-parameter Weibull function, β, fitting the PD height distributions, the skewness (S_k) and kurtosis (K_u) factors of pulse-count vs phase histogram ($H_n(\Phi)$), and the ratio of parameters related with the signal amplitude (Normalized Quantity Number), were found sufficiently robust to be adopted as IM. S_k and K_u corresponds to the third and fourth moments of a statistical distribution. Values of these parameters range in distinct intervals connected with the different defect typologies with low and acceptable degree of overlap.

This group of IM evaluated separately for PD occurring in the positive and negative half-cycle of the applied voltage can describe the shape of the PRPD patterns but they need a suitable organization to be effective in defect identification and to consider the uncertainty when their values overlap.

The defect identification defined above implies a one-to-one correlation between the PRPD shape and the defect typology, but experience shown that this correlation is not always verified and additional definitions have to be considered to better interpret the output result. In particular:

- A variable PRPD pattern is defined when its shape changes due to the evolution of the discharge site;
- Multiple PRPD patterns occur when a single defect typology generates more than one PRPD pattern caused by different stresses and/or degradation mechanisms;
- An ambiguous PRPD pattern is defined when a single pattern addresses to more than one defect typology.

It must be pointed out that, before the application of the identification method, the experimental PRPD patterns must be processed with a separation method to obtain sub-patterns generated by a single signal source, [4], and the sub-patterns must be pre-processed to recognize and reject those due to noise, [5].

III. The Identification-Tree Organization

The structure of the identification-tree emulates the visual inspection approach. It is composed by various levels associated with the following rules (see the scheme of the tree-structure in Figure 1):

1) Consider the experimental PRPD sub-pattern obtained after the application of a separation procedure;
2) First Level: Select the dominant PD polarity using e.g., the NQN ratio ($NQN^+/NQN^- \cong 1$ symmetric, $NQN^+/NQN^- > 1$ positive or $NQN^+/NQN^- < 1$ negative asymmetric pattern). If the NQN ratio is almost 1, select the half-pattern with e.g., the highest repetition rate;
3) Second Level: Analyze the phase symmetry/asymmetry of the dominant polarity (point 2) by means of e.g., the S_k of $H_n(\Phi)$ distribution ($S_k \cong 0$ symmetric, $S_k < 0$ left-skewed or $S_k > 0$ right-skewed).

Nine different classes are thus generated and the defect typologies are classified accordingly. On the basis of PRPD features associated to each defect typology, the nine classes can be grouped into four different categories (see also Table I):

- A single class can be associated to a single defect typology. The output is a predicate that describe this defect typology (class 4: internal delamination; class 5: Void inclusion; class 6: stress-grading deterioration; class 7: insulation-shield delamination). A class can be void. The output "unknown source" is activated when a given PRPD pattern is in this class (class 3) and the diagnostic procedure stops here.

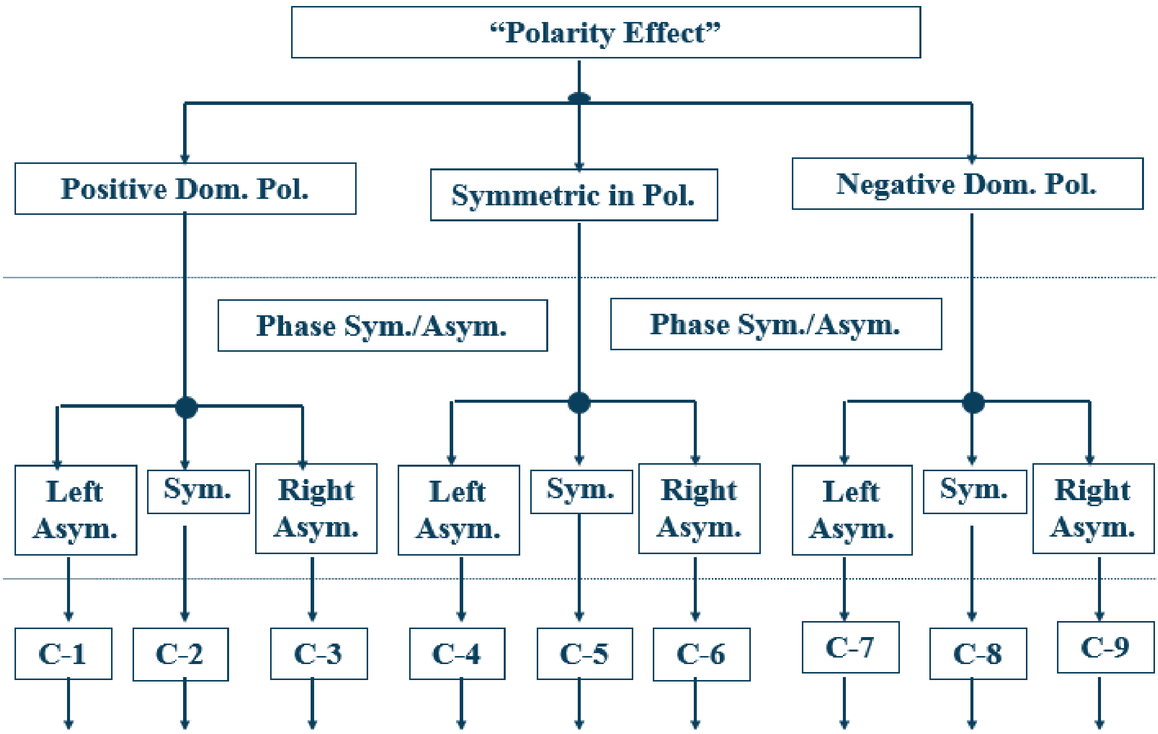


Fig. 1. The basic scheme of the identification tree.

- More patterns can be included in the same class. Additional rules and a fourth level can be considered to distinguish only the few patterns within the class always resorting to the IM such as β or K_u (class 2: conductor delamination or conductor protrusion and surface tracking; class 9: outer semicon deterioration and surface tracking).
- More classes can be connected to the same defect typology since different PRPD patterns can be produced by different degradation processes taking place in the same insulation component. Thus, the same predicate can be associated to more than one class.
- The same PRPD shape can be associated to more than one defect typology making impossible the distinction between the different defects (Ambiguous PRPD patterns. Class 1: conductor delamination vs conductor protrusion; class 8: outer semicon deterioration; insulation shield delamination).

TABLE I: CLASSIFICATION OF THE DEFECT TYPOLOGIES

Class Numb.	Dom. Pol.	Phase Sym./Asym.	Defect Typology	Add.Layer
1	Pos.	Left	1a Conductor Delamination 1b Conductor Protrusion	1a, 1b: Ambiguous PRPD Patterns
2	Pos.	Sym.	2a Conductor Delamination 2b Conductor Protrusion 2c Surface Tracking	2a, 2b: β high; Ku low 2c: β low; Ku high
3	Pos.	Right	Inner Semi-con Deterioration	//
4	Sym.	Left	Internal Delamination	//
5	Sym.	Sym.	Void	//
6	Sym.	Right	Outer Semi-con Deterioration	//
7	Neg.	Left	Insul./Shield Delamination	//
8	Neg.	Sym.	8a Insul./Shield Delamination 8b Outer Semi-con Deterioration	8a, 8b: Ambiguous PRPD Patterns
9	Neg.	Right	9a Outer Semi-con Deterioration 9b Surface Tracking	9a: β high; Ku low 9b: β low; Ku high

A number of PRPD patterns ranging from 10 to 25 and recorded during tests performed on both artificial and real objects, able to trigger discharge phenomena in well-known conditions that cover the above mentioned defect typologies, have been analyzed in order to extract the IM values and their sub-intervals from the characteristic PRPD shapes. Part of them were used to train the algorithm, other for testing. Among them, 25 PRPD patterns were due to voids embedded in polymers, [6]; 13 were generated by to surface tracking and obtained connecting metallic tips HV/LV electrodes and putting them on different insulation surfaces; 15 came from abraded semi-con materials; 20 are due to flat cavities differently located with respect the voltage electrodes. Both training and testing PRPD patterns have been obtained using different instrumentation set-up (different couplers and bandwidths) as well as varying the applied voltage, the location of the defect and during aging tests, [7]. Examples of thes patterns will be presented and discussed in Cap.V.

IV. THE FUZZY-TREE INSPECTION

Due to the stochastic nature of PD phenomena as well as the partial overlap between intervals of the identification parameters and a non-perfect separation of PD patterns due to multiple sources, the identification process cannot be deterministic. The Fuzzy Logic (FL) has been adopted to take into account the uncertainty in the defect identification introduced by the elements described above.

According to the FL theory, trapezoidal membership functions have been adopted to "fuzzyfy" the ranges of the robust parameters and linguistic attributes (i.e., Low-Medium-High) have been associated to each partition. The membership limits have been derived from the confidence limits of the parameter/defect relationship obtained during the identification-marker selection, [7]. When a parameter falls in overlapped intervals, a partial membership is given by using the oblique sides of the trapeze whose values range between $0 \div \mu \div 1$ with the constraint that the sum of the memberships be always 1. Both NQN ratio and S_k as well as the parameters used to distinguish the different PD phenomena within the same class, have been "fuzzyfied" accordingly. A further output, named "Invalid Data", has been introduced to take into account anomalous values that fall outside the defined regions of the markers. The most common FL procedure that associates logical AND and logical OR to the minimum and maximum membership, has been adopted here to provide proper membership profiles to the output linguistic predicates, after the top-down inspection of the Fuzzy-Tree. In this way, the membership of the output predicate provides an indication that considers ambiguous situations, assigning the output to more than one predicate. A μ-value close to 1 provides firm indication that the considered pattern belongs to a specific class. Lower μ-values may indicate ambiguous situations, since the pattern is assigned to more than one class with similar likelihood. Through this approach the user decision is strongly facilitated since, if $\mu=1$ the identification is accurate while $\mu<1$ indicates that different options should be taken into account.

V. Application Examples

Most of the examples discussed here refer to ageing tests performed in RSE laboratory on 16 MV underground-cables of about 10m of length each, provided by joints in the middle, [8]. All these cables are designed for 26kV and 275A of ratings. Two of these cables are insulated with XLPE, two with paper/oil insulation and twelve with XLPE and oil/paper and provided by suitable joints to connect cables with the two different types of insulation. Ten cables are new (XLPE, Oil/Paper and mixed insulation) while six mixed joints have been taken out of the field after a service period of some years. Joints come from three different providers (different design and materials). Twelve cables of providers A and B have been connected together to form a ring in short circuit and the rated current of 275A has been induced using external coils while the rated voltage of 13 kV has been applied to the ring. Cycles of temperature from the ambient to the rated temperature, have been applied by controlling the current in the ring to simulate the service conditions. Figure 2 shows a picture of a XLPE cable used both to prepare artificial defects and in the ageing test. The main insulation, the inner and outer stress grading, the external shield and the outer protection layer, are clearly visible.

Fig.2. Example of XLPE insulated MV cable used in the PD tests.

PD were monitored during the ageing cycles recording PD signals every ten minutes by means of inductive couplers (HFCT) installed in the ground connection of the cable shields. The HFCTs were connected to a commercial PD instrument forming an acquisition system having 60 MHz of bandwidth. Periodically, each MV cable was tested singularly at different voltage levels (0.5, 1, 1.5 and 2 U_0) using both a HFCT and a coupling capacitor of 1nF connected to another PD instrument having higher gain and a 30MHz of bandwidth. Cables and joints of provider C were tested off-line adopting the same procedure only for their initial characterization.

A. Variable PRPD Patterns: Internal Voids

The first example refers to variable PRPD patterns recorded during the evolution of the discharge phenomena. After 43 applications of cycles of current at rated voltage (43 days), the inception of PD was recorded on a cable of provider A having a XLPE ground-wall insulation and a homogeneous joint. Figure 3 shows examples of PRPD patterns recorded during the evolution of the discharge phenomenon. Initially, appeared a PRPD pattern composed by higher and smaller discharges (Figure 3A, Class 5). This pattern is similar to those obtained testing solid insulation having an embedded calibrated void and due to the simultaneous presence of Streamer and Townsend discharges (see [6] for further details.). The Identification System (IS) addressed correctly to "Void type discharges" with membership "1" since the symmetric and rounded shape of both half-patterns.

Progressively, the higher discharges tend to disappear and the recorded PRPD shape shows a slight left asymmetry in the phase distribution (Figure 3B, Classes 4 and 5). The IS result provides a multiple identification, "Void" and "Delamination" discharges with a membership 0.9 and 0.1, respectively. This result reflects the incomplete reduction of the higher PD. At the conclusion of the transition, the PRPD half-patterns returned rounded and symmetric and remained stable during the ageing time. The IS addressed again to "Void discharges" with membership 1, (Figure 3C, Class 5). Previously, PD tests were performed on a 130kV cable, provided by a calibrated void within a joint. PD test results were used to train the procedure. Figure 3D shows the PRPD pattern recorded testing the HV cable at its rated voltage of 130kV. Tests were performed at different voltage levels, using a commercial instrument having 25 MHz of bandwidth and connected to a Ck=0.5nF.

Since the setup remained always the same, the evolution of the PRPD pattern is due only to changes in discharge mechanisms. The IS has been trained to follow this evolution.

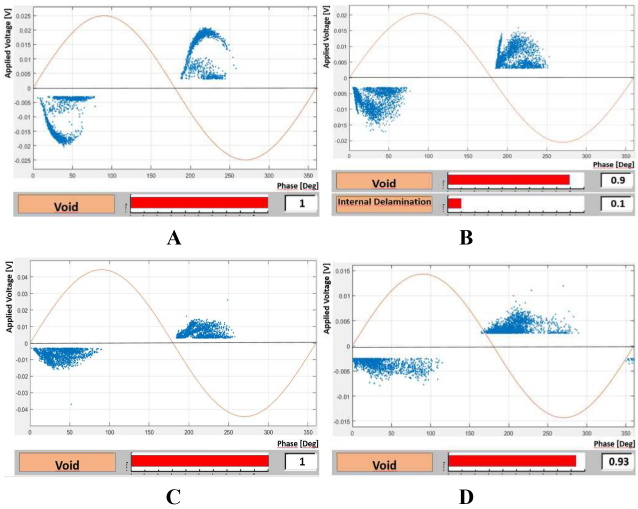
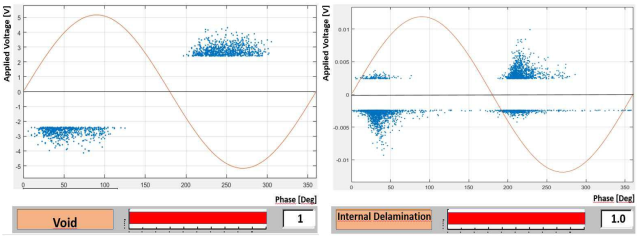


Fig.3. PRPD patterns recorded testing two cables of 26kV and 130kV of voltage rating. A) Initial pattern; B) PRPD pattern during the initial transition; C) stable PRPD pattern recorded during ageing; D) PRPD pattern recorded testing a 130kV at its rated voltage.

B. Variable PRPD Patterns: From Internal to Surface PD

Another example of variable PRPD patterns was found testing a cable composed by XLPE and oil/paper insulation and provided by a mixed joint in the middle (provider B). PD tests were performed at different voltage levels (0.5, 0.75, 1, 1.5 and 2 U_0) using a C_k=2nF. Figure 4 shows the PRPD patterns recorded at 0.75U_0 and U_0. As can be seen from Fig.4A (test at 0.75U_0), the rounded and symmetrical shape in polarity, (Class 5) addresses to "Void" discharges. At higher test voltage (U_0), this pattern became almost triangular, left asymmetric in the phase distribution and symmetric in polarity (Fig.4B). The answer of the IS is "Internal Delamination" with μ=0.1 (Class 4). At higher test voltages, the answer was always "Internal Delamination" PD (Class 4).

This behavior is typical of a delamination (probably in the oil/paper insulated joint) where at lower voltages, discharges incept at the edges of the flat cavity while at higher voltages, discharges develop on the surfaces of the flat cavity. Even in this example, the setup remained the same thus the PRPD pattern evolution was due only to the discharge phenomenon that is a consequence of the electric field distribution within the flat cavity.



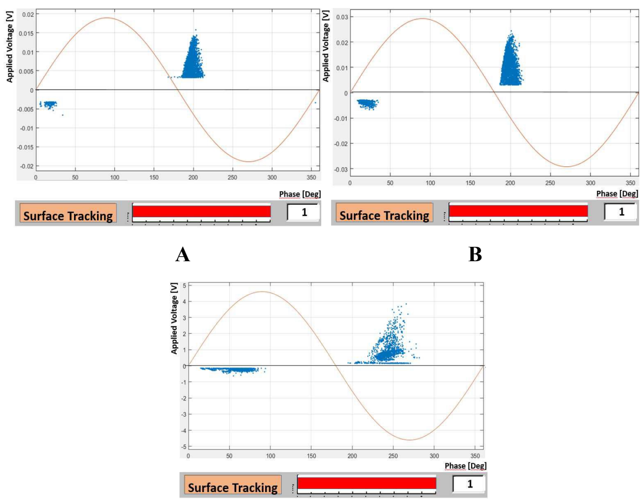
A B

Fig.4. PRPD patterns recorded testing a cable (Provider B) part insulated in XLPE, part in oil/paper insulation and provided by a mixed joint. PD tests performed at (A) $0.75U_0$ and (B) U_0, using a capacitive coupler.

C. *Robustness of the IS results: Surface Tracking*

PD were recorded during off-line tests performed on a cable composed by two types of insulation (XLPE and Oil/Paper insulation) and connected together by a mixed joint. This cable belongs to the set of six cables removed from the service (Provider A). PD incepted after the application of 435 cycles of current (435 days). Figure 5 reports the PRPD patterns recorded testing the cable at $2U_0$. In particular, Figures 5A and 5B show the PRPD patterns recorded almost simultaneously using a Ck=1nF and the HFCT, respectively. Fig.5C reports a PD pattern obtained testing an artificial defect composed by a needle-tip positioned on the surface of a solid insulation to generate tracking PD. The latter pattern recorded using another PD instrument having different dynamic characteristics. PRPD patterns recorded at different voltage levels were used for training.

As can be seen from Fig.5, all the patterns present a negative dominant polarity with an elongated shape. Even if these patterns were recorded using different instruments (different gain and different bandwidth), the IS recognizes the presence of "Tracking Discharges" with membership 1 (Class 8) in every case.



A B

C

Fig.5. Examples of PRPD patterns due to tracking discharges. A) PD recorded with a Ck; B) PD recorded at the same time with a HFCT; C) PD pattern generated by a needle-tip positioned on the surface of a solid insulation and connected to the ground.

D. *Multiple PRPD patterns: Stress Grading Deterioration*

Figure 6 shows examples of multiple PRPD patterns that is, patterns having different shape that address to the same defect typology. After the application of 644 current cycles at rated voltage on a new MV Oil/Paper insulated cable, appeared a PRPD pattern having negative dominant PD polarity, right asymmetric in the phase distribution (Fig.6A, Class 9). This shape is very similar to that obtained testing an artificial defect obtained abrading the surface of stress-grading until the appearance of surface PD (Fig.6B). This similarity suggest the presence of PD on the surface of the outer stress grading. Patterns obtained testing abraded stress grading with a PD instrument having different bandwidth and gain, were used for training.

PD tests were also performed to evaluate the initial conditions of four mixed new joints coming from provider C. In a cable, just at rated voltage, appeared a PRPD pattern having a negative dominant polarity but symmetric in phase (Class 8). The PRPD patterns recorded using a Ck=2nF and the HFCT are reported in Fig.6C and 6D, respectively. Further investigations allowed to discover problems in the outer stress grading.

Even if the four patterns of Fig.6 were recorded using different voltages and different commercial PD instruments (different gain and bandwidth), shapes of Fig.6A and 6B and shapes of Fig.6C and 6D appear similar. The IS identifies these patterns as "Outer Semi-Con Deterioration" with membership 1 since IS was trained to recognized the same defect typology even if differently classified.

E. *Recognition with Uncertainty*

The last example discussed here refers to a non-correct defect recognition. Tests performed on a cable composed by two cables having different insulation (XLPE and Oil/Paper) and connected together with a mixed joint, was tested singularly after 349 and after 435 current cycles. Tests were performed at different voltage levels. Figure 7 reports the test results at $1.5U_0$ (19kV). The PRPD pattern of Fig.7A was recognized as "Internal Delamination" (Class C1) with membership 1 while the PRPD pattern of Fig.7B recorded after 86 current cycles, was identified simultaneously as "Void" and "Internal Delamination" with membership 0.46 and 0.54, respectively. PD tests performed on a solid insulation provided by a calibrated cavity ([6]) shown that this type of patterns can be due to discharges incepted on the cavity surfaces. This result can induce misleading conclusions and it belongs to the 15% of wrong defect identification observed during the verification of the proposed algorithm.

CONCLUSIONS

A Fuzzy-Algorithm for the automatic identification of defects supporting PD in MV cables, has been presented in this paper. It resorts to an organization in a tree-structure of robust parameters capable of describing the shape of the dominant polarity of the PRPD patterns independently of the applied voltage, the instrumentation set-up, the location of the defect and in the presence of multiple signal sources. Fuzzy-Logic has been used to take into account the uncertainty of the defect identification. It is shown how additional characters such as variable, multiple and ambiguous PRPD patterns, are necessary to improve the reliability of the identification. No threshold levels, calibration or data-bases are required.

Further investigations are required to reduce the rate of wrong defect identification, that currently account to about 15%, in particular to solve the problem of the defect identification in the presence of ambiguous PRPD patterns. the influence on the Fuzzy-Algorithm of temperature and humidity will be evaluated in the future.

The above discussion highlights that a more complete information on the possible shapes of PRPD patterns is mandatory before applying AI techniques, thus avoiding misleading results.

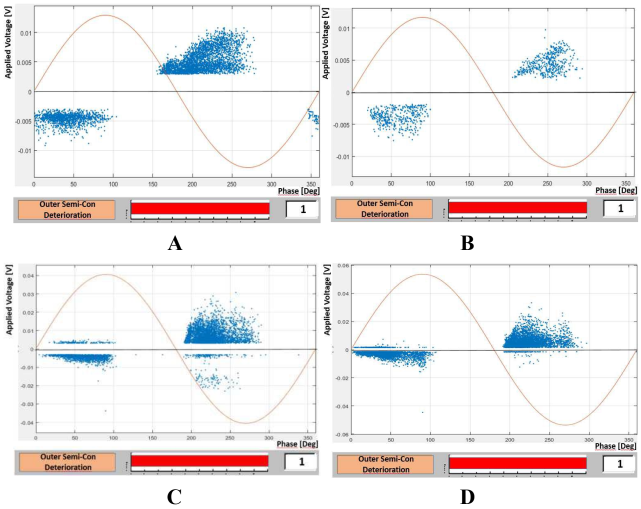


Fig.6. PRPD patterns due to discharges occurring due to deterioration of outer stress-grading layer. PD patterns recorded testing A) a MV cable at its rated voltage of 16kV; B) and artificial defect obtained testing an abraded semi-con material; C) and D) a new cable provided by a joint in the middle. Test performed using a Ck=2nF (C) and a HFCT (D).

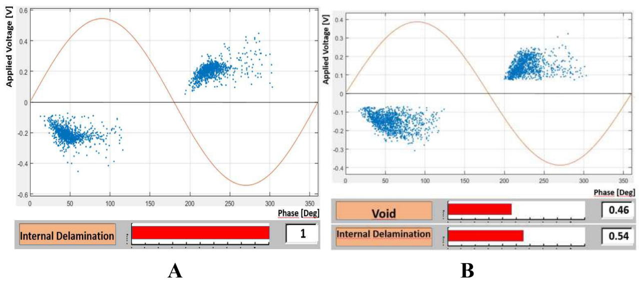


Fig.7. PRPD patterns recorded on a MV cable insulated with Oil/paper and XLPE. PRPD patterns recorded off-line at $1.5U_0$, after A) 349 and B) 435 current cycles.

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