Optimized Deployment of Online Partial Discharge Monitoring Solutions for Distribution Grids

Antonio GONZÁLEZ*[1], Javier ORTEGO[2,4], Fernando GARNACHO[3,4]
(1) EDP REDES ESPAÑA, (2) AMPACIMON, (3) LCOE, (4) UPM
Spain
antonio.gonzalez@viesgo.es

SUMMARY

Distribution system operators (DSO) maintain large number of infrastructures with different levels of criticality where punctual or permanent partial discharge (PD) monitoring strategies could be applied to control the insulation condition.

There is a wide range of sensors, measuring instruments and technologies to diagnose PD defects in the cables, power transformers, GIS and MV cabins. Establishing a common and flexible method to monitor the different elements is not always possible. Each manufacturer provides solutions adapted to the asset type with alternative coverage, level of automation, and cost for the investment in equipment infrastructure.

In this article, essentially it is introduced the results of the project to develop the strategy of EDP REDES ESPAÑA to deploy PD monitoring in the MV grid that can optimally cover the largest number of assets. Several monitoring requirements to optimize the sensor deployment are analysed in the paper as signal processing techniques, sensor bandwidth and sensor position that permits to reach the maximum sensitivity.

The chosen monitoring strategy consist of installing permanent low-cost high frequency current transformer (HFCT) sensor combined with periodic punctual monitoring using portable equipment to arrange the predictive maintenance of the grid, accomplishing the Spanish regulation that requires main insulation review every 3 years. In the initial phase before the deployment of the DSO, a permanent low-cost HFCT sensor has been developed to be installed on cables at strategic positions to diagnose insulation condition of the maximum number of elements.

One of the objectives in the strategy of the DSO is to reduce the high expertise level in the resources used for the measurements and diagnostics, for this reason, different levels of diagnostic are presented in the article applying the AI tools developed by EDP REDES ESPAÑA to automatically discard PD measurements without the presence of insulation defects.

Finally, it is shown the experience of the study of the MV grid to deploy the low-cost sensors following the developed strategy.

KEYWORDS

Partial discharge – PD – Distribution grid – Insulation condition – Predictive maintenance – Defect detection - Smart grids – Sensors – Monitoring - Deployment – Underground cable – Sensitivity – Noise rejection – Artificial intelligence.

1. INTRODUCTION

The greatest difficulty of the widespread implementation of partial discharge measures in medium voltage distribution grids is the cost of measurement infrastructures and the challenge of automatic diagnostics of insulation defects.

This article introduces the development of a robust, low-cost sensor for PD measurement with high technical sensitivity performance, flat frequency response, high noise immunity, self-calibration coil and high dielectric stiffness, which allows to be installed massively at strategic points of the distribution network, as well as the development of intelligent software capable of automatically separating different sources of PDs and recognizing in a basic way the condition "NO DEFECT". This new AI tool leaves the periodic inspections of the insulation condition of electrical grids within the reach of technical maintenance departments, without specific qualification in PDs.

It describes the strategy established by EDP REDES ESPAÑA for mass installation of sensors at certain points in the medium voltage grid to perform fast and effective PDs measurements by maintenance technicians without specialization in PDs. The basic neural network of interpretation "NO DEFECT" allows to screen the grids that are clean of defect of those that may have problems. The second level of screening can also be performed by a company technician with very basic knowledge in PDs. Only doubtful cases, which represent a very small percentage, are those that need to be analysed by specialists who are experts in PDs measures.

2. BASIC CONCEPTS AND REQUIREMENTS FOR ONLINE PD MONITORING IN MV GRID

Different analysis tools are often used to detect PD mixed with the noise of the installation, to locate the PD along the cables and accessories, to cluster the different PD phenomena that could appear in the same location and to recognize the phase resolved PD pattern that identifies the type of defect. Not all of them are available in all the cases neither are automatic always. To use some of those tools sometimes are needed additional resources as sensors, instruments, generators, also could be needed to disconnect the system (offline test) to perform a good analysis with some of the alternatives. And most of them will require a high expertise to perform the diagnosis [1][3][4].

Considering the wide range of available options, it is necessary to establish a good strategy that allows minimizing the costs necessary to apply predictive maintenance using this type of test. The strategy adapted by EDP REDES ESPAÑA is divided in two levels: detection and location.

LEVEL 1: PD Detection

In this level it is only necessary to perform monitoring to detect the existing defects on the installation (cables, switchgears, GIS, transformers). The main goal is to cover the maximum number of assets with the minimum effort and a good sensitivity. As result of this first evaluation, it should be obtained information to [13]:

- Discard assets without PD or with PD not dangerous for the insulation.
- Identification of assets with higher PD activity to be included in the preventive action plan.
- Identification of assets with advance or critical defects to be located (Level 2) and repaired.
- Identification of assets with incipient defects to be follow-up.

It is important to mention that depending on the type of cable insulation (XLPE, EPR, PILC…) the criteria to determine what is advance or incipient could change.

1) Sensor installation for PD detection

To cover this level of monitoring the best approach is using a sensor with the best sensitivity to find PD in the longest distance covering the maximum number of assets. Typically, in distribution grid this is done by using High Frequency Current Transformers (HFCT) [10]. This sensor can work in the range of tens of megahertz been able to cover detection of PD defects up to 2 km in a cable system using solid bonding configuration with a very conservative detection threshold level.

Figure 1 shows the attenuation model for a MV cable system of 2 km [12] considering a sensitivity detection level of 10 pC at 0 m from the position of the sensor. In frequency bands higher than 10 MHz it is not really interesting the measurement because the attenuation having the assumed that the goal of this Level 1 is using a sensor for the maximum coverage. It is also important to consider that frequency band under 1 MHz use to have a high signal noise ratio being impossible to detect any PD pulse under the background noise.

For this reason, from the point of view of detection capabilities, the best option for the deployment of sensors to carry out the Level 1 of this predictive maintenance strategy is using HFCT sensors with the best response between 1 MHz and 10 MHz. However, other important aspects to make a satisfactory deployment should not be underestimated, such as: cost of manufacturing the sensor, robustness, capacity to self-check, noise interference immunity and insulation to protect equipment and operator.

To minimize the number of sensors as this level of PD detection does not require the identification of the affected phase, could be used only one sensor for the three phases to reduce by three the total number of sensors needed to cover the MV grid [7].

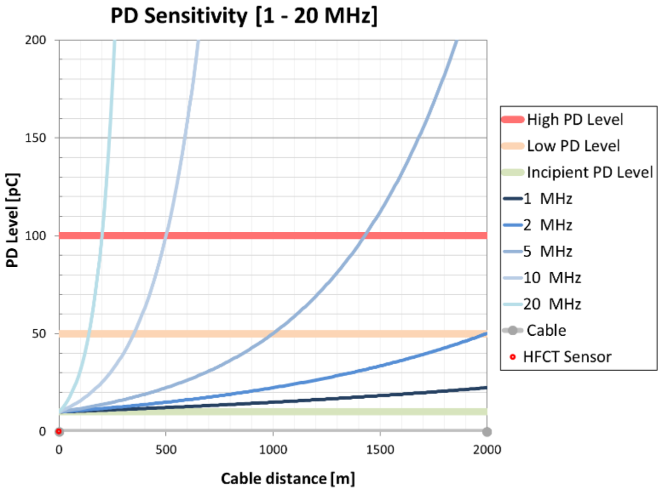

Figure 1. *PD Pulse attenuation model for straight MV underground cable*

2) Analysis tools required for PD detection

The goal of this level is detecting defects with automatic analysis tools to be done by the technicians in the maintenance team of DSOs without the help of a diagnosis PD expert. From the long list of analysis tools available it is only needed:

a) Automatic acquisition and filtering of background noise to detect very small PD pulses.
b) Automatic clustering of different PD phenomena presents in the measurement that have reached the HFCT sensor.
c) Automatic recognition of PD pattern to determine there is or there is no defect.

LEVEL 2: PD Location

In this level it is necessary to perform measurements with the available techniques to locate the PD defect and to repair it later.

1) Sensor installation for PD location

In this case more options appear:

a) Localization in cable by means of synchronized measurements at both terminations (highly recommended).
b) Localization in cable by means of reflectometry (offline test is recommended to have a simpler analysis)
c) Localization in switchgears, GIS or Transformer by means of UHF or acoustic sensors.

It is also important to consider that three sensors for the three phases will be needed to distinguish the affected phase.

2) Analysis tools required for PD location

The goal of this level is location of defects with automatic analysis tools to be done by the technicians in the maintenance team of DSOs without the help of a diagnosis PD expert. Additionally, to the tools uses in Level 1, it will be needed:

a) Automatic pulse polarity identification to distinguish the affected cable section.
b) Automatic identification of PD sources located along the cable system.

3. NEW LOW-COST PD SENSOR

Characteristics required for permanent PD sensor installation

High frequency current transformers, HFCT, are sensors commonly used for the measurement of partial discharge, however, in the absence of an application standard, the characteristics that must be required for this type of sensors are not well known [5]. The following sections describe and compare the five most important characteristics to be met:

1) Transfer impedance better than 8 mV/mA and constant (variation < ± 10%) in the measurement range of 1 MHz to 30 MHz.
2) Self-check capacity by an auxiliary coil for signal injection of PD pulse type
3) Shielding better than -40 dB, for frequencies up to 30 MHz to limit interference.
4) Dielectric strength greater than 10 kV at 50 Hz.
5) Good corrosion performance.

1) High transfer impedance in the range of 1 MHz to 30 MHz

The transfer impedance of the sensor is defined as the transfer function of the output voltage related to the input current when the output is charged with an impedance of 50Ω. Some sensors that have a high transfer impedance (e.g. > 8 mV/mA) in the frequency range of interest from 1 MHz to 30 MHz are not able to keep it constant in this high frequency band (see curves (1) and (2) in Figure 2.a), which produces a distortion of the waveshape of the partial discharge pulse to be measured. Other sensors that keep their transfer impedance constant in the frequency range of interest (for example the sensors indicated with curves (3) and (4) in Figure 2.a) but have a low transfer impedance (< 5 mV/mA).

A sensor designed and built in an optimized way must maintain a high transfer impedance depending on the frequency with flat response (< ± 10%), in the frequency range of interest between 1 MHz and 30 MHz, such as that shown in curve (5) which has a transfer impedance of 8.3 mV/mA thanks to its special design and ideal selection of materials.

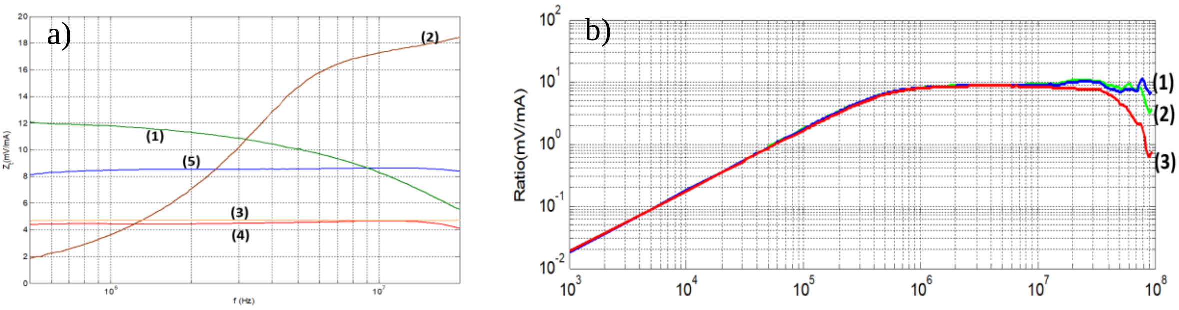

Figure 2. *a) Comparison of transfer impedance between 1 MHz and 10 MHz for different sensors available in the market; b) Transfer impedance of the new low-cost sensor. Prototype (1) with self-check coil, (2) without self-check coil, (3) with self-check coil and internal shielding.*

2) Self-checkable by calibration pulse injection

It is important that the sensor has an auxiliary coil for self-check pulse injection (calibration pulse), since the solicitations in high voltage installations, such as short circuits, surges due to switching or atmospheric discharges, can cause damage to the core of the sensor with degradation of its magnetization curve that would cause changes in its transfer impedance. The auxiliary coil allows the injection of a check pulse without having to disassemble it from the grid that monitors. Although, the existence of this auxiliary coil reduces the amplitude and frequency response of the sensor, a resistance in series with the self-check coil, as shown in Figure 2.b limits this detrimental effect. The curve (1) of Figure 2.b corresponds to the characteristic of the sensor designed in an optimized way when the self-check coil with resistance in series is available and the curve (2) corresponds with the same sensor without including the self-check coil. The comparison between the two curves assumes a negligible transfer impedance loss at frequencies < 30 MHz and up to 5% for a frequency of 70 MHz. The curve (3) in this Figure 2.b corresponds to the sensor with self-check coil and with an internal copper shielding to improve electromagnetic immunity.

3) High interference immunity for frequencies up to 30 MHz

HFCT type sensors that are used for continuous monitoring of partial discharge in high voltage installations under service conditions are exposed to high electric fields, on the order of tens of volts per meter. Therefore, it is necessary to have a metal shielding to avoid electromagnetic interferences.

However, many commercial sensors do not have this shielding, such as the sensor corresponding to the characteristic curve (1) shown in Figure 3.a. The induced interference in the winding of measurement for frequencies up to 30 MHz is on the order of ten times greater than that induced in the sensors that have metal shielding, grouped with the oval (2) in Figure 3.a.

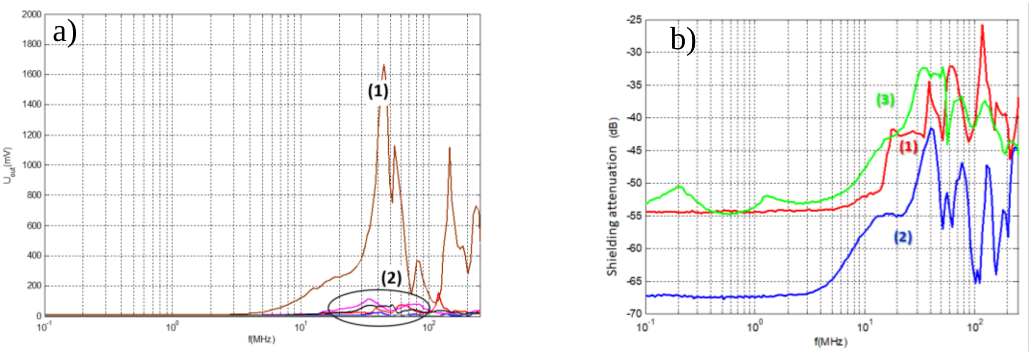

Figure 3. *a) Induced interference in the measurement winding of the sensor. (1) Sensor without metal shielding, (2) sensors with metal shielding. b) Shielding attenuation as function of frequency. (1) 0.2mm copper, (2) 1mm copper, (3) 1mm aluminium.*

When an internal shielding with copper sheet of 0.2 mm thick is available, which shields the measuring and self-check coils together with the ferrite core, all embedded in resin (sensor (1) in Figure 3.b) its characteristic induced voltage is comparable with the characteristic curves of sensors (2) and (3) that have shielding of 1 mm thick in copper or aluminium, respectively. This Figure 3.b shows the sensor shielding attenuation characteristics expressed in (dB) as a function of frequency.

4) High electrical insulation characteristic (>10 kV at 50 Hz)

The external metal shields painted or coated with varnish are effective in terms of electromagnetic immunity but are deficient from the point of view of electrical insulation, since an abrasion or defect of the paint or varnish causes it to deriving on dangerous voltages, endangering the integrity of the measuring instrument and even of the operator that handles it. Protection from internal copper shielding by a thickness of several millimetres (>3 mm) of epoxy resin ensures electrical insulation exceeding 10 kV at 50 Hz, which may appear in the grounded masses of high voltage equipment and installations.

5) High behaviour against corrosion

The sensors embedded in resin have a compact and robust design against the effects of corrosion, as there is no external metal part exposed to the corrosive atmospheric agents that could appear in the installation where it is installed. Salt mist tests must be required to demonstrate the suitability of the constructive solution.

4. NEW ARTIFICIAL INTELLIGENCE TOOLS FOR DIAGNOSIS

In this section are described the new automatic analysis tools developed to permit no expert technicians to carry out PD detection and PD location.

Automatic tools needed for PD Detection

As described previously in the paper, for PD detection there are three main tools. Automatic Filtering of PD pulses has been the biggest challenge for PD monitoring specially when cables are part of the assets to be diagnosed. This has been solved by different techniques, but the most powerful and automatic solution is the technique base on wavelet transform [2].

The other two analysis tools have been improved in the last developments presented in this paper.

1) New automatic clustering tool

For the clustering of the different phenomena has been used a new algorithm base on AI clustering tools on the three wave shape parameters extracted by Ampacimon PD equipment (α, β, ω). These parameters extracted after denoising process by means of a fitting approximation to the mathematical model (see equations 1-3) of the pulse wave shape, permit to distinguish different PD phenomena present in the installation that generate PD pulses reaching the HFCT sensor [9].

$$i_i(t) = g_i(t)\, h_i(t) \qquad (1)$$

$$g_i(t) = A_i \sin(\omega_i t - \psi_i) \qquad (2)$$

$$h_i(t) = {}^{1}\!/_{e^{\alpha_i(t-t_{0i})} + e^{-\beta_i(t-t_{0i})}} \qquad (3)$$

where:
$i_i(t)$ = Mathematical model of the PD pulse
$g_i(t)$ = Sinusoidal function associated with pulse
$h_i(t)$ = Asymmetric hyperbolic secant that modules the sine function
A_i = Amplitude (V)
ω_i= Oscillation frequency (radians)
t = Time variable (s)
ψ_i = Phase displacement (radians)
α_i and β_i = shape parameters
t_{0i} = Temporary displacement (s)

The automatic clustering tool has been implemented to automatically detect the number of clusters present in the measurement been able to generate a list of clusters representing patterns of different PD phenomena.

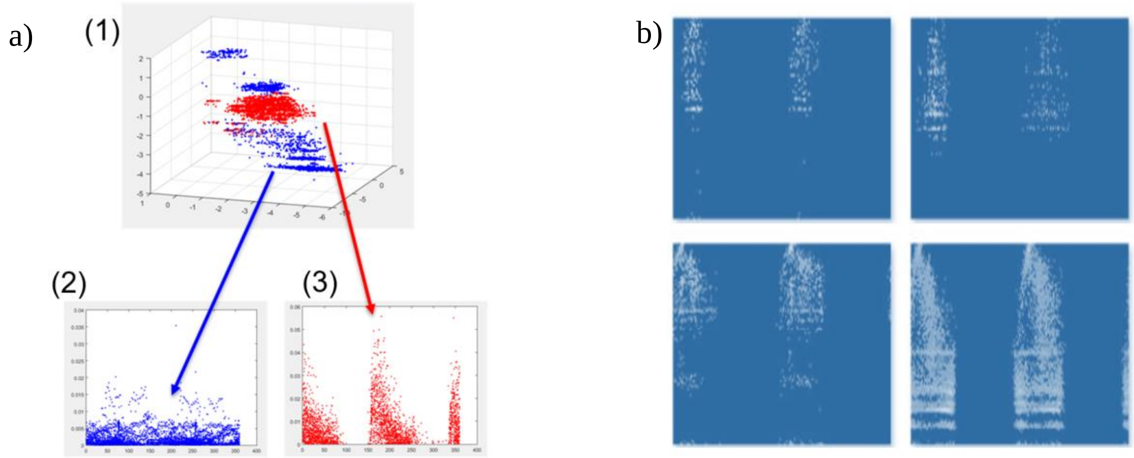

Figure 4. *a) Automatic clustering tool. (1) Three-dimensional space representation of PD detected with α, β, ω parameters, (2) pattern of blue cluster, (3) pattern of red cluster. b) Examples of 2D grid used for the pattern recognition tool.*

To validate this new AI tools has been used a database of 180 real measurements of that has been diagnosed manually by PD experts. After correlating the automatic clustering with the manual results, the effectiveness to cluster internal defect patterns in the internal insulation is 90.5%.

2) New pattern recognition tool

To perform recognition of the PD pattern in AC voltage systems has been developed a new neural network base on a 2D grid to carry out the recognition (see Figure 4.b). The images used for the recognition are equivalent to the PRPD pattern that are used by technicians to perform manual recognition of the PD defect. Logarithmic scale has been used for the recognition tool to be more robust against any mixed noise. Training has been carried out with random offsets in the phase angle to be able to recognize PD defects coming from any of the three phases.

The convolutional neural network has been trained with a database of 2000 real PD patterns classified by PD experts in four categories of the most common PD present in MV grid. As internal void and internal surface discharges tend to have a similar PRPD pattern after some weeks of activity, because both patterns have similar characteristics in terms of phase distribution, they have been categorized together in the recognition tool as Internal. The result of the test with 400 samples is show in the next table.

Table 1. *Confusion matrix for Pattern recognition tool.*

Type	External surface	Corona	Floating potential	Internal
External surface	92.5%	1.5%	1.2%	0.9%
Corona	8.7%	84.5%	1.3%	1.3%
Floating potential	3.0%	0.7%	87.1%	5.5%
Internal	7.6%	0.8%	13.6%	70.1%

Automatic tools needed for PD Location

Two analysis tools have been improved in the last developments presented in this paper to cover location by no PD experts in DSO.

1) Improved automatic pulse polarity identification

Pulse polarity is analysed to determine the direction of the current when PD appears [11]. This analysis applied on the measurements done in Level 1 of the predictive maintenance plan could determine the affected cable section (see Figure 5).

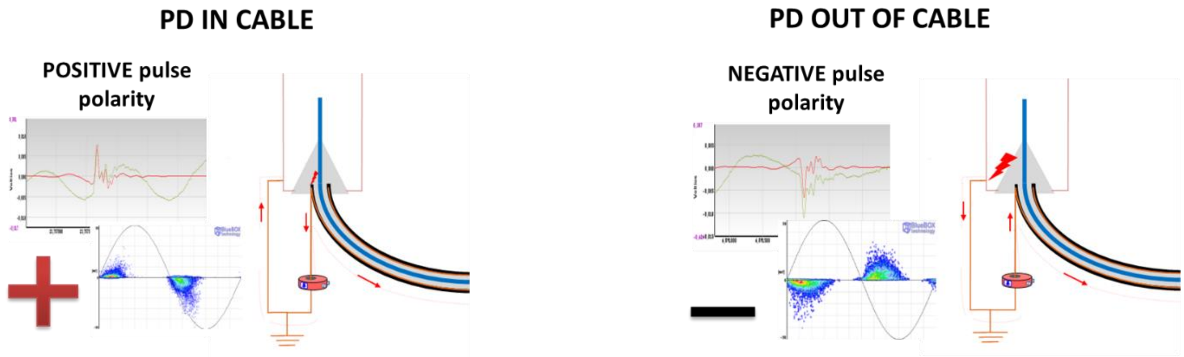

Figure 5. *Polarity analysis using HFCT sensor.*

Depending on the wave shape of the pulse specially on the frequency content and the magnitude could be more difficult to interpretate which is the polarity of the pulse. In this improvement, three different methods have been implemented and compared to determine the polarity of the current pulse of PD. A comparison of the three methods has been done with more than 150k samples of PD pulses, obtained in real measurements during the last 5 years in EDP distribution grid that have been classified (positive/negative pulses) by technician during the diagnostic process.

a) **Method of maximum** is a simple way to determine the polarity base on the polarity of the maximum absolute peak of the signal (see example in Figure 6.a). This method has obtained a success rate of 90% over the total dataset.

b) **Method of derivate** uses the first peak of the derivate crossing the 75% of the absolute maximum of the derivate to determine the position of the front of the pulse and the polarity. In the example of the Figure 6.b can be determined a negative polarity because the first cross of the 75% of the absolute maximum of the derivate occurs when the original pulse has a negative slope. This method has obtained a success rate of 98% over the total dataset.

c) **Method of the accumulated energy** uses the accumulated energy and the slope of the first zero-cross that happens after the maximum of the accumulated energy to determine the front polarity. In the example of Figure 6.c can be determined negative polarity because the first zero-cross that appears after the maximum has a negative slope. This method has obtained a success rate of 65% over the total dataset. This result is very low in comparison to the other two previous methods, but the efficiency of this method is complementary to the others when pulses have low frequency content and low magnitude.

Both methods using the maximum and the derivate are already very accurate. In the new tool has been implemented a final method with the combination of the three described methods, based on a logic of correlation between the three results where final result is taking into account the most common result obtained with the three alternatives. This new combination take advantage of the accumulated energy method to solve cases where the others discrep and it has achieved a success rate of 100% over the 150k samples.

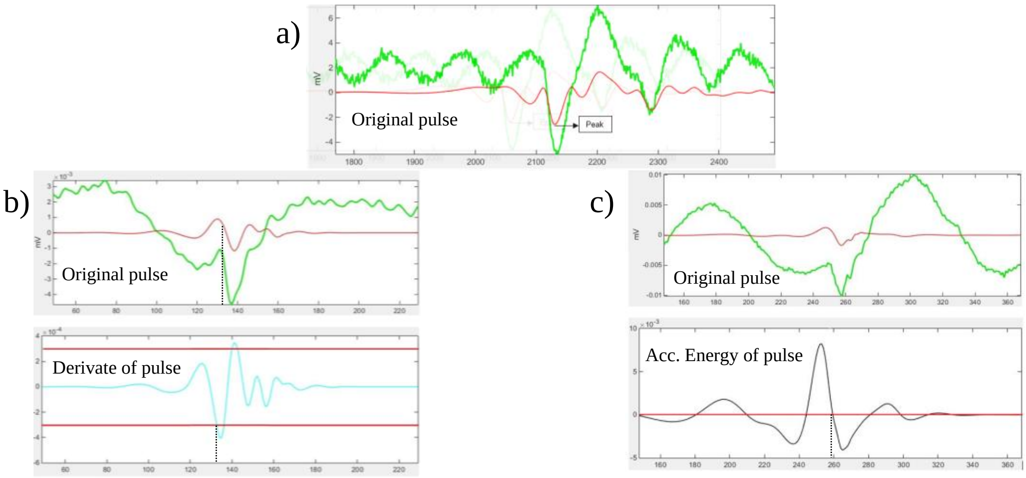

Figure 6. *a) Polarity analysis by peak, b) Polarity analysis by derivate and c) Polarity analysis by accumulated energy. Note: green signal in original pulse is the raw signal acquired by HFCT sensor and red signal is the same signal after automatic denoising.*

1) New automatic PD source location

This tool has been developed to identify automatically when exits a PD source located in the PD mapping. The tool is based on different statistical analysis of the distribution to determine when exists a gaussian distribution representing a PD source [8][6].

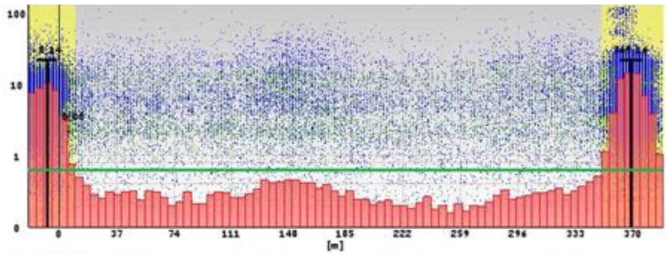

Figure 7. *Example of analysis of the located PD distribution. In the example 2 PD sources at the positions of cable terminations.*

5. DEPLOYMENT EXPERIENCE

Sensor deployment to perform PD monitoring under PD Detection (Level 1) strategy in EDP REDES ESPAÑA's distribution grid has been analysed, that represents 54% of the underground network of EDP REDES ESPAÑA. A total length of 2169 km of underground cable has been analysed. To cover 97% of the installation (cable, switchgear, GIS, transformers) with good sensitivity it is required:

Table 2. *Summary of sensors required*

Sensor position	Quantity
Substation	446
Secondary substation	2892
Pole (OHL connection)	315
Total	**3653**

To run this analysis automatically over more than 8400 cable sections, it has been implemented an analysis software to select the best positions to install sensors base on the rules of attenuation depending on the cable lengths, type of termination and the number of connections in the same substation or secondary substation.

During the last 5 years these measurements have been done using portable equipment and portable HFCT sensors, now permanent deployment has started following this analysis with a plan to install sensors during the next 3 years to cover all the grid and Spanish regulation.

Typically, the HFCT sensor will cover a distance of 2 km of cable with very good sensitivity if there are no ramifications in the middle. To consider the case of secondary substations, a simple criterion has been applied dividing the remaining sensitivity of the closer sensor by the number of branches (cables) connected to the same node. For the case of transitions to overhead lines (OHL) in case of installing HFCT sensors in this point sensitivity has been considered 10 times lower due to the fact that OHL has around 10 times less capacity than the underground cable and propagation of the PD pulse current will be affected.

CONCLUSIONS

Predictive maintenance for underground systems become to be more and more requested due to the aging of the cables and the increase of failures associated. PD monitoring approaches are very popular but not all are designed to optimize the infrastructure of sensors and the professional services linked to the measurement. The development of the new low-cost sensor and the new AI tools presented in this paper permit to implement a viable deployment and a coherent strategy using mainly the internal resources of the distribution system operators as EDP REDES ESPAÑA.

The key factor for an optimal deployment is a sensor with the best sensitivity that it is reached by means of a HFCT design oriented for long scope, robustness, high immunity beside the best acquisition system to find small PD pulses under the high electrical noise of the grid. Developed sensor has very flat response in the band from 1MHz to 10MHz to reach good detection sensitivity up to 2 km in straight cable.

The new AI tools are able to automatically perform the diagnostic of Level 1 covering clustering with 90% of success rate, recognition of internal defects with 70% of confidence. Improvement of the recognition tool to reach higher level of confidence is planned as future work.

Localization of defects has been automatized with very high level of confidence base on localization using synchronized sensors and polarity analysis.

Automatic tools applying very generic rules to standardize the way to select the strategic position to place the minimum number of sensors with the best sensitivity are needed to optimize the infrastructure for PD monitoring in distribution grid. Base con the case study of the deployment experience for 2169 km of cable are needed 3653 HFCT sensors to cover the detection of PD with good sensitivity level. This ratio means that one HFCT sensor is installed every 600m of cable jumping 2 of 3 secondary substations in this particular case.

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