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PS1 – Learning from Experiences

# REE´s commitment to partial discharge monitoring in its underground cable network

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**SUMMARY**

The measurement of partial discharges (PD) is a reliable tool for ascertaining the insulation state in high voltage equipment, especially insulated cable systems, as well as for preventing faults in these installations.

The efficiency of this tool is greatly increased when the information is obtained on a continuous basis as opposed to the periodic inspections, because the analysis of the insulation state is closer to reality. The information obtained is transferred to the company's asset management system.

Technological advances in monitoring of partial discharges have allowed the Spanish TSO to deploy equipment that sends data from each cable circuit, through the internal network, to the Integrated Facilities Maintenance Centre. In this centre a group of experts in line maintenance analyses the information. The main purpose of the analysis is to classify the origin of the partial discharges detected and focus on those ones that come from an internal defect. Once a signal that may be dangerous for the cable insulation is identified and located, a maintenance action must be decided in order to prevent the installation failure.

In 2020, the Spanish TSO has made the forward leap from having a pilot project for monitoring PDs in one circuit to having a significant number of circuits monitored. There are 36 circuits sending PD measurements online continuously. Additionally, the staff has 9 portable devices that measure temporarily, with the capacity to cover around 150 circuits per year. The installation has been carried out in coordination with the different departments and company’s regional areas.

However, the installation of PD sensors and equipment introduced some challenges:

- Programmed outages of the circuits to enable installation of the PD sensors.
- Power supply either via the substation power network or via autonomous systems, where necessary.
- Optimisation of the location and connection option for the equipment.
- Connection to the internal telecommunication network to enable the transfer of the large amount of data generated by the PD equipment.
- Establishing cybersecurity by following the internal security standards and communication protocols.

Monitoring allows having greater control and maintenance management based on the risk and criticality of the facilities. Based on the data analysed, decisions can be made to prioritise maintenance tasks and thus, reduce the time that circuits are unavailable, in addition to anticipating any faults that may occur.

The Spanish TSO has carried out laboratory tests that have shown partial discharges can be measured during existing overvoltages in the network, either due to fast transients such as lightning or due to slow transients such as switching. This research may give rise to change the method of sporadic PD measurement.

In the future, the number of permanently monitored facilities is expected to continue increasing as part of Power Line Monitoring Strategy. This strategy includes monitoring of other parameters like sheath current, temperature, mechanical vibration, etc. At the same time, continuous efforts are being made on awareness and application of the most suitable monitoring technologies available on the market.

**KEYWORDS**

Partial Discharge, Monitoring, Cable Systems, Preventive Maintenance.

## 1. INTRODUCTION

One of the main difficulties in maintenance of cable systems, underground and submarine, is that checking the health state of the installations is not always easy or possible. Indirect parameters must be measured in order to estimate the remaining life or to predict whether a circuit will likely suffer a failure in a short or mid-term. Examples of parameters that can be monitored are the temperature along the whole circuit or in some points, the current measured in the sheaths, the mechanical vibration or the partial discharges detected in the main insulation of the cables and accessories.

An important decision for a utility, in order to optimize the resources dedicated to preventive maintenance, is choosing which parameters should be measured and what is the optimum frequency to perform the different inspections. The choice is normally made between occasional measurements or continuous monitoring.

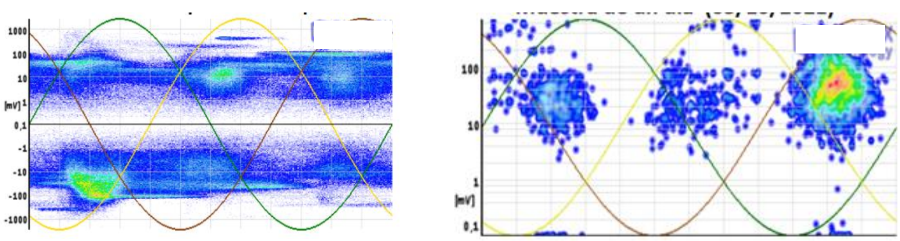
This paper presents the traditional maintenance model of Partial Discharge (PD) inspection performed by the Spanish TSO. In addition, the commitment of the company to PD monitoring, is showed in the inspection strategy for the present and challenges seen for the future.

## 2. IMPORTANCE OF PARTIAL DISCHARGE MEASURING IN CABLE SYSTEMS

The Spanish TSO has more than 2.000 km of cable installation in service. Based on the experience of several years managing the maintenance of these cable systems including analysis of the results, the maintenance team has concluded that online PD measurements are, at this moment, the most reliable tool to know the state of the insulation of the cable and accessories. Therefore, PD can be a very useful tool to prevent failures in the circuits, which is one of the maintenance objectives.

On the other hand, depending on the type of installation, PD measurements are not always easy or even possible. PD measurements are a significant expenditure as measurement equipment, and their installation, entail an important investment for the company. Hence, prior to any investment decision a case study must be done to evaluate the possible benefits of such investment.

Besides, although PD measurement can offer very valuable information about the insulation state, the management and analysis of the data coming from the measurement equipment is not easy. Signal filtering and correct interpretation of the PD parameters must be done to identify if PD exist in the installation and, if so, if the PD corresponds to corona, external surface discharge, e.g., on the outside of the termination, or internal cavity (the dangerous one). In figure 1, an example before and after filtering can be seen.



(a) (b)

*Figure 1. Example of PD signals before (a) and after filtering (b) for external surface discharge*

## 3. TRADITIONAL MAINTENANCE MODEL

The traditional maintenance inspection model in the company included periodic inspections such as thermography, sheath test, PD measurements, etc. in all underground cable circuits. In particular, PD were measured in all the elements of the underground cables, but only making periodic short-term measurements, i.e., measurements performed once every five years and lasting approximately 30 minutes.

The company's maintenance policy is to replace the affected accessory as soon as an internal defect is identified in the PD measurements.

An analysis process was performed to study the efficiency of the periodic inspection of the traditional model. In the last 4 years, around 2000 short-term PD measurements have been performed in high voltage circuits above 100 kV resulting in only one case with patterns of internal PD. In the same period, around 600 short-term PD measurements were performed in circuits below 100 kV, resulting in five detected cases with internal PD.

Even though the above-mentioned inspections have enabled the anticipation of several failures in cables with voltages of less than 100 kV, in general, the low frequency of inspections did not give sufficient information which would enable prevention or avoidance of insulation failures. Consequently, some changes were introduced in the PD inspection strategy.

## 4. CURRENT STRATEGY

### 4.1. General improvements

To solve the weakness detected in the traditional PD inspection model, the current PD strategy includes the following ideas:

- Improvement of the PD inspection quality: continuous monitoring or temporary monitoring instead of periodic short-term measurements.

- Increase of the number of elements to inspect with continuous PD monitoring. Only selected underground circuits will have this type of inspection. The selection criterion is based on the risk and importance of the circuits for the company and on the maintenance criteria.

*Figure 2. Training of company's staff on PD measuring equipment at a substation.*

- Training of company's own personnel to handle the PD equipment. This provides benefits to the strategy, as the internal crew can perform necessary works faster, decreasing the time of unavailability of the circuits. This way internal know-how is increased and more value to the own staff is given. Moreover, internal training reduces the dependency on external providers and their associated costs.

- Acquisition of more versatile and portable PD measurement equipment. PD devices with a multiplexer are sometimes prioritised, as they allow measuring several circuits with only one equipment and installation and thus, lead to cost savings.

*Figure 3. Portable PD equipment*

- Increase of the number of circuits with PD monitoring from one circuit measured in a pilot project, near Madrid [1] in 2014, to 36 measuring points across Spain in 2021. Currently, this equipment is under installation in another 25 circuits.

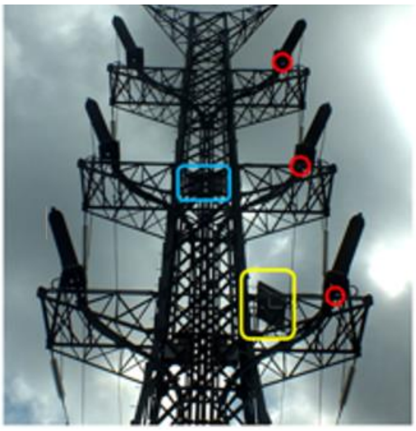
- Integration within maintenance control centre in the company:
  There are several control centres in the company and one of them is dedicated to the maintenance of the installations, the Integrated Facilities Maintenance Centre (CMI2) [1]. The CMI2 is designed as a place to receive information of the installations, analyse the inputs, and take maintenance decisions in real time. At the CMI2, alerts and alarms coming from monitoring systems are managed with different software and connected to the target staff.

During the installation of the PD monitoring systems, different tasks had to be arranged:

- Power outages in circuits: programmed outages or other kind of interventions were planned to install the PD sensors with external and internal staff working coordinated. Normally, an outage of a few hours is enough for this kind of installation.

- Power supply: connection to the substation power network was performed, where available, using a standard AC socket. Where necessary, different autonomous systems were implemented, e.g., power supply photovoltaic panels and batteries were installed in terminations located at transition towers. For example, in figure 4a the photovoltaic panels are shown in yellow, the HFCT sensors in red and the measurement equipment in blue.

- In joint bays, the absence of power supply is usually a limitation for installing PD monitoring systems. Providing alternative power supply systems could be impossible, e.g., in non-accessible joint bays, or too costly, e.g., using circuit power harvesting systems. The consequence of this limitation in measuring is that only some parts of the circuit length can be measured. Sensors must be installed optimizing the measured length and costs.



a)

b)

*Figure 4. a) Installation of continuous PD monitoring systems in a transition tower b) Installation of portable PD monitoring systems inside a GIS substation.*

- Placement of the equipment: complete engineering projects had to be undertaken to find the best location and connection option for each set up inside a substation. Sensor sensibility will vary depending on each circuit configuration, thus, the best place to connect the sensor is very important to be evaluated.

  In figure 5, there is an example of a cable circuit with several joints and with total length of 3120 m. The HFCT sensors are installed in both ends of the circuit at GIS terminations.

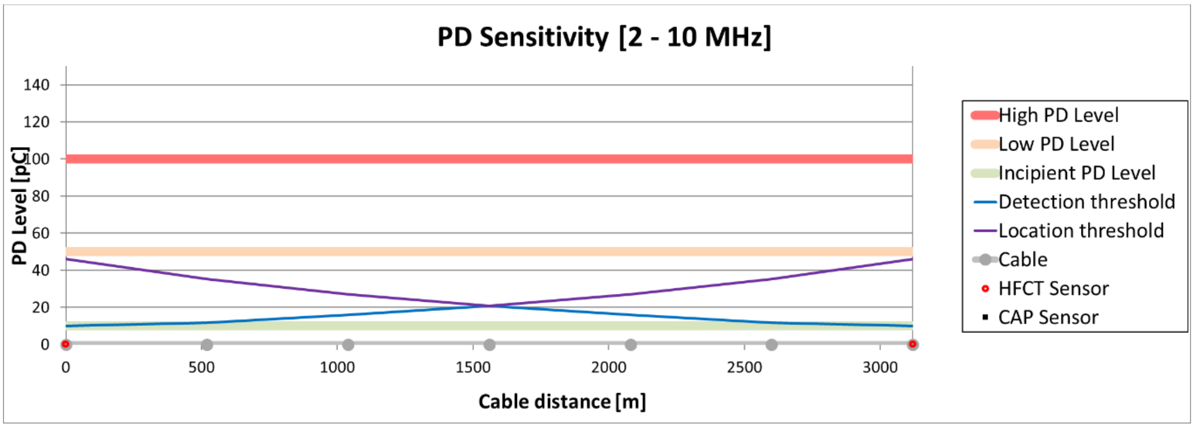



*Figure 5. Analysis of sensor sensibility vs distance for a real circuit in operation.*

  As can be seen in the figure 5, two PD monitoring systems are enough to detect PD at any point of the cable with a low amplitude.

- Communication: Connection to the internal telecommunication network was necessary, due to the amount of data generated by the PD equipment and to enable the scalability of the monitoring of parameters.

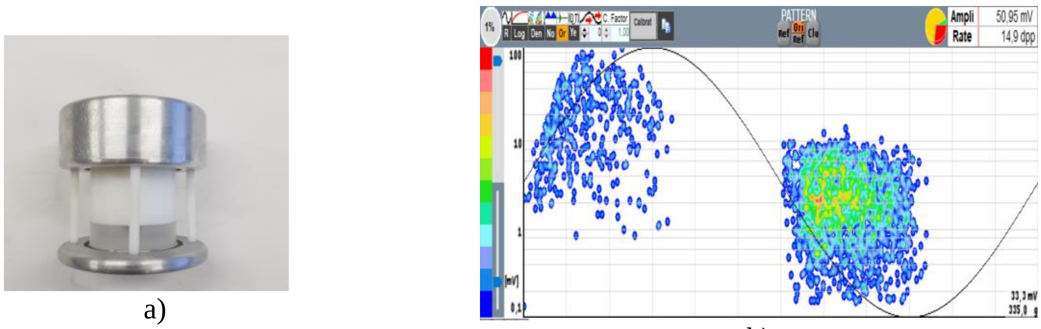
- Cybersecurity: the security standards and internal communication protocols were followed strictly.

### 4.2. New challenge for periodic PD measurements in service in very high voltage systems

As mentioned before, periodic PD measurements, performed at short time intervals (<30 min), have demonstrated low effectivity in very high voltage cable systems. The reason is that in networks above 100 kV at nominal voltage normally there is no detectable PD activity of internal defect type (cavity or internal surface). This circumstance forces to reconsider the way of performing periodic short-term measurements. Recent research [2] has shown that partial discharges can be measured during existing overvoltages in the network, either due to fast transients such as lightning or due to slow transients such as switching. Based on this research, a new PD measurement instrument has been implemented.

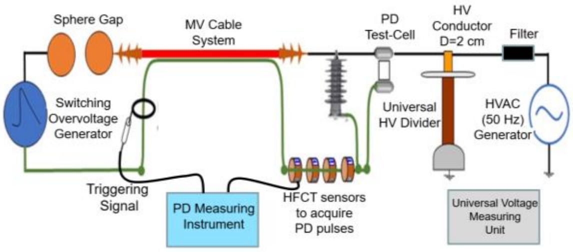
The new developed PD measuring instrument acquires the PD pulse train generated only by transient overvoltages from the network. Research has shown that the PD pulse train lasts for several main cycles, so the PD measuring instrument must be immune to interference caused by the overvoltage itself, but at the same time, must be able to acquire all PD pulses, which occur approximately several grid periods later (say, 1 second) in synchronism with the grid sinusoidal voltage. PD pulses synchronized with the network sine wave will allow the construction of a phase-resolved PD (PRPD) pattern similar to conventional PRPD patterns recorded in continuous PD measurements.

To demonstrate the ability of this new approach the Spanish TSO has performed composite testing in the HV laboratory. The circuit is composed of two HV sources: a 50 Hz HVAC generator (up to 10 kV) and a Marx switching pulse generator (up to 50 kV). The output of the HVAC generator was connected to a small "test cell" with a controlled cavity-type insulation defect through a conductor to simulate an overhead line. The PD inception voltage of this test cell was determined to be $U_i$ = 5.5 kV and its PRPD pattern at 6 kV is shown in Figure 6. A 15 m medium voltage 12/20 kV cable was connected to the opposite end of the HV conductor, and the other termination of the cable was connected to the Switching Marx generator through a sphere gap, generating a switching impulse of 15 kV of peak value. The composite test voltage was measured by a universal measurement system (an universal HV divider and an universal voltage measuring instrument) as shown in Figure 7.



a) b)

*Figure 6. a) Small PD test cell (5 cm height and 5 cm diameter) with a cavity-type insulation defect inside, b) Phase-resolved PD pattern generated by the test cell at 6 kV.*

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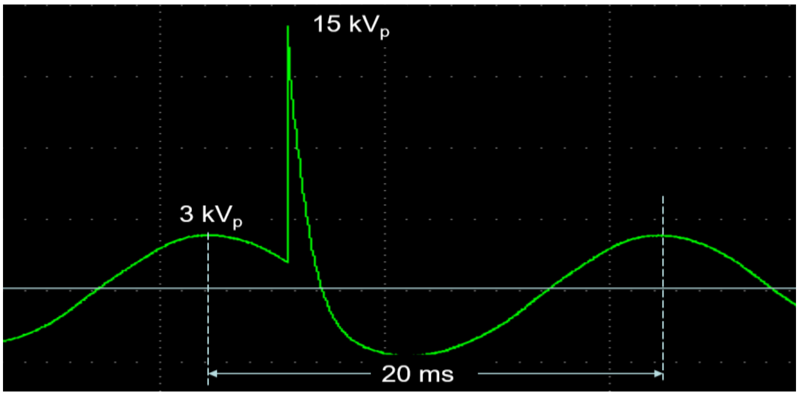
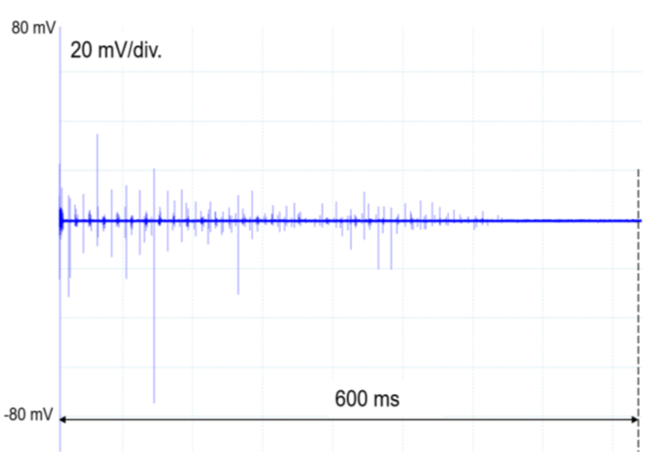


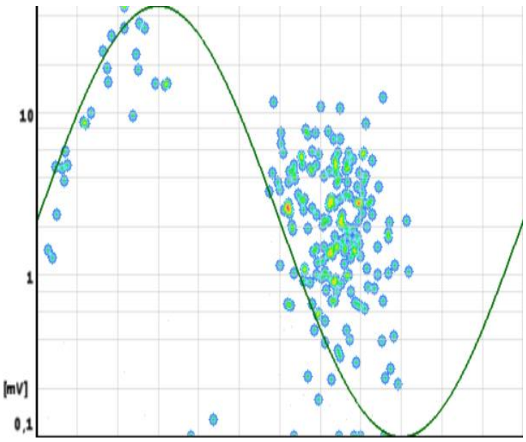

c)

*Figure 7. a) Schematic circuit of a composite voltage test, b) Implemented testing set-up in HV Laboratory, c) Composite voltage waveform measured by the Universal Voltage Measuring Unit.*

Partial discharges in the "test cell" generated by a switching overvoltage were acquired by an HFCT type sensor and processed by the new developed measuring instrument. Figure 8.a shows the record of a PD pulse train for 600 ms (30 periods of 20 ms) and in figure 8.b the corresponding phase-resolved pattern generated by the switching overvoltage.




*a)*




*b)*

*Figure 8. a) PD Pulse train generated by a switching overvoltage, b) Phase resolved pattern of PD pulses from a pulse burst caused by a transient overvoltage*

The phase resolution PD pattern of a PD pulse train caused by a single switching surge may be sufficient to recognize a cavity-type defect in solid insulation because its PD pattern, shown in Figure 8. b, is similar to the PRPD pattern shown in Figure 6. However, overlapping PRPD patterns caused by multiple switching surges (e.g. 7 or 10) give PRPD patterns much easier to recognize as a “cavity type” defect, as shown in Figure 9 and in comparison with Figure 6.

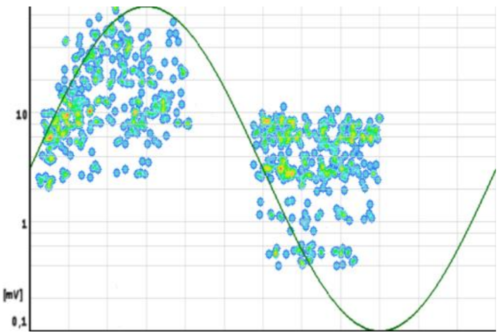



*Figure 9. Phase-resolved pattern of PD pulses for pulse bursts caused by several (e.g. 7) transient overvoltages of the switching type.*

Consequently, synchronized PD measurements during transient overvoltages, e.g. due to the switching operations is a very efficient method for the early detection of insulation faults in high voltage networks.

During the next few years, sporadic PD measurements will be carried out taking advantage of existing overvoltages to demonstrate this research in real installations.

## 5. CONTINOUS MONITORING BENEFITS

The change in the PD inspection strategy has been done to take advantage of the monitoring benefits found for this parameter.

There is a significant improvement in the quality of the measurements. Continuous monitoring equipment collect data continuously ensuring that they capture the PD signals that are not permanent but appear at certain times of the day.

Monitoring means having the information available in real-time, so PD measurements are obtained faster. This helps to prevent possible failures, improve response time and to prioritize maintenance tasks. Monitoring also implies a saving in periodic inspections and travel and can entail a reduction of cost due to reduced unavailability of the circuits.

All company's monitoring projects must follow an evaluation process defined in the monitoring strategy. The reason is to ensure the efficiency of the installed systems and to evaluate the impact of monitoring, cost-benefit analysis must be done for every project.

Within the company, there are synergies between different monitoring projects that are changing and modernizing processes. In general, all these projects require the collaboration of different departments. This allows that the PD monitoring equipment can be used to increase monitoring of other useful parameters, like sheath current [3] [4], temperature, etc.

## 6. FUTURE OF MONITORING

The commitment of the company on partial discharge monitoring for the next years is clear. The number of PD measurement equipment will increase and will be installed at selected circuits.

The health index value, which is defined as a state or technical condition of an asset compared to its ideal state, will be better calculated in underground circuits when monitoring is performed, and these values will be used in the Asset Management System, to optimize the maintenance task of the underground lines.

Automatic analysis and interpretation of PD measurements using artificial intelligence must be promoted. The Spanish TSO is sponsored an artificial intelligence tool. In this way the scalability of PD monitoring will be possible. In this sense, PD alerts and alarms will be generated by this automatic tool.

Additionally, research should continue to resolve the current limits for PD monitoring. An important improvement aspect is development of measurement units with low power consumption as most joint bays do not have power supply. In addition, PD measurements in HVDC circuits are currently not enough developed.

Beyond PD measurements, the installation of PD monitoring systems may be an opportunity to expand monitoring of other parameters, like sheath currents, taking advantage of the synergies of the installation of PD monitoring systems.

## 7. CONCLUSSION

After analysing the maintenance inspections during several years, PD has been identified as a relevant parameter of useful information and a significant change has been performed in the maintenance PD inspections strategy by the Spanish TSO. The current strategy includes selection of critical underground circuits and installation of PD monitoring systems.

In this sense, the commitment of the company to PD monitoring has covered an important investment in PD measurement equipment, training of internal staff and centralizing the PD information at the maintenance control centre (CMI2).

For the future, some challenges must be faced to expand PD monitoring network: PD measurement synchronized with transient overvoltages due to switching operations is a very efficient method to early detection of insulation defects in high voltage networks, the automatic analysis and interpretation of PD measurements using artificial intelligence and the research of technological solutions for the current limits for PD measuring.

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