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# Evaluation of a Low-cost Capacitive Non-intrusive Sensor for the Detection, Localization and Identification of Defects in MVAC Cables

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**Abstract**— Partial discharges (PDs) monitoring is a common tool for diagnosing electrical systems. An innovative, low-cost sensor for distance detection and positioning of partial PDs has been developed. An ambitious challenge for this PD monitoring system is to predict dielectric breakdowns on a grid and particularly in MVAC cables. The first part of the article demonstrates the proper functioning of this sensor on a test bench. In a second part, monitoring measurements of PD activity issued from artificial defects are presented. PD initiated in submillimetric cavities were collected. Parameters and PD patterns have been interpreted with the aim to correlate with the electrical treeing propagation until breakdown. The final section is dedicated to a concise review of electrical treeing monitoring. Analysis of existing approaches are presented, as well as the interesting opportunities offered by the sensor.

**Keywords**— sensor, partial discharge, PD, electrical network, MVAC, cable, defects

## I. INTRODUCTION

Over time and with deterioration, partial discharges (PD) can occur in the insulation of electrical systems. This can lead to the generation of electrical treeing which, as they develop, will lead to the dielectric breakdown of the system [1]. The occurrence of PDs is therefore commonly measured on critical electrical installations such as GIS or transformers. They are used as an indicator of the health of the system, although the evolution of PDs and therefore the remaining lifetime of the system after the occurrence of PDs remains difficult to predict with accuracy.

According to the Altrans Energies company, they have developed a long-distance PD detection system called Translocator [2]. It combines the use of a non-intrusive antenna and signal processing software. This one is based on phase diagram features and has been trained by machine learning to discriminate PD signals from others in real power grid conditions [3][4]. This system aims to significantly reduce installation costs compared with existing solutions. It therefore opens up the possibility of widespread deployment of PD sensors on medium-voltage grids. According to the company, the system has already been deployed on these grids for several years now. It has proved capable of detecting PDs and locating them accurately up to hundreds of meters or even a few kilometers. In the following, it will be referred to as the candidate system.

Although the system is already deployed and in service, it has never yet been formally compared with existing technologies. The second part of this article will be dedicated to this task. The next ambitious challenge for the Altrans company is to estimate the remaining lifetime of a defect before dielectric breakdown, based on its PD activity. In Part

III of this article, we present results on the evolution of PDs over time in dielectric samples. Predictability of dielectric breakdowns will be developed in part IV of the article.

## II. COMPARISON OF THE TWO PD MEASUREMENT TECHNIQUES

### A. Objectives

The aim of this section is to evaluate the candidate system by comparing it with a proven technology on a test bench. To achieve this, a PRPD (Phase Resolved Partial Discharge) pattern is created using a needle-plane device in air. PRPD patterns are often used to identify the type of defects generating PDs. The PDs are measured using both the candidate system and the system based upon the reference technology from ICM [5].

### B. Experimental

The experimental device used is described in fig. 1. The experiments were carried out in a Faraday cage, with a high-voltage transformer which is connected to the needle of a needle-plane test-cell. The distance between the Ogura X-253-9 needle and the plane is 10 mm. The plane is connected by a wire to a 120 k  resistor, the use of which is explained later. This resistor is connected by a wire to the ICM system acquisition hardware. This consists of a CIL4M/V1 0 high-pass filter, which is connected to ground. The voltage signal from the CIL4M is transmitted via coaxial cables to the RPA1 pre-amplifier and then to the acquisition bay, which records the treated data on a computer. Parallel to the transformer's secondary is a capacitive voltage divider bridge which measures a fraction of the applied voltage. This information is used to check the applied voltage and, above all, to determine the phase of the measured PDs.

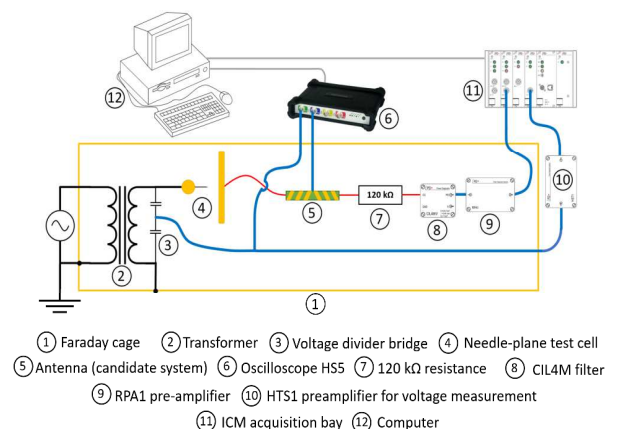


Fig. 1 Principle diagram of the experimental set-up

The wire connecting the plane point device to the 120 k $\Omega$  resistor passes through a tube around which the antenna of the candidate system is wound. This is connected by a coaxial cable to a TiePie Handyscope HS5 oscilloscope, which samples data at 50 MHz and records them on a computer. The recorded data is then processed by Altrans-developed software, which automatically detects PDs and evaluates their amplitude and time.

In a first configuration, where the needle-plane device is directly connected to the CIL4M filter, we observed that the signal picked up by the candidate system is highly oscillatory. We have not clearly determined the physical reasons for this phenomenon, but we are considering two possibilities: the dimensions of the experimental installation are small, which prevents the pulse from propagating under conditions similar to those of the grid, and parasitic impedances (capacitive bridge, CIL4M filter, Faraday cage influence...) can alter the signal. Adding a resistor, in this case 120 k $\Omega$ , between the measurement point of the candidate sensor and the filter reduces oscillation. To further improve signal shaping, a 1 MHz low-pass filter is applied. The result is a signal shape that is characteristic of a PD pulse. Under these conditions, the candidate system performs automatic data processing and identification of PDs.

### C. Résultats

First, we wanted to check the linearity of the candidate system with PD amplitudes. In order to do this, instead of powering the voltage transformer, the CAL1A calibrator is connected to the electrodes of the needle-plane test cell. The calibrator then delivers successive series of pulses of 2 pC, 5 pC, 10 pC and then 20 pC. The signals are recorded and processed by the candidate system. The result is shown in fig. 2, in which each point on the graph is the average of 10 measurements, and the associated error bars are the standard deviation of these 10 measurement points. Fig. 2 demonstrates the very satisfying linearity of the candidate system, even at low PD amplitudes.

In a second step, a peak voltage of 3.6 kV is applied to the needle of the test cell, enabling us to construct the PRPD patterns shown in fig.3. As we can see, the result is very satisfying, since the diagrams obtained with both systems are very similar. Both the systems have been calibrated with a CAL1A calibrator [5] sending 100 pC pulses. In both cases, the total acquisition time is 0.5 s. The ICM system is configured to acquire data for 0.5 s and then save the data. In a different way, the Altrans system is configured to acquire data for 20 ms, save it and repeat this cycle 25 times, the complete process lasting 3 minutes.

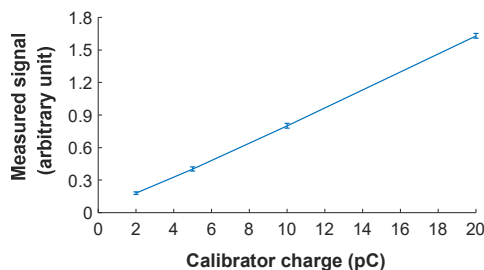


Fig. 2 Checking linearity of the measurements

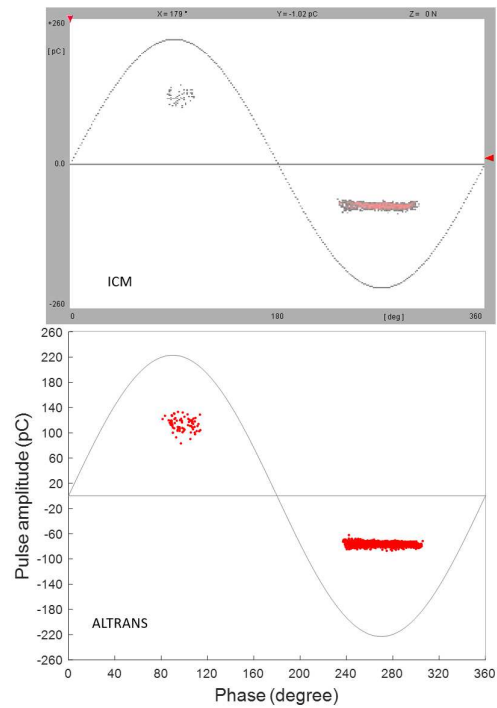


Fig. 3 PRPD patterns obtained with both systems: ICM (above) and Altrans (below). Needle-plane system. 3.6 kV<sub>peak</sub>.

## III. MONITORING OF EVOLVING DEFECTS

### A. Experimental

In this section, we began studying the evolution of PDs initiated in a defect over time, up to the dielectric breakdown. The experimental set-up used is the same as that described in fig.1, with the following differences. To reduce the volume of data processed, only the ICM system is used for the following measurements. The 120 k $\Omega$  resistor is therefore no longer needed and is removed. The needle-plane device is replaced by a plane-plane test cell. To create an artificial cavity, 2 films of polyester 20  $\mu$ m thick are placed on either side of a 300  $\mu$ m thick layer of silicone rubber. Prior to that, this silicone layer has been pierced on a square surface of about 1 mm<sup>2</sup>, creating the cavity in which the PDs will initiate. This stack of 3 dielectric layers is placed between the two flat electrodes of the cell, with the cavity in the center of the electrodes. The cell is filled with silicone oil to prevent surface or corona discharges. The edges of the 3-layer dielectric stack are previously bonded with a silicone paste to prevent oil from penetrating between the layers.

The ICM system acquires data for 10 s every 12 s, during which it aggregates them into a PRPD pattern. For each PRPD pattern, the ICM system calculates 4 values. N+ and N- are the numbers of positive and negative PDs respectively. The maximum amplitude of a PD is called Q<sub>max</sub>. The NQS value corresponds to the average PD current. In both tests, the voltage is increased step by step. The voltage is stepped up when PD activity seems to have disappeared permanently.

### B. Results

In test A (fig. 4), PDs appeared at about 2.3 kV<sub>p</sub>, which is then the PDIV (Partial Discharge Inception Voltage). This is the beginning of the record (time=00h00). The 4 indicators initially evolve continuously, but drop to zero after 6 minutes. Increasing the voltage to 3 kV<sub>p</sub> at 01h14 restarts the

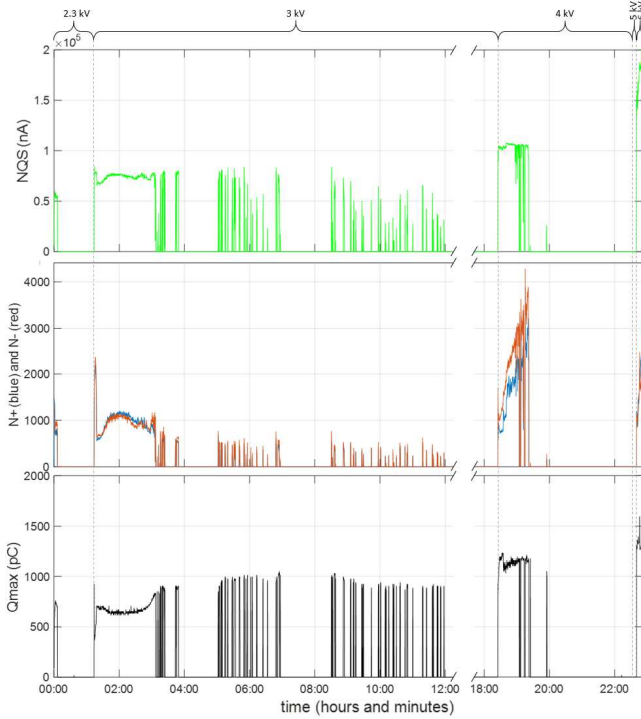


Fig. 4 Evolution of PD activity during test A

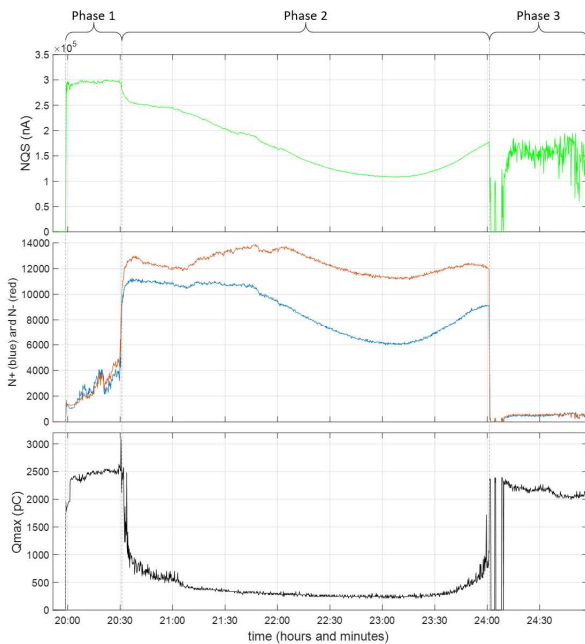


Fig. 5 Evolution of PD activity during last part of test B

continuous activity of partial discharges, but it eventually drops to zero and is followed by sporadic PDs that finally extinct. A rather similar trend occurs when the voltage is stepped up at 4 kV<sub>p</sub> (at 18h25). Then, stepping up the voltage to 5 kV (at 22h34) does not restart the PD activity. Stepping up the voltage at 6 kV<sub>p</sub> (at 22h40) restarts the activity, rapidly followed by electrical breakdown at 22h50. To improve readability, the long periods without PD activity between 12h00 and 18h00 have been removed from the graph.

Sample B initially behaves similarly to sample A, with continuous PD evolution at PDIV (at 1.7 kV<sub>p</sub>) and after voltage increase at 3 kV<sub>p</sub> (at 00h39), followed by sporadic PD

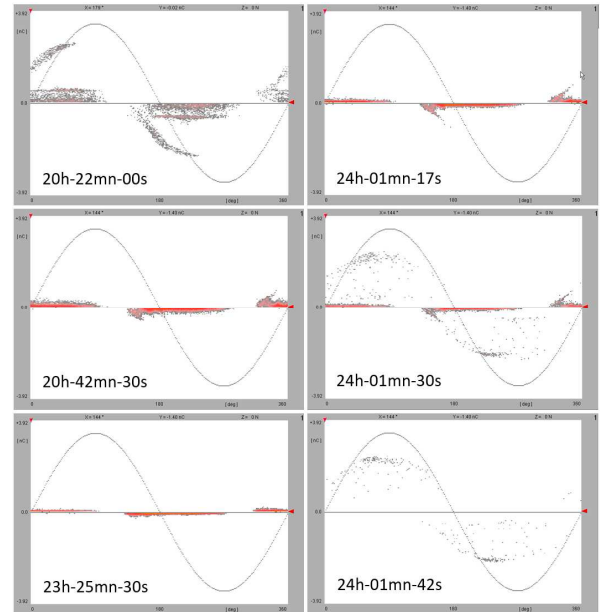


Fig. 6 Evolution of PRPD patterns during last part of test B (horizontal scale: 0-360°; vertical scale: +/- 3.92 nC)

activity. When the voltage is stepped up at 4 kV<sub>p</sub> (at 19h58), the PD activity then follows a significantly different trend than that of test A, which is shown in fig 5. In a first phase up to 20h31, Qmax and NQS rise sharply to around 2400 pC and 290  $\mu$ A, while N+ and N- rise gradually. Then, in a second phase, Qmax falls rapidly, N+ and N- clearly differentiate and evolve slowly. NQS slowly declines until 23h10. At the end of the second phase, all 4 indicators rise until 24h01, where a 3rd phase begins. At the start of this 3rd phase, PD activity sharply drops to zero, then immediately restarts. Qmax returns to roughly the same value as in phase 1, while NQS begins to evolve much more irregularly. N+ and N- become equal again, but their values drop sharply. Dielectric breakdown occurs at 24h57. PRPDs captured at different times are shown in fig. 6. In phase 1, the PRPD pattern displays a highly recognizable wing like pattern. While the evolution of the pattern is gradual from 20h31 to 24h01, the change of pattern between phases 2 and 3 is very abrupt. The 3 patterns shown on the right of fig. 6 follow each other by just 12 seconds. The patterns then remain similar until the breakdown, with PDs distributed in a sinusoidal envelope.

### C. Interpretation

It is difficult to interpret with certainty the signals from tests A and B presented above. Nevertheless, they illustrate a number of observations that have already been reported in literature. The phenomenon of PD extinction is well known, and is explained by the fact that PDs cause reactions and degradation on cavity and tree channels surfaces [6-8]. This alters the pressure and composition of the gas and increases the conductivity of the surfaces. If the pressure equilibrates or the chemical composition of gas and surface changes, new tree channels start growing again triggering new PDs. The divergence between N+ and N- is interpreted in some publications as a sign of the development of electrical treeing [9][10]. According to [7], the amplitude of discharges follows the same trend as their number. However, this is not necessary the case and the number of PDs can increase while their maximum and average amplitudes decrease. This may depend on the evolution of the electric tree type, branch or bush, and

on the conductivity of cavity's surface and channels [8][9][11]. In comparison with [8], the fading of the "wing-like" pattern and the decrease in PDs amplitude between phases 1 and 2 are likely related to an increase of conductivity of the defect surface. Phase 3 of test B, where activity is more irregular, could correspond to the final phase, when the electrical treeing has already reached both electrodes and the microchannel widens and becomes increasingly conductive until the final breakdown [11].

#### IV. DISCUSSION AND PROSPECTS

Tests A and B, although carried out on very similar samples and under very similar test conditions, show radically different trends. This illustrates the difficulty of determining the remaining lifetime of a defect by analyzing its partial discharge activity. Achieving this objective is valuable for grid operators, but there are a number of difficulties involved: irregularity of PDs in cavities, changing treeing types during propagations [11]-[13], diversity of defect types (cavity, protrusion...) [1], different aging phenomenon (electric field, temperature, water...) [1] or insulating materials, influence of temperature [14] or voltage application history [15] on PD activity, inherent randomness, etc... This leads experimenters to multiply tests in order to establish statistical results. In order to increase the number of tests, accelerated aging methods are often used. However, caution is called, as these methods, such as increasing voltage [13] or frequency [16], can lead to PD activity and defect development that are quite different from real cases.

Nonetheless, laboratory tests are invaluable in enabling us to understand various aspects of the link between PD activity and the development of electrical faults, and to identify specific phenomena and key parameters announcing breakdown. According to [8][9], PRPD patterns give valuable information about the state of the defect. Approaches based on aggregate PRPD parameters (such as NQS, kurtosis...) have been used for decades [13][17]. According to [18], the use of PSA (Pulse Sequence Analysis) is more relevant than PRPD to predict a breakdown. The evolution of the pulse shape of discharges with time has also been studied [10][19]. The candidate system presented is potentially adapted to all of these approaches.

The difficulty of solving the problem must therefore be seen in the context of the knowledge already accumulated on the subject and the various possible approaches. The deployment of the candidate system brings interesting perspectives. Indeed, it should enable to accumulate large quantities of data on real cases, for which the evolution of the defect can take place over several years. We believe that combining this approach with the more traditional one of experimentation on a test bench can significantly improve predictions of the lifetime of defects detected on the grid.

#### V. CONCLUSION

It has been demonstrated on a test bench that the candidate system is effective in detecting low-amplitude PDs down to at least 2 pC and in constructing PRPD patterns as traditional PD measurement devices.

Experiments carried out on test benches enable to evaluate the relevant approaches for improving breakdown prediction on grids. This approach would obviously benefit to be combined with extensive data acquisition on real defect cases,

which can develop over several years. The deployment of the candidate sensor on grids could enable such data acquisition.

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