Characterization of partial discharge measuring instruments by the generation of reference insulation defects in an experimental setup

Fernando Garnacho Vecino
Ángel Ramírez Linares
High Voltage Technological Center
LCOE-FFII. Madrid, Spain
fernandog@lcoe.etsii.upm.es,
angel.ramirez@ffii.es

Fernando Álvarez Gómez
Eduardo Arcones del Álamo
Carlos Alberto Vera Romero
Department of Electrical Engineering
Universidad Politécnica de Madrid. Madrid, Spain
fernando.alvarez@upm.es
eduardo.arcones@upm.es
carlos.vera@upm.es

***Abstract*—Partial discharge (PD) measurement has become an effective laboratory and on-site test for the detection, identification and location of defects in the dielectrics of high-voltage (HV) electrical systems and thus to assess their insulation condition. Several PD instruments have been developed to carry out, in situ, on-line temporary or monitoring measurements. However, no standard exists to define what type of evaluation should be required to check the effectiveness of the PD measuring and diagnosis instrumentation implemented. The instruments used for on-line PD measurements must incorporate specific functional features to cope with the following drawbacks, in order to perform a proper diagnosis: the existence of high levels of background electrical noise, the simultaneous presence of multiple PD sources, and the difficulty of identifying the insulation defects and of determining their location. To overcome these drawbacks, adequate selection of the measuring technique and the implementation of effective signal processing tools is essential. In the research presented in this paper, a new method for the evaluation and qualification of the functional features of PD measuring and diagnostic instruments is presented. For the application of the proposed method, a scale modular HV setup has been designed and manufactured. In this setup reference time series of PD pulses are generated in a repetitive and controlled way in individual test cells with real insulation defects.**

Keywords—partial discharges; insulation testing; performance evaluation; interference suppression; pattern recognition

I. INTRODUCTION

The main challenges faced by PD technical analysts when performing diagnoses about the insulation condition of dielectric elements in HV installations are as follows:

- The detection of PD signals with adequate sensitivity in the presence of different electrical noise conditions.
- The identification of the type of insulation defect associated with each of the detected PD sources in order to assess their severity.
- The separation of the PD generated in different defects simultaneously present in a HV installation for their accurate detection.
- And the location of the insulation defects that generate PD in the HV installation under supervision.

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Currently, PD measuring and diagnosis instruments, used in on-line measurements, integrate signal processing and analysis functionalities to reduce the negative effect of electrical background noise in PD detection, to identify the type of defect associated with each detected PD source, to separate the PD generated in different sources and to locate these sources [1-3]. These instruments are frequently used by many companies for the insulation condition assessment of HV grid assets. Therefore, the evaluation of their performance is interesting, in order to check whether they are more or less effective with respect to the indicated functionalities. The most effective instruments will enable the realization of the most accurate diagnoses.

In several studies conducted with the purpose of achieving precise diagnosis in on-line PD measurements, different tests samples with insulation defects and/or experimental setups were performed to test the effectiveness of a certain development and to obtain experimental results with practical case studies [4, 5]. However, in none of these studies, reference insulation defects implemented in a HV setup were performed with the aim to evaluate the effectiveness of the technical functionalities of PD measuring and diagnostic instruments. In this research, reference insulation defects, generated in individual test cells, and a scale modular HV setup were developed for the evaluation of the functional features of PD measuring instruments. This evaluation is carried out in a controlled and homogenous way applying a proposed evaluation method.

In Section II, the method for the evaluation and qualification of the functional features of PD measuring and diagnostic instruments is presented. In Section III, the scale modular HV setup developed to perform the evaluations and an example of a test cell configuration are described. Finally, a practical case study of a PD instrument evaluation is presented in Section IV.

II. EVALUATION METHOD

The proposed method for the evaluation of the functional characteristics of PD measurement and diagnosis instruments is structured in the following stages (see Fig. 1):

1. Generation of at least one time sequence of electric noise. The noise signals are acquired from a function generator of arbitrary signals or from a database of digital noise files, that are converted to analog sequences using a digital-analog (D-A) converter.
2. Adjustment of the electrical noise signal or signals level to a determined value (starting at a low level with respect to the PD pulses).
3. Generation of one or several reference time series of PD pulses originated in representative defects of HV grids. The reference series of pulses are produced in individual plug-in test cells each one containing a characteristic defect.
4. Overlapping, without galvanic connection, of one or more PD time series with at least one sequence of electrical noise.
5. Sequential evaluation of the functional features of a measuring instrument in the following order:
   5.1) Sensitivity analysis in the detection of an electrical defect in the presence of different electrical noise conditions.
   5.2) Capability to identify the types of defect associated with different PD sources in the presence of electrical noise.
   5.3) Capability to separate different PD sources present simultaneously in a HV installation in the presence of electrical noise.
   5.4) Capacity to determine the location of insulation defects in a HV installation under supervision.

   For each considered functional feature, increase the noise signal level in defined steps until the evaluation of a functional feature is unfavorable.
6. Analysis of the results, once all the technical features are evaluated.

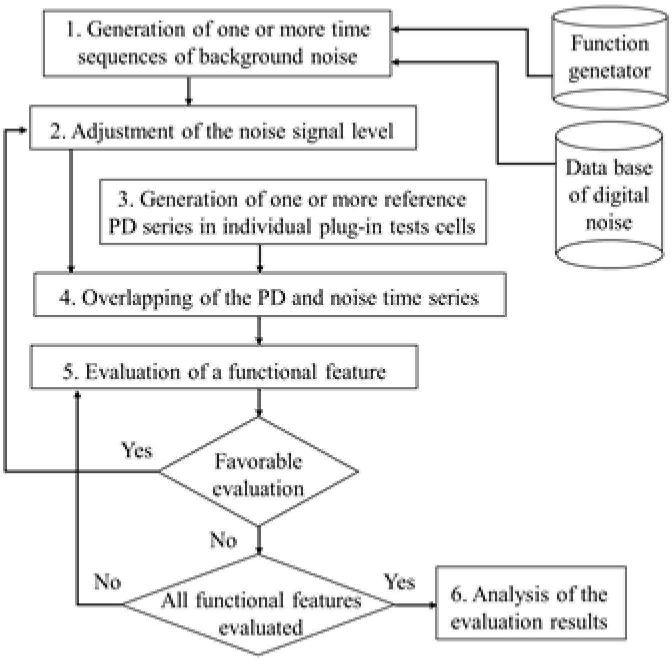


Fig.1. Flow chart of the proposed evaluation method.

For the evaluation of the functional features, the representative defects where the reference time series of PD pulses are originated can be: cavity in an internal solid dielectric, surface defect in air, floating potential electrode or various types of corona effects.

In addition, the electrical noise signals to be superimposed to the reference time series of PD can be: white noise, pink noise, power line communications (PLC) noise, modulated noise of varying frequencies or pulsating noise from power electronics.

III. Scale Modular HV Setup

The HV installation used for the evaluation of the functional characteristics of PD measuring and diagnosis instruments is based on a scale modular HV setup consisting of the following elements (see Fig. 2):

- A HV generation module (1) that enables the regulation of the AC voltage applied up to 10 kV.
- A HV cable (2) connected to the generation module.
- A cabinet module (3) connected to the previous cable that simulates the metallic enclosure of a HV asset (e.g. a switchgear cabinet). In the top of the cabinet module there is a generation submodule of PD reference time series (4) originated in different test cells (5) that are plugged in a HV disk-shaped flat electrode. At the bottom there is an isolation submodule (6).
- A cable module (7) that simulates an insulated HV power cable of 60 meters in length.
- An electrical grid module (8) with a capacitor (9) connected to the cable module in order to simulate the continuity of the electrical power network.
- A measurement module (10) installed in the earth connection of the cable termination connected to the cabinet module. In this module a high frequency current transformer (HFCT) sensor (11) is installed inside a coaxial metallic structure (12) specially designed to superimpose, by galvanic insulation, the background noise signals to the reference PD time series. The background noise time series are acquired from a function generator of arbitrary signals or from a database of digital noise files that are converted to analog sequences using a digital-analog (D-A) converter (13). The HFCT sensor (11) is connected to the PD measuring instrument under evaluation (14).
- A second HFCT sensor (15) installed in the earth connection of the cable termination connected to the electrical grid module. This sensor is also connected to the PD measuring instrument under evaluation (14).

An example of the test cells developed to generate the reference DP time series is presented in Fig. 3. In the configuration shown, an internal insulation defect is created in a solid dielectric sample with a semi-spherical hole on its base. A cavity is performed on the concave part of the sample hole to produce an internal cavity defect. The rod radius is 7.5 mm and the dielectric thickness between both electrodes is 7 mm.

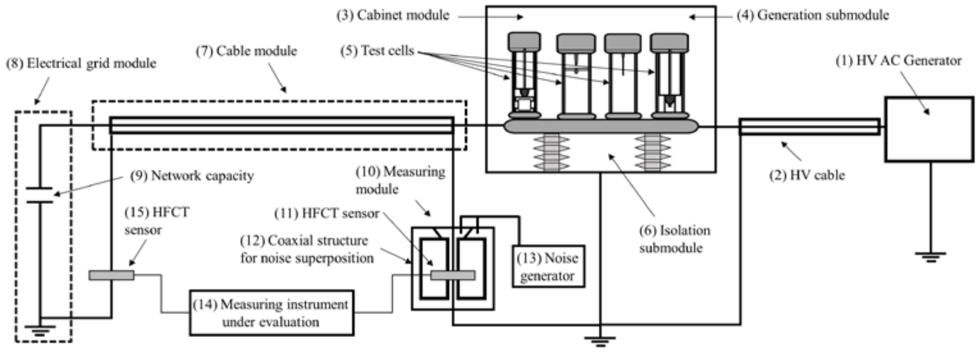


Fig. 2. Layout of the developed scale modular HV setup.

a) b)

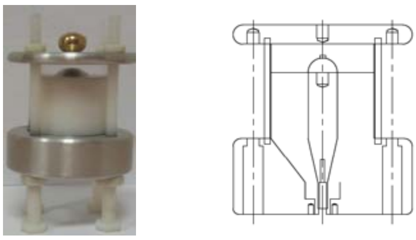


Fig. 3. a) Test cell with an internal insulation defect. b) Schematic view.

IV. Practical Example of a PD Instrument Evaluation

The functional features of a commercial PD measurement and diagnosis instrument were evaluated in a controlled way, according with the evaluation method presented in Section II and using the scale modular HV setup described in Section III. The technical characteristic of this instrument are 50 MHz of bandwidth and 100 MS/s of sampling frequency. The bandwidth of the HFCT sensor used in the measurements is from 100 kHz to 20 MHz. In the following subsections the results obtained for the five functionalities specified in point 5 of section II are presented.

A. *Sensitivity analysis in the detection of an electrical defect*

In this evaluation a sensitivity curve was determined measuring a time series of PD pulses in the presence of different levels of a synthetic pink electrical noise. The PD time series corresponded to an internal insulation defect generated in one plug-in test cell. Fig. 4 shows the superimposed noise signal in the time and frequency domain.

a) b)

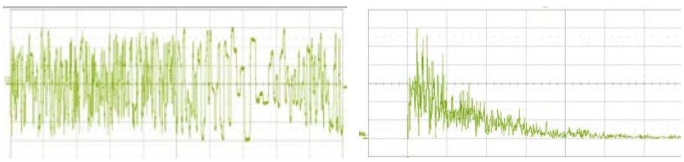


Fig. 4. Synthetic pink electrical noise superimposed to an internal PD time series. a) Signal in the time domain. b) Signal in the frequency domain.

The commercial PD measurement under evaluation applies a noise filtering tool based on the wavelet transform [3]. PD activity was measured with module (10) in the earth connection of the cable termination connected to the cabinet module, see Fig. 2.

The quantification of the superimposed noise signal was established by means of the relationship between its amplitude and the maximum amplitude of the PD pulses measured in the positive-half-cycle of the reference voltage signal. This amplitude in the absence of noise was 40 mV and it is expressed in 1 p.u. The noise signal was overlapped in four consecutive steps (0.5 p.u., 4 p.u., 5 p.u. and 6 p.u.), until the pulses of the PRPD pattern were not detected in the positive-half-cycle of the reference voltage signal. The results of the sensitivity evaluation and the PRPD patters obtained, after the application of the wavelet filter in each step, are shown in Fig. 5.

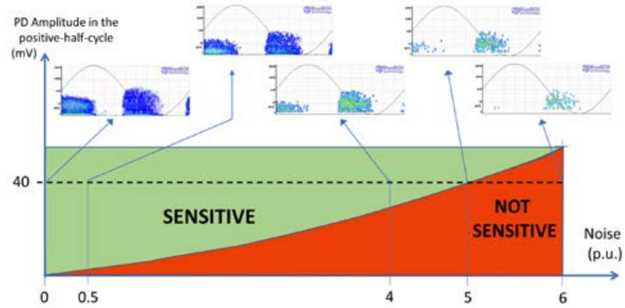


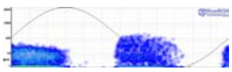
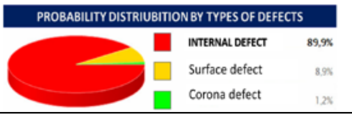
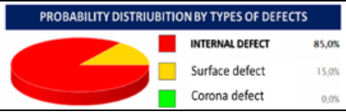
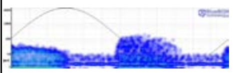
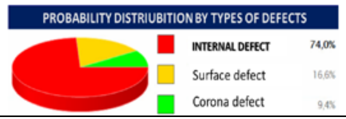
Fig. 5. Result of the sensitivity evaluation for the PD pulses measured in the positive-half-cycle.

It can be observed that the sensitivity in the detection decreases when the noise level increases. For a noise level of 5 p.u. it can be considered that the instrument is no longer sensitive in the detection of the pulses that were generated with a maximum amplitude of 40 mV in the negative-half-cycle.

B. *Capability to identify the types of defect associated with different PD sources*

In this evaluation, the PD time series correspondig to the internal insulation defect used in the previous evaluation were measured with module (10), overlapping the pulse-type noise interferences of a power electronic device. The second column of Table I shows the PRPD patterns obtained in the measurements of the PD time series when the noise signal was not present and when it was superimposed with a level of 4 mV and 10 mV. The commercial PD measuring instrument used includes an automatic defect identification tool based on an artificial neural network approach. The third column of Table I shows the result obtained in the identification of the internal defect. The accuracy in the identification depends on the noise signal level overlapped.

TABLE I. IDENTIFICATION OF THE TYPE OF DEFECT

Noise	PRPD pattern	Result of the identificatiom
--		
4 mV		
10 mV		

C. *Capability to separate different PD sources present simultaneously in a HV*

In this evaluation three PD time series were generated simultaneously in three test cells. The defects were the same internal cavity used in previous evaluations, a surface defect in air and a corona effect. Furthermore, the same pulse-type noise signal generated in the former test was superimposed. The PD instrument under evaluation includes a 3D clustering tool based on the calculation of three parameters, which characterize the wave shape of the individual registered pulses [3]. Fig. 6 shows the PRPD pattern obtained for the complete acquisition and the clusters formed by the 3D clustering tool. The individual PRPD patterns corresponding with each cluster are shown in Fig. 7. It can be observed that in this test, the separation of the PD pulses generated in different sources was successful.

a) b)

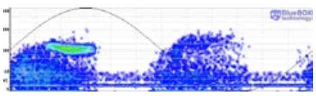


Fig. 6. a) PRPD pattern of the complete acquisition. b) Result of the 3D clustering tool.

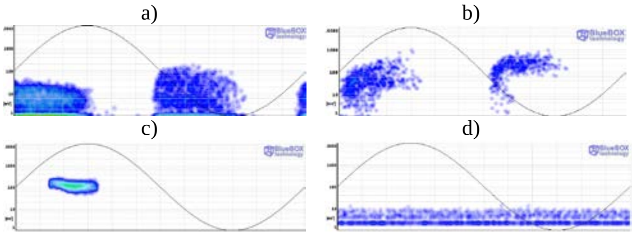


Fig. 7. Individual PRPD patterns obtained for each cluster. a) Internal defect, b) surface defect in air, c) corona effect and d) pulse-type noise.

It can be noted that after the separation of the PRPD pattern corresponding to the internal defect, the result of the automatic identification shown in the last two rows of Table I can improve significantly.

D. *Capacity to determine the location of insulation defects in a HV installation under supervision*

In this evaluation the internal defect was measured simultaneously with both HFCT sensors (11) and (15), see Fig. 2. The distance between them was 60 m. The measuring instrument used in the evaluation incorporates an analysis tool for the location of PD sources. This software tool is based on the calculation of the time delay between the arrival times of correlated PD pulses at different HFCT sensors [3]. In this case, the evaluation test was performed without overlapping any noise signal. The result of the location of the defect is shown in Fig. 8.

a) b)

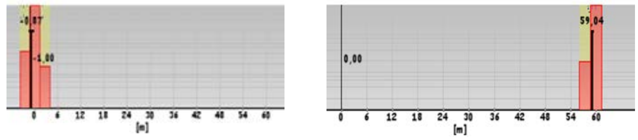


Fig. 8. PD mapping obtained with the location tool. a) Distance of the defect from the position of sensor (11), b) distance of the defect from the position of sensor (15).

V. CONCLUSIONS

For electrical utilities, maintenance companies and large electricity consumers, the characterization of the PD measurement and diagnostic instruments is interesting, because it enables them to check whether these devices are more or less effective with respect to their functional features. The most effective instruments used by these companies for the insulation condition assessment of HV assets will enable the realization of the most precise diagnoses.

The evaluation method proposed together with the scale modular setup developed allows the evaluation of the functional characteristics of PD measurement and diagnosis instruments used in on-line measurements. The generation of the reference PD pulses series and the superposition of electrical noise, enable it to reproduce in the scale model real conditions of in situ and on-line PD measurements.

With the practical example performed, it has been proven that the application of the proposed evaluation method and the use of the developed HV scale installation are appropriate to assess the functional characteristics of PD instruments used in on-line measurements.

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